Combining hydraulic modelling with partnership working: Towards a practical natural flood management approach

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Abstract

The UK Governments Future Flooding Inquiry called for more integrative methods to respond to flood risk management challenges. The 25 year plan for the environment ‘A Greener Future’ (2018), has reiterated the requirement for integrated catchment management. There is growing acceptance that Natural Flood Management (NFM) can complement traditional urban flood defence schemes. This paper examines the outcomes of a Knowledge Transfer Partnership (KTP) between Waterco Consultants and the University of Liverpool which explores some of the challenges of implementing what appear to be relative simple NFM measures. Through a multidisciplinary partnership, the KTP project explored multiple delivery challenges. Using case study evidence from North West England, the paper demonstrates the need for combining partnership working with more traditional hydraulic modelling approaches that can predict the potential flood risk reduction benefits of multiple NFM features, combined with the need to design structurally resilient interventions, so that appropriate permits can be approved. One of the key findings is that while NFM can contribute to flood risk alleviation, with multiple socio-environmental benefits, NFM can only be part of a more holistic approach. Primary evidence for hard and soft engineering measures, combined with use of automated attenuation management, could provide opportunities for more significant integrated flood risk benefits.

Keywords

Floods & flood works; hydraulics & hydrodynamics; natural resources; river engineering; sustainability; climate change.

1. Introduction

Fluvial flooding is an event caused when a channel's capacity becomes volumetrically exceeded, leading to overtopping of river banks and spill entering the floodplain (Smith, 2013). Recent events have highlighted how some 12,200km^2 of land in the UK is at flood risk, including 1 in 6 properties, in total affecting approximately 5 million people (Hall *et al.,* 2003; Environment Agency, 2009; House of Commons, 2016). Future flood risks are being compounded by a combination of climate and land use change (Putro *et al.,* 2016; DEFRA, 2018). Present policy failings mean that flood risk is likely to increase in real terms; both in terms of frequency and effect (Committee on Climate Change, 2012; House of Commons, 2016). A family of scenarios for: climate change impact; long-term increasing development on the floodplain (Committee on Climate Change, 2012); and increasingly impermeable catchments cumulatively result in more property exposure to flood risk by ever closer proximity to flashier watercourses (Donaldson *et al.,* 2013; Kendon *et al.,* 2014; Putro *et al.,* 2016).

One response, that has been gaining increased purchase, is an emphasis on what is known as a Natural Flood Management (NFM). An earth systems engineering approach which followed the Pitt review recommendation No. 27 - greater 'Working with Natural Processes' (WwNP) (Allenby, 2007; Pitt, 2008; Wilkinson *et al.,* 2010), which was reinforced by the Flood and Water Management Act 2010 (S.3, SS.3). The Department for Environment, Food and Rural Affairs (DEFRA) 'Making Space for Water' (2004) approach has been trialled in several places on an *ad hoc* basis, for example Pickering, Peak District Moors for the Future Partnership, and schemes in Belford, Stroud and Holnicote. The ability for many schemes to demonstrate conclusively that they reduce flood risk remains largely unproven; in observational catchment-scale study terms (House of Commons, 2016). This paper reports on some of the findings of a National Environmental Research Council (NERC) KTP funded project between the University of Liverpool and Waterco Consultants (a water engineering consultancy) which sought to identify whether NFM ideas could be embedded, from a commercial perspective, into their business portfolio. This paper reflects on these experiences and the challenges of effectively using NFM techniques as part of mainstream practice, with a case study, Blackbrook, St. Helens, North West England. The evidence presented here also recently featured as case study 17 in the Environment Agencies (2017) WWnP guidance. Specifically, the study has informed approaches to scheme appraisal (see Hankin *et al.,* 2017:4) and guidance on rivers and floodplain restoration (see Burgess-Gamble *et al.*, 2017:34).

2. Conventional methods of flood risk management

Traditionally, the UK policy response to flooding has been to identify clusters of residential properties most at risk and, if strict Treasury cost benefit requirements can be satisfied, seek to defend these dwellings through the construction of hard-engineered measures. Statistical hydrology methods and hydraulic modelling is used to predict peak discharge (flow) and water height (stage), based on the statistical probability of a flood event occurring in a given year. Conventionally, many in practice then defended against this peak water height via linear defences, or control heights through dam construction upstream, which retains design flood peaks. Two complementary approaches have traditionally been used, namely flood defences and Flood Alleviation Schemes (FAS). Flood defence measures are designed to exclude flood-water from the developed floodplain, to a designed Standard of Protection (SoP), and includes the construction of flood walls and embankments. Currently, there are over 25,400 miles of flood defence in England (Environment Agency, 2009). A FAS is designed to attenuate the peak discharges of a design unit flood hydrograph, and in so by doing, manage water heights in the urban environment downstream. A FAS introduces flow restriction to the watercourse at a stage-discharge threshold, typically an enclosed water conduit (pipe or culvert) sometimes with penstocks (~sluice), with a raised dam embankment over the culvert to temporarily store peak flows in the landscape. Peak flows may be captured passively, with a purposefully small diameter culvert to cause surcharge, the backing-up of excess water that cannot be conveyed through the culvert, leading to raised water levels at the inlet above the soffit, and hence temporary reservoir attenuation. Or actively, through flow monitoring and penstock control, managing discharges exiting the dam via the culverts, and in so by doing, manage volume held in the reservoir, and stage-discharges passing down-river.

More recently, the approach of raising defences has come under more intense critical scrutiny, as a convention of risk management (Pitt, 2008; Krause, 2016), and as a long-term practice for dealing with climate change (Environment Agency and Cumbria County Council, 2015). Newly issued guidance for dealing with the vertical distance between probabilistic water height and feature crest, for a dam or defence, termed freeboard, has introduced a risk based approach on vertical allowance to account for (un)certainty around factors including subsidence, settlement and wave height, has also led to questions about the how high it is reasonable or feasible to go with an in-town defence (Beven, 2009; Robinson *et al.,* 2017). On 5 – 6th December 2015 Storm Desmond resulted in 2,150 properties in the Minsfeet and Sandylands areas of Kendal being flooded (Environment Agency and Cumbria County Council, 2015). There were formal defence walls and embankments in Minsfeet, and a flood storage basin upstream of Sandylands, both of which had a recently raised SoP following a previous flooding event in 2007. These assets had a designed SoP, but overtopped, leading to flooding of multiple properties when a peak discharge of 403m^3 s^{-1} passed through Kendal (CEH, 2010; Environment Agency and Cumbria County Council, 2015). The magnitude of the event exceeded the normally accepted design standards, historically a 1.3% or 1% Annual Exceedance Probability (AEP) event peak stage-discharge. Following the event, questions were raised concerning the reasonableness of building existing defences higher, with many concerned about the impact on the urban landscape aesthetic and character. A timely modelling investigation by Hankin *et al* (2016:73) on the effects of NFM on Cumbrian river flows noted 'large scale NFM interventions have been shown to have a significant effect for a range of catchment conditions including and up to the streamflow's experienced for the extreme Storm Desmond event in December 2015'. Hankin *et al.'s* (2016) modelling outputs suggest that NFM can play a role in reducing risk, and may even improve the operational performance of traditional engineered measures – through helping to control peak stage-discharges.

The second form of conventional flood risk engineering, Flood Alleviation Schemes, are also being called into question. Theoretically, catchment-scale diffuse NFM may not exacerbate floodplain groundwater levels to the same extent as FAS reservoirs, particularly when schemes store a considerable floodwater volume above superficial porous glacial till or coarse alluvium. Hut *et al* (2008) and Mack *et al* (2014) have demonstrated dams have increased groundwater levels in unconstrained valley sections, compared to free-flowing rivers. Logically therefore, it is reasoned that during large magnitude, long duration and/or successive storms events, that a FAS may exacerbate floodplain groundwater flood risk. Particularly, where downstream properties stand above hydrogeologically connected river alluvium along valley corridors, with general isotropy (Hancock *et al,* 2005). Where in effect, the FAS reservoir recharges groundwater through valley-scale piston flow (Wainwright *et al,* 2011), and more readily through the interstices of alluvium, which have high bulk transmissivity values. Floodplain properties are invariably at risk of groundwater level rise, and flooding, but the premise here presented is that greater recharge of that groundwater may be trading one risk for another: fluvial to groundwater (Sayers *et al*, 2002; Krause, 2016).

What these brief accounts shows is that traditional engineered measures cannot provide a simple panacea to the risk of flooding. The conventional engineering orthodoxy may often perceive the challenge from a uni-functional perspective, with many of the multifunctional consequences of an NFM approach being ignored.

3. Natural flood management: An alternative multifunctional approach?

Not all communities within a catchment experience the same risk of flooding. Often flooding affects different specific locations across the catchment, sometimes at different times, in response to different events. Catchments, furthermore, often face a range of environmental challenges including failures to achieved defined naturalistic water quality standards, under the objectives of the European Union Water Framework Directive (2000/60/EC) (Newson and Large, 2006; Norbury, 2015:1). A more holistic approach to land management based on a re-conceptualisation of stewardship has been suggested as a more sustainable practice, a form of water farming and integrated catchment management (Norbury *et al* 2016; Green Alliance, 2017). The origins of the word steward implies those with responsibility for managing a piece of land, or resources, should do so not just for their sole benefit, but also so that future users of the resource can obtain equal or more benefit. Furthermore, the site should be managed in such a way that it does not damage immediate neighbours, nor those whom may be affected through a lack of stewardship. From this perspective, stewardship implies that land managers might be given more responsibility for managing natural assets collectively, thereby building greater resilience into the catchment-system.

NFM is, *sensu latto*, defined as the alteration, restoration of use of landscape features to spatially target and engineer measures to slow, store, disconnect and filter river and overland flows in sufficient volume to alleviate downstream flood risk whilst introducing rate change allowing river systems to more readily cycle nutrients (Wilkinson *et al.,* 2010; Nicholson *et al.,* 2012; Quinn *et al.,* 2013; Burgess-Gamble *et al,* 2017). The approach requires stewarding of the land to manage water. From this perspective, it needs to be emphasised, that NFM does anticipate human interference with natural processes, but is intended to mimic, or restore, more natural processes compared with what might be described as the hard or heavily engineered approaches (Burgess-Gamble *et al,* 2017). NFM draws upon multiple sets of expertise including natural scientists, hydrologists, engineers and social scientists, combined with knowledge from local communities. Proponents of this holistic and partnership-based approach advocate that:

> *These practices could be taken up more widely in the UK, and internationally, to manage floods, droughts and pollution*
>
> (Quinn *et al.,* 2016:1)

3.1 The Runoff Attenuation Feature (RAFs) approach

Recent evidence has suggested that cumulative changes in land-use management practices has increased runoff production and flows (Bracken *et al.,* 2013; Putro *et al.,* 2016). One method of alleviating these impacts is through the Runoff Attenuation Features (RAFs) approach (after Nicholson *et al.,* 2012; Marshall *et al.,* 2015). The hydrological premise is that, if a sufficient number of these features are deployed around a river catchment, targeting the multiple sources and pathways of quick-flow, then runoff can be attenuated at numerous spatial-scales, diffusing and retaining the tributary flood-pulses, before they coalesce to create peak flow synchronicities, and hence, floods in the urban receptor (Wilkinson *et al.,* 2010; Nicholson *et al.,* 2012; Quinn *et al.,* 2013 Fig. 1). The rationale of RAFs is embedded in the well-established 'time of concentration theory', and seeks to reduce 'the time required for a parcel of runoff to travel from the most hydraulically distant part of a watershed to the outlet' (Thompson, 2006:4; Fig. 1). The principle anticipates the need to slow the flow of runoff as soon as possible, before velocities and discharges become unabated, particularly in areas of intense drainage density, steepness or impermeable surfaces (Bracken and Croke 2007; Wilkinson *et al.,* 2010; Nicholson *et al.,* 2012; Bracken *et al.,* 2013). Flow synchronicity, in terms of flooding at a given location is a multifaceted phenomenon (Burt, 2005), and determination of its occurrence requires spatially comprehensive monitoring and tracing of hydrologically (dis)connected elements (Allenby, 2007; Beven, 2009; Bracken and Croke, 2007; Bracken *et al.,* 2013). Present NFM literature has not fully determined whether catchment RAFs 'lop' peak flow downstream, or simply creates mass desynchronization of coalescing tributary flood-flows, again having the effect of removing peak flow (Fig. 1). Augmented RAF effects on the unit flood hydrograph, whether associative or causative, is an element of equifinality and hydrograph theory which requires further research (Bracken and Croke, 2007; Wilkinson *et al.,* 2010;; Nicholson *et al.,* 2012; Bracken *et al.,* 2013; Quinn *et al.,* 2013; Burgess-Gamble *et al*, 2017).

RAFs can include many different features (see Nicholson *et al.,* 2012), often combined in a variety of ways across the catchment, which can collectively, increase the lag-time and reduce the peak of the storm hydrograph (Wilkinson *et al.,* 2010; Quinn *et al.,* 2013; Hankin *et al.,* 2013: Fig.1). Such measures may include:

- **Offline RAFs.** A field-scale measure that intercepts an overland flow pathway. Examples may include earth bunds with draining pipes on field units, wooden dam barriers and excavated ponds, coupled with bunded earth.

- **Online RAFs.** Measures that can add functional floodplain attenuation through outlet channels into side swales, reconnected relict channels, nested ponds and wetlands that attenuate channel flows and reduce velocities.

- **Engineered Log-Jams (ELJs).** Tree trunks, 2.5 times stream width keyed into the river banks to allow sufficient passage of base flow through the obstruction. Then, during high-flows, the logs trap and inundate water behind the jam. To avoid feature bypass, willow-woven trunks can be planted across the floodplain perpendicular to flow. Planting on both sides of the logs, encasing them, makes the structure a living bio-filter, resilient to movement.

- **Ditch barriers.** These are landscape interventions at field-scale margins or rills, intercepting overland flow, the structure facilitates the free passage of base flow, whilst during high-flows slows the additional flow, and hence, de-phases coalescing overland flow pathways.

However, there are many challenges in delivering sufficient numbers of these features to make a significant difference to peak flows at catchment-scale. These can include:

- Gaining access to different landowners who are willing and able to allow such features to be placed on their land across the whole of the catchment;
- Ensuring that the features are properly designed, and built into the landscape. The installations need to be sufficiently robust, in order not to cause additional damage downstream, if they fail. Currently, the Construction Industry Research and Information Association (CIRIA) are working with the Environment Agency on RAF design guidelines, which currently exist for SUDs (Sustainable Urban Drainage systems);
- Acquiring the appropriate permits, notably a Flood Risk Activity Permit (FRAPs) from the Environment Agency, so that, some of the challenges noted above can be permissioned under a legal framework of activity (The Environmental Permitting (England and Wales) (Amendment) (No. 2) Regulations 2016). Or, a Local Authority Ordinary Watercourse Consent, for mainly streams.
- Considering other stakeholder interests and other potential multifunctional benefits from such interventions in the landscape. This might lead to some unorthodox ways of finding funding to implement such features, and;
- Establishing a robust and wide-ranging partnership so that the variety of different delivery partners agree on the projects trajectory.

Despite a decade of advocacy from ‘Making Space for Water’ (2004), NFM approaches, as part of the normal toolkit for improving flood resilience remain limited. However, recently there are signs that such an approach is gaining increased purchase and momentum (Green Alliance, 2017; DEFRA, 2018). The experiences documented in this paper highlight some of the challenges for delivery. The Blackbrook case study suggests a practical approach, which combines hydraulic modelling as a mechanism of informing interventions to quickly store water to ameliorate flashy flows, combined with partnership working, can modestly reduce the risk of flooding, particularly, for more isolated ‘communities at risk’, where hard-engineered measures are often simply not viable, on financial grounds. The remainder of this paper explores how such an approach was be applied to a small catchment in part of St Helens, in the North West of England.

4. St. Helens study site

Blackbrook in St. Helens, Merseyside, has had a long history of flooding. In recent years, floods have occurred at least three times since 2000; on 28th – 29th October 2000, 24 – 26th September 2012 and 26th December 2015. Approximately fifteen residential properties, (mostly belonging to social registered landlords), three commercial properties along with a major trunk A-road (A58) and major gas infrastructure are all at risk (Fig. 2). The ward of Blackbrook is amongst one of the most deprived communities in England, sitting within the lowest quartile of the wards according to the index of multiple deprivation.

Blackbrook is located at the confluence of five principle tributary catchments namely: Cliplsey Brook, Stanley Brook, an unnamed tributary, the Goyt (Carr Mill East) and Blackbrook (Carr Mill West) (Fig. 3). Blackbrook is part of the wider Sankey Valley, which also has a long legacy of industrialisation with many abandoned mining shafts (predominantly coal), a slitting mill where the previous dam wall has been breached, a canal and a dam (Carr Mill) originally designed for storing water to provide power to the local industry. Agricultural, urban and industrial change through the Sankey Valley has led to the rivers systems being trained and manipulated to the water users various means. At present, many waterbodies are classified as heavily modified or artificial, under the European Union Water Framework Directive (Environment Agency, 2016). With many channels straightened, impounded, canalised and flows interrupted by weirs. Most of the land to the north of the A580 (East Lancs. Road) is currently used as arable agriculture (Fig. 3), although there is pressure for new housing in this area. Below Car Mill Dam much of the land is in public ownership, namely the local authority, St Helens Metropolitan Borough Council (MBC).

The easiest mechanism for alleviating flood risk would be to actively manage water heights in Carr Mill Dam (as in Fig 2), thereby temporarily increasing the storage capacity of the reservoir, and subsequently, with say a hydraulic weir plate, allowing for controlled release of water. However, for many reasons, including costs, the user rights associated with the reservoir (it is used for speed boating and fishing) and public liability issues if the dam is modified, such an alteration is not considered practical nor viable.

The catchment then provided the spatial unit and opportunity to deliver more innovative ways of alleviating flooding through NFM, based on flood modelling of the area and exploring how best to reduce the peak flow.

A multidisciplinary steering group was established to pursue the work, involving:

- St Helens MBC: Including the Environmental Planning Department and Highways, the sections responsible for flood and water management and the Ranger Service responsible for managing the local wildlife site;
- The University of Liverpool and Waterco, who appointed an associate, and whom together were the KTP;
- The Environment Agency who were responsible for strategic flood management and keen to see more natural approaches being introduced;
- Natural England who were responsible for ensuring the rich biodiversity of the area was being protected, including Stanley Bank Meadows, a Site of Special Scientific Interest (SSSI).

5. Peak-lopping: Developing an approach to define the required catchment attenuation volume

The approach adopted was a simple and pragmatic one; define the volume of water that results in flooding for various AEPs, by undertaking hydraulic model analysis. In sum, how much water is forced into the floodplain by the exceedance of the bridge and culvert structures in Blackbrook (as in Fig 2 and 3). The returned AEP spill volume of water, became the upstream catchment attenuation target (as in Table 1 and Fig. 4; Waterco 2016, 2016A). The rationale is the basis for extrapolating a target cumulative runoff attenuation feature volume, or ‘peak-lopping’ volume requirement; a AEP spill volume; and a calculation of how much peak flow could be intercepted, thereby reducing the risk of flooding further downstream (as in Fig. 1). In taking such an approach, the authors acknowledge the uncertainties in the modelling approaches, but in taking a pragmatic stance, the modelling was being used as part of a process to support some of the NFM interventions and contextualise their effect. The authors also acknowledge the limitations of the approach. Since to intercept and attenuate only the flood peak in Blackbrook above the flooding threshold water height, each upstream catchment RAF requires careful hydraulic ‘tuning’ to capture only flow peaks, and not attenuate before a set-point (See Fig. 1). This represents an uncertainty element and in outlining the conceptual framework the authors do not profess this approach to be the most robust, simply a Best Available Technique (BAT) when faced with a paucity local hydrometric data, as is so often the case. The reverse-engineering approach of attenuation could be criticised as being an over simplification of the catchment system, yet the approach enabled a reasoned understanding of how much water needed to be held in the landscape, enabling proactive catchment-systems engineering (Allenby, 2007).

No gauging stations exist in Blackbrook, or nearby. In the absence of observational data, three parallel methods of model analysis were used to define floodplain spill volume for a given return period. Firstly, depth grid zonal analysis (ESRI, 2017), secondly, 2D TUFLOW reporting locations (PO lines) – analogous to a floodplain weir (TUFLOW, 2016:18). And thirdly, hydrograph clipping, scaling and volume calculation. Historic flood outlines, photos and event narratives enabled approximate validation of model results.

The approach to define a peak-lopping volume was embedded within a conceptual 'source, pathway, receptor model', where sources of flooding were identified, as were the runoff pathways, all of which had impact on Blackbrook, the urban receptor. Catchment walkovers, incidents of property flood data, the Environment Agency's '*Risk of Surface Water Flooding*' (RoSWF) and overland flow routing models were all used to assess pathways. This approach combined modelling with observations on the ground.

The Flood Estimation Handbook (FEH CD3) was used to generate catchment descriptors for the Blackbrook catchment. The FEH parametric data can sometimes be imprecise, and therefore, data were down-scaled against more high-resolution information including landcover (OS Master Map 1:10,000), catchment size (from 1m LIDAR DTM) and watercourse length data. The higher resolution data from Geographic Information System (GIS) was then used to revise the FEH input parameters, making the analysis more sensitive to the local environment, despite still being a synthetic hydrology method. The catchment descriptor parameters were input into rainfall-runoff software, the Revitalised Flood Hydrograph (ReFH v1). This was set to produce hydrographs for the 50% (Q2), 20% (Q5), 10% (Q10), 5% (Q20), 2% (Q50), 1% (Q100), 1%+ Climate Chance Allowance (Q100+CCA) and 0.1% (Q1000) AEP fluvial events. The hydrographs were then scaled and the peak flows altered against WINFAP pooled local gauge sites; for catchments of similar description. Direct rainfall was applied to the active gridded area extent of Blackbrook (as in Fig. 2 and 5). FEH precipitation values were validated against the most local of the Environment Agency's rain gauge records. WINFAP hydrograph scaling was used as the BAT, in the absence of long-term, or nearby gauges sites, which could serve to validate hydraulic model outputs.

A fully integrated 1D/2D Flood Modeller Pro (FMP) – TUFLOW model was constructed for the study site. Return period inflows were input into the model for the respective sub-catchments, with direct rainfall applied to the 2D grid domain of TUFLOW, whilst the 1D domain was represented in FMP, formerly ISIS. Trash line studies and photographic evidence from previous flood events, along with existing 1D model flood outlines enabled validation.

Accurate determination of RAF volumes is vital to the efficacy of an NFM scheme. The GIS Global Mapper (bluemarblegeo) helped to calculate RAF volume in any given feature. A water level rise and fall simulation was performed, for specified metres above channel base (Thalweg) (Global Mapper, 2018), corresponding to a maximum crest elevation. The flood outlines were then used to calculate a topographical void cut, and fill volume, above given design elevations compared with the underlying 1m LiDaR Digital Terrain Model (DTM). The polyline drainage network was derived from the Global Mappers overland flow routing model, which uses an eight-direction pour point algorithm (D-8) to calculate the flow direction at each location, along with a custom algorithm for automatically filling depressions in the terrain data (Global Mapper, 2018). Inspection of global mapper overland flow routes, RoSWF outlines, and the underlying hill shaded topography, enabled RAFs to be sited in the landscape – both online and offline. The process outlined above enables potential retention volumes to be calculated, then, cumulatively added for all the sites where RAFs could be identified.

In order to define peak-lopping volume, the AEP 2D depth grid volume was calculated, then 2D reporting locations (PO lines) data were analysed, which analogously gauged model flow at set locations in the floodplain. Using these values as a minimum threshold, the hydrographs were cut and scaled, at the appropriate Blackbrook stage trigger level, namely, the point of bank overtopping. Figure 4 and Table 1 presents the AEP required attenuation volumes. Fig 5 annotates model scenarios, including a wetland (Dev 5) and Black Brook de-culverting (Dev 7). These measures, in addition to Stanley Brook four ELJs and sixteen other catchment RAFs (Fig. 6), could cumulatively remove flood risk for all properties during 17% event. The NFM measures, only shown in Figure 4, could lead to a general reduction of 400mm of flow in the 5% event and 900mm in the 1% event, but not remove the risk of flooding completely (as shown in Figure 5). A catchment attenuation volume of 249,177m^3 would be required to remove all flooding risk during a 1% AEP event, and NFM measures including a flood defence wall or bund can only go some way to meeting the required volume. In fact 10 per cent of the requirement (Table 1, Fig. 3). However, 16 discreet catchment RAFs (1m max barrier) and a mechanical weir plate with 2m range on Car Mill dam could provide 268,321m^3 of catchment attenuation and a removal of flood risk for a

0.84%. event. In lieu of the new DEFRA climate change allowances on peak flow, which includes an allowance of up to 70% addition, a combined defence, NFM hard engineered approaches is one means of getting closer to the required vast volume of attenuation to 'lop' or 'flatten' the flood hydrograph in large magnitude events. However, as noted earlier, any proposed alterations to Car Mills dam have so far proven unfeasible.

6. From theory to practice

Having been able to demonstrate how much water needs to be slowed and attenuated the next step was to identify whether and where certain RAFs could be located within the catchments. RAFs required considered design, flood risk reduction potential calculated, permitted by the appropriate Risk Management Authority (i.e. Environment Agency or Local Authority) and then the projects implemented. One of the quick and easy way of creating RAFS was the building of a series of ELJs, across what used to be the floor of the reservoir for the slitting mill (Fig. 6).

Figure 6 shows that ELJs were able to attenuate peak flows on Stanley Brook during a summer spate, which corresponded to the 5% AEP 1D depth grid produced during the preliminary modelling phase (Environment Agency, 2017).

Whilst the potential of these ELJS to attenuate peak flows could be demonstrated through the modelling approach outlined above, actual implementation proved to be much more challenging, and the need for effective partnership working and an ability to think laterally was required. A small grant was received from Natural England, who were willing to make resources available, not directly to deal with the threat of flooding, but to enhance the condition of a SSSI, Stanley Bank Meadows. Stanley Bank riparian woodlands have been designated as wet woodland. Since the World War One breaching of the Slitting Mill dam (St. Helens MBC, 2014), entrenchment of the stream through reservoir alluvium has occurred and, the woodland was not being wetted frequently enough. In-turn, this was depressing the species diversity of ground flora. Himalayan Balsam (*Impatiens glandulifera*) was also invading the site (Natural England, 2018). Hence, the financial resources were not provided for flood management reasons *per se*, but for the restoration of priority habitat wet woodland, and the associated SSSI. The land is owned, and managed, by St Helens MBC. Gaining both access to the site and their permission to install the features was relatively easily. The design of the features, particularly making them secure within the landscape meant a Local Authority Ordinary Watercourse Consent needed to be secured.

The next step was how to acquire the labour to construct the ELJs. Two sources were used. First, a group of trainees 'green' apprentices ('Green Energizers') through the Groundwork charity built the ELJs under the guidance of the KTP Associate and secondly, Environment

Agency staff, as part of their volunteering requirements, undertook further work. So, most of the labour used to create the features was voluntary meaning the implementation costs were minimised.

Whilst four ELJs are insufficient to protect the properties from flooding, they are able to attenuate some of the flow and reduce the concentration of dissolved nutrients such as Orthophosphate-P (PO_4^{3-}) by a significant amount – 94% (See Fig. 6; See Case Study 17 at Environment Agency, 2017). The volume of water that these features capture has been calculated at 2,000 m^3 representing 0.80% of the attenuation required to alleviate the 1% event (Fig. 1 and 4).

However, it is important to realise that the effectiveness of such features may reduce over time as increased sedimentation will reduce the storage capacity of the dams. This could be up to a third, over a 20-year period (McParland *et al.,* 2016). McParland *et al* (2016) study was based on a snap-shot of 108 samples, 30 of which were for suspended sediment concentration over a limited duration of two months, following which probabilistic and deterministic twenty-year storage reduction calculations were performed (McParland *et al.,* 2016). Given the rates of sedimentation, there is much uncertainty regarding long-term attenuation capacity, and hydro-morphological feedbacks and responses of RAFs (Hooke, 2015).

From start to finish, these relatively simply interventions took about two years to implement. There was a desire among the partners to take some action recognising that the ‘solution’ of modifying Cart Mill dam was, neither cost effective nor practical, although some advocated a single solution and were sceptical as to what NFRM options could deliver. The modelling, whilst imperfect was important to demonstrate the contributions that RAFs could make. Other partners had different agendas, whom were not focused on flood prevention at all, and this needed to be harnessed and understood in order to take the project forward. Ultimately the key for delivery was which partner organisation was going to take responsibility for implementation. Resource availability was key to implementation and even though resource requirements were small, creative and innovative partnership working was necessary in order to unlock access to money, people and the means of building the interventions. Once completed they have proved to be useful *in situ* features which can demonstrate the value and importance of such features in contributing, holistically, to better resource management which includes alleviating flood risk.

7. Conclusion

In this paper, it is argued that more natural approaches to flood risk management offers some potential to alleviating flood risk, through small increments, and equally importantly demonstrating to the community at risk that something is being done. Such approaches are *more* natural, but still require a range of engineered measures. Furthermore, hydraulic modelling of the catchment and a clear understanding of the capacity of the attenuation features to increase the resilience of those communities vulnerable to flooding must be undertaken to clearly demonstrate the benefits of such an approach. The key is to reduce the peak flow of a river, often for a relatively short period of time, before the water can be released slowly back into the system.

NFM should be an integral part of an engineer's toolkit to alleviate the risk. More than a decade has elapsed since 'Making Space for Water' (2004) was introduced, and the government seems committed to continuing to promote the concept (DEFRA, 2004; 2018). The Green Alliance (2017:26) have shown how NFM can be a cost effective contributory delivery mechanism – a market for slow, clean water, with some of their analysis having been informed by the evidence presented in this paper (Green Alliance, 2017:26). What this paper has demonstrated is that by a careful and considered use of hydraulic modelling and mapping of a catchment the volume of water to be attenuated to 'lop' the top off the hydrograph combined with and understanding of the volumetric capacity of various RAFs can help to build an argument that such features have an impact. Such approaches will not eliminate flooding, particularly with extreme and increasingly unpredictable climate change, but with small and isolated 'communities at risk,' it might offer some recognition of their needs and identify, with modest investment, scope for some action. The language of alleviating rather than defending risk will become important (Sayers *et al*, 2002), as will 'be prepared' over 'once in a lifetime' (Cologna *et al.,* 2017).

So what of the future? There are many projects taking place across the country across a range of catchments and scales where various NFM interventions are being implemented (Environment Agency 2017). Given the evidence presented herein, such schemes may be better embedded into more formal and traditional hydraulic modelling processes where both the scale and capacity of the interventions can be modelled, and therefore understood overall, at least in the scenario form. Hydraulic models will require new NFM units, so that the benefits of interventions can be comprehensively determined on a parity with conventional hydraulic units. Delivery in practice will be dependant of a range of stakeholders working in partnership to deliver action on the ground. Recognition of the importance of land managers and their willingness to provide opportunity and access to where such features can be introduced will be critical. This in turn might require ongoing compensatory payments, when the stewardship of the land provides clear and agreed multifunctional societal benefits. Instead of treating flooding as a single problem orthodoxy, practitioners of engineering may need to start thinking more holistically about how waters are managed, that increased flooding can be a signal of landscape change (as a landscapes ability to capture store and slowly release water is denuded), recognising the multi-functional benefits that good water management can bring and be prepared for innovative and creative approaches to managing flood risk.

To this end, historic legacy assets can play a role, Car Mill Dam has a volumetric retention capacity currently unmatched by the catchment NFM capacity. The hydraulic modelling suggested that because no water level management occurs, the reservoir may be recharging the flood peak and prolonging the flood, and hence, the use of active management systems may be able to capture the flashy peaks of summer storms, which have historically flooded Blackbrook. Smart Flood Management (SFM) can be conceptualised as a system that uses sensors (gauges, weather stations) to capture data (rainfall, flows) in real time to process information (remaining capacity, storm duration) which combined with active management can control SFM infrastructure (valves, gates, embankments and warning systems) to reduce local flood frequency (Meijer, 2012; Pyayt *et al.,* 2013). SFM could be the more intelligent system of capturing flashy flow peaks, whilst RAFs augmented to SFM systems can passively and actively manage flood-flows as they travel through the catchment, analogous to smart systems that already manage the flow of traffic or sewer flows. The critical advantage of adding SFM, particularly on smaller catchments, where the hydrograph may be very responsive to precipitation, is its ability to choose when to store and when release water, to optimise the reduction in the main flood peak. And hence, multifunctional, multipurpose approaches to flood risk management need to be harnessed through effective partnership working if some of the risks are to be better managed and alleviated.

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8. Bibliography

Allenby, B. (2007) Earth systems engineering and management: A manifesto. *Environment Science and Technology*. 7960 – 7965.

Beven, K. (2009) Environmental modelling: An uncertain future? An introduction to techniques for uncertainty estimation in environmental prediction. London: Routledge

Bracken, LJ, Croke, J (2007) The concept of hydrological connectivity and its contribution to understanding runoff-dominated geomorphic systems. *Hydrological Processes*, **21**: 1749 – 1763.

Bracken, LJ, Wainwright, J, Ali, GA, Tetzlaff, D, Smith, MW, Reaney, SM, Roy, AG. (2013) Concepts of hydrological connectivity: Research approaches, pathways and future agendas. *Earth-Science Reviews*.**119**: 17 – 34.

Brassington, R. (2007) Field Hydrogeology. Chichester: John Wiley

Brown, AG, Tooth, S, Chiverrall, RC, Rose, J, Thomas, DSG, Wainwright, J, Bullard, JE, Thorndycraft, VR, Aalto, R, Downs, P (2013) ESEX Commentary - The Anthropocene: is there a geomorphological case? *Earth Surface Processes and Landforms*, **38**: pp. 431 – 434.

Burgess-Gamble, L., Ngai, R., Wilkinson, M., Nisbet, T., Pontee, N., Harvey, R., Kipling, K., Addy, S., Rose, S., Maslen, S., Jay, H., Nicholson, A., Page, T., Joncyzk, J., Quinn, P. (2017) Working with Natural Processes – Evidence Directory (SC150005). Bristol: Environment Agency. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/654431/Working_with_natural_processes_evidence_directory.pdf (Accessed: 2nd February 2018).

Burt, T.P. (2005) General/Particular. In: N. Castree, A.P. Rogers, and D. Sherman Questioning Geography. Oxford: Blackwell, 117-130

CEH (Centre for Ecology and Hydrology).(2010) National River Flow Archive: 73012 - Kent at Victoria Bridge. Available at: http://nrfa.ceh.ac.uk/data/station/peakflow/73012 (Accessed: 12th February 2017).

Cologna, V, Bark, R.H, Paavola, J. (2017) Flood risk perceptions and the UK media: Moving beyond “once in a lifetime” to “Be Prepared” reporting. *Climate Risk Management* **17:** 1 – 10.

Committee on Climate Change. (2012) Adaptation sub-committee report: Chapter 2: Flooding indicators. Available at: https://www.theccc.org.uk/flooding-indicators/ (Accessed: 12th February 2017).

Environment Agency (2009) Flooding in England: A national assessment of flood risk. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/292928/geho0609bqds-e-e.pdf (Accessed: 12th February 2017).

Environment Agency and Cumbria Country Council. (2015) Kendal flood investigation report: Sandylands and Mintsfeet on 6th December 2015. Available at: http://www.cumbria.gov.uk/eLibrary/Content/Internet/536/6181/42557103755.pdf (Accessed: 12th February 2017).

Environment Agency. (2016) North West river basin district river basin management plan. . Available at: https://www.gov.uk/government/collections/river-basin-management-plans-2015#north-west-river-basin-district-rbmp:-2015 (Accessed: 2nd February 2018)

Environment Agency. (2017) Research and analysis: Working with natural processes to reduce flood risk. Available at: https://www.gov.uk/government/publications/working-with-natural-processes-to-reduce-flood-risk (Accessed: 2nd February 2018)

ESRI. (2017) Zonal Statistics. Available at: http://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/zonal-statistics.htm#S_GUID-3919C7B4-6663-484D-A377-9E2E8B3EC5FE (Accessed: 2nd February 2018)

DEFRA. (2004) Making space for water: Developing a new Government strategy for flood and coastal erosion risk management in England. Available at: https://www.look-up.org.uk/2013/wp-content/uploads/2014/02/Making-space-for-water.pdf (Accessed: 2nd February 2018)

DEFRA. (2015) 2010 to 2015 government policy: flooding and costal change. Department for Environment Food and Rural Affairs. Available at: https://www.gov.uk/government/publications/2010-to-2015-government-policy-flooding-and-coastal-change/2010-to-2015-government-policy-flooding-and-coastal-change (Accessed: 12th February 2017).

DEFRA. (2018) *A green future: Our 25 year plan to improve the environment*. Available at https://www.gov.uk/government/publications/25-year-environment-plan (Accessed: 2nd February 2018)

Donaldson, A, Lane, S, Ward, N, Whatmore, S. (2013) Overflowing with issues: following the political trajectories of flooding. *Environment and Planning C: Government and Policy* **31**: 603 – 618.

Dudgeon, D, Arthington, AH, Gessner, MO, Kawabata, Z, Knowler, DJ., et al. (2006) Freshwater biodiversity: importance, threats, status and conservation challenges. *Biology review* ***81***: 163 – 182.

Green Alliance.(2017) Natural infrastructure schemes in practice: How to create new markets for ecosystem services from land. Available at: http://www.green-alliance.org.uk/resources/Natural_infrastructure_schemes_in_practice.pdf (Accessed: 2nd February 2018)

Global Mapper (2018) Guidance: Calculating Cut-and-Fill Volumes for Area and Line Features. Available at: http://www.bluemarblegeo.com/knowledgebase/global-mapper-18-2/Cut_and_Fill.htm (Accessed: 2nd February 2018)

Hall, JW, Dawson, RJ, Sayers, DB, Rosu, C, Chatterton, JB, Deaton, R. (2003) A methodology for national-scale flood risk assessment *Water and Maritime Engineering* **156**(WM3): 235-247.

Hankin, B., Craigen, I., Chappell, N.A., Page, T., Metcalfe, P., Rose, S. (2016) Strategic Investigation of Natural Flood Management in Cumbria. Skipton: Jeremy Benn Associates. Available at: http://naturalcourse.co.uk/uploads/2017/04/2016s4667-Rivers-Trust-Life-IP-NFM-Opportunities-Technical-Report-v8.0.pdf (Accessed: 2nd February 2018).

Hankin, B., Arnott, S., Whiteman, M., Burgess-Gamble, L., Rose, S. (2017) Research and analysis: Working with Natural Processes – Using the evidence base to make the case for Natural Flood Management (SC150005). Bristol: Environment Agency. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/654435/Working_with_natural_processes_using_the_evidence_base.pdf (Accessed: 2nd February 2018).

Hancock, PJ, Boulton, AJ, Humphreys, WF. (2005) Aquifers and hyporheic zones: Towards an ecological understanding of groundwater. *Hydrogeology Journal* **13**: 98 – 111.

Harnish, RA, Sharma, R, McMichael, GA, Langshaw, RB, Pearsons, TN, (2014) Effect of hydroelectric dam operations on the freshwater productivity of a Columbia River fall Chinook salmon population. *Canadian Journal of Fisheries and Aquatic Sciences* **71(4)**: 602-615.

Harris, K, (2016) Investigating the effects of Engineering Log Jams on Flood Risk and Aqueous Nutrient Concentration. Unpublished BSc Thesis: University of Newcastle upon Tyne.

Hooke, JM. (2015). Variations in flood magnitude–effect relations and the implications for flood risk assessment and river management. *Geomorphology*. **251 (15)**: 91 – 107.

House of Commons (2016) Environment, Food and Rural Affairs Committee: Future Flood Prevention: Second Report of Session 2016-17. **HC 115**. Available at: https://www.parliament.uk/business/committees/committees-a-z/commons-select/environment-food-and-rural-affairs-committee/inquiries/parliament-2015/inquiry/ (Accessed: 12th February 2017).

Hut, R, Ertsen, M, Joeman, N, Vergeer, N, Winsemius, H, Van de Giesen, N. (2008) Effects of sand storage dams on groundwater levels with examples from Kenya. *Physics and Chemistry of the Earth*. ***33:*** 56 – 66

Kendon EJ, Roberts NM, Fowler HJ, Roberts MJ, Chan SC, Senior CA. (2014) Heavier summer downpours with climate change revealed by weather forecast resolution model. *Nature Climate Change*. **4:** 570 – 576.

Krause F (2016) "One Man's Flood Defense Is Another Man's Flood": Relating Through Water Flows in Gloucestershire, England. *Society and Natural Resources*. **29:6**: 681-695

Ligon, FK, Dietrich, WE, Trush, WJ. (1995) Downstream ecological effects of dams: A geomorphic perspective. *Ecology of Large Rivers*. **45(3)**: 183 – 192.

Mack, TJ., Chornack, MP, Vining, KC, Amer, SA, FahimZaheer, M, Meldin, JH. (2014) Water Resources Activities of the U.S. Geological Survey in Afghanistan From 2004 Through 2014. United States Geological Survey. Fact Sheet 2014–3068; USGS Afghanistan Project Product No. 265. Available at: https://pubs.usgs.gov/fs/2014/3068/pdf/fs2014-3068.pdf (Accessed: 12th February 2017).

Marshall, MR, Ballard, CE, Frogbrook, ZL, Solloway, I, McIntyre, N, Reynolds, B, Wheater, HS. (2014) The impact of rural land management changes on soil hydraulic properties and runoff processes: results from experimental plots. *Hydrological Processes*, **28**: 2617-2629

McParland, MC, Hooke, J, Cooper, J, Li, M, Norbury, M, Rogers, R, Brown, D. (2016) Modelling and Monte Carlo Simulation of the Trapping Efficiency of Multiple On-line Flood Storage Areas in a Peri-Urban Catchment. MRes Thesis: University of Liverpool.

Meijer, RJ. (2012) Urban Flood 'the story': The impact of UrbanFlood on combating climate change induced disasters – D7.9. EU Seventh Framework Programme Theme ICT-2009.6.4a – ICT for Environmental Services and Climate Change Adaptation. Available at: http://www.urbanflood.eu/Documents/UrbanFlood%20D7%209%20The%20Story%20v1.1.pdf (Accessed: 12th February 2017).

Natural England. (2018) Stanley Bank Meadows SSSI. Available at: https://designatedsites.naturalengland.org.uk/SiteDetail.aspx?SiteCode=S1002821&SiteNa

me=&countyCode=28&responsiblePerson=&SeaArea=&IFCAArea= (Accessed: 12th February 2017).

Newson, MD, Large, ARG. (2006) ‘Natural’ rivers, ‘hydromorpholigical quality’ and river restoration: a challenging new agenda for applied fluvial geomorphology. *Earth surface processes and landforms* **31 (13)**: 1606 – 1624.

Nicholson AR, Wilkinson ME, O’Donnell GM, Quin PF. (2012) Runoff attenuation features: a sustainable flood mitigation strategy in Belford catchment, UK. *Area* **44(4):** 1 – 7.

Norbury, MT. (2015) The hydrochemistry of the hyporheic zone: Assessing ecotone properties for juvenile freshwater pearl mussel (Margaritifera margaritifera L.) survival in the River Esk, NE England. Masters thesis, Durham University. Available at: http://etheses.dur.ac.uk/11276/ (Accessed: 12th February 2017).

Norbury, MT, Shaw, D, Barrett, S, Harris, K. (2016) Holding Water. *RICS Land Journal.* 24-26*.* Available at: http://www.rics.org/Global/Land_Journal_December_2016_January_2017.pdf (Accessed: 12th February 2017).

Pescott, O, Wentworth, J., (2011) Natural flood management: Parliamentary office of science and technology note. POST Note: 396. Available at: http://researchbriefings.parliament.uk/ResearchBriefing/Summary/POST-PN-396 (Accessed: 12th February 2017).

Pitt, M. (2008) Learning lessons from the 2007 floods – June 2008. Available at: http://webarchive.nationalarchives.gov.uk/20100702215619/http://archive.cabinetoffice.gov.uk/pittreview/thepittreview/final_report.html (Accessed: 12th February 2017).

Putro, B, Kjeldsen, TR., Hutchins, MG, Miller, J. D., (2016) An empirical investigation of climate and land-use effects on water quantity and quality in two urbanising catchments in the southern United Kingdom. Science of the Total Environment, 548-549, 164-172.

Pyayt, AL, Mokhov, II, Kozionov, AP, Kusherbeava, VT, Lang, B, Krzhizhanovskaya, VV, Meijer, RJ. (2013) Data-driven modelling for flood defence structure analysis. In F. Klijn, & T. Schweckendiek (Eds.) *Comprehensive flood risk management: research for policy and practice*. 301-306. Boca Raton, FL: CRC Press.

Quinn, P., O'Donnell, G., Nicholson, A., Wilkinson, M., Owen, G., Jonczyk, J., Barber, N., Hardwick, M., & Davies, G. (2013). Potential use of Runoff Attenuation Features in small rural catchments for flood mitigation: Evidence from Belford, Powburn and Hepscott. Joint Newcastle University, Royal Haskoning and Environment Agency Report. Available at:

https://research.ncl.ac.uk/proactive/belford/newcastlenfmrafreport/(Accessed: 12th February 2017).

Quinn, PF, Wilkinson, ME, Strutter, M. (2016) Policy note: Working with nature to ease floods and droughts. Newcastle University: Institute for Sustainability. Available at: http://research.ncl.ac.uk/proactive/holdingwater/Holding%20Water%20Briefing%20Note.pdf (Accessed: 12th February 2017).

Ricciardi, A., Rasmussen, J., (1999) Extinction rates of North American Freshwater Fauna. *Conservation Biology*, **13 (5)**, 1220 – 1222

Robinson, A, Ogunyoye, F, Sayers, P, Van Den Brink, T, Tarrant, O (2017) Accounting for residual uncertainty: updating the freeboard guide. Report – SC120014. Bristol: Environment Agency. Available at: https://www.gov.uk/government/publications/accounting-for-residual-uncertainty-an-update-to-the-fluvial-freeboard-guide (Accessed: 12th February 2018).

Sayers, P, Hall, JW, Meadowcroft, IC. (2002) Towards risk-based flood hazard management in the UK. *Civil Engineering*, **150 (5)**, 36-42.

Smith, K (2013) Environmental hazards: Assessing the risk and reducing the disaster. Oxford: Routledge

St Helens MBC. (2014) Stanley Mill: Background to the Project and Future. Available at: http://www.stanleymill.org.uk/about.htm (Accessed: 12th February 2017).

Thompson, DB. (2006) The Rational Method. Engineering Hydrology. (*in press)* Available at: http://drdbthompson.net/writings/rational.pdf (Accessed: 12th February 2017).

TUFLOW. (2016) TUFLOW User Manual: Reporting Locations (Build 2016-03-AA). Available at: https://www.tuflow.com/Download/TUFLOW/Releases/2016-03/TUFLOW%20Release%20Notes.2016-03.pdf. (Accessed: 12th February 2017).

Wainwright, J., Turnbull, L., Ibrahim, T.G., Lexartza-Artza, I., Thornton, S.F., Brazier, R.E. (2011) Linking environmental regimes, space and time: Interpretations of structural and functional connectivity. *Geomorphology*, **126**:387 – 404.

Waterco (2016) Sankey Valley Park, St. Helens. Flood Management Study (w3193-151210-Sankey FMR v6). Ruthin: Waterco.

Waterco (2016A) Sankey Valley Park, St. Helens. Flood Management Study – Technical Report (w3193-151210-HMR_v1.docx). Ruthin: Waterco.

Wilkinson, ME., Quinn, PF. Welton, P. (2010) Runoff management during the September 2008 floods in the Belford catchment, Northumberland. *Journal of Flood Risk Management*, **3(4)**: 285 –295.

9. Figures

Figure 1) Conceptual removal of peak-flows using the Runoff Attenuation Features Approach

Source: Quinn et al. (2013)

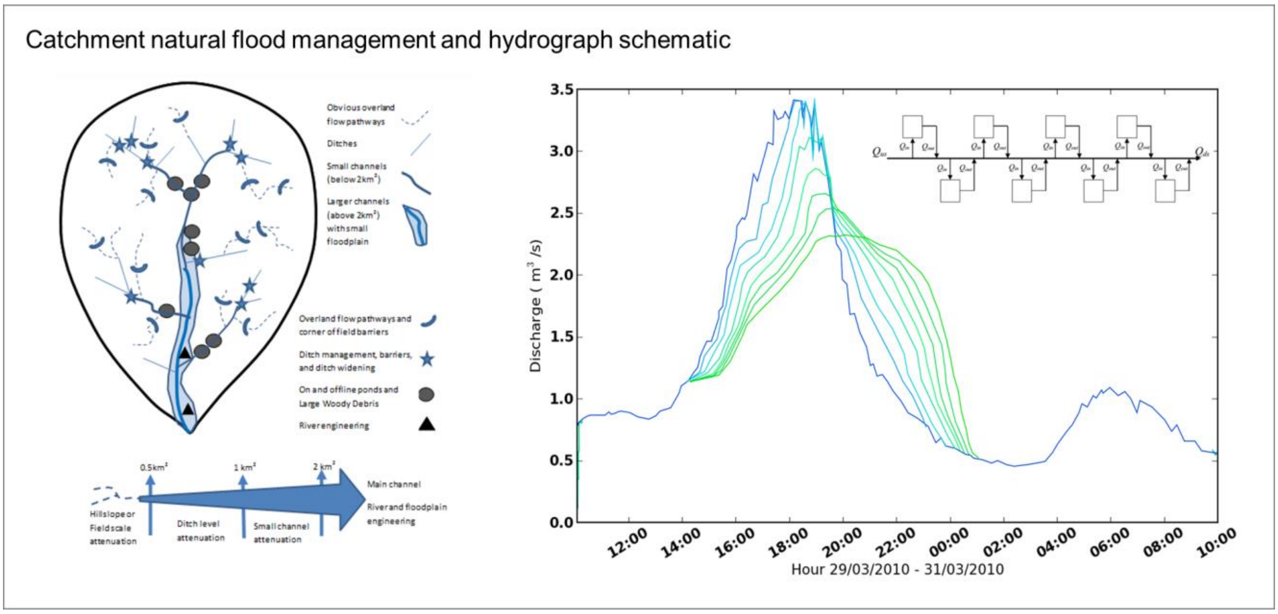

Figure 2) 1 in 100 Year (1% AEP) Flood Risk in Blackbrook, St. Helens

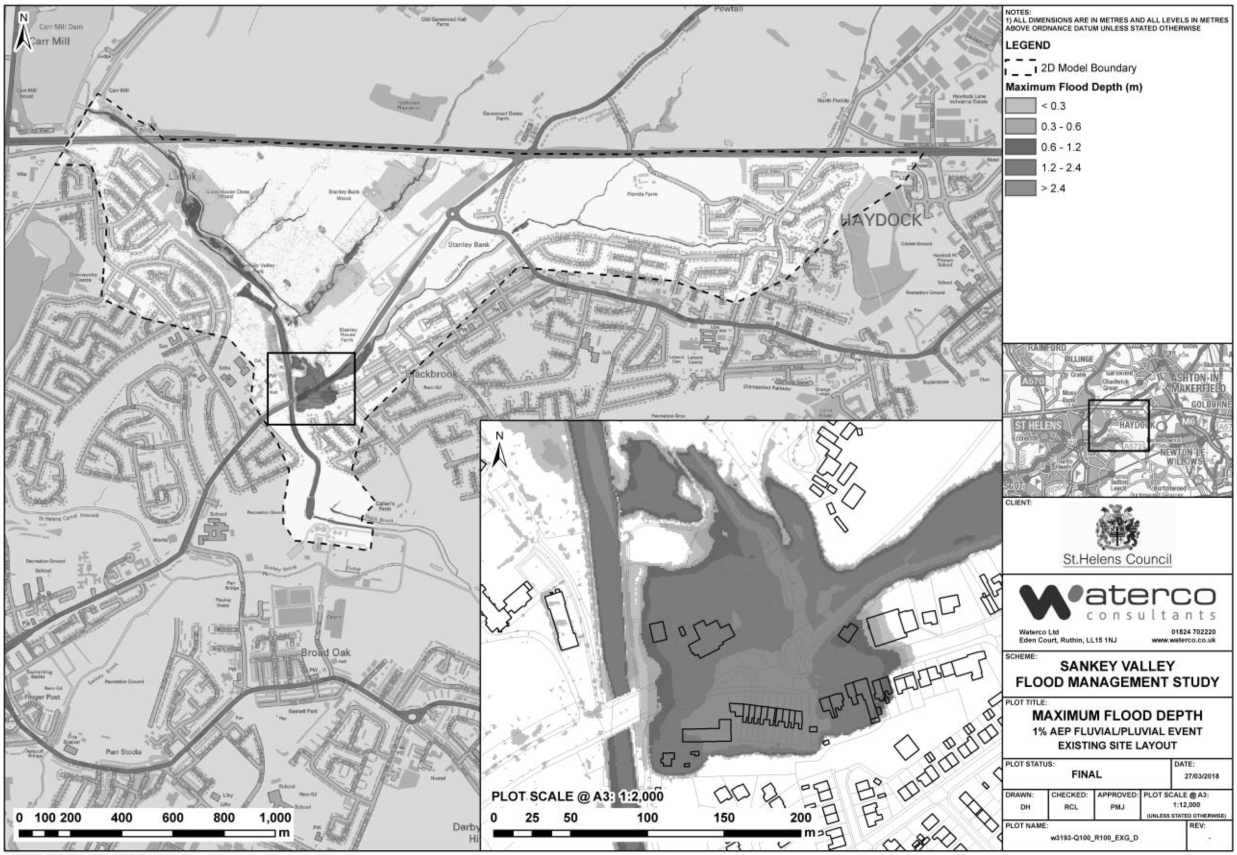

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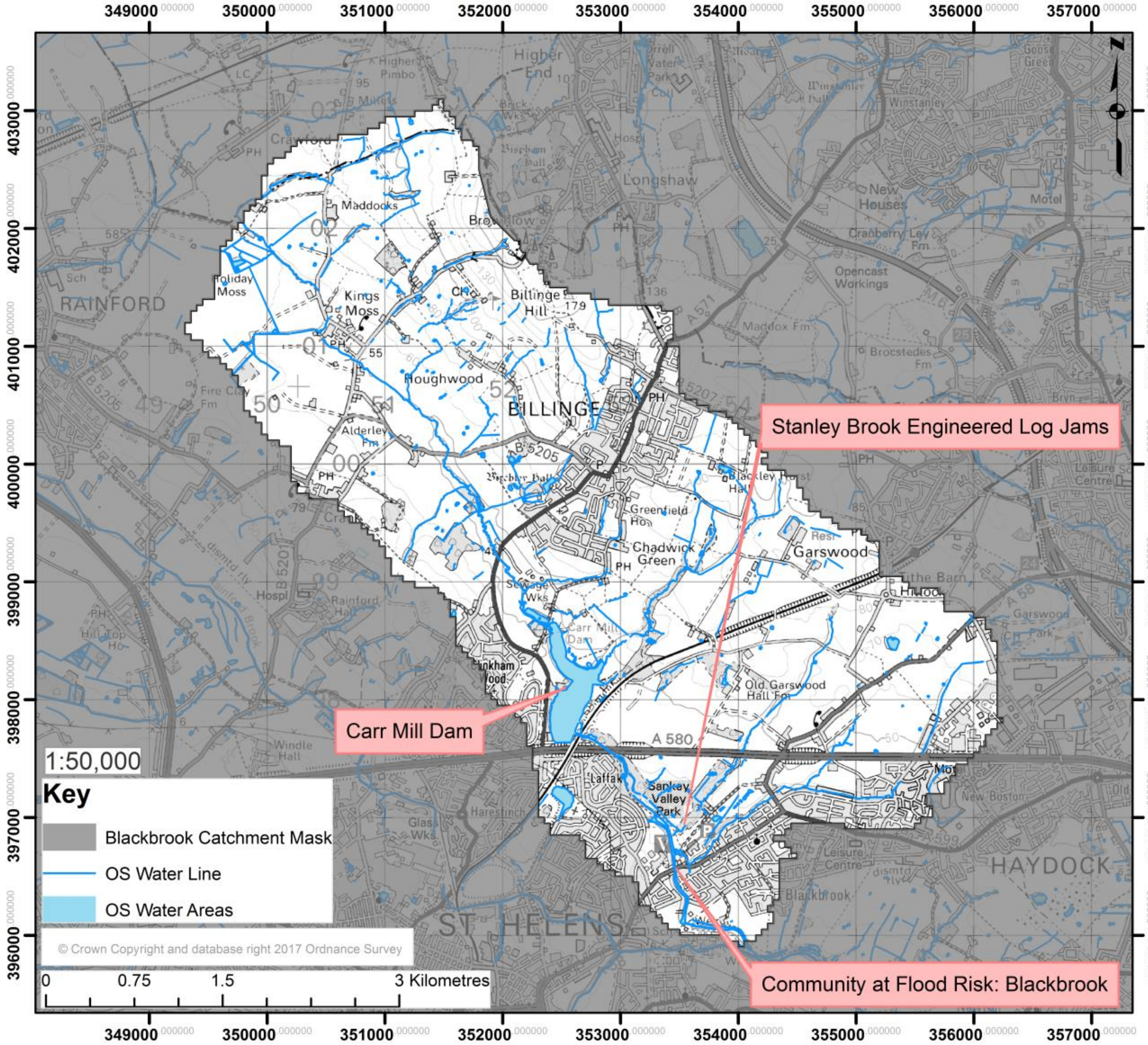
Figure 3) Blackbrook Catchment (21km2)



Stanley Brook Engineered Log Jams

Carr Mill Dam

Community at Flood Risk: Blackbrook

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Figure 4) Target Catchment Attenuation Volume Against Return Period: Attenuation Delivered by Runoff Attenuation Features and Combined Measures

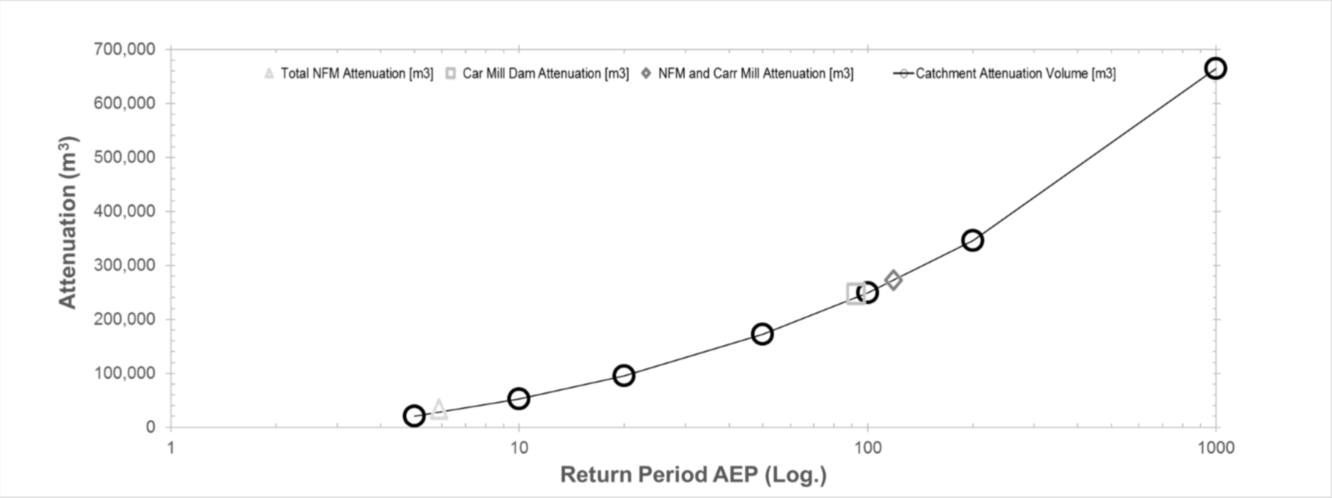

Figure 5) 1 in 100 Year (1% AEP) Reduced Flood Risk in Blackbrook, St. Helens - By the Measures Annotated on the Map (Dev 5,7,9 and 10).

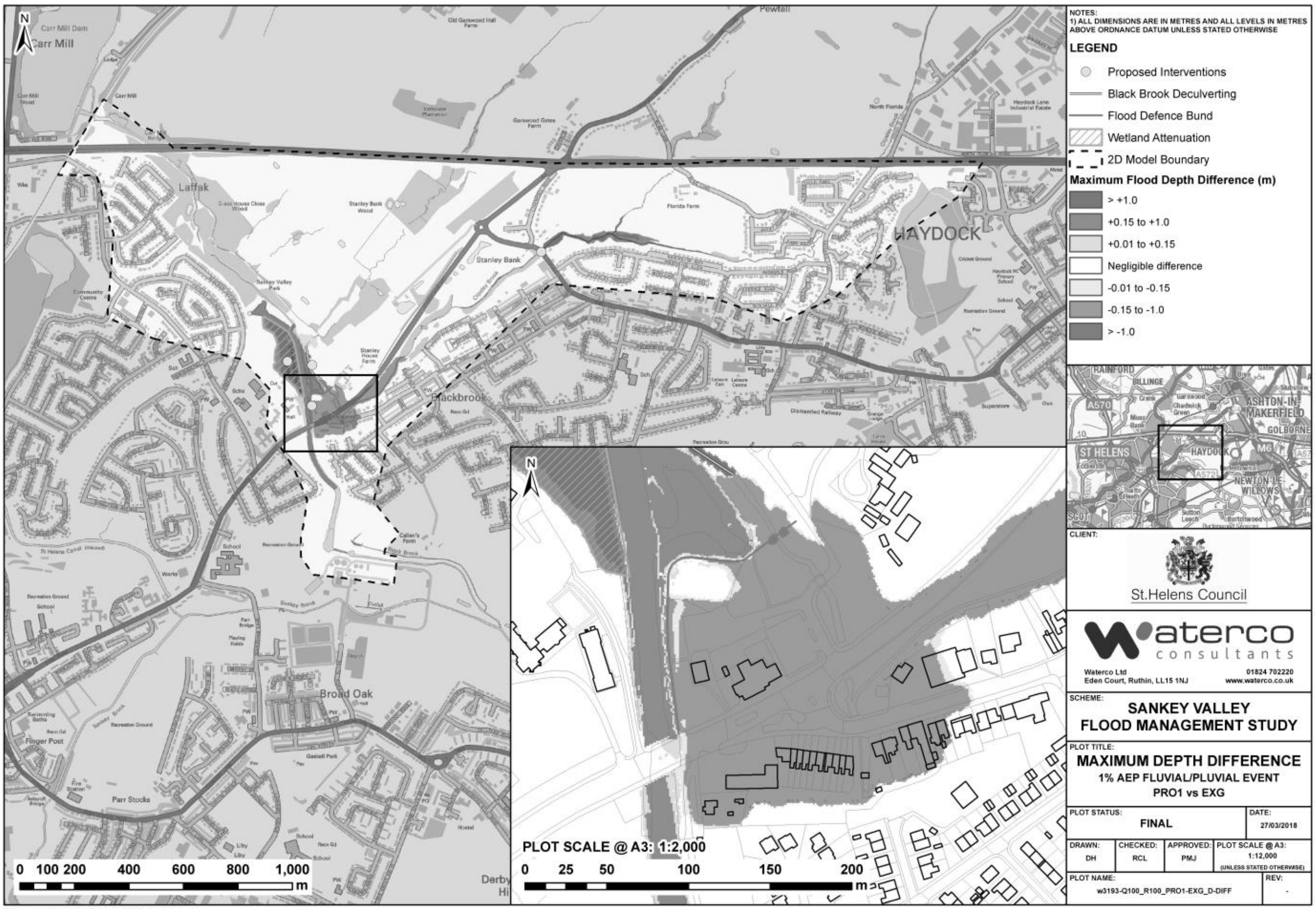

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Figure 6) Stanley Brook Engineered Log-Jams

Flood depths derived from 1D Flood Modeller Pro.

Environment Agency LiDaR DTM (1m) and Ordnance Survey data.

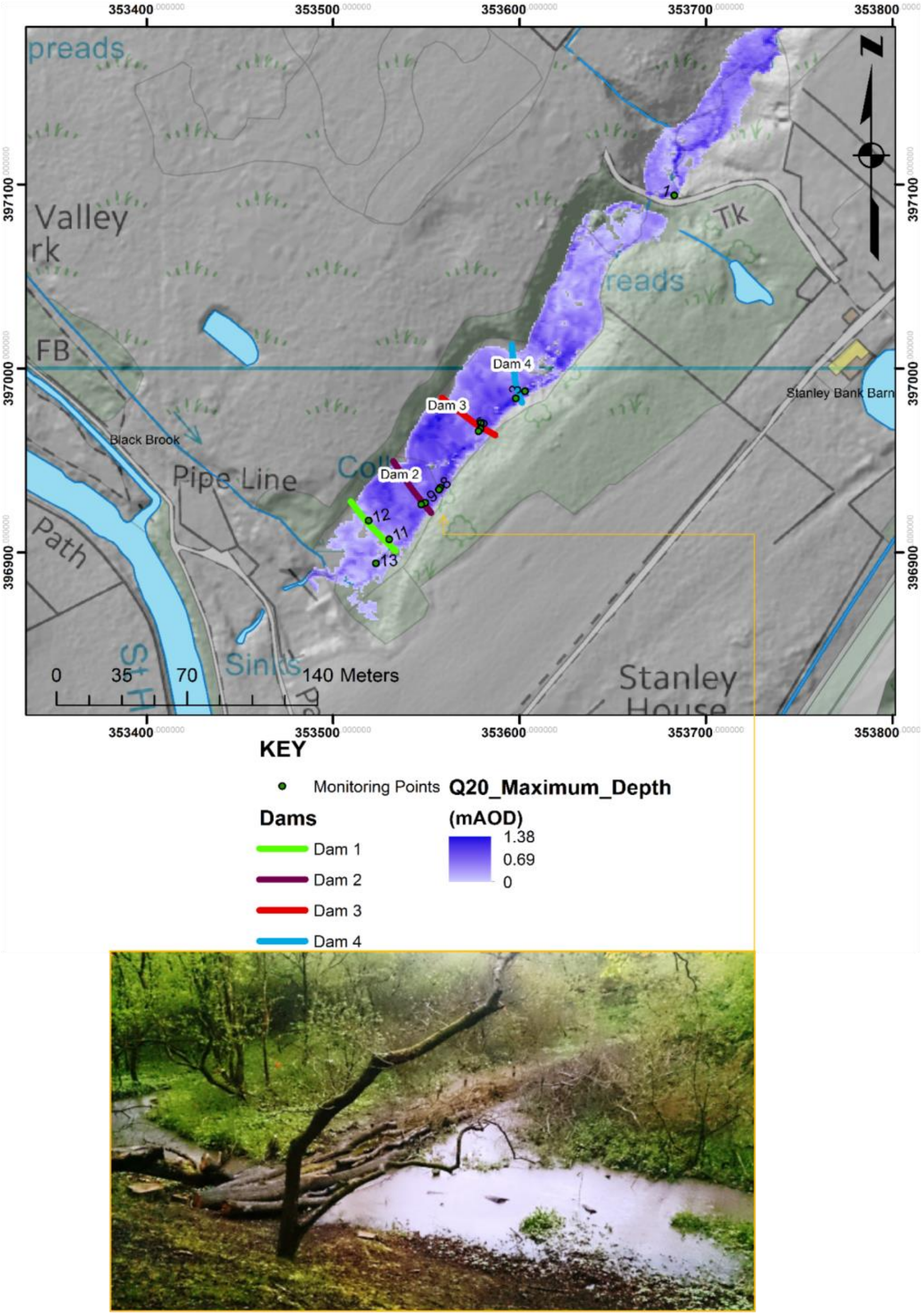
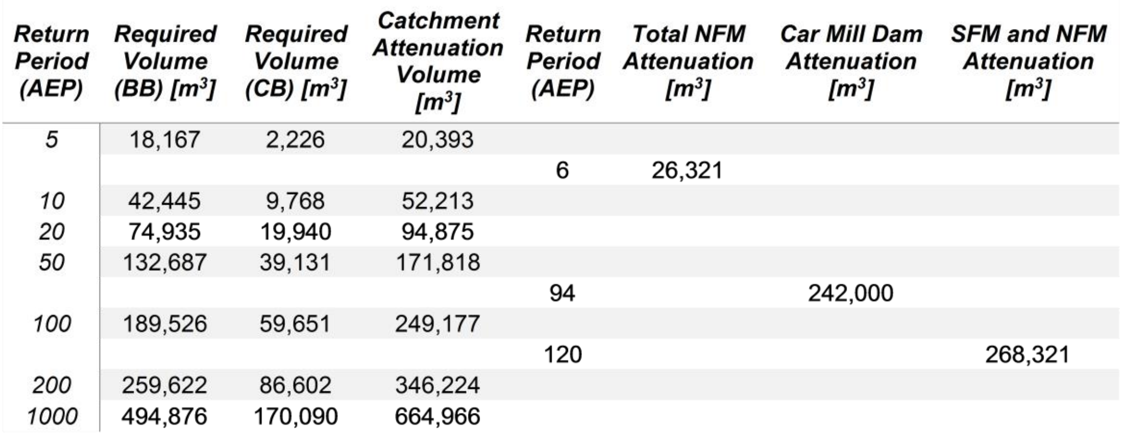


Photo: 08/05/2015. Courtesy of Matthew Catherall (St. Helens MBC).

Table 1) Target Catchment Attenuation Volume Against Return Period: Attenuation Delivered by Runoff Attenuation Features, Smart Flood Management (SFM) and Combined Measures



Return Period (AEP)	***Required Volume (BB) [m^3]***	***Required Volume (CB) [m^3]***	***Catchment Attenuation Volume [m^3]***	***Return Period (AEP)***	***Total NFM Attenuation [m^3]***	***Car Mill Dam Attenuation [m^3]***	***SFM and NFM Attenuation [m^3]***
5	18,167	2,226	20,393				
				6	26,321		
10	42,445	9,768	52,213				
20	74,935	19,940	94,875				
50	132,687	39,131	171,818				
				94		242,000	
100	189,526	59,651	249,177				
				120			268,321
200	259,622	86,602	346,224				
1000	494,876	170,090	664,966				