ASSESSMENT OF THE IMPACT OF UPSTREAM LAND MANAGEMENT MEASURES ON FLOOD FLOWS IN PICKERING BECK USING OVERFLOW

(Example debris dam built with large woody material, in an upland stream,
Cropton Forest, 25th March 2010. Photograph by Nick Odoni, Durham University)

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EXECUTIVE SUMMARY

- This report outlines a distributed hydrological model calibrated for two events in the Pickering Beck catchment, North Yorkshire, and a set of interventions that might contribute to reductions in downstream flood risk. These interventions take two forms:

    (a) crims – **c**atchment **r**iparian **i**ntervention **m**easures associated with, in this case, woodland planting to slow river flows; and
    (b) woody debris dams – small, in-channel blockages designed to assist in the transfer of water from the river to the floodplain.

- The analysis is designed to optimise the location of interventions, recognising that the location of an intervention may have a positive, a neutral or a negative impact upon downstream flood risk, as measured by a reduction in peak flow or flood volume.

- The analysis shows that:
    (1)   the best site locations are in the upper half of the catchment and the least suitable sites are in the lower third of the catchment;
    (2)   that the judgement of impact (i.e. positive, neutral, negative) depends on the interaction between individual interventions (i.e. an intervention that is negative on its own may be neutral or even positive when combined with other interventions);
    (3)   main Beck sites have a greater effect on downstream flood risk reduction than non-main Beck sites;
    (4)   the impacts on flood risk reduction increase with the number of debris dams installed, and where debris dams are used in combination with crims;
    (5)   the effectiveness of the interventions (i.e. impact upon peak flow reduction) is greater for the large event than the small event studied, which is an unusual but important finding; and
    (6)   the generally optimal locations for interventions do not move with the size of the event, suggesting that they are effective across events of different magnitude.

- In relation to Pickering, peak flow reductions range from 3.0 cumecs to 0.8 cumecs for the larger 2007 event according to the set of interventions used. These figures translate into reductions of flood volume of between 99,000 and 19,000 m^3. The figures are lower for the smaller flood event in 2000, and it is important to avoid a small number of interventions that would marginally increase flood risk.

Contents

1. Introduction

Durham University were contracted by Forest Research under the Defra funded *Slowing the Flow at Pickering Project* to develop and to apply a mathematical model originating under the Rural Economy and Land Use programme's project *Knowledge Controversies: the case of flood risk management* to Pickering Beck so as: (1) to identify the optimal locations of a series of catchment-wide interventions to reduce flood risk; and (2) to quantify the impacts of these interventions. The RELU model is called *OVERFLOW* and has been developed to allow rapid assessment of multiple combinations of interventions to identify optimal solutions in terms of downstream flood risk reduction. OVERFLOW is a simplified, coupled, hydrological-hydraulic model. Here, it is developed to allow exploration of riparian interventions (such as woodland planting) and instream woody debris dams to reduce flood risk. It is applied to two events: (1) June 2007; and (2) November 2000. Application of advanced numerical experimentation techniques identifies which interventions and combinations thereof work well i.e. have a strong effect on slowing the flow at Pickering and reducing the severity of the flood, and so are the intervention combinations that the Project should concentrate upon in the first instance with regard to implementation on the ground. It also identified those interventions which, because of their location, may have adverse impacts on downstream flood risk.

This report provides
  (1) a summary overview of the OVERFLOW methodology including its development and application for this case (Section 2);
  (2) the description of model set up and calibration for the June 2007 event (Section 3);
  (3) identification of interventions and impacts of those interventions for the June 2007 event (Section 4);
  (4) application of the model including calibration and assessment of the impacts of interventions, for the November 2000 event, one with a double flood peak (Section 5); and
  (5) summative conclusions (Section 6).

2. Methodology

2.1 Overview

OVERFLOW is an exploratory modelling tool designed to allow optimal identification of upstream interventions that might be used to reduce downstream flood risk. This section provides an overview of the basis of OVERFLOW, including some definitions of special terms that should assist the reader with understanding how OVERFLOW is applied to a catchment and how to interpret the model predictions (Table 1).

Table 1: Definition of special terms used in this study.

Term	Definition
Segment reach	For stream order 1 reaches, this is the reach from its source at the channel head to its confluence with the next reach in the channel network. For stream order 2 and higher reaches, this is the reach between its upstream and downstream confluences.
Subcatchment	All the area draining into the outlet cell of a segment reach.
Crim	An acronym for 'catchment riparian intervention measure', and describing generally an intervention site where any combination of up to five factors may be varied in order to influence locally the flow characteristics of the stream network. The five factors are: (1) channel width, (2) channel depth, (3) stream sinuosity, (4) channel flow resistance (roughness) and (5) overbank/floodplain flow resistance. In this research only the latter two, channel and overbank flow resistance, are varied in the interventions. It should also be noted that a crim can occupy part or all of a segment reach; similarly, it is possible to have two or more crims sited in the same segment reach.
Overbank section	The buffer strip in a crim running along the reach either side of the channel. In this study, the overbank flow resistance factor is assumed to be varied by planting denser or different vegetation in the overbank sections, assumed to extend 30 m either side of each stream, as directed by Forest Research (Nisbet, 2009, pers. comm.).
Debris dam section	A segment reach or part thereof in which one or more large woody debris dams are installed. In this study, the channel flow resistance factor is assumed to be varied as a consequence of installing large woody debris dams in the channels. Since the debris dams are initially intended to be spaced 7-10 times channel widths apart, as directed by Forest Research (based on work by Linstead & Gurnell, 1998), there will therefore be multiple individual debris dam sites within a crim or along the segment reach; the term 'debris dam section' therefore helps to distinguish between individual debris dam sites and the length of the reach occupied by the dams.
Flood critical discharge	The hypothesised discharge at Ropery Bridge in Pickering above which extensive flooding to property is expected to occur, assumed here to be 15 cumecs. Present best estimates are that bankfull discharge at the Beck Isle, just upstream of Ropery Bridge, occurs at about 12 cumecs, but only a few properties are actually flooded at this point. The discharge has to rise to 15 cumecs and over before the number of properties flooded rises sharply (based on latest gauging data from the Environment Agency, in Autumn, 2009, and current best understanding of Pickering's flooding characteristics from a review of recent flood histories and modelling, including consultants' reports).
Excess flood volume	This is the total volume of water contributing to extensive flooding of property in Pickering, the flooding being assumed to occur when the discharge is above 'flood critical' at Ropery Bridge, as defined above.

2.2   Rationale for OVERFLOW

There is not the space in this report to provide a detailed description of OVERFLOW. Rather, this will be written up in due course with a view to publication in the main scientific literature. It is helpful here, however, to consider briefly why OVERFLOW has been developed and used, and to comment on some of its differences compared with other models.

OVERFLOW has been developed at Durham University as part of the RELU Knowledge Controversies project (http://www.relu.ac.uk/research/projects/SecondCall/Whatmore.htm). Although it was initially expected that conventional models such as CRUM3 (Lane *et al.*, 2009) for hydrology and ISIS for hydraulics would be used in that project, it was found that these were very difficult to apply to catchment-wide, spatial explorations, of the kind also required in this study. In particular, such models are slow and awkward to set up for each individual combination of interventions, this having to be done manually in each case. The models may also take many hours per simulation to run (in the case of CRUM3). Such models, therefore, neither allow practical assessment of multiple possible small interventions in a catchment, nor optimisation of where those interventions have most effect. This is particularly important as these interventions will commonly change the magnitude and timing of runoff from different river tributaries and this, if not checked carefully and optimised, may exacerbate flood risk downstream rather than reducing it.

OVERFLOW, as with other hydrological models (e.g. the FEH's rainfall-runoff modelling system) simplifies many of the components of more physically-based models, whilst being able to justify such simplification by restricting application of the model to the particular places and events, e.g. flood events, that occur in a known location. The model therefore is not generic in the manner other models are intended to be, but rather has to be run after paying close attention to how it is set up for the site and flood event of interest. The main simplifications and their justification are briefly outlined below.

2.3   Working simplifications and set up requirements

OVERFLOW is intended to be applied to very wet events, of limited duration (just a few days, rather than weeks or months), so a number of simplifying assumptions are permissible concerning how the catchment will respond to rainfall input. With respect to Pickering, using stream gauge data at Ropery Bridge and from upstream sites in the catchment for a given event, and after comparing these with rainfall for the same period, a calculation can be made of the estimated runoff percentage i.e. how much of the rain is transformed into runoff through the stream network. Similarly, examination of the stream gauges allows estimates of 'baseflow' – the contribution from deeper water stores in the catchment – to be made, which may lead to further adjustment of the runoff percentage.

At the same time, using elevation data, field knowledge from the catchment and well known hydraulic geometry relationships (e.g. Leopold and Maddock, 1953), it is possible to infer the stream network, together with a first approximation of the width and depth of the perennial channels. The calculations are based on accumulating and routing a notional bankfull rainfall rate over the catchment, applying this to a DEM at 20 m resolution (Figure 1), the latter resampled from the Ordnance Survey's 5 m 'NEXTMAP' of Great Britain data series. It is also possible to make assumptions about stream channel and overbank flow resistance, again based in part on field knowledge of the catchment and other sources. These values for simplicity here are expressed in terms of a roughness coefficient, Manning's *n*. In the absence of more detailed information, overbank flow resistance assumptions are also applied to the hillslopes and wider catchment more generally, so that the entire catchment can be mapped for its Manning's *n* values, forming the 'Manning map' used in the model. Throughout this study, the default *n* values used were 0.035 for all channels and 0.06 for all overbank and wider catchment areas, these values corresponding to respectively a generally unimpeded stream and a semi-

open rough pasture, with some mixed low shrubs. Table 3, in Section 4.3, lists the range of Manning's *n* values applicable for the crims and debris dam sections in this study, and Figure 2 shows the perennial stream network derived as explained above.
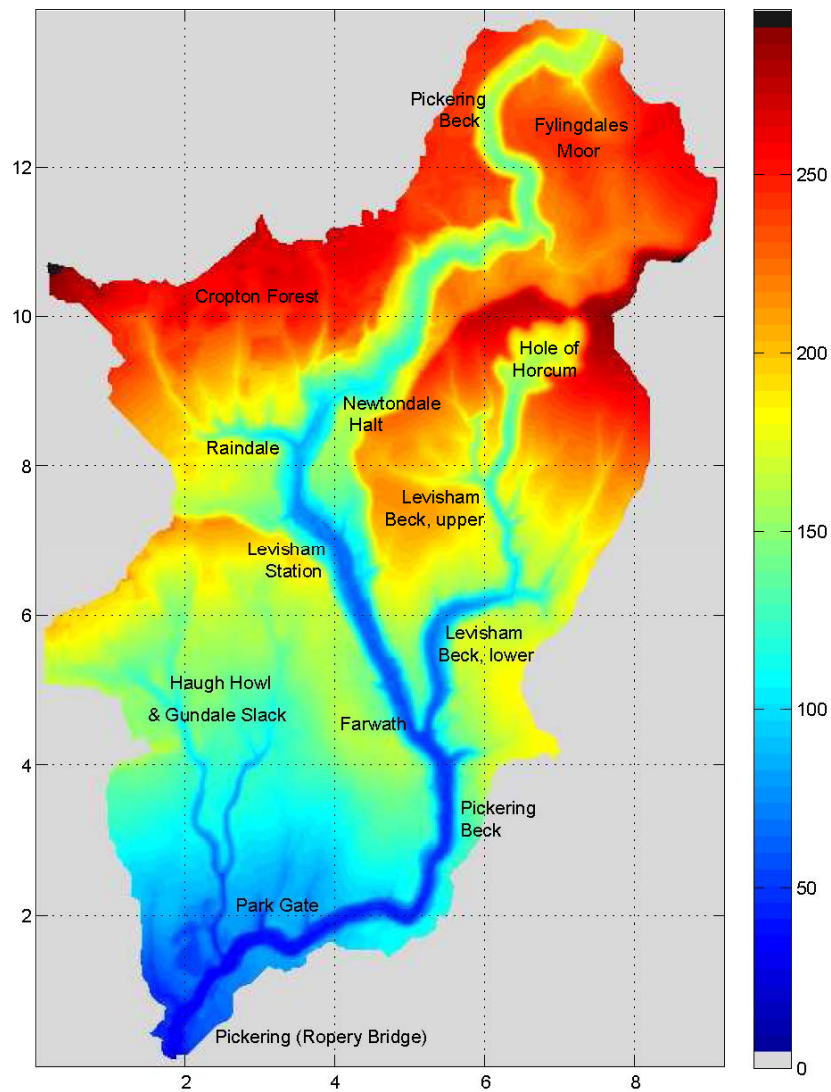

Figure 1: Digital topographic data at 20 m resolution for the Pickering Beck catchment, abstracted from 5 m resolution Ordnance Survey 'NEXTmap ®' data (© Ordnance Survey, 2007), elevations in metres a.s.l., with approximate locations of Pickering and other sites in the catchment marked. Grid squares are shown at 2 km spacing; catchment area is *c.* 68.6 km^2.
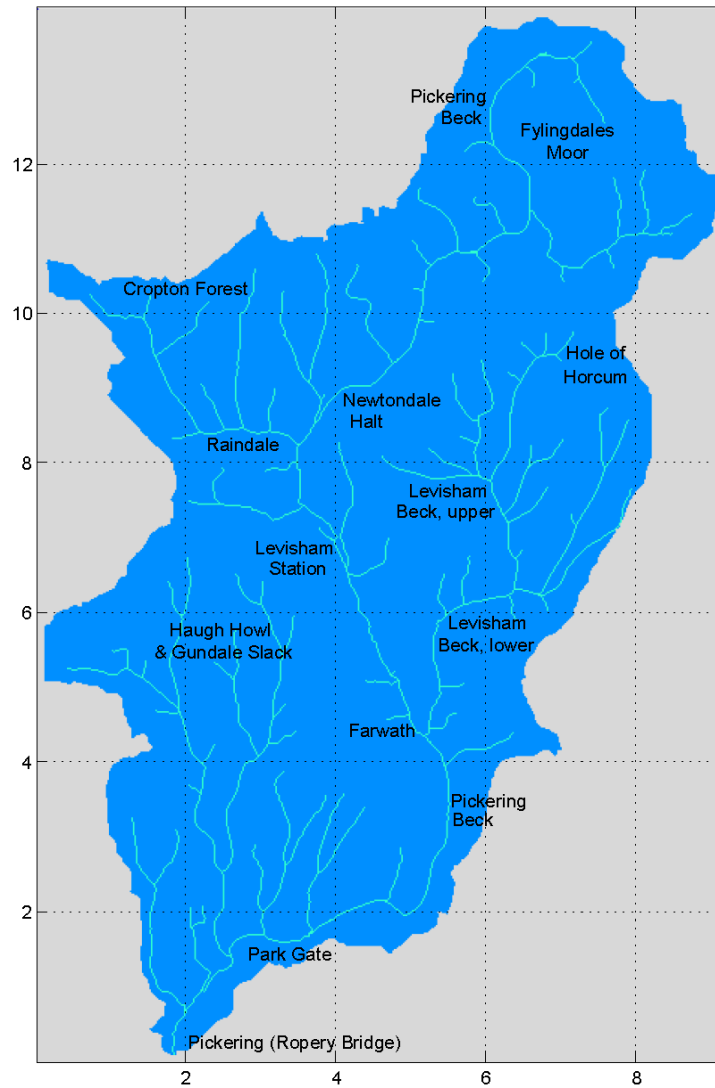
Figure 2: Perennial stream channel network for the Pickering Beck catchment, derived by applying OVERFLOW's flow accumulation and routing rules as described in Section 2.3. Locations of Pickering and other sites are approximate and for general guidance. Grid squares are shown at 2 km spacing; catchment area is *c.* 68.6 km^2.

With assumptions made concerning input rainfall, baseflow, runoff percentage, channel geometry and the Manning map, the model has all the components needed in order to run. A flow accumulation and routing algorithm calculates how rain falling on the catchment is made to flow through the landscape, with the assumption that the catchment is largely wetted up and the water that contributes to the flood wave moves primarily by overland flow. Flow paths are allowed to vary as a function of rainfall depth, as well as in situations where some of the flow is out of bank and routed across floodplains. The flows are converted to inferred flow depths (based also on the Manning map) and thence flow velocities. These are then inverted for the cell scale, to give flow passage times for each cell and different rainfall rate. By accumulating these along flow paths, starting at the outlet, a 'flow time map' is generated for the rain rate in question (e.g. Figure 3). The time maps can then be divided into time interval bands, and flow volumes calculated for each time interval of interest in a flood event by summing the area of the catchment within that time interval band and multiplying this by the rainfall falling in that time; thus, a series of summations for different times and areas produces a volume series at the outlet, which is then converted to an estimated discharge simply by dividing by the length of the model time step.
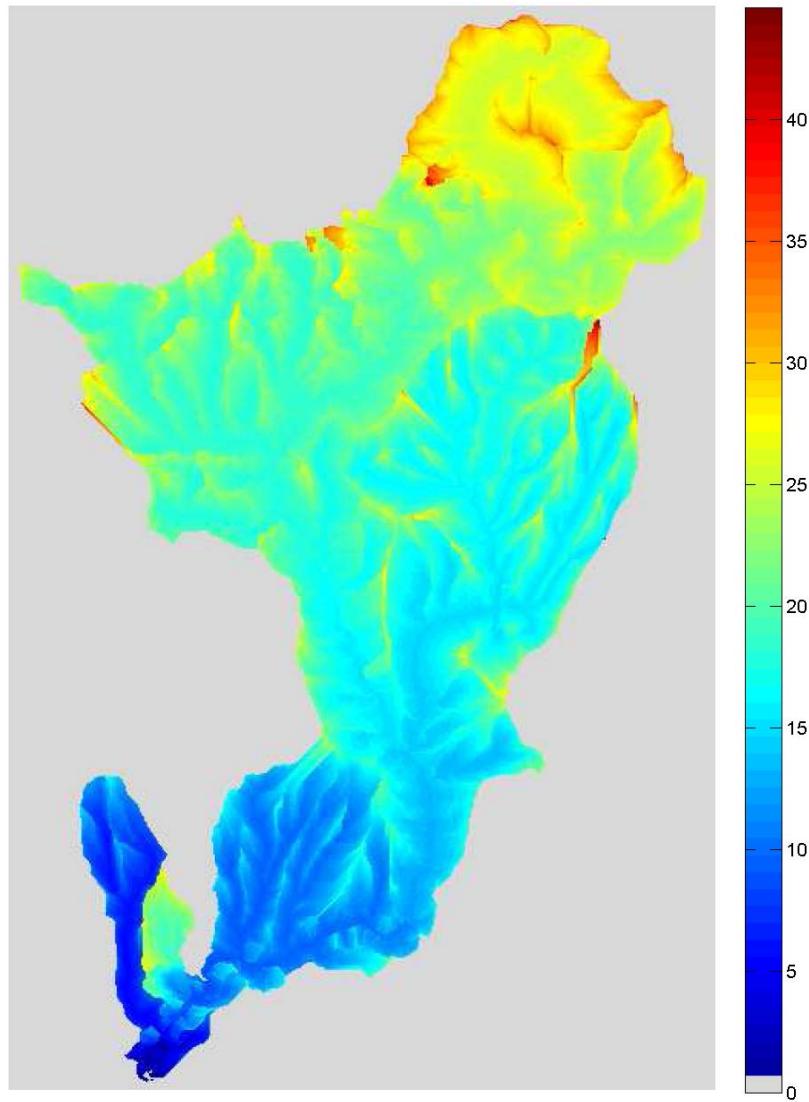
Figure 3: Example of a time map generated by OVERFLOW for the Pickering Beck catchment, in this instance for 14 mm per day gross rainfall, and assuming a runoff percentage of c. 55% after adjusting for evaporation and groundwater losses. Note also that the Haugh Howl/Gundale Slack subcatchment has been removed, as this is thought to contribute very little to overland flow during the June 2007 flood (for explanation, see Section 3.1). The time scale is in hours to Ropery Bridge; thus, much of the water at the farthest limits of the catchment, for example on Fylingdales Moor, takes 25 hours or more to reach Pickering, whereas in the lower half of the catchment, most arrives in under 15 hours. Scale as in Figures 1 and 2; grid squares and place names omitted here for clarity.

In the simplest application, OVERFLOW can be used by employing one time map whose wetness and flow times approximate a mean condition for the catchment during the whole of a particular event. However, in this study, rather than use just one flow time map, OVERFLOW is calibrated for an event of interest by using a temporal series of time maps, as appropriate for each time step in the simulation. In this respect, wetter maps, such as those corresponding to a higher rain rate, are faster than drier ones, and are therefore more likely to be correct to apply during periods of higher rainfall. By using different maps, the correct volumes are moved down catchment to simulate the flow hydrograph. How this is done for the June 2007 flood, together with the set up of the model, is explained in Section 3. Once calibrated, OVERFLOW is then intended to be used with a range of interventions, the main ones shown in Table 2.

Table 2: Types of catchment interventions possible in OVERFLOW and whether used in this study, together with their manner of implementation.

Type of change (factor)	Availability in exploratory version of OVERFLOW	Used in this study	Example use, and manner of implementation
Channel flow resistance	Yes, within a crim or debris dam section	Yes	To simulate changing the roughness characteristics of the stream bed or banks by reason of sediment or vegetation changes, or installing throttle controls in the stream e.g. woody debris dams. Applied by changing the values of the channel roughness in the Manning map (see text).
Overbank flow resistance	Yes, within a crim	Yes	To simulate changing the character of the riparian zone overbank areas, mainly by reason of vegetation changes. Applied by changing the values of the overbank roughness sections in the Manning map (see text)
Channel width	Yes, within a crim	No	To represent stream widening or narrowing operations in a segment reach or part thereof. Potentially useful because a wider stream should, for the same discharge, accommodate shallower within bank flows, with slower flow velocities, than a narrower stream. Applied by changing stream widths in the stream width map.
Channel depth	Yes, within a crim	No	To represent stream dredging or infilling operations, in a segment reach or part thereof. Potentially useful because a shallower stream should reach bank full at lower discharges and thus encourage shallow water overbank flows to occur more readily. Applied by changing stream depths in the stream depth map.
Stream sinuosity	Yes, within a crim	No	To represent stream re-meandering (or straightening) operations, in a segment reach. Potentially useful because more sinuous streams have gentler gradients and encourage secondary circulation at the meander bends, both of which help to slow flow velocities. Flow paths are also made longer, so the flow response in the system is generally slowed, with more flows forced out of bank. Applied by changing local stream gradient and flow length values at the sub grid scale in the relevant stream maps. Re-meandering at larger than grid scale is also possible, but requires changing DEM elevations and also associated slope and flow path maps.
Woodland or crop areas	Yes, applied to catchment areas as required	No	To represent changes in land management and cropping. Changing land cover from open fields to woodland should help to increase delays between water interception at the canopy or ground and its appearance as runoff e.g. by increasing infiltration, overland flow resistance and so on. Applied by changing the value of the overland roughness in the Manning map.
Woodland strips and hedges	Yes, applied to locations as required	No	To represent changes in land management. Introducing hedges has a similar effect to woodland, but locally may lead to increased flow delays upslope of the hedge as the elevation of the soil tends to rise over the years in response to accumulated soil washed down slope and the build up of woody and leafy detritus. Applied in linear arrangements by changing the overland roughness in the Manning map. May also be accompanied by changing elevations in the DEM and associated slope and flow path maps.
Ponds (field)	No: full version of model needed	No	Currently under development. To provide temporary upland water storage, so as to delay water reaching low order streams.
Bunds (stream)	No: full version of model needed	No	Currently under development. To provide temporary water storage, delaying the progress of the floodwave down the system. Assumed to be of low elevation (<2 m) and placed across a stream channel and adjoining flood plain, with a flow restriction in the channel.

3. Setting up and calibrating the model to simulate the 25th-26th June 2007 flood

3.1 Rainfall, discharge record and runoff percentage

The 2007 flood was chosen as the event of interest as this is both the most recent serious flood and also one of exceptional severity, probably the worst in terms of excess flood volume since the flood during the winter thaw in early 1947. Since the DEM and channel network are as shown in Figures 1 and 2, and the Manning map follows directly from assignments of *n* values to the channels and hillslopes as appropriate, the main model component of concern here is the runoff percentage, which needs to include an adjustment to allow for estimated baseflow. Both calculations depend in some manner upon using observed stream discharge data, but there were found to be some difficulties with regard to uncertainties in the stream data at Pickering, so two model calibration exercises had to be conducted in this research.

Specifically, with respect to the first calibration exercise, when this was conducted there were still difficulties estimating the most appropriate stage-discharge relationship for the stage data at the Ropery Bridge gauge, and also the flood critical discharge. To exercise some caution, it was decided to adopt a relationship that produced a peak discharge of about 31.5-32.0 cumecs in the June 2007 flood. These estimates were later revised, as part of the second calibration, discussed in Section 3.2. Since the rainfall radar data are not complete for this event, the gross rainfall rates used here are the mean of the two rain gauge records, from Brown Howe (situated just on the NW edge of the catchment, in Cropton Forest) and Keld Head (situated just outside the catchment, about 1.5 km SSW of Pickering).

Site visits and Environment Agency experience, coupled with local knowledge from Pickering residents and incorporating their observations during the 2007 event, indicated that the subcatchment of Haugh Howl and Gundale Slack contributed very little to the overall flood peak and flood volume. Most of the water falling on this area was probably lost into the limestone that dominates this subcatchment, and emerged in springs downstream of Pickering, near Keld Head. The subcatchment was therefore removed from the wider catchment for the purposes of calculating the discharge and flood wave. However, a notional rainfall rate was applied to the catchment generally to allow for a mean baseflow contribution from Haugh Howl and Gundale Slack, estimated here to be about 0.8 cumecs, although this had a negligible impact upon model calibration for the 2007 event.

The subcatchment of Levisham Beck, fed from the Hole of Horcum and adjacent areas, is known to include areas of limestone, but some limited field work in the area indicated that the streams there had experienced overland flow during the 2007 event, so no reduction was made in the first calibration exercise to the runoff percentage for this subcatchment compared with that for the rest of the catchment generally. With regard to the wider catchment (minus Haugh Howl and Gundale Slack, as noted above; see also Figure 3), initial estimates suggested a runoff percentage of about 50% initially, rising to about 65% as the rainfall rate increased during the event, probably as a consequence of the catchment wetting up over time, and a simple quadratic relationship was applied to take this into account. Thus, the rainfall rate applied in each time step of the model was the gross rate multiplied by the runoff percentage for that rate. Spatially uniform rates were applied in all simulations.

3.2 First calibration of the model for the 25th-26th June 2007 flood and initial exploration of crim effectiveness

A calibration routine was written specifically to generate a set of acceptable calibrations of the model, it being assumed that no calibration, however good, would necessarily be the best one to use. Flow hydrographs were generated by running simulations testing different combinations of time maps for each hour of the event, and calibration indices were checked for their acceptability. More specifically, the procedure generated two Nash-Sutcliffe indices, one for the 36 hour period from midnight (00:00) on 25th June to 12:00 on 26th, thus covering the build up of the flood, the peak and the first 9 hours or so of the recession limb of the flood wave; and the second the 72 hour period from midnight (00:00) on 26th to midnight on 28th, thus including 2 to 3 hours before the flood peak, and most of the recession limb of the flood wave.

On analysing the output, the calibrations chosen were those which exhibited a suitably high score for both indices i.e. a high score for one was not allowed to compensate for a poor score for the other. A set of two hundred possible calibrations were selected in this way, the minimum Nash-Sutcliffe indices being about 0.975 or more for each calibrated period (as described above). The mean flow hydrograph from these was used as the basis for comparing the calibrated model output with the observed discharge record. The same calibrations are also used to conduct the exploratory work with the crims and debris dam sections, again examining the mean predicted hydrograph from the 200 calibrated solutions, but this time comparing the output with the mean 'base case' (the control, being the model case in which no interventions are made). This allows incorporation of some elements of model uncertainty into model results. An initial assessment was made of the potential usefulness or otherwise of each individual crim site on this basis, dividing them between (1) ones which appeared to be useful in reducing the flood peak – 'positive' sites - and (2) those appearing to have little effect or to increase the flood peak, respectively 'neutral' and 'negative' sites (see Section 4). However, after this initial work, it became necessary to conduct the calibration again, and this is explained below.

3.3 Revised calibration for the June 2007 flood

After the first calibration and the initial exploratory work with the model, to investigate the effectiveness of the crims individually, more detailed analysis of the output, looking at locations upstream and comparing predicted discharge with gauge data (at Levisham Station and Levisham Mill), showed that the model was over-predicting runoff from Levisham Beck and its tributaries. Although a limestone effect had been expected from Levisham Beck, as noted above, the differences were more than expected and have now been allowed for.

A further change was necessitated following a 'near miss' flood event in Pickering, in Autumn, 2009, when the Beck reached just over bank full, and the Environment Agency was able to take flow readings from the Beck at Ropery Bridge. This led to revision of the stage-discharge relationship for the Ropery Bridge gauge, with the peak flow reduced to 29.5 cumecs. The hydrograph for the event, together with the mean gauged rainfall used in the revised calibration, are shown in Figure 4.
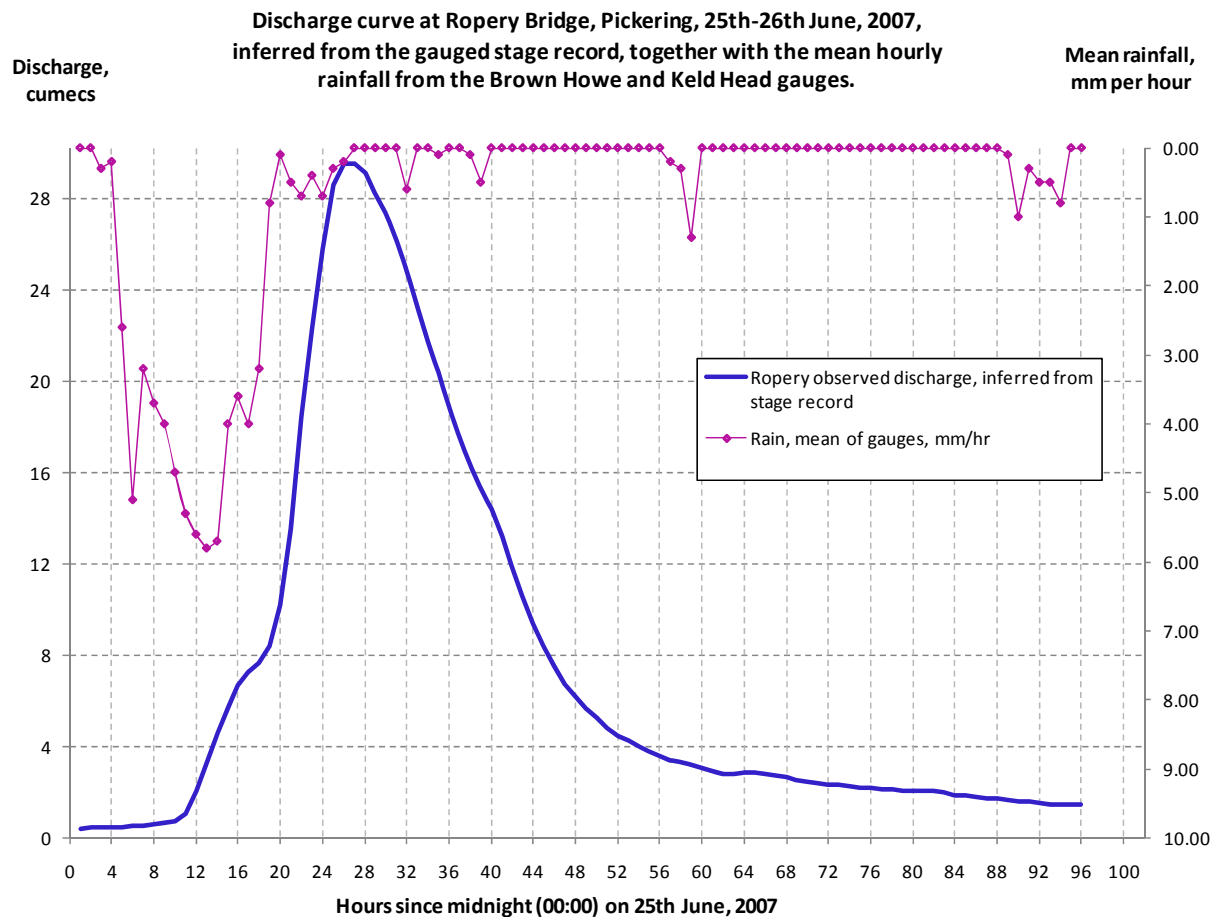
Figure 4: Ropery Bridge revised stream discharge record for the June 2007 flood, together with the mean gauged hourly rainfall of the Keld Head and Brown Howe gauges. Analysis of these figures, and similar figures from other high flow events at Pickering, allows an estimation of the percentage runoff to be made for this event, and also of the baseflow component of the discharge during the flood.

The impact of these changes is to increase slightly the percentage runoff for the wider catchment to around 60% generally, this rising with increases in rain rate to about 70%, whereas the percentage runoff from Levisham Beck is reduced to about 25%, rising to 30% or so for the wetter periods. The main effect of these changes has been to reduce runoff from Levisham Beck (and its tributaries), making the crim sites there appear to be less effective than before (as based on the first calibration) at reducing peak discharge and the excess flood volume. There is also a slight reduction in the effectiveness of some of the other crim sites, caused in part by the slowed delivery of the Levisham Beck flood wave to that in Pickering Beck itself. However, there is also probably another effect (a model artefact), caused by the lack of spatial variation in the rainfall input, that is reducing crim effectiveness somewhat. A more complete implementation of rainfall would allow for much heavier rain on the northerly parts of the catchment, particularly in Cropton Forest, than is now modelled, and gentler rain on the more southerly part of the catchment, for example around Cross Dale or High Hunter's Bridge. Implementing a rainfall gradient would in likelihood make the crims outside Levisham Beck more effective than they appear to be currently. The same point applies with respect to the extra debris dams in Cropton Forest i.e. they become more effective than they appear to be at present. Notwithstanding the above points, and the need to approximate further the runoff percentage and baseflow contribution, the second calibration exercise still achieved very close fits of the modelled output to the observed, with the highest Nash-Sutcliffe indices comparable with those achieved in the first calibration. The observed data and the mean calibrated curve from the second calibration are shown in Figure 5.

Modelled discharge curve at Ropery Bridge, Pickering, 25th-26th June, 2007, generated by OVERFLOW, compared with the discharge inferred from the gauge record. The predicted curve is the mean of 200 calibrated runs with the model .
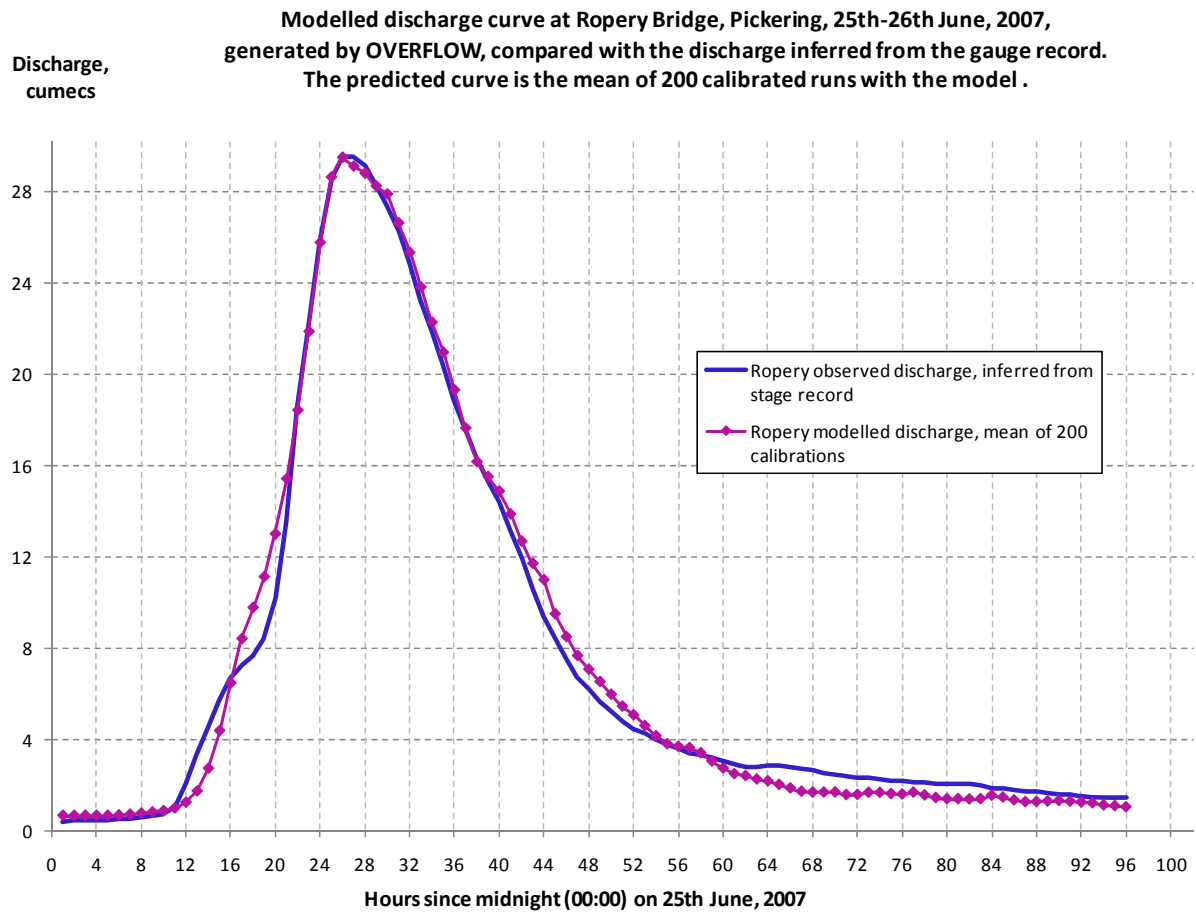
Figure 5: The second (revised) calibration, showing the Ropery Bridge revised stream discharge record for the June 2007 flood (as in Figure 4), together with the mean predicted discharge from 200 calibrations with the model. The modelled discharge now forms the 'base case', against which the results obtained in the various intervention cases to be tested with the model are compared.

4. Intervention measures for the 2007 event and assessing their effectiveness in slowing the flow

4.1 Initial mapping of the crims

Forest Research initially provided suggested locations of 96 sites in the catchment where there was an opportunity to plant riparian woodland, which were assumed in the first instance to comprise debris dam (which would develop naturally through time) and overbank sections combined, the latter present on the ground as woodland buffer strips. No adjustments were made at this stage for any sites which might already be partly wooded. Likewise, the debris dams were assumed to be packed in where possible at their highest density *viz.* 7-10 times stream width, or as high as the local stream width and the model's cell resolution would allow if the target density could not be achieved. The initial crim map based on these directions is shown in Figure 6.
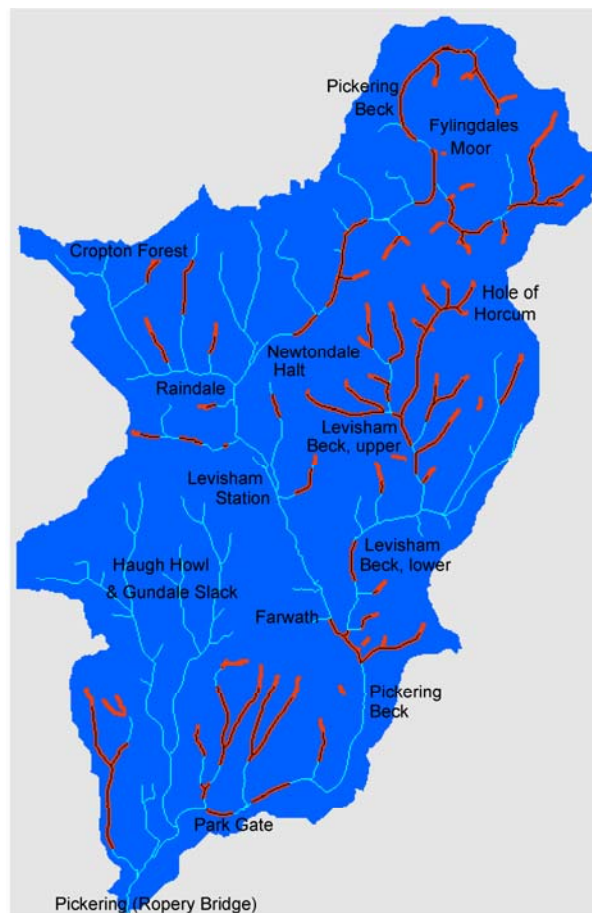

Figure 6: Initial mapping of the crims proposed by Forest Research in the catchment of Pickering Beck. Overbank sections are shown in pink, debris dam sections within the latter in black (sections appear red), and perennial stream network otherwise in the paler blue. Place locations are marked for general guidance only; scale as in Figure 2, grid squares omitted for clarity.

Later in the study, Forest Research asked us to modify the crim map, removing from it some overbank sections (mostly in Cropton Forest), where it was considered that additional tree planting was unnecessary or impractical, or, in non-Forestry Commission areas, for the same reasons or where planting would be resisted by the landowner. We were also asked to treat all channels in Cropton Forest as potential debris dam sections, as the initial modelling with the first calibration had indicated that debris dams generally were potentially very effective intervention measures if sited in suitable

locations. The revised crim map, illustrating the additional debris dam reaches and the modifications to the original crim arrangement, is shown in Figure 7. There was some difficulty in mapping the extended additional debris dam section network in Cropton Forest, and this is discussed below.
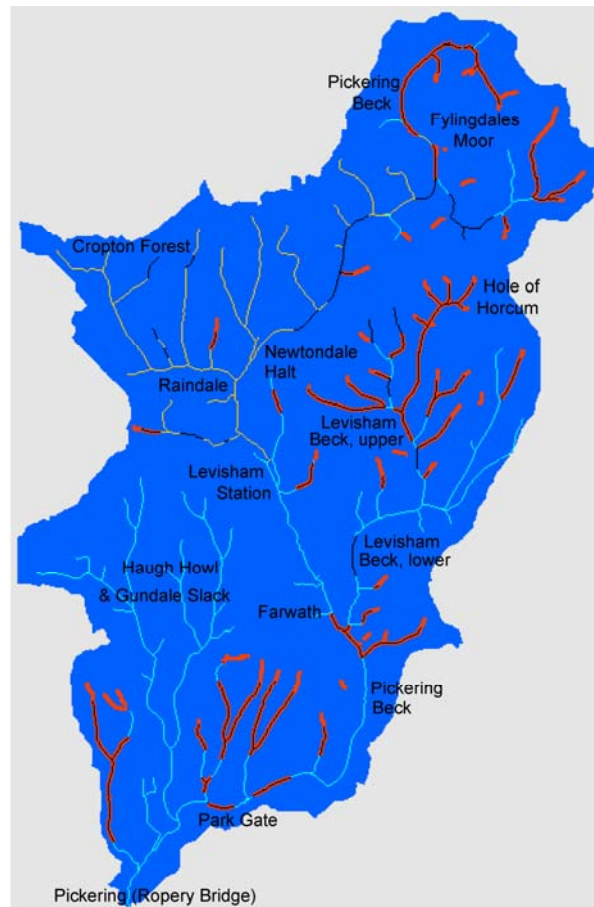

Figure 7: Revised mapping of the original crims proposed by Forest Research in the catchment of Pickering Beck. Overbank sections are shown in pink, debris dam sections within the original crims (Figure 6) in black, additional debris dam sections in the Forestry Commission's Cropton Forest estate in yellow, and the perennial stream network otherwise in the paler blue. Place locations are marked for general guidance only; scale as in Figure 2, grid squares omitted here for clarity.

4.2 Comments on the additional debris dam sections in the Forestry Commission's Cropton Forest estate

Figure 8 shows part of the map prepared by Forest Research showing land ownership in the catchment, but concentrating particularly on the channel network in Cropton Forest, in which the additional proposed debris dam sections were to be implemented in OVERFLOW. These were somewhat difficult to map in the revised crim map, since the flow paths in OVERFLOW are driven by topography, whereas in Figure 8, the channel network includes drains dug along courses that do not conform with the normal flow path rules used in the model. Rather than try to guess the exact courses of the complete drain and ditch system, we used our best estimate (Figure 9), according to OVERFLOW's usual rules of calculation. This is slightly different from what the Forest Research map shows, but the discrepancies are thought unlikely to be important within the *overall* assessment of the usefulness or otherwise of the extra woody debris dams. Note in particular that, as discussed below, the modelling indicates that none of these additional debris dam sections is 'negative', and all are at least neutral or beneficial at reducing the flow peak or excess flood volume. The view at present is that, if anything, OVERFLOW is under-estimating the combined effect of these additional dam sections. For example, at present, we are assuming a lower overbank flow resistance in the

forested areas than is likely to be the case. If additional denser planting in the buffer areas (implemented in the model as overbank sections) is possible, beyond what is maintained at present, then the effectiveness of these extra debris dam sections may be increased.
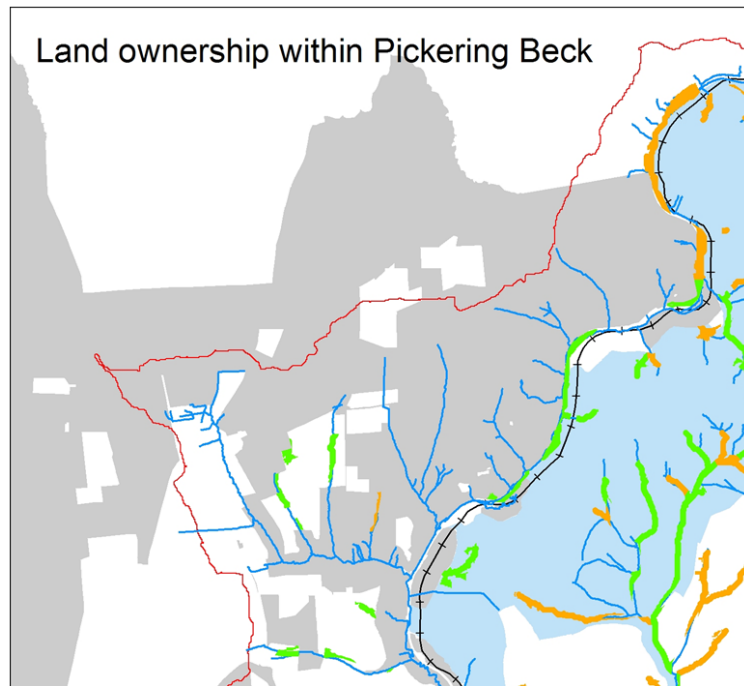

Figure 8: Close up of part of Forest Research's map of land ownership in the catchment, showing detail of the drainage channel network (in deeper blue) in the Forestry Commission's Cropton Forest estate (the grey areas in the figure). Note also areas owned by the North York Moors National Park (pale blue), and some of the original crim locations (green and buff-yellow). The catchment boundary is marked by the thin red line.
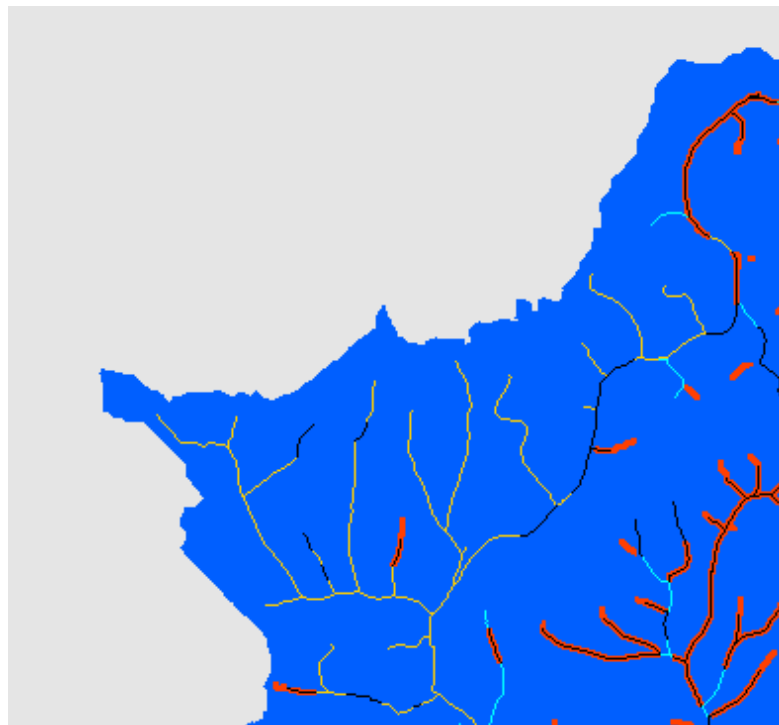

Figure 9: Close up of the same area of the catchment as shown in Figure 8, but here showing the catchment channel network as modelled in OVERFLOW. The additional debris dam sections in the FC's Cropton Forest estate are shown in yellow. Overbank and debris dam sections (respectively pink and black) associated with the original crims, and other sections of the perennial channel network (paler blue) also shown. With respect to the additional debris dam sections, there are some differences between the network in OVERFLOW and that in Figure 8, but generally the OVERFLOW representation is thought to be adequate enough to make the point about the usefulness or otherwise of the additional debris dam sections.

4.3 Range of Manning's n values applicable for the interventions

It was important to define the range of Manning's *n* values that would be permissible or suitable for use in the simulations, and this is set out in Table 3 for each intervention type, as agreed with Forest Research (Nisbet, 2009, pers comm.):

Table 3: Manning's '*n*' values corresponding to the different levels of intervention for the two factors varied in this study.

Factor level	Symbol or notation	Overbank sections (woodland buffer strips)	Debris dam sections (applied only to cells containing a dam)
Base case (no intervention)	Null	0.06	0.035
Minimum	- α	0.07	0.06
Lower working value	-1	0.12	0.10
Central	0	0.16	0.14
Upper working value	+1	0.20	0.18
Maximum	+ α	0.25	0.22

In the eventuality of running a more comprehensive optimisation procedure, all the above values would be used in a multiplicity of combinations, both within each site and across different sites in the catchment. Such a procedure would require many hundreds of simulations, however, and project delivery pressures prevented this being possible. For the simulations here regarding interventions singly or in combination, only the upper working value and maximum values were used, these corresponding to the +1 and +α factor levels in the table; how this was done is described below.

4.4 Testing each crim site individually – 'positive', 'neutral' and 'negative' sites

In these simulations, the effect of each crim site individually was tested by setting both its overbank and debris dam section values in the Manning map to the maximum in Table 3, so as to obtain the clearest signal of the effect of the crim in question. The results for each test, called here a 'case', were then analysed to see what effect the crim had had on the peak flood wave, as predicted by the mean of the 200 calibrated runs with the model. In marginal cases, where the change in the mean peak discharge was small, the excess flood volume was also calculated as a further check on the effect of the crim. The results obtained in this way indicated that some crim sites were 'positive', in that the crim was predicted to reduce the peak mean discharge compared with that in the base case; similarly, some sites were clearly 'negative', in that the peak mean discharge appeared to increase compared with the base case value. Other sites were rated as 'neutral', in that the crim appeared either to have very little effect on the peak mean discharge (only very slightly higher or lower than that of the base case), or the results were contradictory e.g. the peak mean discharge appeared to fall, suggesting a positive site, whereas the excess flood volume appeared to rise, suggesting a negative site.

The results obtained from the first calibration identified that most of the positive sites are clustered in the upper half of the catchment, whereas the negative sites are in the bottom half, generally in reaches much closer to the town. This general picture was altered only slightly when the revised calibration was applied, and including the extra debris dam sites required by Forest Research in Cropton Forest: the negative crims sites were mostly found in the lower part of the catchment, in tributaries to the main Beck near the town, and the positive sites were clustered in the upper parts of the catchment, with the neutrals scattered at sites in between (Figure 10). The importance of sites in the upper

catchment is as expected, as they increase the potential of decoupling runoff delivery between the upper and the lower catchment.
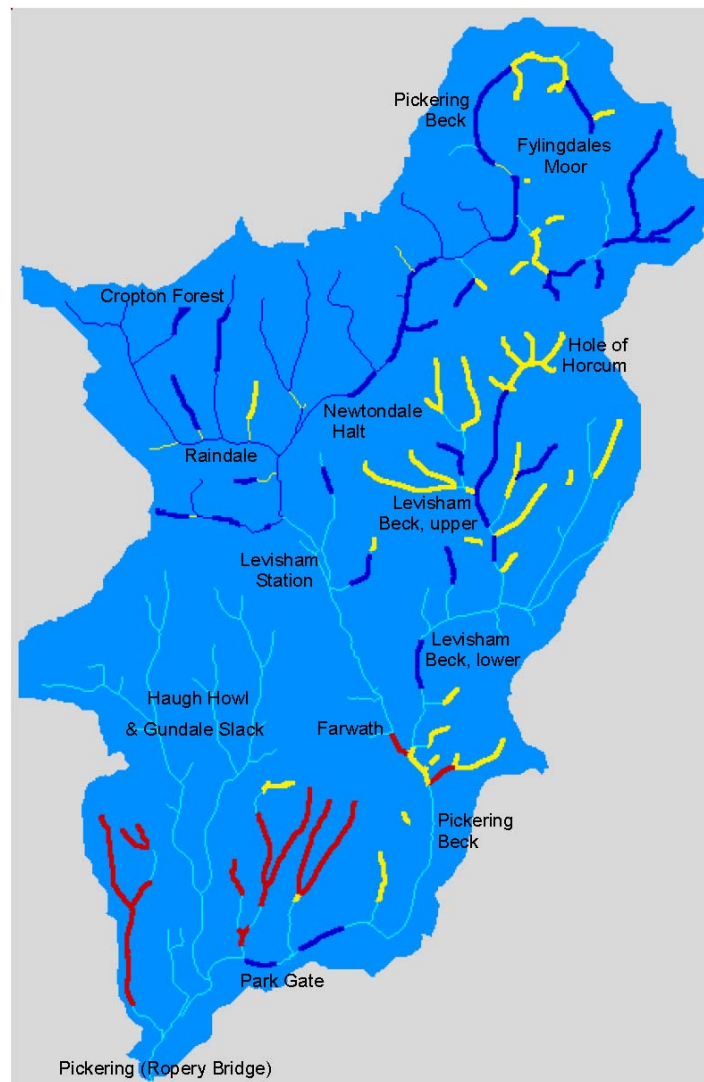

Figure 10: Initial assessment of the individual influence of each crim and additional debris dam section proposed by Forest Research in the catchment of Pickering Beck, these assessments based on results obtained simulating the June 2007 flood event. Crims and debris dam sections marked in thin or thick dark blue are 'positive' i.e. they are generally suitable for placement of intervention measures, since they are predicted by OVERFLOW to reduce the peak mean discharge or excess flood volume. Sites marked in yellow are broadly neutral, and appear to have little effect one way or the other, or exhibit contradicting results (see text). Sites marked in red are negative, interventions there causing an increase in peak mean discharge or excess flood volume. Note that the two positive sites on the main course of Pickering Beck near Park Gate (close to Pickering) are very similar in location to the proposed bunding sites being investigated by the Environment Agency. Place locations for guidance only; scale as in Figure 2.

4.5   Testing the more promising sites in combination

In Table 4 are listed the main results from the modelling work for the sites in combination, the combinations being guided by the directions from Forest Research in this respect. A number of runs were made taking into account the revised calibration. Later revisions suggested by Forest Research and Natural England, following visits to the various crim sites and proposed debris dam sections, were taken into account in forming a more focused suite of simulations. In particular, we were asked to ensure that the total area of any overbank sections should be as close as possible to 50 ha, this being the project's initial target for extra woodland planting and, if necessary, including other crim sites to those which had appeared to be the most useful following the first calibration results. We were also

asked to consider what effect including and excluding sites along the main Beck would have, and how limiting the total number of debris dams in the Cropton Forest estate to the target of 100 would affect the results. These tests together are accommodated in 8 simulation cases with the model (Table 4). In all of these simulations, crims and debris dam sections were tested using their upper working values (+1 level) as listed in Table 3. Figures showing the detail of the arrangement of the interventions in each case are provided in the Appendix.

Table 4: Description of the eight simulation cases used in the tests of crim and debris dam section combinations, following the latest directions from Forest Research (FR). The selection of sites is based on Forest Research's choice of the best sites following initial results with the first calibration, but also includes the additional debris dam sections in Cropton Forest and omits various overbank sections, pursuant to guidance from Natural England and the Forestry Commission after field visits to the crim sites. For further detail, see figures in the Appendix.

Case number	Description
1	All sites, including the main Beck and FR's preferred sites based on the first calibration and initial assessment of the crims
2	As case 1, but excluding sites along the main Beck
3	As case 1, including sites along the main Beck, but excluding some of FR's originally preferred sites and including in their place others which appear more useful based on the revised calibration.
4	As case 3, but excluding sites along the main Beck
5	As case 1, but only 100 or so debris dam sites in the Cropton Forest estate
6	As case 2, but only 100 or so debris dam sites in the Cropton Forest estate
7	As case 3, but only 100 or so debris dam sites in the Cropton Forest estate
8	As case 4, but only 100 or so debris dam sites in the Cropton Forest estate

4.6 Summary findings for 2007 event

In spite of the reduction in effectiveness of the crims that appears to occur following the correction of the Levisham Beck groundwater flow problem and after recalibrating for a lower peak discharge (discussed in Section 3 above), OVERFLOW presently predicts that suitable arrangements of crims and extra woody debris dams in Cropton Forest should be able to reduce both peak discharge at Pickering and the overall excess flood volume in a June 2007 type flood event. It seems likely that, for the reasons stated above, the model is somewhat under-predicting the effectiveness of these measures. That aside, the widest implementation of the measures, at all possible neutral and advantageous sites, and at all of the possible Cropton Forest estate dam sites, as detailed in Table 4 (cases 1 and 3), leads to a reduction in peak discharge in Pickering of the order of 2.5–3.0 cumecs, as shown by the results in Table 5. Similarly, if the widest implementation is applied (again, cases 1 and 3), the potential excess flood volume reduction with these measures appears to be about 100,000 m^3. The flow discharge curves are shown in Figure 11, and cumulative excess flood volume curves in Figure 12.

The results also indicate, however, much lower benefits from these measures if sites along the main course of the Beck are not used, the reduction in effectiveness being about ⅔ of the figures stated above. If the Cropton estate debris dam total is limited to 100 or so dams, then the effectiveness also falls, although this effect is not as marked as that predicted by removing the main Beck sites.

Table 5: Summary of main results from running cases 1 to 8 (Table 4, *q.v.*), to simulate the testing of different combinations of crims and extra debris dam sections during a June 2007 flood event.

Case (See also table 4)	Peak discharge, cumecs	Flood volume reduction 000s m^3
Base case – no interventions	29.5	-
Case 1: all sites, including the main Beck and FR's preferred sites based on the first calibration and initial assessment of the crims	26.7	94
Case 2: as case 1, but excluding sites along the main Beck	28.5	24
Case 3: as case 1, but excluding some of FR's first preferred sites and including instead others which appear more useful based on the revised calibration.	26.5	98
Case 4: as case 3, but excluding sites along the main Beck	28.4	29
Case 5: as case 1, but only c. 100 debris dam sites in the Cropton Forest estate	27.4	51
Case 6: as case 2, but only c. 100 debris dam sites in the Cropton Forest estate	28.6	20
Case 7: as case 3, but only c. 100 debris dam sites in the Cropton Forest estate	27.3	53
Case 8: as case 4, but only c. 100 debris dam sites in the Cropton Forest estate	28.7	23

Discharge, cumecs

Test runs for the June 2007 flood, showing the effect of different intervention combinations on discharge at Ropery Bridge. For clarity, only output above 12 cumecs is shown. See text for explanation of the intervention arrangement in each case.

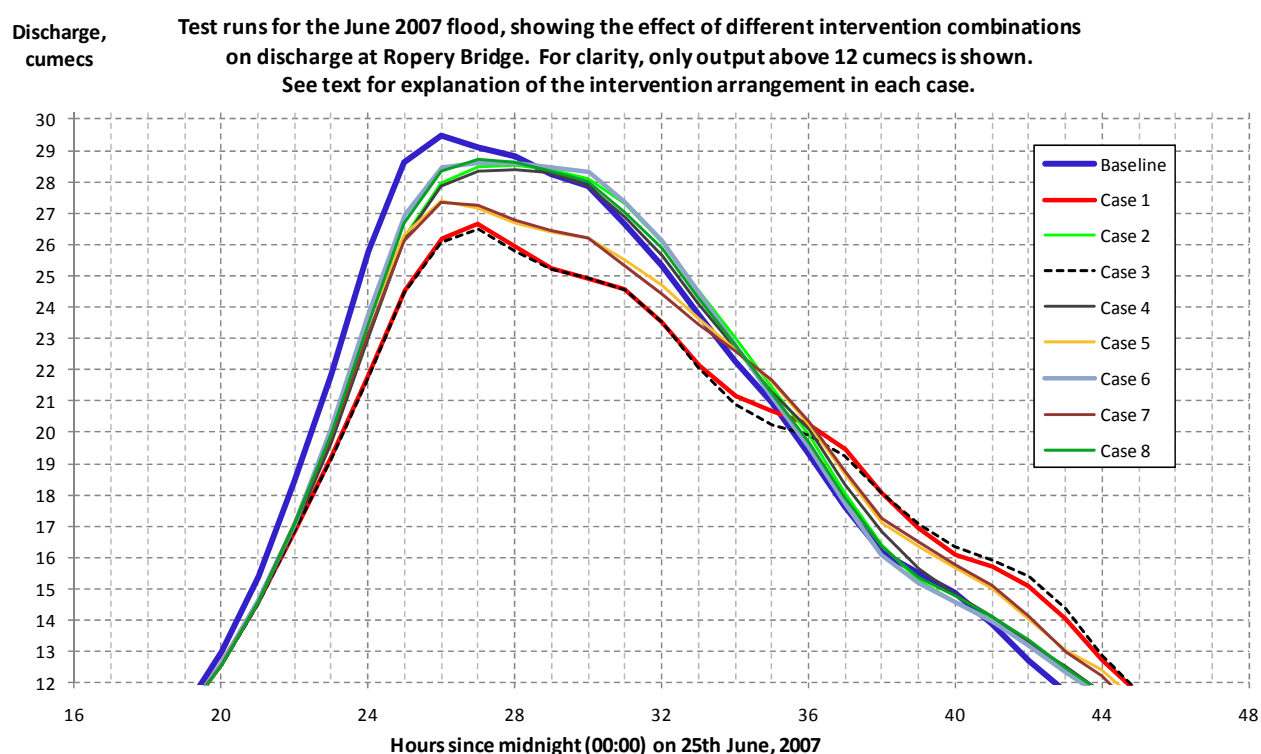**Hours since midnight (00:00) on 25th June, 2007**

Figure 11: Predicted discharge results at Ropery Bridge during the simulated June 2007 flood for the 8 test cases listed in Table 4, to explore the effects of different crim and debris dam section combinations. The base case result is also shown for comparison. Each curve is the mean of the 200 calibrated runs for that intervention case.

Test runs for the June 2007 flood, showing the effect of different intervention combinations on cumulative excess flood volume. Assumed 'flood critical' discharge is 15 cumecs; see text for explanation of the intervention arrangement in each case.
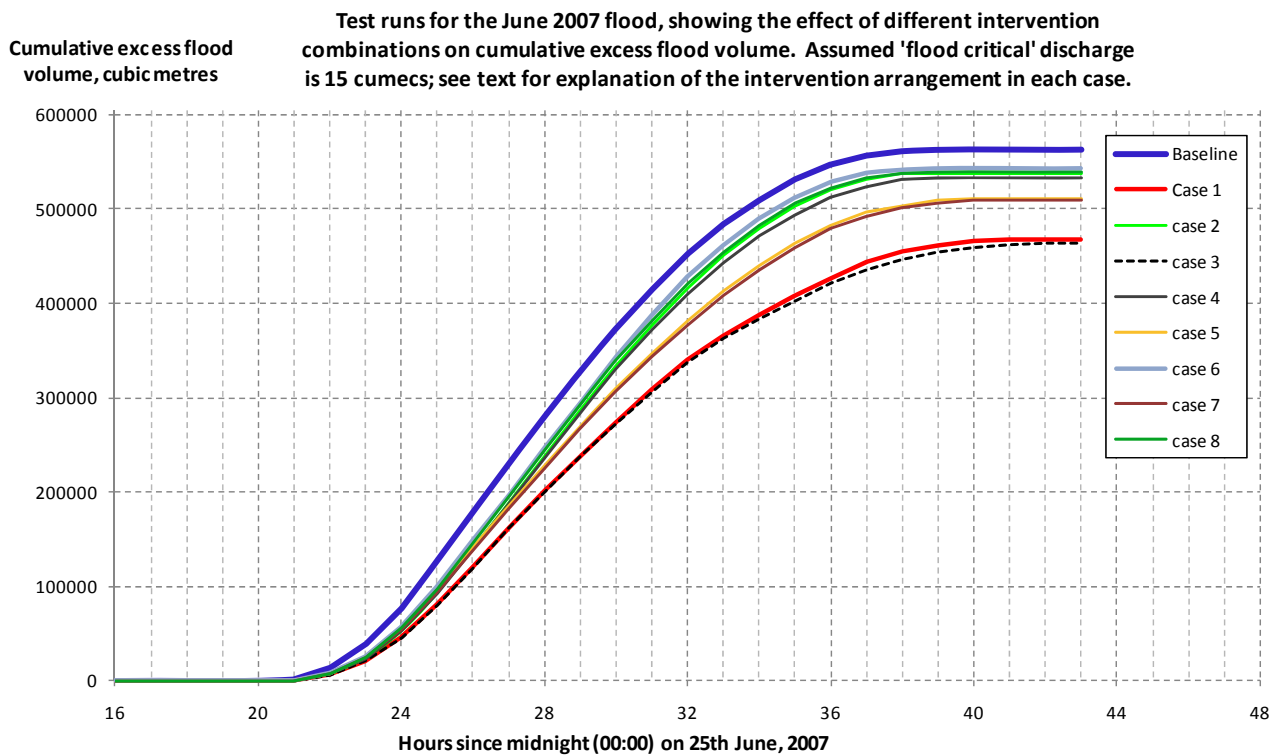
Figure 12: Predicted cumulative excess flood volumes at Pickering during the simulated June 2007 flood for the 8 test cases listed in Table 4, to explore the effects of different crim and debris dam section combinations, and assuming a flood critical discharge of 15 cumecs. The base case result is also shown for comparison. Each curve is derived by summing from the mean discharge curve of the 200 calibrated runs for that intervention case.

Another point needs comment here. Drawing on results from wider explorations conducted earlier (for simplicity and reasons of space not reported) as well as these results, it appears to be important that debris dams sections be used with overbank sections (buffer strips) if possible. Although debris dams exert by far the stronger effect of the two factors in a crim, their effectiveness in slowing the flow is increased where there is an accompanying buffer strip.

5. Extension to the November 2000 event

5.1 Setting up for calibration

The results reported above are derived by setting up the model specifically to simulate the June 2007 flood event, so it is important to consider how the crims and debris dam sections would affect the flows during a different flood. Of particular importance is a simple question: *do the optimum locations of interventions remain the same for smaller floods, with different characteristics, as larger floods?* If they do remain the same, then the interventions are robust. A secondary question is what impact these interventions have upon smaller floods.

Of those floods in the records, the one of August 2002 appeared particularly suitable as a comparator, being an event with one main flood peak, but regrettably there are problems with the stage record that make it very difficult to derive a usable discharge curve at Ropery Bridge. The 1999 flood would also be useful, but at time of writing we have no rainfall data for that event. However, we do have rain and stage data for the major event in autumn, 2000. This is not ideal as a comparator, as it was very different in character from the 2007 flood. In particular, there are in fact three distinct floods, one at the end of October, and then two more in close succession, around 6th and 8th November, the biggest being the last. The discharge curve shows clearly that there must have been a much greater baseflow component in the second and third events, both of which were imposed upon the recession limb of the preceding flood hydrograph. Also, the catchment appears to have been much wetter generally than during June 2007, with much higher runoff percentages, around or over 80% for the main catchment, perhaps 50% or so for Levisham Beck, and unknown as regards Haugh Howl and Gundale Slack. Moreover, the Ropery discharge curve itself is quite hypothetical, being based on the same relationship used to derive the 2007 flood event curve, whereas the possibility arises that this is not correct and is introducing significant bias (under or over estimation).   Despite all these difficulties, it was decided to attempt a calibration for the November 2000 floods, trying to model the double peak of the latter two floods, and including a high baseflow rain input to the model to simulate estimated baseflow throughout (about 3 cumecs over the four days, compared with only about 0.5-1 cumec for the June 2007 event). The rainfall and discharge curves for these floods are plotted together in Figure 13.

Discharge curve at Ropery Bridge, Pickering, 5th-10th November, 2000, inferred from the gauged stage record, together with the mean hourly rainfall of the Brown Howe and Keld Head gauges.
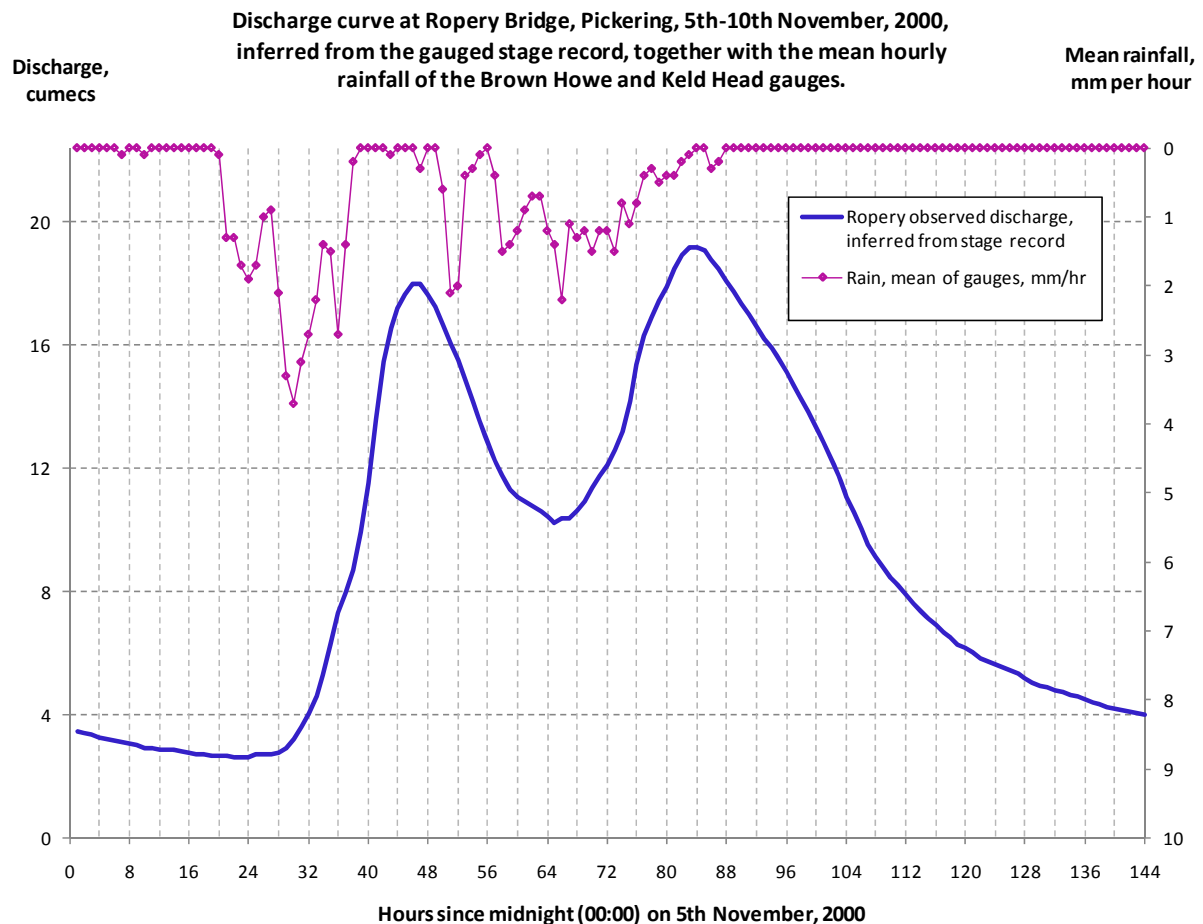

Figure 13: Ropery Bridge revised stream discharge record for the November, 2000 floods, together with the mean gauged hourly rainfall of the Keld Head and Brown Howe gauges. As with the 2007 flood (Figure 4 *q.v.*), analysis of these figures, and similar figures from other high flow events at Pickering, allows an estimation of the percentage runoff to be made for this event, and also of the baseflow component of discharge during the flood.

5.2   Calibration results

A similar approach was used to calibrating the model for the June 2007 flood, deriving Nash-Sutcliffe indices, one for the first flood and then another index for the second, with an overlap in the interim. The best 200 calibrations were then chosen, and the mean of the 200 used as the base case simulation to compare with the observed. These curves are plotted in Figure 14, from which it can be seen that the calibration was not as good as that achieved for the 2007 flood (N-S indices generally in the 0.7-0.8 range, rather than well above 0.9 for the 2007 flood, although these lower values would be considered acceptable by hydrological modellers). The inability to capture the smoothness of both curves, and also the rise in the peak discharge for the second event, even though the rainfall total was somewhat lower during that flood, suggests some errors in model setup, including the omission of Haugh Howl and Gundale Slack. Despite these problems, however, the calibration is good enough to give a reasonable idea of how crims and debris dam sections may affect the flows during these floods.

Modelled discharge curve at Ropery Bridge, Pickering, 5th-10th November, 2000, generated by OVERFLOW, compared with the discharge inferred from the gauge record. The predicted curve is the mean of 200 calibrated runs with the model .
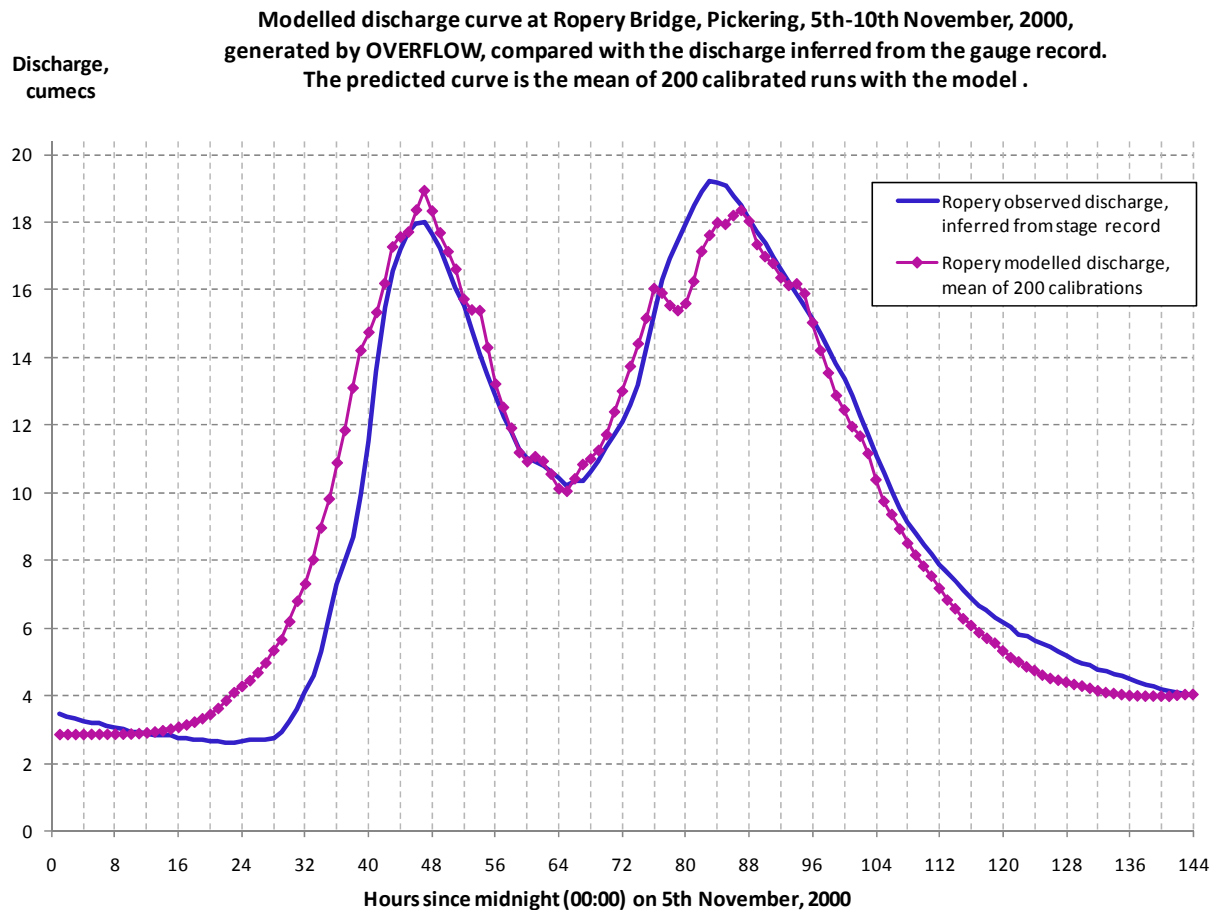
Figure 14: The calibration for the November 2000 floods, showing the Ropery Bridge inferred stream discharge record, together with the mean predicted discharge from 200 calibrations with the model. As with the 2007 flood, the modelled discharge now forms the 'base case', against which the results obtained from the various intervention measures are tested and compared.

5.3   Comparison of 2000 event CRIM locations with those for 2007

As before, each crim and debris dam section was tested individually, as described in Section 4.4, using the maximum case values for the overbank and debris dam sections ($+\alpha$). Again, it should be noted that the extreme high case values are only used here to help demonstrate as clearly as possible the likely effect of each intervention site on its own. The crims were then rated as positive, neutral or negative, this time trying to take into account not simply any reduction in peak mean discharge, but also in peak median discharge, as well as in the excess flood volume. The judgment in many instances was to treat a site as neutral as the various metrics did not indicate clearly enough whether a positive or negative assignation was correct. However, the resulting pattern, shown here in Figure 15, is quite similar to that in Figure 10 for the 2007 flood, in that the negative sites are mainly in the southern third of the catchment and the positive ones in the northern half.
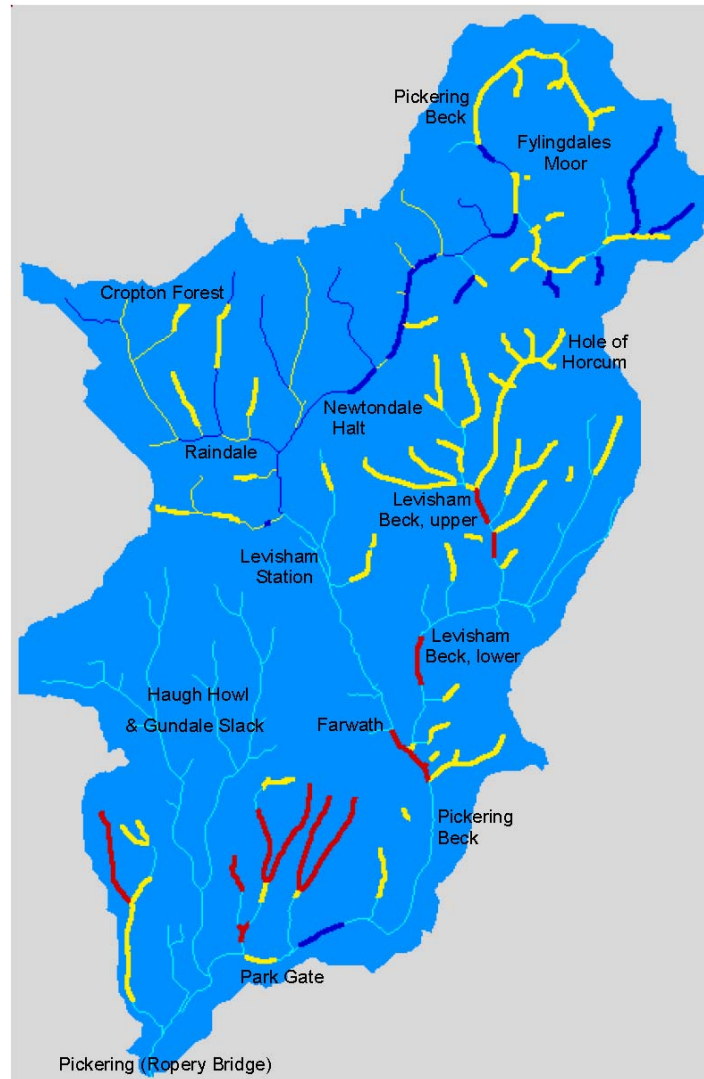
Figure 15: Initial assessment of the individual influence of each crim and additional debris dam section proposed by Forest Research in the catchment of Pickering Beck, with respect to the November 2000 flood event. Crims and sections marked in thin or thick dark blue are 'positive' i.e. they are generally suitable for placement of intervention measures, since they are predicted by OVERFLOW to reduce the peak mean discharge or excess flood volume. Sites marked in yellow are broadly neutral, and appear to have little effect one way or the other. Sites marked in red are clearly negative, interventions there causing an increase in peak mean discharge or excess flood volume. Note that the two sites along the main course of the Beck near Park Gate (close to Pickering, one site positive and the other neutral) are very similar in location to the proposed bunding sites being investigated by the Environment Agency. Place locations for general guidance only; scale as in Figure 2.

A further comment is needed here. Referring to Figure 10, the negative sites close to the town, in the tributaries to the West of Park Gate, reflect the fact that any delaying effect they exert on the flow is almost always likely to make the flood problem worse, making the proximal wave more coincident temporally with the flood wave coming down the main system, unless the latter is itself considerably delayed by many interventions higher up the catchment. By contrast, referring to Figure 15, several of the crim sites in Levisham Beck that were positive in the 2007 event now appear to be negative. This is not necessarily a problem though, as these have many other possible sites upstream of them, in the lower order reaches leading up to the Hole of Horcum for example, that could be used to slow the flow. In this way, there may be an interaction effect between the use of the crims here such that, in combination, the overall effect along the Levisham Beck crims is still positive, reducing peak mean discharge and excess flood volume in Pickering.

5.4 Results from crim combinations, cases 1 to 8, for the 2000 floods[1]

The results are summarised and plotted here in the same way as for the 2007 event, but separated for individual flood peaks. Each case is run using the same Manning's *n* values used for the intervention measures in simulating the 2007 flood viz. the upper working values (+1 design level) as listed in Table 3. The main results are summarised in Table 6, and the discharge and cumulative excess flood volume curves are shown in Figures 16 to 19.

Notwithstanding the slightly poorer calibration results, the findings show that, as with the 2007 flood, it is better to use more dams rather than fewer, and to use the sites along the main Beck if possible. With regard to peak discharge, the reduction in effectiveness through not using sites along the Beck is broadly the same as it is for the 2007 flood: about ⅔ of the effect of the interventions is lost if the Beck sites are not used. The loss of effectiveness if restricting the number of dams in the Forestry Commission's Cropton Forest estate to only 100 or so is much more marked, however. For the 2007 flood, comparing cases 1 and 3 with cases 5 and 7 (all including the main Beck), about 40% of the effect is lost by reducing the number of dams, whereas for the 2000 floods and the same case comparisons, across both flood peaks, about 60% of the effect is lost. For cases 2 and 4 compared with cases 6 and 8 (all excluding the main Beck), only about 15% of effectiveness is lost in 2007 by restricting the number of debris dams, whereas the same restriction in 2000 cancels out their effect, and actually reverses it in cases 6 and 8 for the earlier of the 2000 floods.

All the intervention cases in the 2000 floods demonstrate a reduction in peak mean discharge compared with the base case, although the range of the reductions achieved across the two flood peaks – between 1.5 and 0.1 cumecs – is noticeably lower than was achieved for the 2007 flood. Similarly, the excess flood volume reductions are also smaller than for the 2007 flood, ranging between about 58,000 m^3 to a net increase of about 5,000 m^3. The fact that two of the cases, 6 and 8, appear to increase marginally the excess flood volume, albeit for the first flood only, is difficult to explain, particularly since the flood peak discharge is reduced in all cases; possibly it arises as an artefact of the model set up used for the 2000 event and the poorer calibration achieved compared with the 2007 flood.

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[1] The calibration results obtained simulating the November, 2000 floods were generated during the main research phase of the project work and, as with the 2007 flood, were based on best judgement of the conditions pertaining during those floods and estimates of the applicable flow data at the time, including the possibility of bypass flows at Ropery Bridge. The calibration results and the outcome of the tests of the interventions to which it was applied are included in the main body of the report as presented here. However, subsequent to completion of the research and the writing of the report, the Environment Agency submitted a special request for an updated calibration exercise to be conducted, based on a reassessment of the flow data at Ropery Bridge, and for use specifically by the Environment Agency in their hydraulic modelling of the effects of the main bunds near the town. The eight test cases of the interventions were also re-run, but this time applying the revised calibration. We have noted from the results obtained thereby that there are some differences between the initial calibration of OVERFLOW for the 2000 floods and the later calibration for the Environment Agency, in particular that discharges generally are somewhat lower (c. 1-2 cumecs) in the revised calibration. Notwithstanding these differences, we see nothing in the revised calibration or in the test case results based on it to alter our main interpretations of the effects of the crims and additional LWD dams on reducing flood risk. Accordingly, the main findings and conclusions in the report remain unchanged.

Table 6: Main results for the 8 combination trial cases listed in Table 4, arising from the simulated floods on 6th-7th and 8th-9th November, 2000. Two of the intervention cases, numbers 6 and 8, are just negative during the first flood in terms of total excess flood volume i.e. they increase the excess flood volume very slightly (but see text).

Case (combination trial)	5th-6th November flood		8th-9th November flood	
	Peak discharge, cumecs	Flood volume reduction 000s m³	Peak discharge, cumecs	Flood volume reduction 000s m³
Base case – no interventions	18.9		18.3	
Case 1: all sites, including the main Beck and FR's preferred sites based on the first calibration and initial assessment of the crims	17.4	38	17.6	19
Case 2: as case 1, but excluding sites along the main Beck	18.5	5	18.0	4
Case 3: as case 1, but excluding some of FR's first preferred sites and including instead others which appear more useful based on the revised calibration.	17.5	37	17.5	18
Case 4: as case 3, but excluding sites along the main Beck	18.5	5	18.0	5
Case 5: as case 1, but only c. 100 debris dam sites in the Cropton Forest estate	18.2	13	18.0	14
Case 6: as case 2, but only c. 100 debris dam sites in the Cropton Forest estate	18.8	5 (increase)	18.2	0
Case 7: as case 3, but only c. 100 debris dam sites in the Cropton Forest estate	18.1	15	18.0	16
Case 8: as case 4, but only c. 100 debris dam sites in the Cropton Forest estate	18.7	3 (increase)	18.2	1
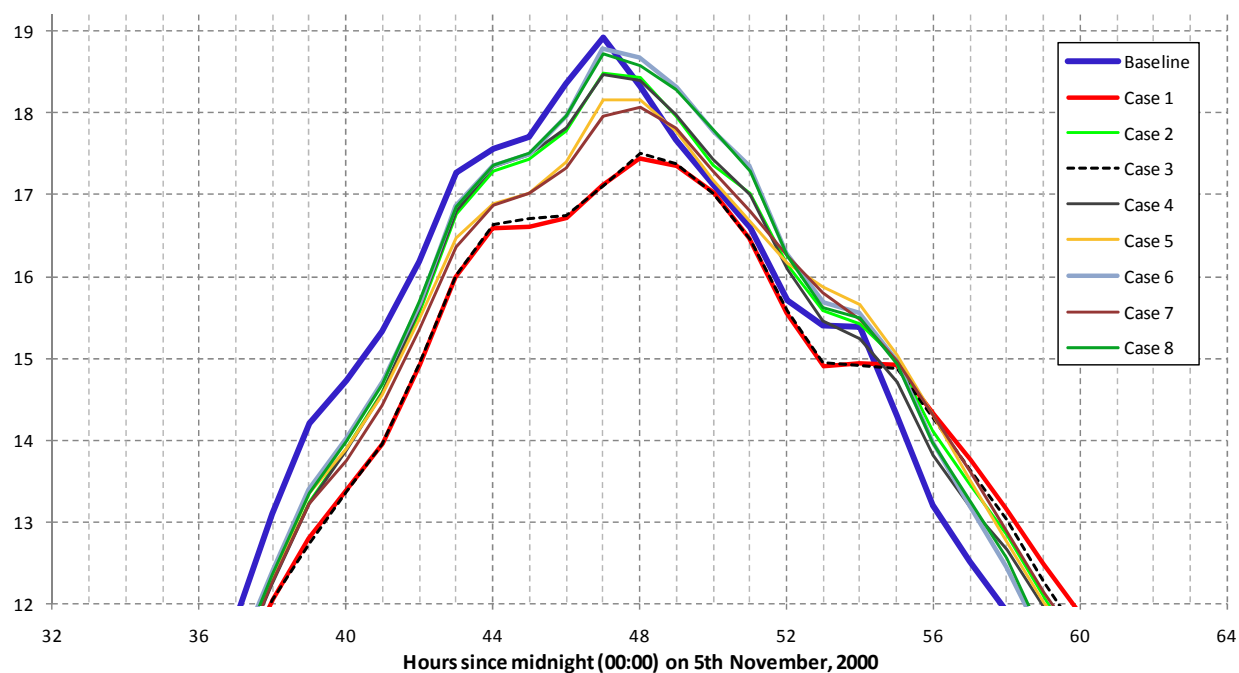
Figure 16: Predicted discharge results at Ropery Bridge during the simulated 6th-7th November 2000 flood for the 8 test cases listed in Table 4, to explore the effects of different crim and debris dam section combinations. The base case result is also shown for comparison. Each curve is the mean of the 200 calibrated runs for that intervention case.
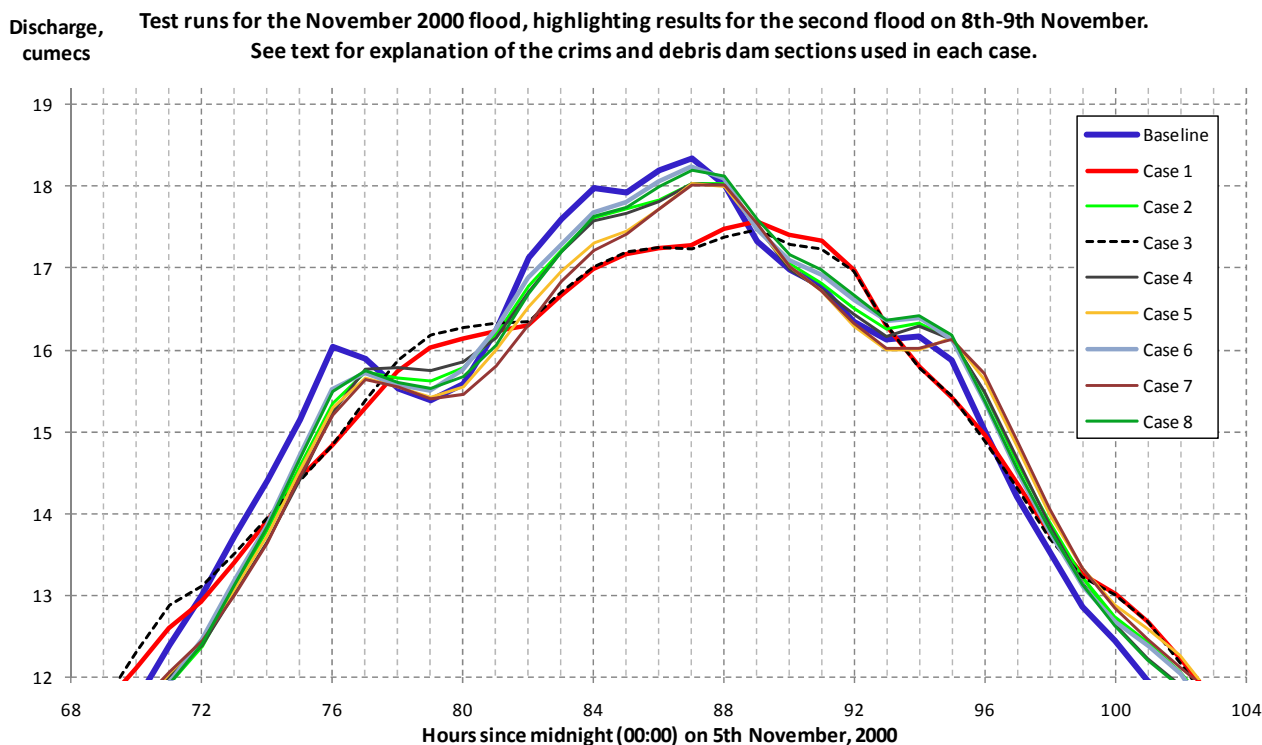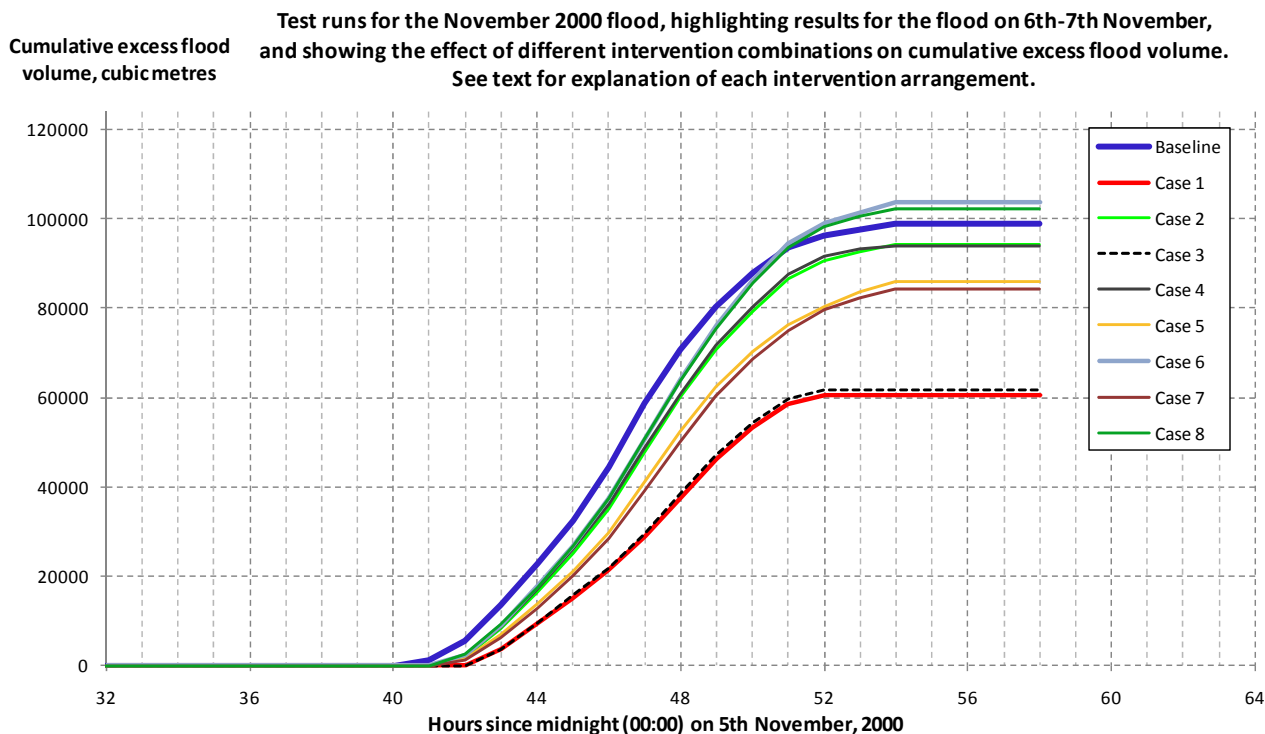
Figure 17: Predicted discharge results at Ropery Bridge during the simulated 8th-9th November 2000 flood for the 8 test cases listed in Table 4, to explore the effects of different crim and debris dam section combinations. The base case result is also shown for comparison. Each curve is the mean of the 200 calibrated runs for that intervention case.

Figure 18: Predicted cumulative excess flood volumes at Pickering during the simulated 6th-7th November 2000 flood for the 8 test cases listed in Table 4, to explore the effects of different crim and debris dam section combinations, and assuming a flood critical discharge of 15 cumecs. The base case result is also shown for comparison. Each curve is derived by summing from the mean discharge curve of the 200 calibrated runs for that intervention case.

Figure 19: Predicted cumulative excess flood volumes at Pickering during the simulated 8th-9th November 2000 flood for the 8 test cases listed in Table 4, to explore the effects of different crim and debris dam section combinations, and assuming a flood critical discharge of 15 cumecs. The base case result is also shown for comparison. Each curve is derived by summing from the mean discharge curve of the 200 calibrated runs for that intervention case.

6.   Conclusions

Two important points emerge from this study:

- First, although the results from the 2000 event tests do not conform exactly with those for 2007, and there are some problems with the model set up and calibration for the 2000 event tests, there is nothing in the results that suggests a serious difference between the effects of the interventions when comparing the two modelled events. Thus, the arrangements of the interventions that appear to work best for one event also appear to work best for the other. Also, there is nothing to suggest that the crim and debris dam section arrangements being considered in the test cases are materially wrong or should not be used.

- Second, the sizes of the peak flow and excess flood volume reductions are lower for *smaller* events. This is an important property of the kinds of interventions being discussed: as the size of the event increases, so the contribution that the interventions make to reducing flood risk increases. It arises from the fact that bigger events are more able to transfer water into the interventions (e.g. the crims) and reflects the general property of the Pickering Beck system *viz.* that the river is relatively incised into floodplain material, reducing the natural attenuating effect of floodplains on peak flows. However, this is also a different effect to what is observed in other interventions (e.g. bunds), where the effectiveness of the measure decreases as the size of the flow peak increases.

Of the other findings from this study, an important conclusion is that some sites are clearly more useful at reducing flood risk than others, and some sites should be avoided as they are always likely to increase rather than reduce flood risk. Better locations for intervention are to be found in the upper half of the catchment, whereas tributaries and low order streams close to the town should not be used. Moreover, even sites that appear to be negative (to increase flood risk) if used in isolation may turn out to have a positive effect if used in the correct combination with other sites upstream of them. This is something that needs to be assessed carefully, however, by running test cases where the effect of these combinations can be demonstrated.

With regard to the nature of the interventions, debris dam sections appear to be more useful generally than overbank sections (buffer strips), the former exerting a much stronger effect than the latter on attenuating and slowing flows. However, if debris dam and overbank sections can be used together, in a crim for example, the attenuating effect is increased. This implies that crims should used where possible, rather than isolated debris dam sections. The other finding to note here is that more dams should be used in a debris dam section if the situation allows i.e. they should be installed or allowed to evolve at their highest spatial density, so as to maximise the attenuation from the debris dam section.

In relation to Pickering specifically, the research here shows that with respect to a 2007 type flood event, peak flow reductions ranging between about 0.8 to 3.0 cumecs may be possible from a suitably arranged set of intervention measures in the catchment, with excess flood volumes reduced accordingly, although the value of the latter depends up the estimate of flood critical discharge. If the 15 cumecs estimate is accepted, then the excess flood volume reductions range between about 20,000 and 100,000 m^3 for a 2007 type flood event. For the smaller, November 2000 event, the same intervention measures lower the peak discharge and excess flood volume, but to a lesser extent.

7. References

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Leopold, L.B. and Maddock, T., 1953. The hydraulic geometry of stream channels and some physiographic implications. *U.S. Geological Survey Professional Paper* no. **252**, 56 pages.

Linstead, C. and Gurnell, A.M., 1998. Large woody debris in British headwater rivers: Physical habitat and management guidelines. R&D Technical Report W185, School of Geography and Environmental Sciences, University of Birmingham.

APPENDIX: Details of the simulated intervention cases, nos. 1 to 8 (Table 4 *q.v.*)

The figures here are provided to clarify the intervention arrangements listed in Table 4.
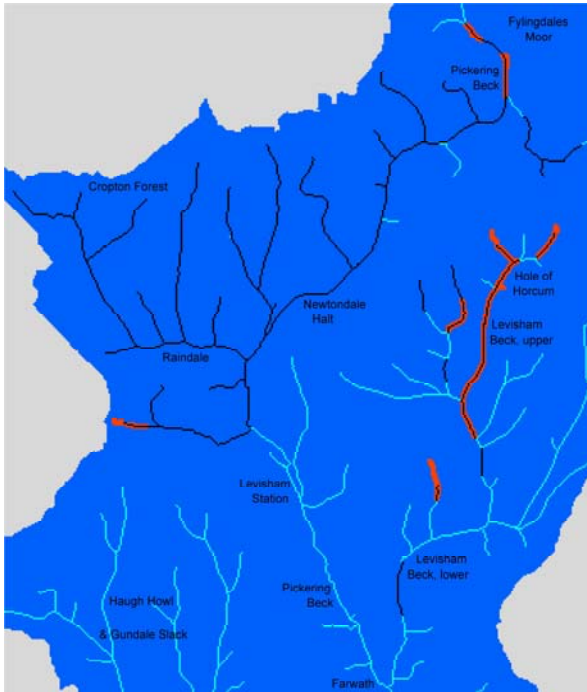
Figure A1: arrangement of interventions in case 1, overbank and debris dam sections shown respectively in pink and black, perennial channels in pale blue, with place locations for general guidance.
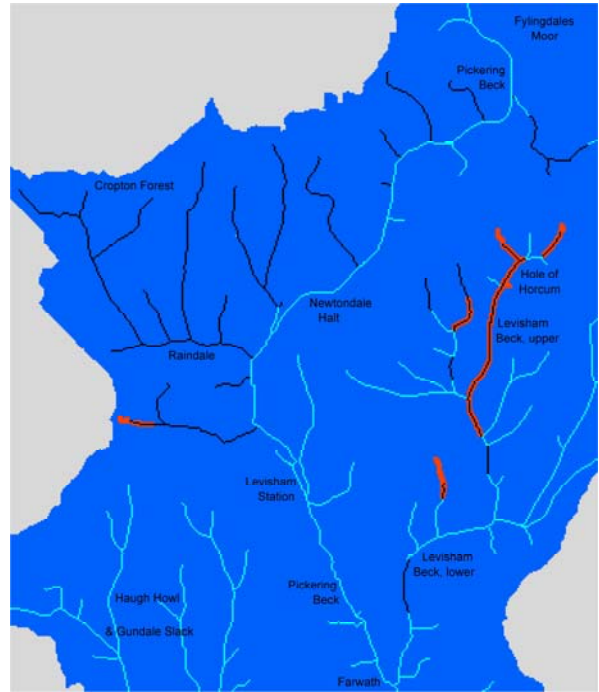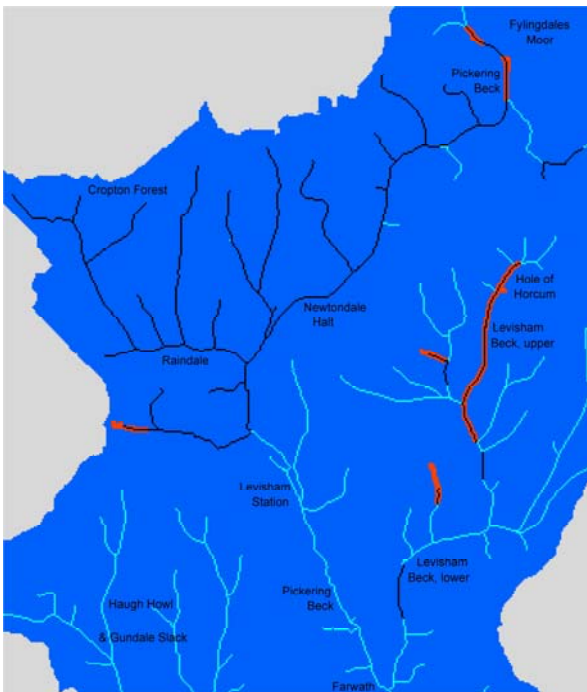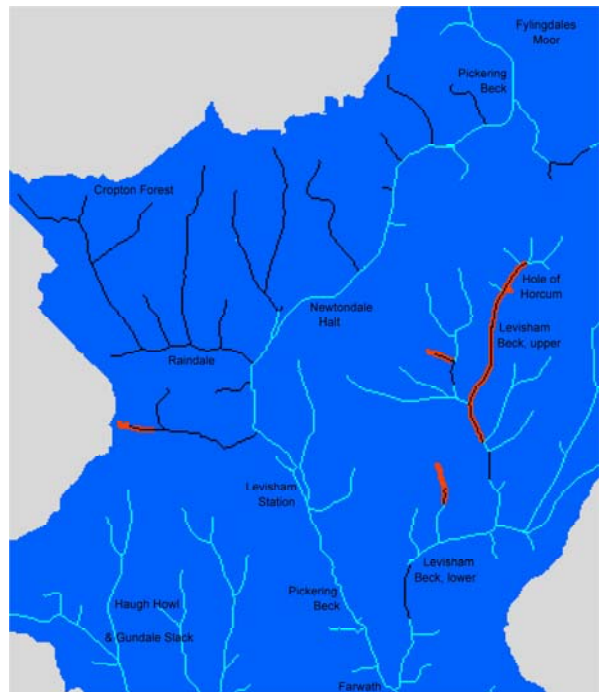

Figure A2: arrangement of interventions in case 2, overbank and debris dam sections shown respectively in pink and black, perennial channels in pale blue, with place locations for general guidance.
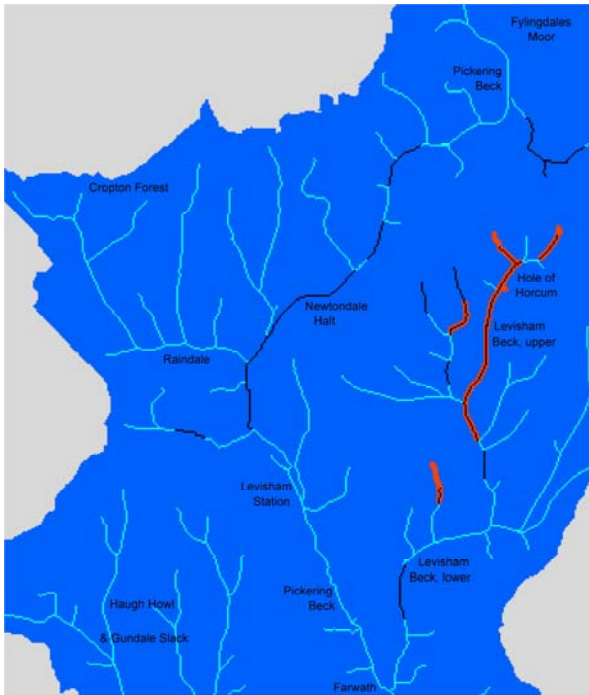

Figure A3: arrangement of interventions in case 3, overbank and debris dam sections shown respectively in pink and black, perennial channels in pale blue, with place locations for general guidance.

Figure A4: arrangement of interventions in case 4, overbank and debris dam sections shown respectively in pink and black, perennial channels in pale blue, with place locations for general guidance.
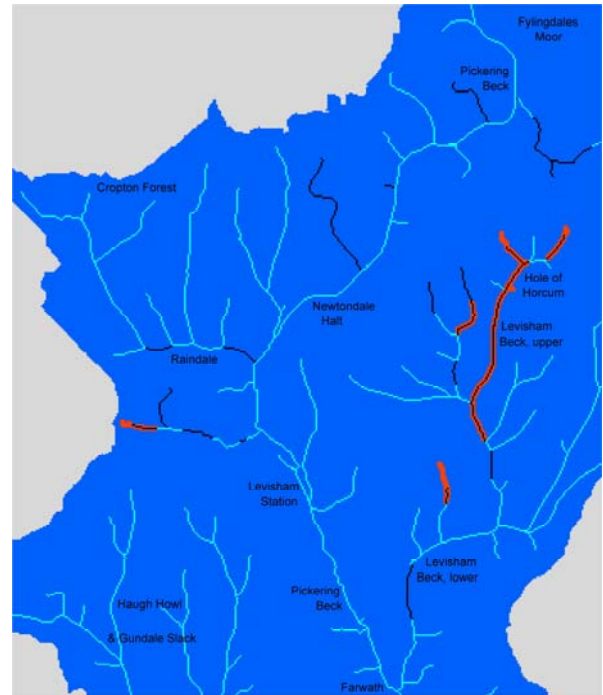
Figure A5: arrangement of interventions in case 5, overbank and debris dam sections shown respectively in pink and black, perennial channels in pale blue, with place locations for general guidance.

Figure A6: arrangement of interventions in case 6, overbank and debris dam sections shown respectively in pink and black, perennial channels in pale blue, with place locations for general guidance.
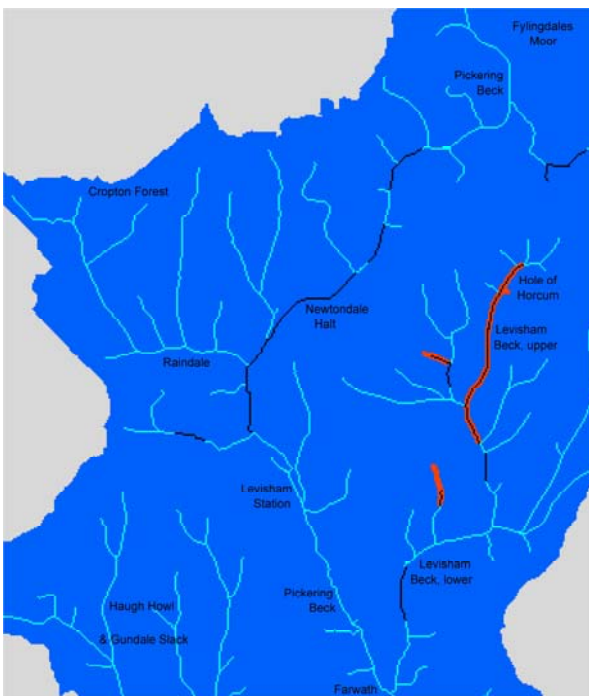

Figure A7: arrangement of interventions in case 7, overbank and debris dam sections shown respectively in pink and black, perennial channels in pale blue, with place locations for general guidance.
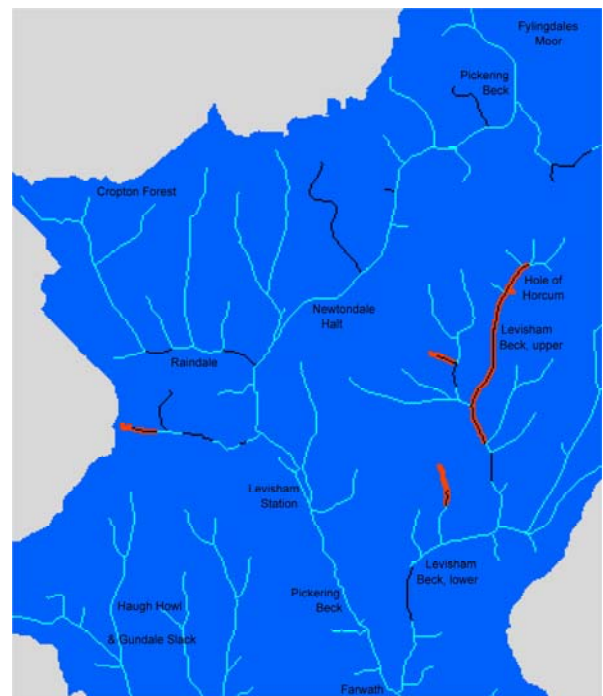

Figure A8: arrangement of interventions in case 8, overbank and debris dam sections shown respectively in pink and black, perennial channels in pale blue, with place locations for general guidance.