Supplementary Work and Conclusions, to accompany the 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."

Date: delivered 21st July, 2016

Author: Dr Nicholas A. Odoni, Honorary Fellow, Department of Geography, Durham University

For (research client): Treesponsibility, 10 Broughton St, HEBDEN BRIDGE, W. Yorkshire, HX7 8JY

Introductory notes/cover points:
(i) except and unless as stated otherwise here, the main assumptions, Aim, Model Setup, Rainfall-Runoff Scenario and method of applying burns in the Simulations are as described in the Summary Short Study;
ii) further details of assumptions, model set up, results, etc. are available on request.

A. OTHER BASE CASES; BURNING VERSUS CONSERVATION

The supplementary work has been conducted to extend the work reported in the Summary Short Study, and in particular to consider the effects of including more *Sphagnum* and bog species in the base case. Rather than assume one base case of this type, however, several have been modelled, as follows:

(a) '***Sphagnum-rich***' base case. Slopes <=5º are modelled with dominant *Sphagnum* and bog species vegetation cover; slopes >5º degrees are modelled with a mix of 50% *Sphagnum* and bog species and 50% cotton and moorland grasses and heather.
(b) '***Sphagnum-intermediate***' base case. Slopes <=5º are modelled with dominant *Sphagnum* and bog species vegetation cover, as in the *Sphagnum*-rich case above; slopes >5º are modelled with a mix of cotton and moorland grasses and heather only, as in the grass-heather base case used in the Summary Short Study (*q.v.*).
(c) '***Sphagnum-poor***' base case. Slopes <=5º are modelled as a mix of 50% *Sphagnum* and bog species and 50% cotton and moorland grasses and heather; slopes >5º are modelled with a mix of cotton and moorland grasses and heather only, as in the grass-heather base case used in the Summary Short Study (*q.v.*).

The results generated using these base cases, whether with or without burning, may be compared with each other and also with the grass-heather base case. The base cases including *Sphagnum* may also be viewed as set of possible conservation or restoration conditions on the moor i.e. what the WME and the wider catchment of the Hebden Water may develop into if burning is reduced or ceases altogether, and *Sphagnum* and bog species are encouraged to grow in place of the cotton and moorland grasses and heather.

Before considering burning or conservation, the peak flows generated by the additional *Sphagnum* base cases are of interest. Under the *Sphagnum*-rich case, the peak flow is 38.74 cumecs; for the *Sphagnum*-intermediate case, 40.45 cumecs; and for the *Sphagnum*-poor case, 42.03 cumecs. By comparison, the peak flow at HB under the grass-heather base case is 43.94 cumecs, which is 5.20 cumecs (*c.* 14 cm) higher than under the *Sphagnum*-rich case, 3.49 cumecs (*c.* 9.5 cm) higher than under the *Sphagnum*-intermediate case, and 1.91 cumecs (*c.* 5.1 cm) higher than under the *Sphagnum*-poor case. The effect of increasing *Sphagnum* and bog species is therefore to reduce the peak flow and stage height at HB when compared with the grass-heather case or any case including a lower proportion of *Sphagnum* in the vegetation over.

Presenting the burning and conservation interpretations together, when discussing the same or similar burn case simulations and results, is somewhat confusing, so for greater clarity the different emphases are presented separately, dealing first with the effects of burning.

NOTE: as in the Summary Short Study, it is assumed that no burning takes place on the catchment of the Hebden Water outside the boundaries of the WME.

B. ADDITIONAL BURN SIMULATIONS

1. *Single year burns of 2%, 4%, 6% and 8% of the area of the WME.*

(a) *Sphagnum*-poor case
Under a 2% area of burn, the peak flow increases by *c.* 0.08 cumecs (0.2 cm); for 4%, the increase is *c.* 0.17 cumecs (0.5 cm); for 6%, *c.* 0.27 cumecs (0.7 cm); and for 8%, *c.* 0.38 cumecs (1.0 cm).

(b) *Sphagnum*-intermediate case
Under a 2% area of burn, the peak flow increases by *c.* 0.10 cumecs (0.3 cm); for 4%, the increase is *c.* 0.21 cumecs (0.6 cm); for 6%, *c.* 0.30 cumecs (0.8 cm); and for 8%, *c.* 0.40 cumecs (1.1 cm).

(c) *Sphagnum*-rich case
Under a 2% area of burn, the peak flow increases by *c.* 0.12 cumecs (0.3 cm); for 4%, the increase is *c.* 0.25 cumecs (0.7 cm); for 6%, *c.* 0.35 cumecs (0.9 cm); and for 8%, *c.* 0.47 cumecs (1.3 cm).

As in the Summary Short Study, for each of the base cases any burning increases the peak flow and stage at HB. Specifically, there is a strong positive correlation between the area burnt and the size of the increase in the peak flow (all cases combined, adj. R^2 *c.* 0.994, overall $p \ll 0.001$, $p \ll 0.001$ for all variables). There is also a subtler effect caused by increasing the proportion of *Sphagnum* in the base case. Thus, the increase in the peak flow at HB caused by burning in the *Sphagnum*-rich case is *c.* 1.17 times more than in the *Sphagnum*-intermediate case and 1.28 times more than in the *Sphagnum*-poor case; similarly, the increase in the peak flow at HB in the *Sphagnum* intermediate case is *c.* 1.1 times more than in the Sphagnum-poor case. Taking these results together, and other things being equal, the results imply that burning *Sphagnum* has a bigger effect on increasing the flow peak than does burning grass. Similarly, the more *Sphagnum* there is in the catchment generally, albeit dominant or providing part of the ground cover in some areas and absent in others, then the more likely it is that annual burns will have to include some areas of *Sphagnum* and hence the increase in the peak flow will be greater than would be expected if the burn was applied to a moorland vegetated by grass and heather alone.

2. *Burns in long rotations, 2%, 4%, 6% and 8% per year, burn effect periods of 4, 8 and 12 years but declining exponentially, vegetation able to recover fully to its prior condition.*

The results are complicated to present and are therefore tabulated separately for each base case. Also, the *Sphagnum*-rich case probably includes a much greater proportion of bog species than would have been found on the WME at any time in the last 500 or so years[1], so long term rotation burns have not been modelled under this particular base case. This leaves only the *Sphagnum*-poor and *Sphagnum*-intermediate base cases to be considered.

(a) *Sphagnum*-poor case

	Annual burn area, %			
Burn effect, years	**2**	**4**	**6**	**8**
4	0.17 (0.5 cm)	0.35 (0.9 cm)	0.51 (1.4 cm)	0.70 (1.9 cm)
8	0.20 (0.5 cm)	0.35 (0.9 cm)	0.54 (1.4 cm)	0.72 (1.9 cm)
12	0.20 (0.5 cm)	0.40 (1.1 cm)	0.60 (1.6 cm)	0.74 (2.0 cm)

Table 1. Predicted increases in the peak flow at Hebden Bridge, figures in cumecs (stage shown underneath, in cm), as compared with the *Sphagnum*-poor base case (peak flow 42.03 cumecs), after applying long burn rotations on the WME, using different percentages of annual burn and assuming an exponential decline in the burn effect on each burnt patch, with full recovery of the vegetation thereafter to its prior (unburnt) condition.

(b) *Sphagnum*-intermediate case

	Annual burn area, %			
Burn effect, years	**2**	**4**	**6**	**8**
4	0.20 (0.5 cm)	0.37 (1.0 cm)	0.57 (1.5 cm)	0.75 (2.0 cm)
8	0.21 (0.6 cm)	0.41 (1.1 cm)	0.59 (1.6 cm)	0.79 (2.1 cm)
12	0.19 (0.5 cm)	0.43 (1.1 cm)	0.63 (1.7 cm)	0.80 (2.1 cm)

Table 2. Predicted increases in the peak flow at Hebden Bridge, figures in cumecs (stage shown underneath, in cm), as compared with the *Sphagnum*-intermediate base case (peak flow 40.45 cumecs), after applying long burn rotations on the WME, using different percentages of annual burn and assuming an exponential decline in the burn effect on each burnt patch, with full recovery of the vegetation thereafter to its prior (unburnt) condition.

(c) Brief discussion

The pattern of the results under both of the *Sphagnum* base cases above conforms with that found in the Summary Short Study, under the grass-heather case. For a given percentage annual burn, the effect of modelling the burns over a long rotation is roughly to double the increase in the flow peak at HB compared with the increase predicted under one year's burn in isolation (*Sphagnum*-poor, all cases combined, adj. R^2 c. 0.994, overall $p<<0.001$, $p<<0.001$ for all variables; *Sphagnum*-intermediate, R^2 *c.* 0.996 , overall $p<<0.001$, $p<<0.001$ for all variables). There is also a small increase in the effect with lengthening of the time taken for the effects of the burns to be eliminated by recovery of the vegetation to its prior, unburnt condition. The latter finding again conforms with that found in the Summary Short Study, using the grass-heather base case.

C. BURNING *vs* MANAGEMENT FOR CONSERVATION AND RESTORATION

Effects of conservation and restoration of the moor so as to increase the proportion of Sphagnum and bog species in the vegetation cover.

The results above may be worked in reverse, so as to form a preliminary assessment of how peak flows at HB may be affected if the moor is managed so as to reduce grass and heather vegetation cover and replace it by increasing *Sphagnum* and bog species vegetation. There are numerous combinations that might be considered, including a reduction in burning rather than complete cessation, and also whether the moorland restoration occurs on the WME only or across the whole of the catchment of the Hebden Water. The table below summarises what appear to be the main possibilities that are of interest, showing comparisons of various burning regimes under different base cases with the output under long term burning of the grass-heather case. Therefore, to understand the figures in the table, the difference in flow peak at HB has been calculated as follows:

Change in peak = {Peak flow, grass-heather burn case} - {Peak flow, conservation-restoration case}

By this definition, a positive value in the table means a ***reduction*** in the peak flow at HB i.e. that the intended or modelled conservation-restoration condition generates a reduced peak flow, compared with the long term rotation burning at the given percentage of the WME and assuming the grass-heather base case. For simplicity and greater clarity, the results from the different burn effect periods have been averaged, so as to show just the one value in each box in the table. Also, it should again be emphasised that no burning occurs in any of the conservation-restoration cases.

Vegetation cover achieved by conservation, restoration or different land management		**Annual burn area, %, on the WME, under the grass-heather case**			
Hebden Water, outside the WME	**On the WME**	**2**	**4**	**6**	**8**
Grass-heather	*Sphagnum*-poor	1.22 (3.3 cm)	1.37 (3.7 cm)	1.53 (4.1 cm)	1.69 (4.5 cm)
Grass-heather	*Sphagnum*-intermediate	2.06 (5.5 cm)	2.21 (6.0 cm)	2.38 (6.4 cm)	2.53 (6.8 cm)
Sphagnum-poor	*Sphagnum*-poor	2.05 (5.5 cm)	2.21 (5.9 cm)	2.37 (6.4 cm)	2.52 (6.8 cm)
Sphagnum-poor	*Sphagnum*-intermediate	2.10 (5.6 cm)	2.25 (6.1 cm)	2.41 (6.5 cm)	2.57 (6.9 cm)
Sphagnum-intermediate	*Sphagnum*-poor	2.79 (7.5 cm)	2.95 (8.0 cm)	3.11 (8.4 cm)	3.27 (8.8 cm)
Sphagnum-intermediate	*Sphagnum*-intermediate	3.64 (9.9 cm)	3.79 (10.3 cm)	3.95 (10.7 cm)	4.11 (11.2 cm)

Table 3. Predicted *reductions* in the peak flow at Hebden Bridge, figures in cumecs (reduction in stage shown underneath, in cm), calculated by comparing the peak flows under the different land management and vegetation conditions of the WME and remainder of the Hebden Water catchment, assuming no burning, with the peak flows generated under different burn percentages over long

rotations on the WME, assuming the grass-heather base case. For simplicity, only one figure is shown for each comparison, averaging the results across the three burn effect periods (4, 8 and 12 years) for each burn percentage. See above text for explanation.

Table 3 shows the same general pattern revealed in the previous results, but presented with the opposite emphasis, namely the reduction achieved in the peak flow at HB if burning is ceased and management of the moor is applied to increase the proportion of *Sphagnum* and other species. The effect of *Sphagnum* and bog species restoration is striking, the general result being that conservation and restoration of *Sphagnum* lead to a marked lowering of the flow peak at HB. Moreover, even if the rest of the catchment of the Hebden Water is left unchanged - as shown in the first two rows of Table 3 - ceasing the burns on the WME and encouraging conservation and restoration of areas of *Sphagnum* and bog species in place of grass and heather leads to reductions ranging between *c.* 1.2 and 2.5 cumecs (*c.* 3.3 – 6.8 cm), or roughly 2.5-5% of the flow peak. If the remainder of the catchment is also managed with the aim of increasing the amount of *Sphagnum* and reducing grass and heather, then the reductions in peak flow are greater still, rising to *c.* 4.1 cumecs (*c.* 11 cm) in the *Sphagnum*-intermediate case, compared with the heather-grass case under 8% burning and a 12 year burn effect - vegetation recovery cycle. The 4.1 cumecs reduction is almost 10% of the peak flow at HB.

<u>CONCLUSIONS from the supplementary work</u>

NOTE: These conclusions are subject to the provisions, comments and recommendations made above and all those included in the Summary Short Study (*q.v.)*.

1. The results using the additional base cases, with more *Sphagnum*, conform with those already obtained, namely that any arrangement of burn patches on the WME, wherever situated, increases the flow peak at HB. Similarly, the greater the area burnt, the bigger the increase in the peak flow. There is also a small additional effect caused by the increasing presence of *Sphagnum* and bog species. This implies that even though the moorland has a general mixture of grasses and bog species, burning areas of *Sphagnum* still has a discernibly greater effect on the increase in the peak flow than burning areas of moorland grasses and heather. Such an effect is conformable with what would be expected, based on the resistance curves deduced from published research (Holden *et al.*, 2008) as outlined in the Summary Short Study.

2. Again, conforming with the previous results using the grass-heather base case, if burns are conducted in long rotations, for a given burn area percentage the effect of the burns is roughly doubled compared with the effect of an annual burn of that percentage in isolation. This occurs because at any one time, a proportion of the WME is recovering from burns that took place in previous years. Similarly, lengthening the burn effect period (and also therefore the vegetation recovery time) also raises slightly the increase in the flow peak at HB for a given burn percentage of burn. This occurs because the total area of the moor still in some stage of recovery increases with the length of the burn effect period.

3. A new result arising from this supplementary work is the impact of ecological conservation and restoration. The comparisons can be rather complicated, so for simplicity the burn case is based on the grass-heather results reported in the Summary Short Study, which provide the higher flow reference value, and with which the *Sphagnum* enriched base cases, without burns, are compared. The results are very clear, namely that management which eliminates burns and encourages conservation and restoration of *Sphagnum*, so that the

latter over time replace some or much of the cotton and moorland grasses and heather, leads to a marked reduction in the flow peak at HB. Specifically, management in this manner on the WME only, leaving the rest of the Hebden Water catchment unchanged, causes a reduction in the flow peak at HB of about 2.5-5%. By extending the same management to the catchment more generally, outside the WME, the peak flow is further reduced. The range of flow reductions depends upon the eventual state of the moorland vegetation and the initial reference 'burnt' state, but in the scenario explored here lies between *c.* 1.2 and 4.1 cumecs, which is roughly between 2.5 and 10% of the flow peak at HB. More generally, these findings and those outlined above and in the Summary Short Study indicate strongly that management focused on such conservation and restoration is likely to assist and reinforce the effects of other measures introduced on the moorland to reduce peak flows at HB.

Notes:

1. This comment – above the extent of bog species cover on the catchment over the last 500 years – is somewhat speculative, although it seems to that author a reasonable assumption. Strictly speaking, however, it needs to be checked, referring to any published palaeoecological studies or similar research, covering pollen and other palaeo indicators, from which a history of the moorland vegetation cover may be inferred. There may also be some historical studies or maps in the local archives which would be helpful in this respect.