Summary Short Study:

"A modelling study and investigation into how annual burning on the Walshaw Moor estate may affect high river flows in Hebden Bridge."

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<u>Introductory notes/cover points:</u>
(i) in this summary, "WME" means 'Walshaw Moor Estate', and likewise "HB", Hebden Bridge;
ii) further details of assumptions, model set up, results, etc. are available on request.

AIM: simulate the effects of annual patch burning on the WME; use OVERFLOW[1] to generate flow hydrographs at HB; compare peak flows under different burn cases with the base case (control) peak flow; from the results assess whether burns are likely to raise or lower peak flows, and by how much.

MODEL SET UP: use a 50 m source DEM of the whole HB catchment, with the channel network and geometry inferred therefrom; devise a base case 'Manning map' - the '***grass-heather***' case - for the whole of the catchment, comprising a mix of cotton and moor grass species and heather; trees and woodland ignored (omitted) from the modelling; reservoirs assumed to be storage-neutral and to allow unimpeded through passage of water; channels all assumed to be unimpeded and allow free flowing, open passage of water; grips, ditches and drains ignored; bankside areas all assumed to be unimpeded and free flowing; use Natural England images to derive and map the approximate outline and extent of the WME for implementation in the model and simulations.

MAIN RAINFALL-RUNOFF SCENARIO: run the numerical experiment (simulations) as an uncalibrated model application, using a hypothetical rainfall-runoff scenario (no observed data available at the time the work was conducted and during first writing of this Summary); rainfall is assumed as a steady, wet day, based on a multiple of the observed rain at Pickering, North Yorkshire, on Christmas and Boxing Day, 2015; total applied rainfall *c.* 73 mm over the first 24 hours, and a total *c.* 82 mm over 29 hrs; prior ground condition assumed to be thoroughly wet following weeks of rainy weather.

SIMULATING 'BURN' CASES: Manning's '*n*' relationships for burnt ground derived using data in Holden *et al.* (2008)[2]; segment hillslope[3] burns mapped according to the geomorphology of the catchment and structure of the stream network; patch burns mapped as random patches of cells within larger, 250 m x 250 m blocks, these in turn randomly sited in the WME; simulate 1st - burns of each individual segment hillslope; 2nd - burns of 2%, 4%, 6% and 8% of the area of the WME; 3rd - long period burns (10-18 yrs) using the same annual percentage burns as before, with burn effect periods of 4, 8 and 12 years, the burn effect declining inverse exponentially as the vegetation recovers; assume vegetation recovers to its previous, unburnt condition at the end of the burn effect period; run replicates of simulations to stabilise variance in results; assume that no over-burning[4] is allowed; assume that no burning is allowed in any cells immediately next to streams or water bodies; assume that no burning occurs on any part of the catchment of the Hebden Water outside the boundaries of the WME.

MAIN RESULTS (details available on request):

NOTE: the stage heights are estimates only, being the middle value from a range of stage height calculations at HB based on the supposed hydraulic geometry of the channel there, and ignoring possible backwatering effects during high flows caused by the Hebden Water flowing into the River Calder

1. ***Whole segment hillslopes, tested one at a time.***
(a) Burns in 63 of 68 individual segment hillslopes increase flow peaks in HB (mean increase is 0.04 cumecs, 0.1 cm; max. increase 0.146 cumecs, 0.4 cm). (b) There is a clear positive correlation between the hillslope area burnt and the increase in the flow peak (R^2 of 0.29, p<<0.001). (c) In the other 5 segment hillslopes, complete burns *reduce* the peak flow, but the reduction in each case is negligible (<0.003 cumecs, <0.01 cm).

2. ***Grouped patch burns, total area of burns ranging from 2%-8% of the area of the WME.***
(a) All combinations and spatial arrangements of burn patches raise the peak flow in HB (2% burns, mean increase 0.07 cumecs, 0.2 cm; 4% burns, mean increase 0.15 cumecs, 0.4 cm; 6% burns, mean increase 0.22 cumecs, 0.6 cm; and 8% burns, mean increase 0.30 cumecs, 0.8 cm). (b) There is a strong correlation of the total area burned in patches with the increase in the flow peak (R^2 of nearly 1.00, p<<0.001).

3. ***Grouped patch burns, 2%-8% annual burn areas as above; burn effect periods lasting 4, 8 and 12 years, but with exponential declining effect as the patch vegetation recovers to its prior, unburnt condition; simulations run for 6 years beyond whole burn effect (vegetation recovery) cycle to explore wider long term effects.***
(a) The effect of long term burning and burn rotation management at a given annual percentage rate is roughly double that of the same percentage burn area for one year only. This is found for all burn effect and vegetation recovery periods. For a 2% annual burn area, the mean increase in the flow peak at HB is *c.* 0.14 cumecs (0.4 cm), 1.95 times the effect of a single 2% burn; for a 4% annual burn area, the equivalent figures are 0.30 cumecs (0.8 cm) and 2.02 times; for 6%, 0.46 cumecs (1.2 cm) and 2.07 times; and for 8%, 0.61 cumecs (1.6 cm) and 2.07 times. (b) For a given annual percentage burn area, the increase in the flow peak is itself increased by lengthening the burn effect and vegetation recovery time, although the additional effect is *c.* 1/10th that of applying long term burn rotations. Together, the annual percentage burn area and burn effect (recovery) account for most of the variance observed in the flow peak increase at HB (adj. R^2 of *c.* 0.996; for both variables, p<<0.001).

MAIN CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK:

1. Any arrangement of burn patches on the WME, wherever situated, increases the flow peak at HB.

2. There is a clear (p<<0.001) positive correlation between the area burnt each year and the increase in the flow peak at HB. Thus, the bigger the annual burn area, the higher the increase in the flow peak is likely to be compared with the base case. This implies that for the rainfall-runoff scenario modelled here, patch burning on the WME is likely to work in opposition to any measures implemented on the moor to reduce the flood peak at HB.

3. Long term annual burning at a given percentage rate roughly doubles the increase in the HB flow peak compared with a burn of that percentage area for one year only. This result is to be expected because long term rotation burning will increase the overall area of the WME which is to some extent affected by burning, whether a particular patch has only just been burnt or is in partial recovery of the vegetation. Depending upon the density of present and previous burning, therefore, the number of patches so affected by burning may range from between about 20% and 100% of the moor's area.

4. Longer vegetation recovery times also raise the increase in the peak flow predicted at HB, although the effect is about 1/10th of the burn rotation effect. This implies that provided the vegetation in any patch is able to recover fully from previous burns, the increase in the flow peak at HB caused by burn rotation should broadly stabilise over the longer term. This raises the question as to whether repeated burns, over a rotation cycle, themselves affect vegetation recovery times. This is possibly significant if the cycle of burning leads to a change in the species cover of burn patches which have been repeatedly burned over decades or longer, although this aspect of the ecology and hydrology of the moor-peatland system has not been explored here.

5. Possible further work to consider: repeat the tests using calibrated applications of the model, the calibrations derived from two or more observed rainfall-runoff events; set up the model to apply to the catchment at a finer spatial resolution, preferably 5 m or 10 m, so that grips and drains can also be modelled and their influence included; incorporate a more nearly correct base case land cover and channel geometry, for example including areas of trees or scrub where known, also areas dominated by *Sphagnum* and bog sympathetic species; also consider incorporating any stream obstructions or local modifications of the flow path or stream geometry. A more detailed study using a model incorporating more complete physics e.g. JFLOW, would also be informative and provide greater physical realism over a wider range of different rainfall-runoff scenarios and prior wetness conditions. Such a model could also possibly incorporate a treatment of reservoir storage and discharges that is more realistic than the 'storage-neutral' treatment used here.

REFERENCES AND GLOSSARY

1. Odoni NA and Lane SN, 2010. Assessment of the Impact of Upstream Land Management Measures on Flood Flows in Pickering Beck using OVERFLOW. Report for Forest Research as part of "Slowing the Flow at Pickering and Sinnington Project"; see http://www.forestry.gov.uk/pdf/stfap_final_report_appendix12_2_Apr2011.pdf/$FILE/stfap_final_report_appendix12_2_Apr2011.pdf

2. Holden J, Kirkby MJ, Lane SN, Milledge DG, Brookes CJ, Holden V, and McDonald AT. 2008. Overland flow velocity and roughness properties in peatlands. *Water Resources Research*, **44**, WO6415, doi: 10.1029/2007WR006052, 2008. 11 pages.

3. "Segment hillslope": every reach in the network receives water from both the upstream reaches flowing into it and the hillslopes adjacent to it, on either side of the channel. The latter are termed 'segment hillslopes'. The area of segment hillslopes varies from one reach to another, owing to the variations in the geomorphology of the landscape and the

connectivity of the stream network. Odoni and Lane (2010), referenced above, provides more explanation.

4. “Over-burning”: where patches are burnt in the long period scenarios (burn rotations), it is assumed that the vegetation cover on the patch recovers over a period of years after the burn. Burning is generally assumed to occur only on patches that have recovered completely from prior burning, so that the vegetation and ground cover have regained the same density and composition as they had before the burn occurred. Over-burning therefore refers to those occurrences of burning of a patch of ground before completion of the recovery cycle, so that full recovery of the vegetation to its prior (unburnt) condition has not been achieved.