Appendix 4 of BD5104
Hydrological monitoring

The purpose of this Appendix is to further describe the methods relating to aspects of hydrological monitoring, stream flow and water balance which are described in sections 4.2.7, 4.2.8 and 4.2.9, respectively, of the main body of the report. The method summaries, results and discussions are not repeated here but instead provide a more complete level of detail of the methods and statistical analysis.

WTD meters

Within the metal mesh cage on each monitoring plot (see **Figure 49** in the main report), a peat core of 1 m depth (or less if the bedrock was reached) was removed using a stainless steel 5 x 5 cm box corer and a 3 cm wide perforated (2 mm holes on two sides at 5 cm intervals) plastic tube (with an end cap) was inserted to prevent infilling. A water table depth (WTD) meter (WT-HR 1000, TruTrack, New Zealand) was placed inside this tube so that the zero-line on the meter was flush with the peat surface, any difference to the peat surface was recorded as an offset (for later WTD adjustments).

Moreover, regular manual readings allowed the recording of and ensured rectifying any otherwise undetected offset or changes over time. A manual fibre optic rod attached to a metal ruler (1.1 m length) was used to measure water table depths in the dipwells (see **Figure 43** in the main report) by conveying light to the water level within the dipwell (i.e. the light reflection stopped as soon as the water fibre optic rod entered the water), and logger water table depths were corrected based on these manual measurements. If sunshine was too dim, a torch was held above the light rod.

Average daily and monthly WTDs were calculated from the automated WTD meter measurements. All statistical analyses were carried out in R version 3.3.1 (R Core Team, 2016). Following Zuur *et al.* (2009), residuals were plotted against fitted values and visually assessed for normality and homogeneity of variance. The critical p value chosen for significance was 0.05.

Linear mixed effects models employing the "lmer" function from the "lmerTest" package (Kuznetsova *et al.*, 2016) were used to test for management and site effects on the daily and monthly WTD data. Due to WTDs often being close to 0 and deep only infrequently, the data were square-root transformed for analysis. The managements, sites and time period (either pre-management, i.e. before management implementation, or post-management, i.e. after management implementation) were used as fixed effects, as were the interactions between them. The month in which measurements were made was also included as a fixed effect. However, as plots were only managed once yet the entire catchment is being managed differently (and thus is anticipated to change over time), only the combined post-management period was included. A separate year-by-year analysis would most likely result in potentially misleading comparisons. For example transient effects could result in significant differences in certain years, whereas the overall post-management impact (and thus the ecologically meaningful trend) would not be. However, more robust 3-year post periods (effectively providing a mean value) could be assessed, but so far the project period did not allow such analysis (i.e. only 4 years of post-management). Soil temperature (Tsoil), relative humidity and daily rainfall were included in the daily WTD model. The monthly data were also split by site, with management, period, the interaction between them and the month of measurement used as the fixed effects, and by season (summer: June-August; winter: November-January), with management, period, site, the interactions between them and the month of measurement used as the fixed effects. A random intercept was included in each model, with a nested structure of blocks in sites (to account for spatial heterogeneity) in years (to account for repeated measurements).

Following the 10-step protocol in section 5.10 of Zuur *et al.* (2009), variables were dropped stepwise from each linear mixed effects model and the log-likelihood ratio and AIC value were used to assess whether a variable should be dropped or kept in the model. For the final models, the "satterthwaite" option was used to calculate the denominator degrees of freedom as the time periods resulted in an unbalanced design (Spilke *et al.*, 2005). Where significant interactions were found, the "glht" function with the "Tukey" option from the "multcomp" package (Hothorn *et al.*, 2008) was used to compare groups within the interaction terms.

Stream flow weirs

The flow weirs (see **Figure A4.1**) were custom build at the Biology mechanical workshop at the University of York. Large PVC sheets of 9 mm thickness were cut into individual sheets of 150 cm width and 130 cm height. PVC was the preferred choice as a metal weir section could not be installed effectively due to rocks (requiring adjustments on site, see below). A 90^0 v-notch was cut at the centre of the sheet with chamfered edges for the 65 cm high v-notch. Sheets were installed at the flow weir location by using a custom made sturdy metal cutter (10 mm thick) to prepare the section for the PVC sheets. If rocks were hit the PVC sheet was cut by hand (saw) to achieve a best fit to the underlying bedrock. However, this affected only some of the lower parts of the PVC sheet. The flow weir was supported by four wooden posts at the front of the weir. To improve the level accuracy during high flow, a pond of about 2 m^2 was dug out behind the flow weir and the sides were build up with stones and vegetation swards to 50 cm (measured from the V-notch base). Two water table depth (WTD) meters (WT-HR 1000, TruTrack, New Zealand) were positioned inside perforated plastic tubing within the upstream weir pool to monitor the stream level and allow calculation of actual flow rates.

Figure A4.1 The six flow weirs at (in pairs **from left to right**) Nidderdale, Mossdale and Whitendale for the burnt (C) and mown sub-catchment for each site. Pictures were taken in December 2016.

Stream flow rate calculations

The height of the water flowing over each 90^0 v-notch weir was measured using a 30 cm ruler during most site visits and for nearly all stream sampling dates. The hourly recordings of the two WTD loggers (one as a backup in case of logger failure) in each pool upstream of each flow weir were compared to the manual readings and if needed corrected (due to some gradually sinking into the pool base over time) using these heights (using recording time to align measurements to the hourly WTD measured by the flow weir loggers). The instantaneous stream flow rate, Q, was calculated using the **Eq.A4.1**:

$$Q = 4.28 \times Ce \times \tan\frac{\theta}{2} \times (H + k)^{\frac{5}{2}} \qquad \textbf{Eq.A4.1}$$

where Ce is the effective discharge coefficient, θ is the angle of the v-notch in radians, H is the measured head over the weir (i.e. the corrected WTD) in feet (i.e. to obtain values in cm this needs to be divided by 30.48; or x0.0283168 to convert f^3 to m^3) and k is the head correction factor (Bengtson, 2010). The effective discharge coefficient, Ce, was calculated using **Eq.A4.2** and the head correction factor, k, was calculated using **Eq.A4.3**:

$$Ce=0.61-\left(8.7x10-4\times\theta\right)+\left(6.1\times10^{-6}\times\theta^{2}\right) \qquad \textbf{Eq.A4.2}$$

$$k=0.014-\left(3.4x10-4\times\theta\right)+\left(3.3\times10^{-6}\times\theta^{2}\right)-\left(1.1\times10^{-8}\times\theta^{3}\right) \qquad \textbf{Eq.A4.3}$$

where θ is the angle of the v-notch in degrees (Bengtson, 2010). The stream flow rates were then expressed in m^3 h^{-1}.

Water balance

The water balance for each catchment and thus management scenario was based on monthly stream flow rates (i.e. output) calculated from the hourly water levels at each flow weir *versus* the monthly rainfall totals (i.e. input) obtained from the weather station at each site (see **Figure 49** in the main report). Monthly rainfall totals (water input) were up-scaled to the entire catchment area (m^3 $month^{-1}$) which could then be related to the corresponding stream flow rates (m^3 $month^{-1}$) in each catchment (water loss). Therefore, this enabled calculating the percentage of water loss per catchment as defined by: water output x 100 / water input. However whilst losses from evapotranspiration and underground drainage were not included, these were reflected in stream flow rates and would only account for a small part of the water balance. Moreover, the amount of water lost from the streams was used to predict implications on peak flooding, which would be largely independent of much lower evapotranspiration rates and slower underground drainage processes.

Flood peak implications

The observed 20% reduction in water loss (i.e. monthly incoming precipitation vs. monthly stream outflow volume) from mown compared to burnt catchments (see **Table 12** in the main report) was applied across the entire Ouse catchment area (which includes both the Nidderdale and Mossdale sites) for areas visually managed as grouse moors (using Google Earth to identify rotational burning). The below **Figure A4.2** of a Google Earth view indicates the location of York, its Ouse catchment extent and the Mossdale and Nidderdale catchment locations within the Ouse catchment. The total area of the identified 18 burn areas was 389 km^2 within the total Ouse catchment of 3,397 km^2.

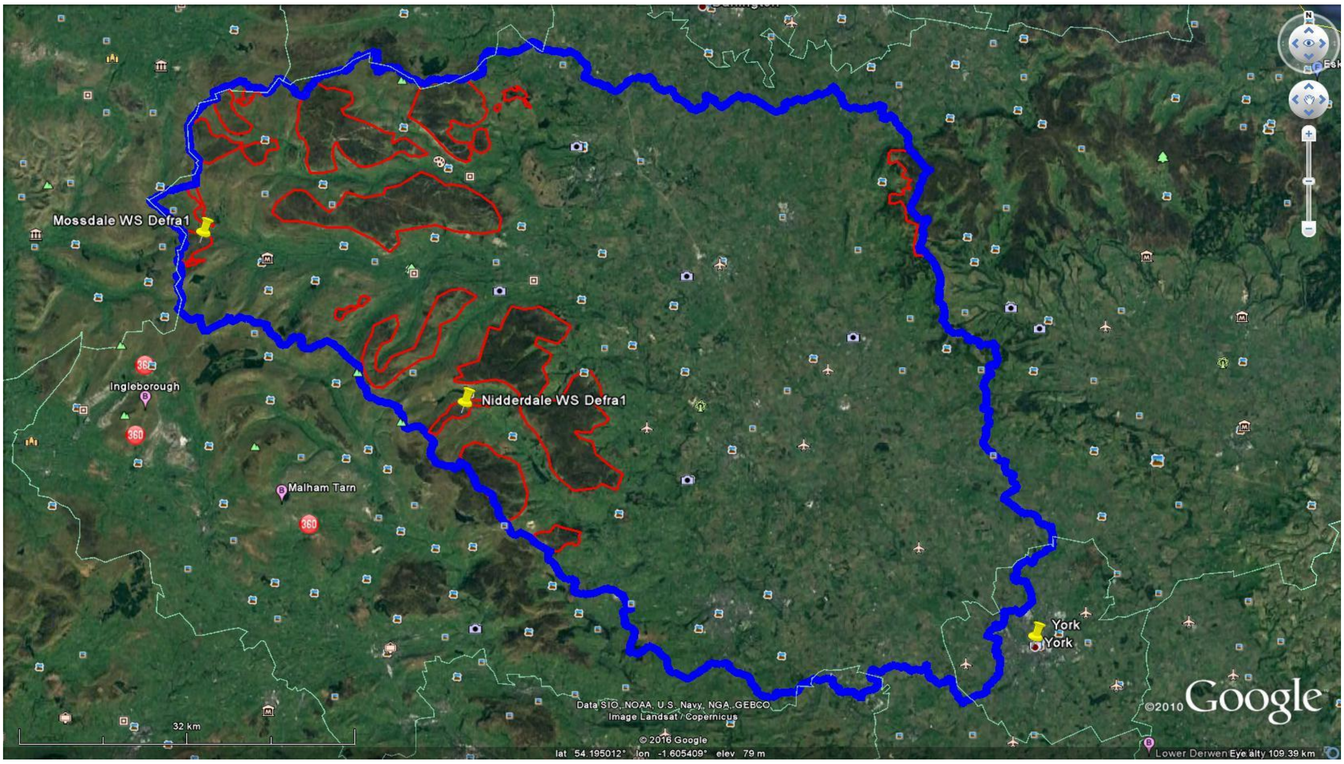

Figure A4.2 Google Earth picture indicating the location of York, its Ouse catchment extent (blue polygon outline) and the Mossdale and Nidderdale catchment locations (yellow markers) within the Ouse catchment. All 18 identified active burn management areas (red polygon outlines) were based on visual burn patches.

An average water loss of 60% from grouse moors under burn rotation was assumed as this was observed across all three sites (see **Table 12** in the main report). This allowed calculating the potential reduction in total water volume entering the Ouse just north of York assuming the entire grouse moor areas were managed by mowing (with a 20% reduction in flow, see above). This flow volume reduction was then related to a potential decrease in river levels based on the available river station data on flow rates and river stage levels.

The Skelton gauge location on the River Ouse, the river flow and stage level data (National River Flow Archive: https://nrfa.ceh.ac.uk/) enabled an estimation of the relationship between the extremes (days) in river level and peak flow rates during the 1982 – 2004, with peak flow rates identified as > 250 m^3/s and river level heights of > 4.5 m. For this, a best fit polynomial equation (forced through zero) was derived between peak river height and flow rates (river height (m) = $-0.000016*\text{flow}\ (m^3/s)^2 + 0.020667*\text{flow}\ (m^3/s)$; $R^2 = 0.92$). This relationship enabled a change in the River Ouse level to be predicted from calculated changes in flow volume due to mowing, which was taken to be 20% based on the observed flow reduction averages at the two Ouse catchment sites, Nidderdale and Mossdale (**Table 12** in the main report). This reduction in flow volume was then applied across all visually identified grouse moor managed areas within the Ouse catchment based on rainfall amounts, which were adjusted for altitude according to Brunsdon et al., 2001 (see next paragraph).

For this the average polygon elevation (442 ± 93 m) was related to rainfall amounts observed at the two project sites of known altitude and their observed average peak monthly and daily amounts (~200 mm and ~80 mm, respectively) and rainfall was adjusted for the other sites based on elevation differences. Rainfall amounts were assumed to be similar for sites grouped by proximity to either Nidderdale or Mossdale. However, elevation impacts on rainfall amounts vary considerably between regions across the UK (Brunsdon et al., 2001) with up to +3 mm/m elevation increase across the Yorkshire Dales. Therefore, annual rainfall was altered by ±300 mm per ±100 m elevation but monthly amounts were only adjusted by ±100 mm per ±100 m elevation to reflect that short term heavy rainfall events likely have less of an altitude effect (as rainfall is very heavy across the entire region) than overall annual rainfall. Moreover, whereas for monthly averages the annual amounts were divided by 12, to derive daily amounts, the monthly averages were divided only by 6 to reflect that on average most rainfall occurs on around 6 days per month (based on the site rainfall records).

The rainfall adjustments resulted in an average monthly and daily rainfall across the Ouse catchment burn areas of 180 mm and 70 mm, respectively. Rainfall totals were then up-scaled to the entire burn polygon area (ha) and the 60% loss factor allowed calculation of the flow volume. Finally, the 20% reduction in flow volume of the mown scenario reduced this total, which then related to the flood peak implications at York considering the total sum of all burn polygons across the Ouse catchment. The two considered scenarios were monthly and daily rainfall events, with daily events being the most likely to be related to large floods in York (as was the case during the 'unprecedented' Christmas floods in 2015). Peak rainfall events (monthly: ~180 mm vs. daily: ~70 mm rainfall totals) related to monthly (-5.03 m^3/s) or daily (-55.6 m^3/s) scenario flow volume reductions at the Skelton gauge location (average peak flow volume of 380 m^3/s), which were then translated into river level changes using the polynomial equation for the Skelton location (see above).

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