Case study 2

Brompton runoff attenuation modelling - North Yorkshire

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1. Catchment summary

Study location

The Brompton catchment (Figure 1) is upstream of the confluence of the Brompton Beck with the River Wiske in Northallerton, North Yorkshire. The catchment upstream of this comfluence is 27.4km² in area and is predominately well-drained, undulating arable land with a mean elevation above sea level of 68m.

Catchment summary

Water End in the village of Brompton flooded in 2000 and again in September and November 2012. A scheme similar to that implemented in Belford, Northumberland (see the Belford Case Study) has been suggested for Brompton, but the 2 catchments are quite different. Brompton is intensively farmed: the Agricultural Land Classification (ALC) classifies the entire catchment upstream of Water End as Class 1 agricultural land and 95% of its area is improved or arable grassland. This is in contrast to Belford where only the lower half of the catchment is arable and improved grassland, with rough pasture and upland grazing in the higher reaches (Nicholson et al. 2012). There are few areas of woodland in Brompton, which largely precludes the use of low-cost woody dams such as those used in Belford (Wilkinson et al. 2010, Nicholson et al. 2012).

The scheme at Belford used 20 run-off attenuation features to add a potential 20,000m³ of detention storage (Nicholson et al. 2012). Brompton is approximately 5 times larger than the catchment area, so the amount of storage needed to reduce flood risk is much greater than in Belford. To significantly attenuate the storm hydrograph in Brompton, between 1 and 10% of the catchment area will be needed to store flood waters (Quinn et al. 2010). Arable land prices at time of writing were between £17,300 and £21,000 per ha (RICS 2014), which means that the floodplain storage area in this case would be prohibitively expensive. Instead it is planned to place features within the river channel or in areas of marginal land with steep-sided banks around it.

The Brompton channel network is heavily modified with many enlarged and artificial ditches, increasing the channel density considerably to 1,203m per km². The Detailed River Network obtained from Ordnance Survey (OS) Master Map data indicates that most reaches do not coincide with natural topographic drainage lines. This reduces the opportunities for installation of other Working with Natural Processes (WwNP) measures that intercept overland flow before it enters a watercourse.

The catchment has an extensive network of well-maintained subsurface field drains that connect directly to the ditch network. This means that saturated surface run-off is unlikely and will have limited effect on the storm response.

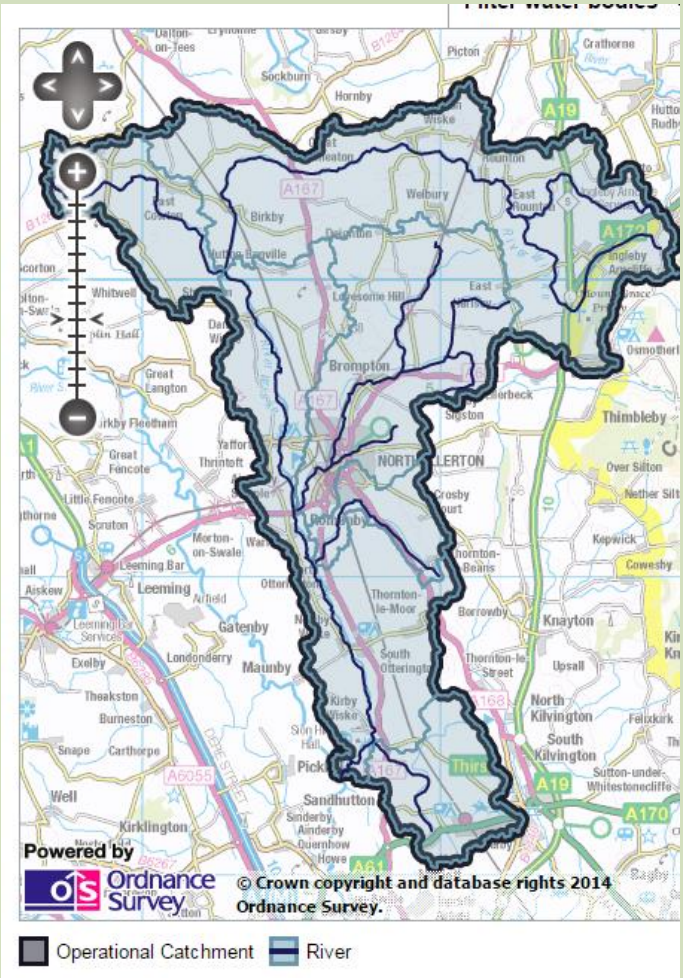

Figure 1: River Wiske catchment, North Yorkshire

Source: Yorkshire Dales Rivers Trust (http://www.yorkshiredalesriverstrust.com/)

Study summary

The aim of this study was to model the effect of implementing a number of run-off attenuation features within the Brompton catchment. In-channel barriers that can pass low flows beneath a sluice and overtop in high flows were modelled. The study used an enhanced version of Dynamic TOPMODEL (Metcalfe et al. 2015), which simulates subsurface and surface flows.

The impact of introducing 60 in-channel barriers at different locations in the catchment was modelled. The model was used to evaluate their effectiveness at attenuating flows based on flood event data from 2012.

The model showed that by adding these in-channel barriers it would be possible to reduce the specific discharge by up to 0.38mm per hour. It also showed that the features could store up to 65,000m³ of water, which slowed the watercourse's time-to-peak by up to 45 minutes. While this might be sufficient to reduce flooding in moderate events, it would not be effective in double peaked storm events of greater magnitude.

The study identified that:

- land drainage practices restricted the types of WwNP measures that could be used
- land prices were prohibitive for managing risks using the approach taken at Belford

The approach was therefore to add additional in-channel storage through the use of dams with an

underflow sluice for low flows which overtop during high flows. A total of 60 of these features were distributed around the channel network and a modified version of Dynamic TOPMODEL was used to simulate their effect. This helped to gain a good understanding of the interactions between flood peaks from different tributaries and also how the storage was made use of during a real event.

Community involvement

Working with the Brompton Flood Prevention Group, model visualisations were shared to show the impacts of different WwNP options.

2. Data summary

Datasets and analysis techniques used

Table 1 gives details of the datasets and analysis techniques used in the study.

Data restrictions

1m LiDAR data are commercial products but have been used under a free academic licence; LiDAR is an open source dataset and is readily available.

Table1: Datasets and analysis techniques used in the Brompton case study

Dataset	Source	Use
10m Digital Terrain Model (DTM)	EDINA Digimap	Setup of Dynamic TOPMODEL project
15 minute stage or level water level data recorded by an automatic gauge at the catchment outlet in Water End	Environment Agency	Model calibration
HEC-RAS1 project for North Beck, which connects Brompton Beck with the Wiske. Detailed channel profiles and rating curves are supplied for every reach, including one for the reach through the Green at Water End.	JBA Consulting feasibility study for a flood mitigation scheme in Northallerton	Used to derive an observed discharge from the stage data above. The first data point was at 1.1m, which in 2012 was exceeded only 0.25% of the time. The curve was extrapolated to zero by back-solving for a Manning n roughness given the rated discharge at the first level. Flow area A and wetted perimeter R were estimated from the channel profile provided and the discharge for level h calculated using the calculated n value as: $$Q(h) = A(h)\frac{1}{n}R(h)^{\frac{2}{3}}\sqrt{S}$$ where S is the local bed slope (also supplied in the HEC-RAS data and assumed constant over the reach).
Detailed River Network	OS MasterMap via EDINA Digimap service	Definition of channel and routing network

1m LiDaR2	Environment Agency Geomatics Group	Estimates of flooded extent and storages behind embankments, examination of

Notes: 1 US Army Corp of Engineers Hydrologic Engineering Center's River Analysis System

2 Light detection and ranging

The following tools were also used:

- Dynamic TOPMODEL (Beven and Freer 2001, Metcalfe et al. 2015) – although this is freely available at the CRAN library (see Metcalfe et al. 2015), the way it has been combined with kinematic channel routing would require bespoke setup on a catchment by catchment basis
- SAGA GIS (www.saga-gis.org) – an open source free geographical information system (GIS), which can be used to delineate catchments and channel networks
- EXTERRM (EXTensible Reach-Routing Model) (Metcalfe et al. in press)

3. Model summary

Catchment processes investigated

The modelling involved simulations of real events rather than design events, since design events can overlook situations where one rainfall event is rapidly followed by another. This type of event is responsible for many UK floods because flood storage is used up in the first peak and the second peak then causes the damage. The following catchment processes were investigated:

- run-off generation
- the effects of in-channel barriers along river systems which includes impacts of bridge/ culvert blockages and failures

Model assumptions

Dynamic TOPMODEL accounts for surface and subsurface hydrology, with base flows and overland flows collected into the simulated river reaches. TOPMODEL divides the catchment into hydrological response units that have different run-off characteristics based on typology factors such as soils, land use and slope. For each unit, the following outputs were generated every 15 minutes:

- subsurface downslope flows
- any saturated overland flow
- storage deficit
- unsaturated soil moisture content
- unsaturated gravity drainage flows

A simple routing model is then used to route these flows throughout the channel network. A series of 60 units representing ‘leaky dams’ with underflow sluices was incorporated into the channel network, thus influencing the progression of the flood wave. The effect of these WwNP measures is to store water during medium to high flows, through causing water to back-up in the channel. The locations of the 60 in-channel barriers on Ing Beck and its tributaries are shown in Figure 2. A sluice opening height of 0.3m from the bed was used along with a maximum height of 1.8m to the top of the barrier, above which flows spill over the structure. The effectiveness of these WwNP measures was assessed for the 2012 event by recording the:

- peak storage added to the catchment
- theoretical brim-full maximum capacity for each configuration
- highest percentage of that capacity that was used

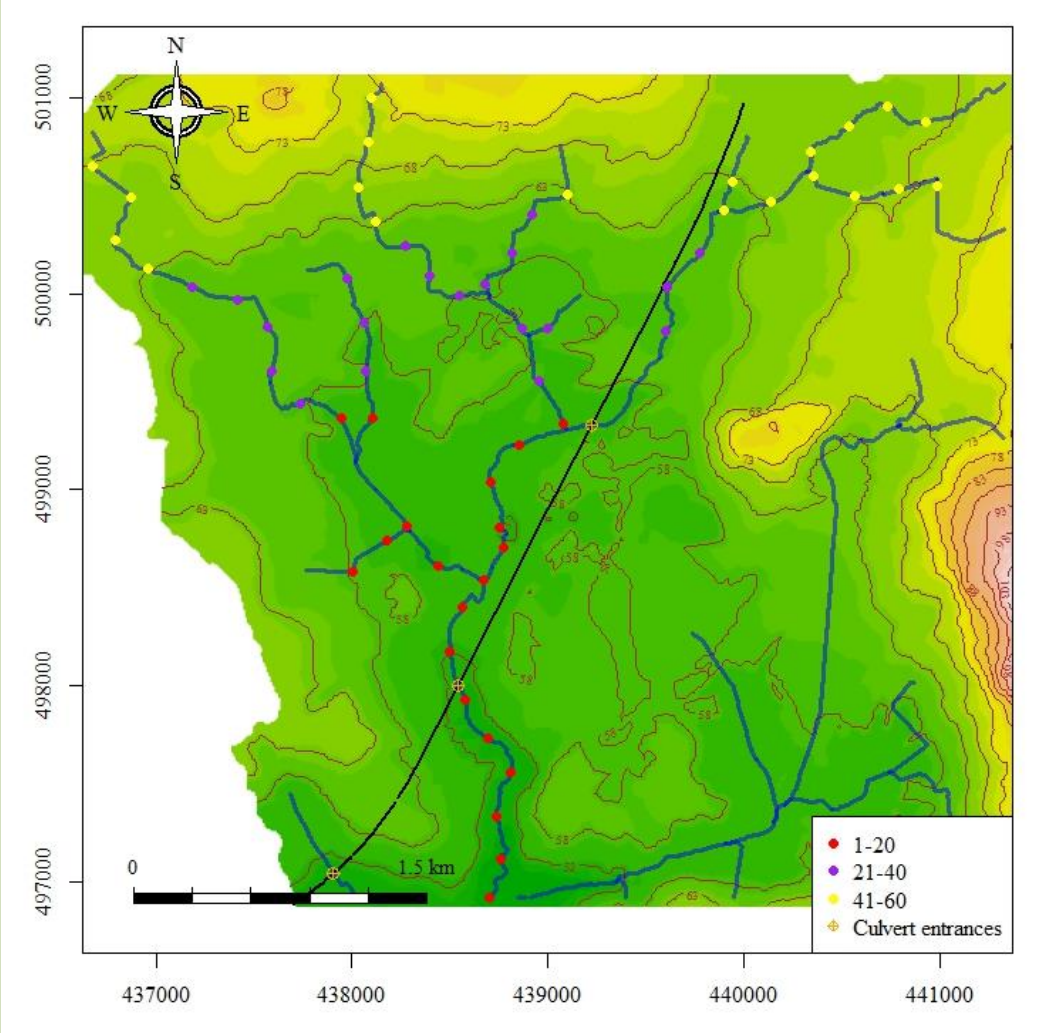

Figure 2: Map showing locations for proposed in-channel barriers on Ing Beck and several unnamed tributaries

Notes: The Northallerton to Middlesbrough railway line is shown in black and the points at which channels pass through its embankment are indicated.

The red, purple and yellow dots indicate the location of 3 sets of proposed barriers.

Source: P. Metcalfe, Lancaster Environment Centre

For each modelled run-off attenuation feature or culvert, the following hydraulic properties were computed every 15 minutes:

- discharge through the barrier
- overflow discharge over the barrier (if any)
- water level immediately upstream of the barrier
- specific storage

It was found that the addition of barriers further upstream had an increasingly small effect, with 75% utilisation of the storage volume for the first 20 features, dropping to 25% utilisation when all 60 features were used. The distribution of flows around the catchment and how they interact to cause flooding is variable, so without this type of modelling, it is difficult to assess where storage will be most effective.

A second configuration making use of lower barriers higher upstream and higher clearances

downstream was also trialled. This was designed to improve the utilisation of the higher features and allow lower features to drain between storm peaks. A 15 minute interval time series of specific catchment discharge (flow per unit area) through the catchment outlet at the Green in Water End was also developed (Figure).

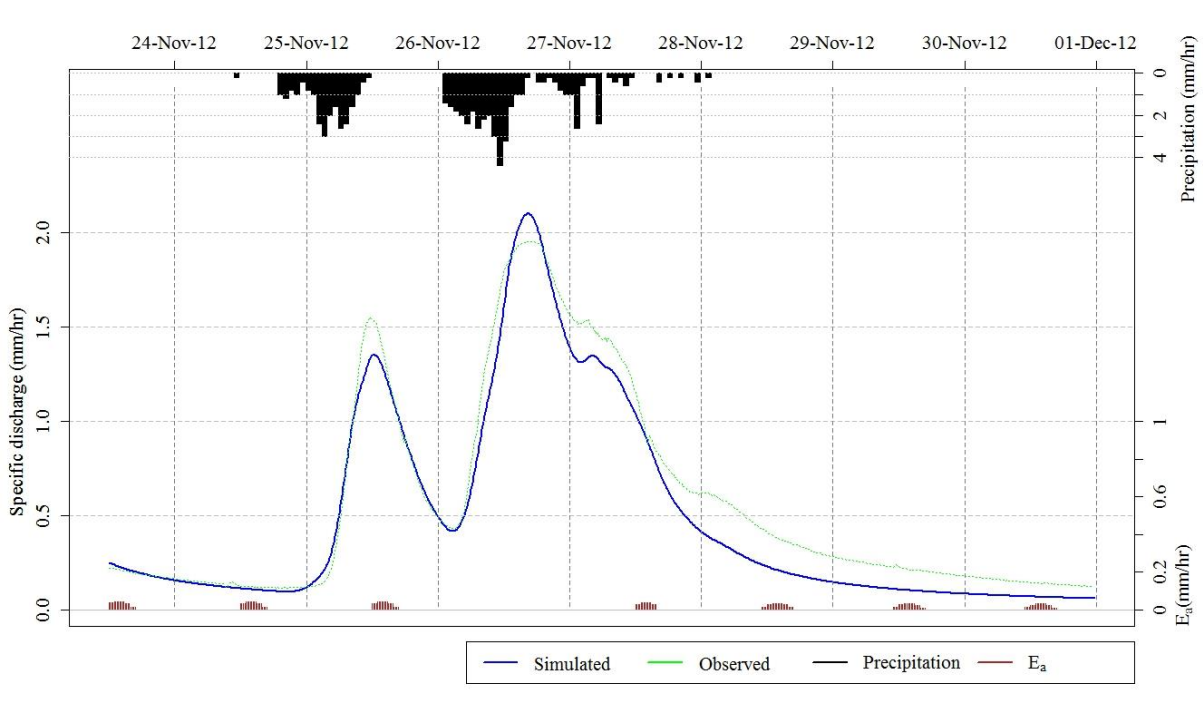

Figure 3: Simulated hydrograph for a storm event in late November 2012 in the Brompton catchment

Notes: Rated discharges from observed water levels are shown in green.

Source: P. Metcalfe, Lancaster Environment Centre

Data and model outputs

The Ing Beck is crossed twice by the embanked Northallerton to Middlesbrough railway line (Figure 3), with the beck passing through the embankment via low arched bridges. The existing embankment culverts could potentially be used to help attenuate flood waters by reducing the culvert diameters within the model, throttling flows and causing water to back up onto the floodplain behind the embankment. Reducing the culvert diameter to 1m results in a significant positive effect on the flood response downstream (Figure 4). Reducing the diameter even further to 50cm forces water to back up, leading at the height of the storm to potentially catastrophic embankment overtopping.

In the study, 1m resolution LiDAR data were used to estimate the flooded extent and storage associated with various water levels at the inlets to the culverts. These estimates gave an indication of the likelihood that the railway embankment would be overtopped during storm events and, in particular, the potential for debris dams and other in-channel features to fail and the associated debris to block the culverts. The storm event of November 2012 produced a run-off of around 5.9 million m³ upstream of the lower culvert on the Ing Beck. It was estimated that the brim-full capacity of the storage behind the embankment would be 5.2 million m³, so in the event of the culvert being blocked, such an approach would not be viable. Figure 5 shows Flooded water depths with a water level of 3m at the culvert entrance.

Model performance

Given the relatively poor performance of the in-channel features in attenuating the significant volumes required to prevent flooding, a final hypothetical arrangement using the culverts through the railway embankments was evaluated as described below in the section on future research needs.

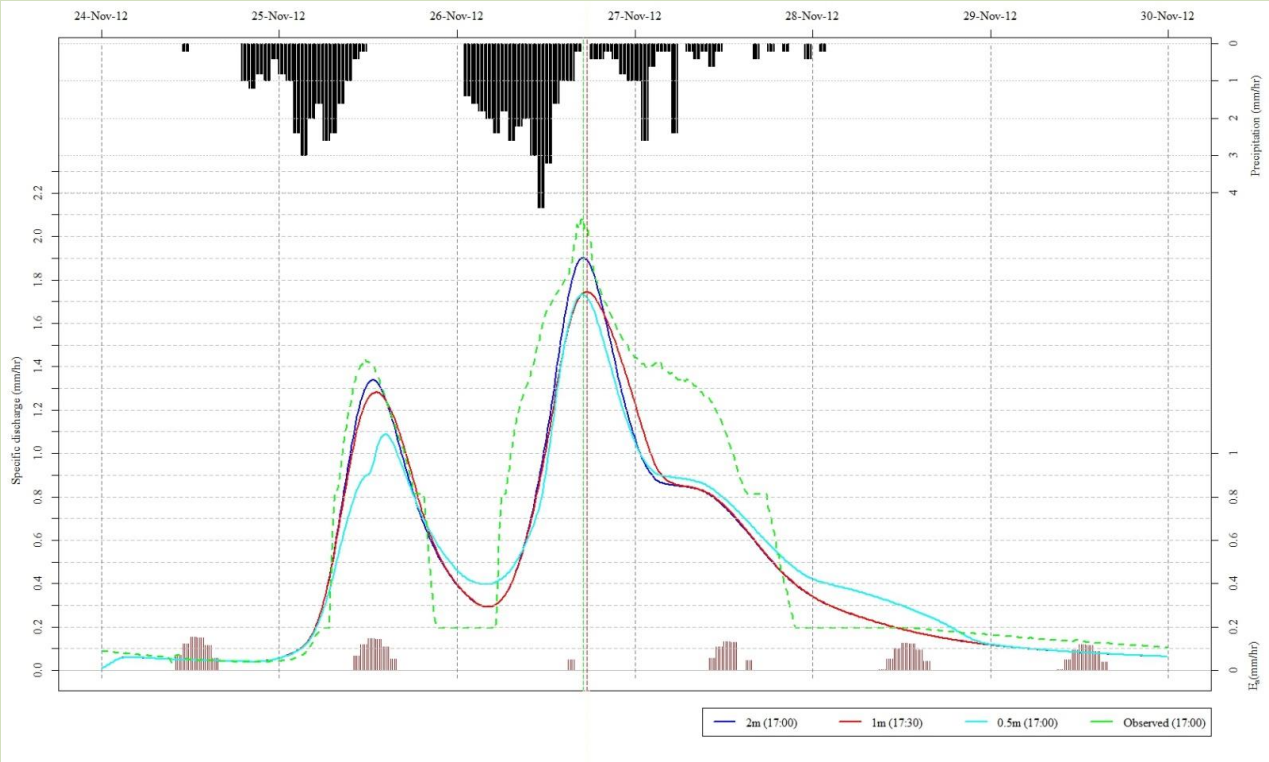

Figure 4: Run-off response to varying diameters of the culverts carrying Ing Beck under the railway line

Notes: Restricting the diameter to 1m attenuates peak flows by the equivalent of 0.2mm of rainfall and delays the peak by 30 minutes. Reducing this even further causes the beck to overtop the embankment and the peak to arrive at the same time as for the unaltered catchment. There is no further attenuation of the peak flow.

Source: P. Metcalfe, Lancaster Environment Centre

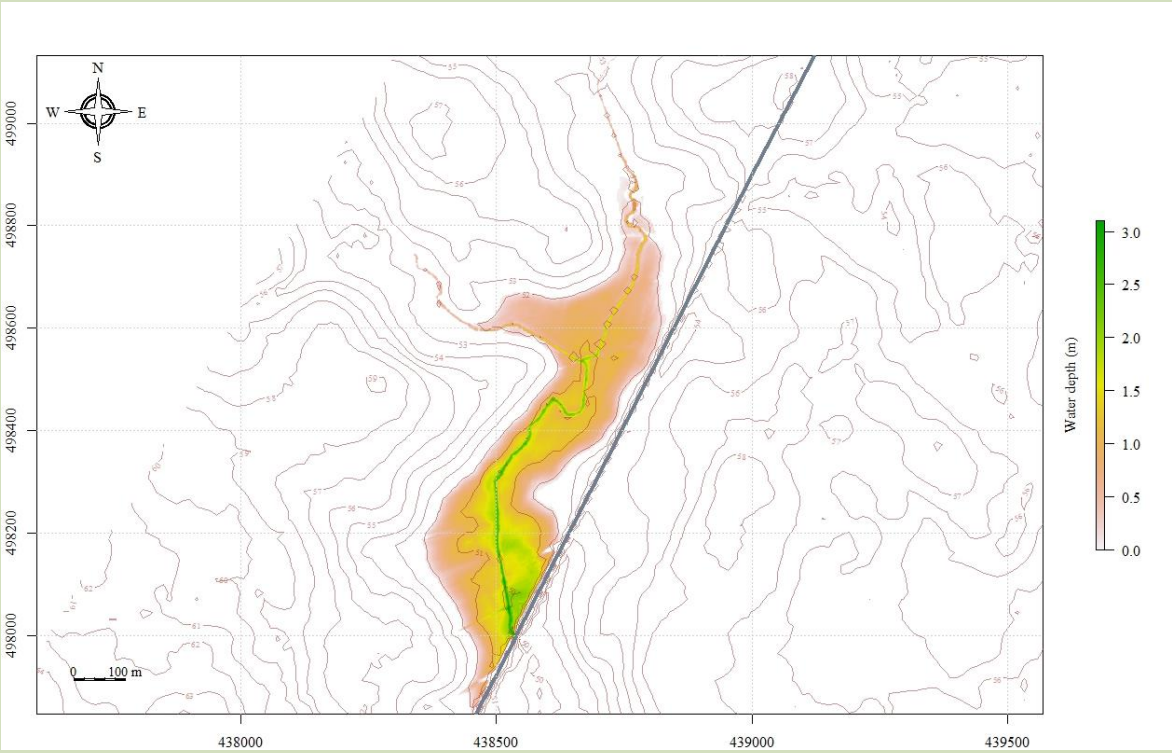

Figure 5: Flooded water depths with a water level of 3m at the culvert entrance in the mid-part of Ing Beck

Notes: Storage is 150,000m3 and the area flooded is ~16ha.

Source: P. Metcalfe, Lancaster Environment Centre

4. Lesson learnt

Choice of tools

The modelling approach used was suitable for this catchment for a number of reasons:

- It was able to make use of existing features as potential opportunities for flood risk management.
- Visualisation was excellent.
- It was possible to consider what would happen to storage during a real double peaked flood event.
- It enabled the analysis of the dynamics essential to ensure the storage comes into play at the optimum time.

Catchment scale and typology

Visualisation was found to be very helpful for engagement and promoted a better understanding of what the modelling was saying.

Although dynamic TOPMODEL is scalable, setting it up takes a long time and requires a high level of skill. However, it is an ideal framework for investigating the interaction between run-off generated through subsurface and surface pathways as it accumulates down through a complex channel network. This permits a better understanding of how water can be dynamically stored using in-channel WwNP measures such as barriers with underflow sluices. The run-off generation is based upon the concept of hydrological response units. These take into account local typology since they reflect different soil, land use and slope properties.

Wider benefits

Visualisation was found to be very helpful for engagement and promoted a better understanding of what the modelling was saying.

Future research needs

The investigation highlighted the importance of understanding that the dynamic utilisation of opportunity storage through an event is critical to its effectiveness in reducing flood risk downstream.

Investigating the timing of filling and unfilling for a real double peaked event, as opposed to a design event, is essential since this type of double peaked event often gives rise to flooding.

There is a need to be more opportunistic by making use of large features in the landscape since modelling has shown that use of in-channel features alone may not offer sufficient attenuation and storage.

To achieve the same levels of attenuation in the Brompton catchment as in the Belford catchment using similar storage features was found to be prohibitively expensive due to land values in the catchment and the area of land needed for attenuation. It was found that:

- the in-channel barriers with under-sluices were not always utilised
- the timing of how these run-off attenuation features fill during an event is important to understand whether full and effective use of the additional storage was achievable
- during a real double peaked event, the stores require time to drain down between events and this is not always possible.

As an alternative to in-channel flood storage, modelling that made opportunistic use of storage behind a railway embankment was explored by throttling flows using smaller diameters causing water to back

up and spill onto the floodplain. This was found to provide the order of magnitude of storage that would be required to have an effect on the 2012 flood event. However, system failure through blockage or scour of embankments would need to be fully assessed and the cooperation of the owner of the infrastructure would be needed to explore this as a realistic option.

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Project background

This case study relates to information from project SC120015 'How to model and map catchment processes when flood risk management planning'.

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