Burbage Brook Monitoring Project: evidencing the impacts of woodland cover change on water flows and quality
Report for 2016/17

Report to

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1. Executive summary

In the autumn of 2014, approximately 23 hectares of conifer plantation in the Burbage Valley within the Peak District National Park was clear felled as part of a capital works programme within the Dark Peak Nature Improvement Project. Woody debris from the conifer felling work was windrowed to reduce overland flow velocities and used to install dams in the tributaries that join Burbage Brook, with the aim of reducing run-off and sediment. In spring 2015, the former plantation area was then planted with native broadleaf woodland species, including oak (*Quercus* spp.), ash (*Fraxinus* spp.) and birch (*Betula* spp.).

The aim of this project is to monitor the impacts of the removal of the coniferous plantation and the subsequent replacement by native broadleaved woodland on water flows and water quality within Burbage Brook. Specifically:

1) The impact of felling of coniferous woodland plantation on storm water flows within Burbage Brook
2) The subsequent year on year impacts of the establishment of native broadleaf woodland on water flows and water quality within Burbage Brook
3) The broad impact of the transition from mature coniferous woodland to mature broadleaved woodland on storm water flows within Burbage Brook.

In this report we present results for 2016/17 which presents data from the second year after felling and broadleaf woodland establishment.

Limited water flow data were available from before the works began; comparison of these with data from after the completion of the clear felling works suggests that the works have had no significant impact on the flood risk impact of Burbage Brook.

No water quality data were available from before the works began; comparisons of data from the monitoring station upstream and downstream of the works area suggest that no significant water quality issues have been caused by the works.

Baseline conditions have been recorded; further monitoring is required to establish whether any longer term trends in water flow and/or quality may be affected by the establishment of the new broadleaved woodland in the valley.

2. Introduction

The Burbage Brook Monitoring project has received funding from the Environment Agency (EA) and Natural England (NE). The purpose of the project is to demonstrate and understand the benefits of woodland creation (and also the impacts of the interim measure of clear-felling existing conifer plantation) on flood risk and water quality in the upper Derwent catchment (Environment Agency waterbody catchment: Derwent from River Westend to River Wye; ID: GB104028057880).

The study site is located within the Burbage Valley, on the eastern side of the Peak District National Park, approximately three miles east of Hathersage and eight miles west of the centre of Sheffield. A 34 hectare conifer plantation was planted in the valley between 1968 and 1971, containing principally Lodgepole pine (*Pinus contorta*) with Scots pine (*Pinus sylvestris*) and Japanese larch (*Larix kaempferi*), none of which had grown well on the poor acid soils. Approximately 23 hectares of the plantation was clear-felled between August and December 2014 and replanted with native broadleaf woodland species, including oak (*Quercus* spp.), ash (*Fraxinus* spp.) and birch (*Betula* spp.). Woody debris from the conifer felling work was windrowed to reduce overland flow velocities and used to install dams in the tributaries that join Burbage Brook, with the aim of reducing run-off and sediment. A livestock exclusion fence was constructed around the woodland area to protect the newly planted trees, and reseeding conifers have since been removed. All principle works were completed by March 2015 (Talbot, 2015).

In order to monitor the effect of these land management interventions, two water flow monitoring stations, located upstream and downstream of the proposed works area, were installed on Burbage Brook in 2012 by Wallingford HydroSolutions (WHS). The baseline hydrological conditions were monitored between 26th October 2012 and the 21st January 2014 (see WHS, 2014). This phase of the project was funded by the Environment Agency.

The current Burbage Brook Monitoring project continues the monitoring on Burbage Brook, which aims to achieve the following:

- Develop an understanding of the current flow regime, following changes in vegetation cover and installation of log jams, since baseline monitoring was undertaken in 2013.
- Develop an understanding of water chemistry following changes in vegetation cover; in particular changes in sediment and orthophosphate concentrations.

3. Site description

Two water flow monitoring stations were reinstated in January 2016 on Burbage Brook (upstream and downstream of the conifer plantation works area). The catchment size of the upstream monitoring station is 3.3km^2; the catchment of the downstream monitoring station is 5.95km^2.

WHS (2014) observed that stage height recorded by the logger at the downstream monitoring station exceeded the floodplain height during storm events. For this reason, a new monitoring station was installed, as recommended, at Burbage Brook weir, with the intention of replacing the Burbage Brook downstream station. The monitoring locations are as follows: Burbage Brook upstream SK 26208 82601; Burbage Brook downstream SK 26090 80816; Burbage Brook weir SK 26090 80816 (see Figure 3.1).

The geology of the catchment is dominated by Chatsworth Gritstone overlain by peat (about 50% of the downstream catchment area), mineral soils, sands and gravels (WHS, 2014). Average annual rainfall for the downstream catchment was reported in WHS (2014) as 1021mm with an annual reference Potential Evaporation demand of 517mm.

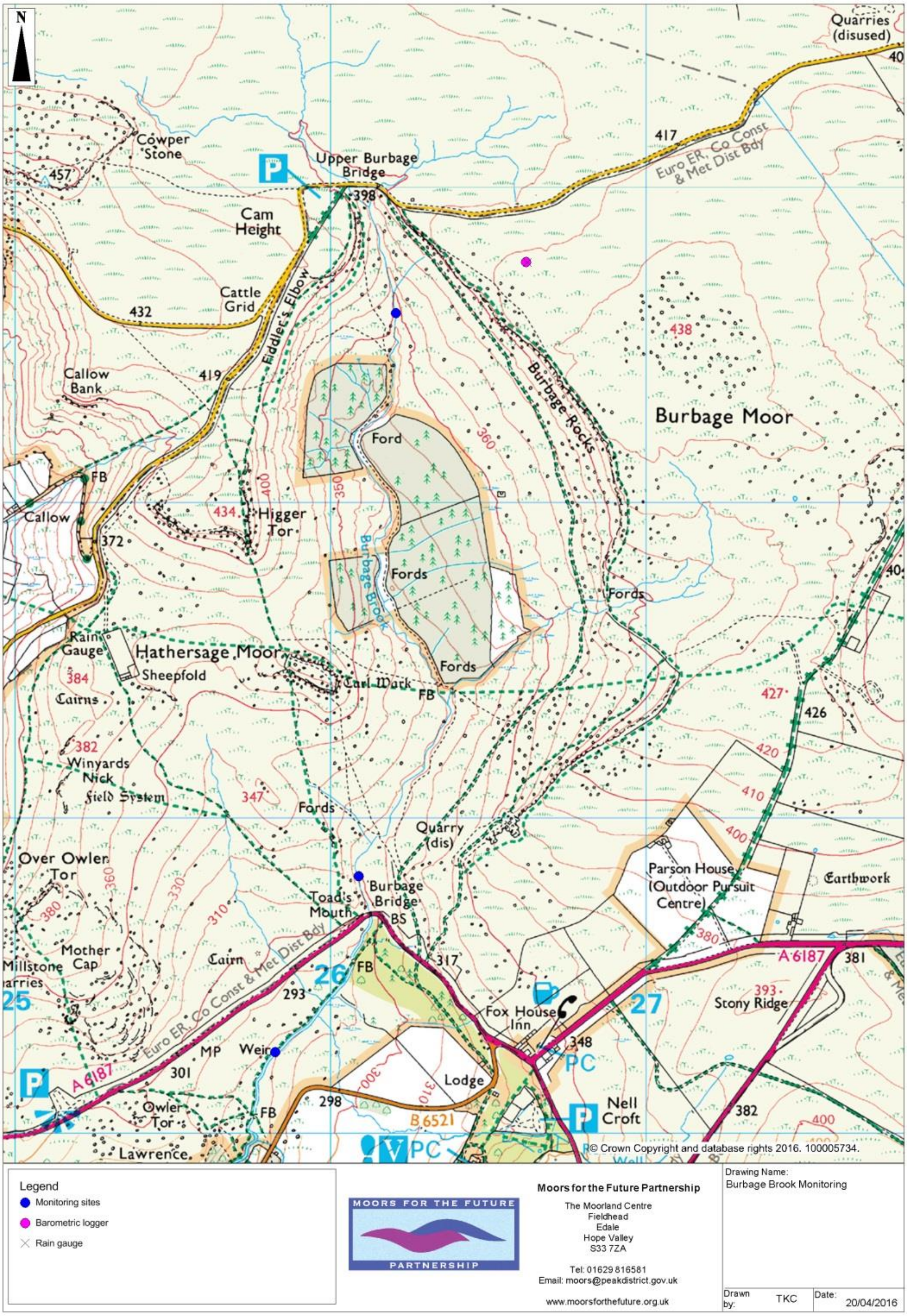

Figure 3.1: Monitoring sites and equipment locations.

4. Water Flow Monitoring

4.1. Methodology

4.1.1. Monitoring station set-up

The water flow stations located at Burbage Brook upstream (Figure 4.1) and downstream (Figure 4.2) consist of a water level data logger (HOBO U20-001-04) suspended inside a stilling well, constructed of scaffolding tube. The stilling well is attached to a wooden structure, with a stageboard for measuring stage height. Loggers were installed into the existing structure on 21st January 2016.

Figure 4.1: Monitoring location at the Burbage Brook upstream site (image from WHS, 2014)

Figure 4.2: Monitoring location at the Burbage Brook downstream site (image from WHS, 2014)

The new flow station was installed at Burbage Brook weir (Figure 4.3) on the 10th February 2016. This is very similar in design to those located at the upstream and downstream sites, consisting of a water level data logger (HOBO U20-001-04) suspended inside a stilling well, constructed of plastic pipe. The stilling well is attached to a steel dexion structure, with a ruler for measuring stage height.

Figure 4.3: Monitoring location at the Burbage Brook weir site

The loggers are programmed to record water pressure data every 10 minutes. The water pressure data is converted to stage height data using a compatible air pressure file from a barometric logger located at the upstream monitoring station (SK 26204 82602).

4.1.2. Water flow gauging

Since January 2016, a total of 13 site visits have been made to all three monitoring stations, in order to carry out flow gauging. The procedure for each flow gauging visit is as follows:

1. Stage height on the fixed stage board/ruler is recorded (m)
2. The width of the river channel is divided into 7-10 subsections
3. Cross-sectional area of each subsection is calculated (m^2)
4. Rate of flow (m/s) at the centre of each subsection is measured using a Valeport 801 Electromagnetic Open Channel Flow Meter
5. Total rate of discharge (Q) for each subsection is calculated (area x flow; m^3/s)
6. Total rate of discharge for the river is calculated (sum of all subsections; m^3/s)

4.1.3. Rating relationships

Once flow gauging has been carried out at a range of stage heights, a rating relationship may be established between stage height and discharge.

In the baseline study (WHS, 2014), ratings were derived at the upstream and downstream monitoring stations. The ratings derived in the current study suggest that the relationship between stage height and discharge has not changed significantly at either location.

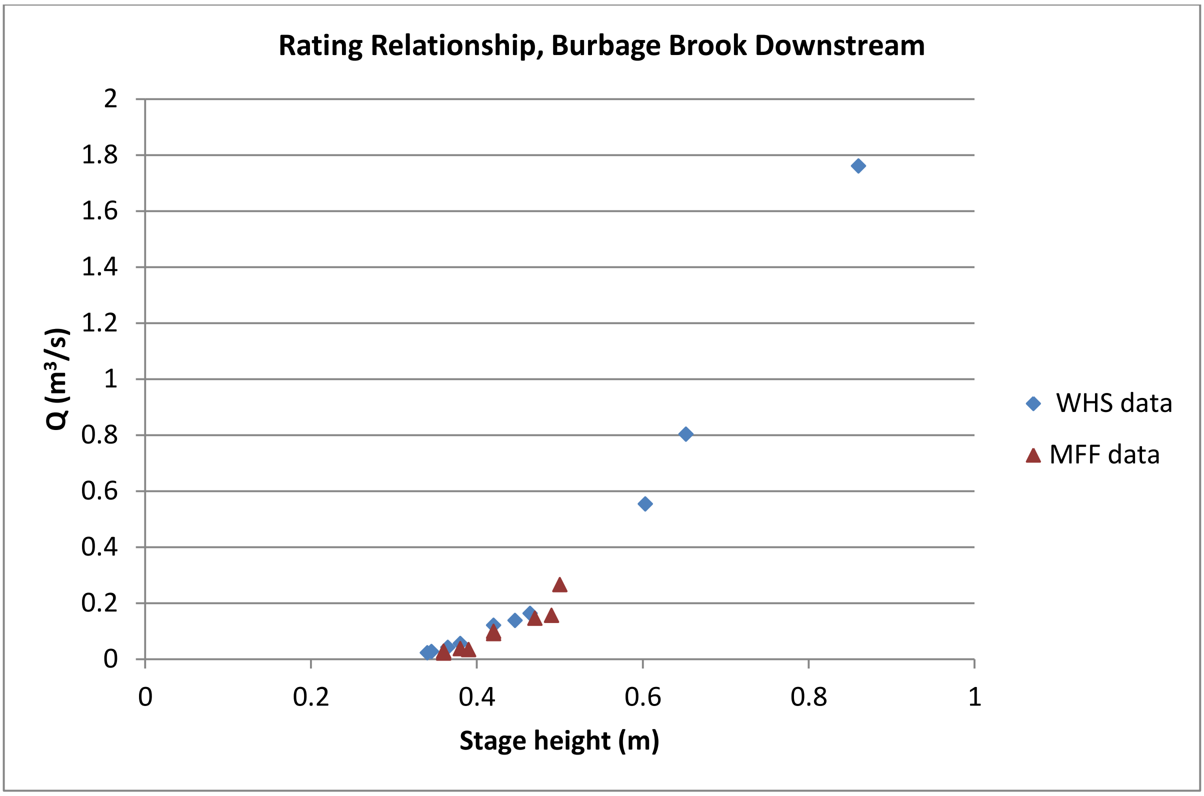

Figure 4.4: Rating data from WHS and MFF flow gauging, Burbage Brook downstream

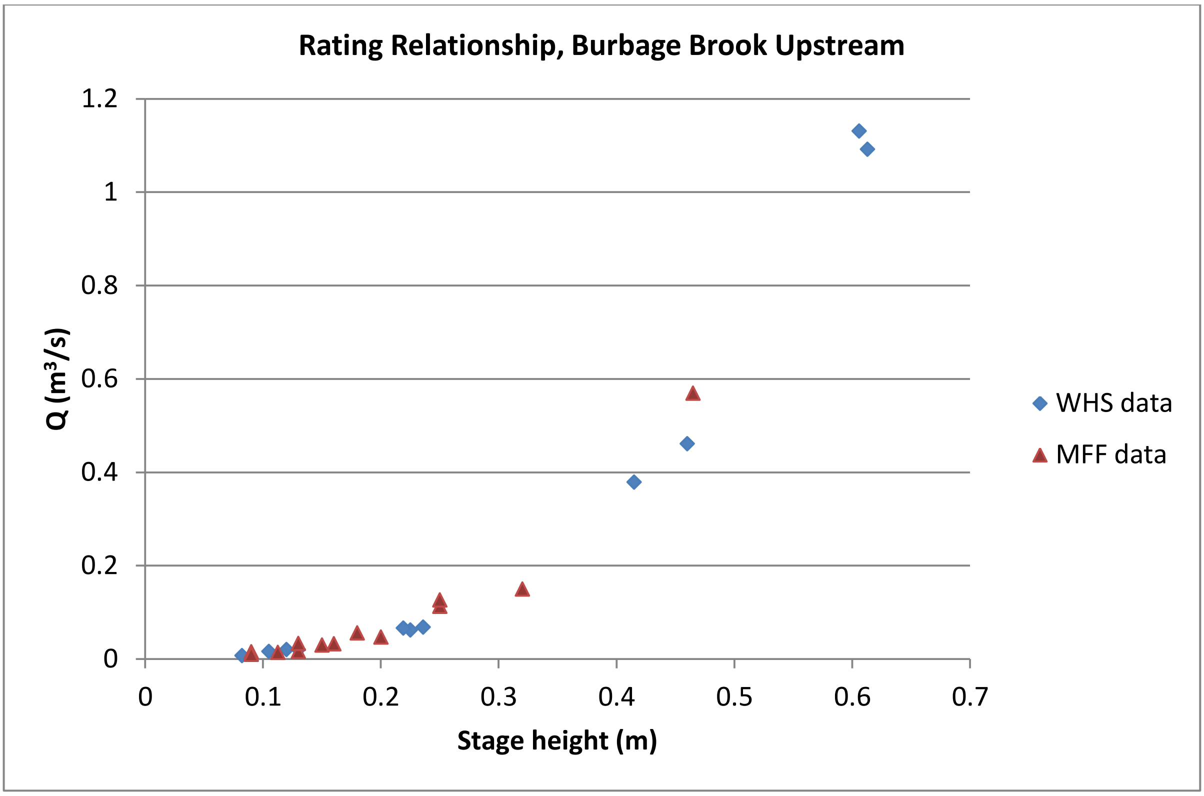

Figure 4.5: Rating data from WHS and MFF flow gauging, Burbage Brook upstream

Therefore, in order to maximise the number of values used to construct the rating equation for each monitoring station, flow gauging data from WHS and Moors for the Future (MFF) were combined. The rating equations, using the form $Q = a(h+c)^b$ (Q=discharge, a, c and b = rating curve coefficients, h = river stage), along with the rating coefficients, are presented in Table 4.1 and rating curves for the two stations are presented in Figure 4.6 and Figure 4.7.

Station	**Coefficients**				**Rating Equation**
	a	*b*	*c*	h_{max}	
Downstream	5.284	0.317	1.790	0.860	$Q = 5.284\ (h - 0.317)^{1.790}$ for stage heights up to 0.860m (r^2=0.995, p<0.001, SE=0.029)
Upstream	4.101	0.042	3.044	0.613	$Q = 4.101\ (h + 0.042)^{3.044}$ for stage heights up to 0.613m (r^2=0.995, p<0.001, SE=0.025)

Table 4.1: Rating coefficients and equations for Burbage Brook River flow monitoring stations

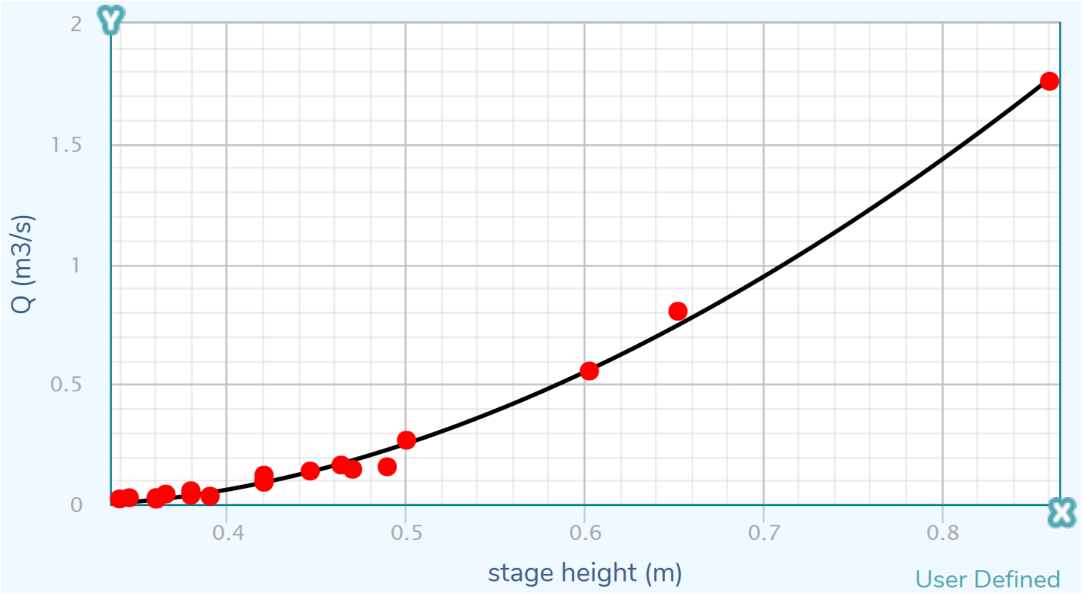

Figure 4.6: Rating curve at Burbage Brook downstream monitoring station, using combined WHS and MFF data

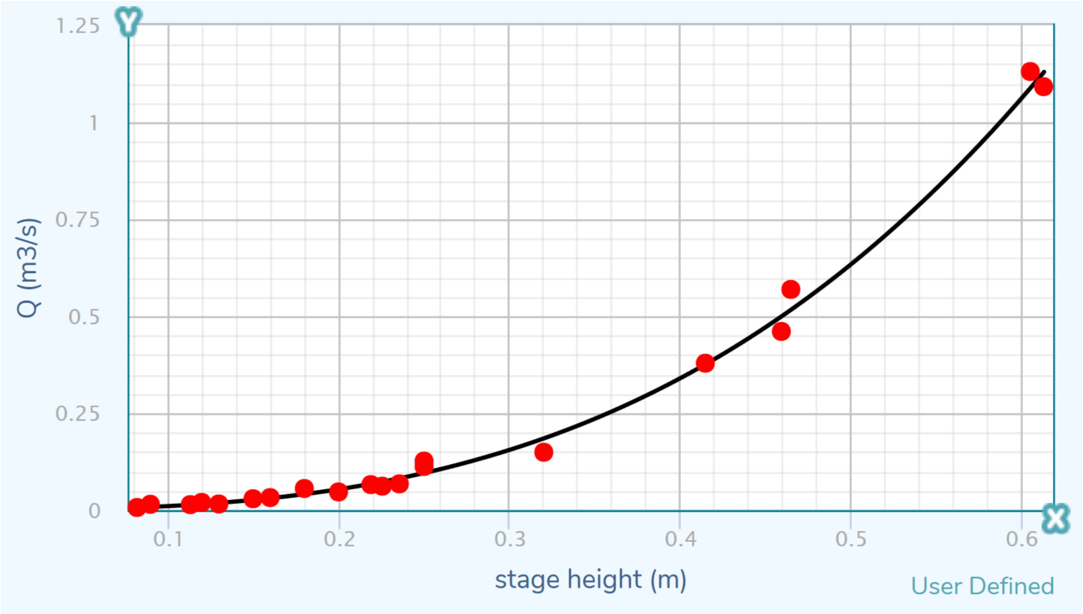

Figure 4.7: Rating curve at Burbage Brook upstream monitoring station, using combined WHS and MFF data

In order to assess the accuracy of the rating equations, stage heights recorded during flow gauging visits were used to estimate Q using the rating equations, and these values were compared to observed Q as calculated by manual flow gauging. Excellent agreement was observed at both stations, as shown in Figure 4.8 and Figure 4.9.

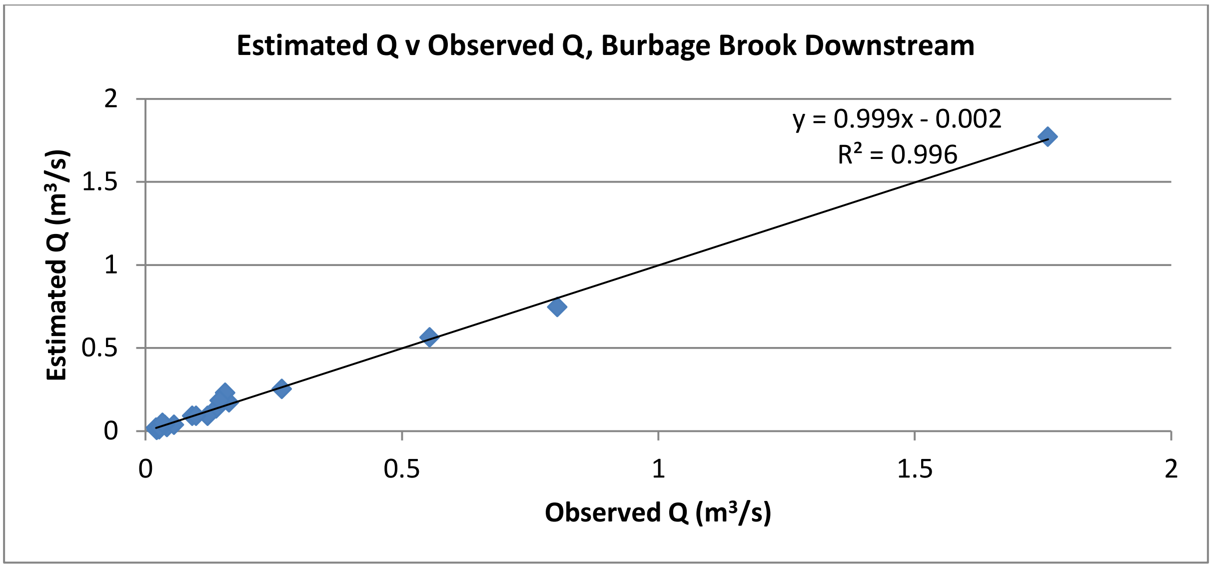

Figure 4.8: Suitability of rating equation for predicting Q at Burbage Brook downstream

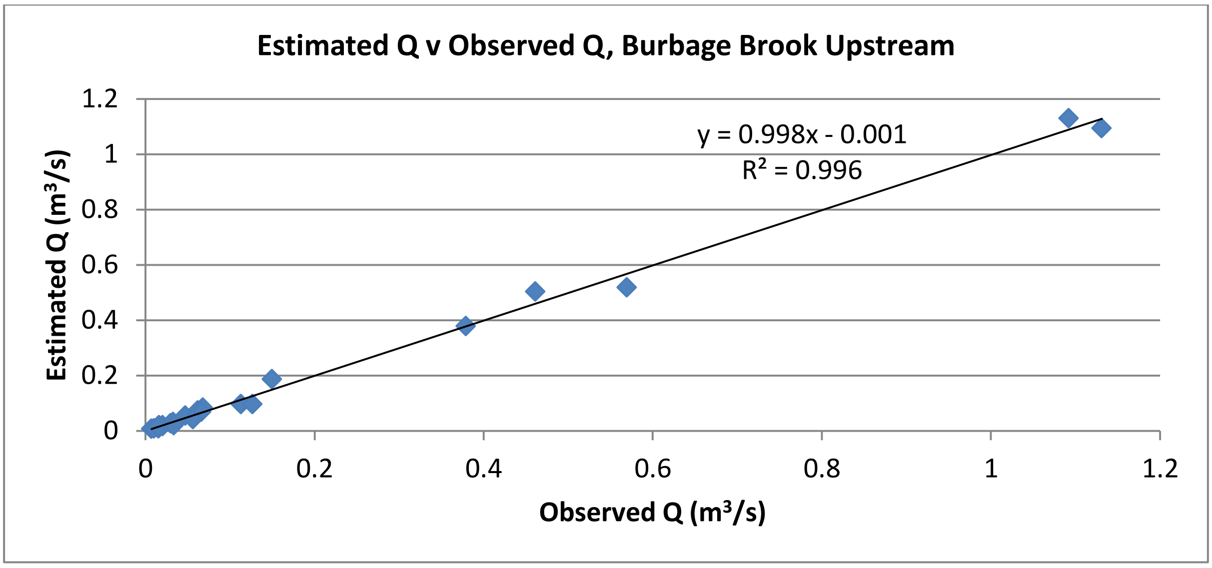

Figure 4.9: Suitability of rating equation for predicting Q at Burbage Brook upstream

4.1.4. Reliable limits of ratings

The reliable limits of these ratings are determined by the range of flow conditions in which flow gauging was carried out. At both stations, the highest stages (h_{max}) recorded during flow gauging were by WHS, and so the h_{max} values remain unchanged from WHS (2014).

An additional limit may be the stage height at which water flow will overtop the banks of the main channel (the floodplain). At this point, the cross-sectional shape of the channel changes significantly at both stations, and would require extensive additional work to model. Increases in stage height above the floodplain would result in significantly higher increases in cross-sectional area than increases in stage height below the floodplain. The floodplains are covered in vegetation, which will increase surface roughness as compared to within the main channel. This is likely to result in reduced water velocities. To some extent, these two factors may cancel each other out, although this is extremely difficult to predict with any certainty, and would require extensive further flow gauging in flood conditions, which is challenging both logistically and from a health and safety perspective.

While some elements of data from flow events beyond these limits may be used (for example, timings), estimates of Q should be treated with caution, meaning that it is only possible to evidence the impact of the works on flow for the ‘smaller’ events.

4.1.5. Burbage Brook weir monitoring station

Following the recommendations of WHS (2014), a new monitoring station was installed at Burbage Brook weir, in order to replace the monitoring station at Burbage Brook downstream. WHS observed that the floodplain height was exceeded in some storms at the downstream station, making flow data unreliable. The weir was identified as a regularly shaped, steep-sided section with a large capacity for in-channel flow. Flow gauging was performed on 13 visits to the weir. However, following a major rainfall event on 21/11/2016, a large amount of sediment was deposited in the centre of the river channel at this location, and as described in Shaw *et al.* (2011), this modified the relationship between stage at the river bank (where the logger is located) and Q. As shown in Figure 4.10, a new rating relationship is emerging, with reduced Q for the same stage height, due to the reduced cross-sectional area of the centre of the river channel.

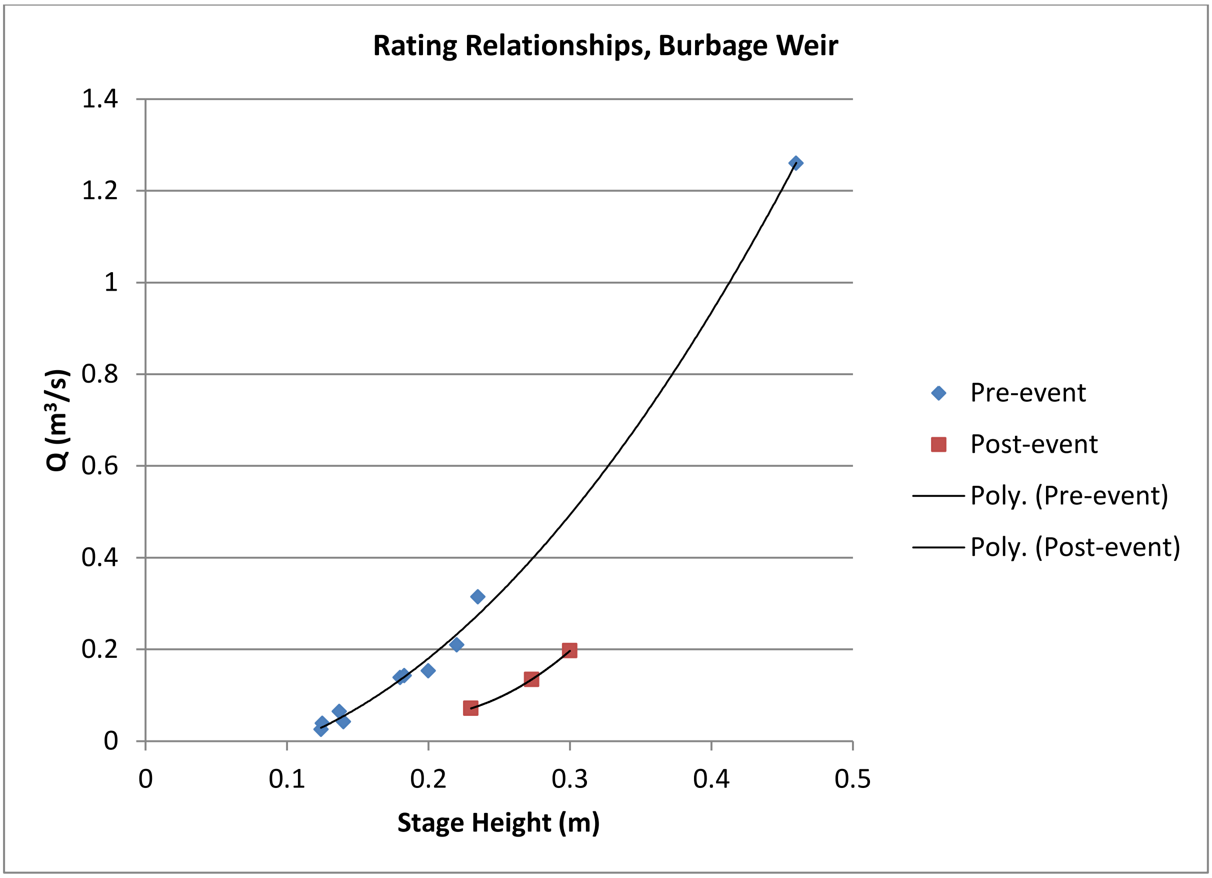

Figure 4.10: Rating relationships at Burbage Weir monitoring station, showing the emergence of a new relationship following a major storm event

The available data for Burbage weir are insufficient to derive a reliable rating equation, either for pre-2016 deposition event or post-event periods. Furthermore, this evident modification to the rating relationship suggests that this monitoring location is vulnerable to further modifications in the future, meaning that any rating equation derived now may well become inaccurate in the future. By contrast, rating data collected at Burbage Brook downstream in the present study correlated well with the previous WHS data. Additionally, stage height exceeded the floodplain height in only one storm during the current study. For the purposes of this report, data from Burbage Brook downstream and upstream are analysed and presented, while data from Burbage Brook weir are excluded.

4.1.6. Selection of storm events for analysis

As described above, the derived rating equations were used to estimate Q from 10-minute logged stage height values at Burbage Brook downstream and upstream monitoring stations. The full time series from these two loggers are presented in Figure 4.11 and Figure 4.12. Storm events were then identified for analysis. The ideal criteria used for the selection of storm events for analysis were:

- Rainfall and water flow data available
- Noticeable water flow response to rainfall
- Single discrete period of continuous or near-continuous rainfall
- Baseflow conditions immediately before the onset of rainfall
- Return to baseflow conditions following the cessation of rainfall, and before the next storm event
- Peak Q within the limits of reliable estimations of Q as determined by floodplain height and/or limit of rating data

The seven most suitable storm events were selected (see Figure 4.11 and Figure 4.12), although not all of them met all of the above criteria, as shown in Table 4.2.

Storm No.	**1**		**2**		**3**		**4**		**5**		**6**		**7**	
Date (start of stormflow)	8/3/2016		28/3/2016		10/5/2016		21/5/2016		13/9/2016		18/11/2016		1/1/2017	
Monitoring station (Downstream/Upstream)	**D**	**U**	**D**	**U**	**D**	**U**	**D**	**U**	**D**	**U**	**D**	**U**	**D**	**U**
Rainfall data available?	Y		Y		Y		Y		N		Y		Y	
Water flow data available?	Y		Y		Y		Y		Y		Y		Y	
Noticeable water flow response to rainfall?	Y		Y		Y		Y		Y		Y		Y	
Suitable rainfall characteristics?	Y		Y		Y		Y		Y		Y		Y	
Baseflow conditions pre-event?	Y		Y		Y		Y		Y		Y		Y	
Return to baseflow conditions post-event?	Y		Y		Y		Y		Y		Y		Y	
Peak Q within estimated floodplain limit?	Y	N	Y	Y	Y	N	Y	Y	Y	Y	N	N	Y	Y
Peak Q within rating limit?	N	N	Y	Y	N	N	Y	Y	Y	Y	N	N	Y	Y

Table 4.2: Suitability of selected storms for analysis. Y/green=suitable; N/red=unsuitable

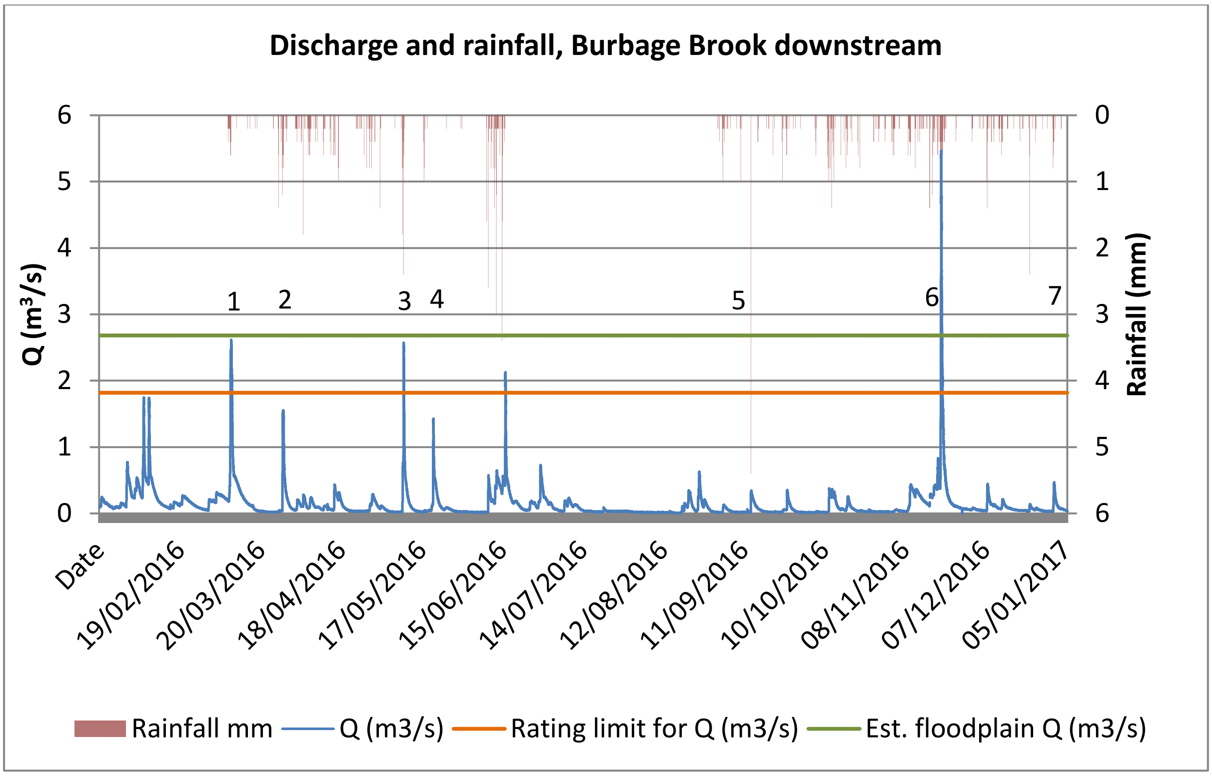

Figure 4.11: Discharge and rainfall data at Burbage Brook downstream. Note the limits of reliable estimations of Q

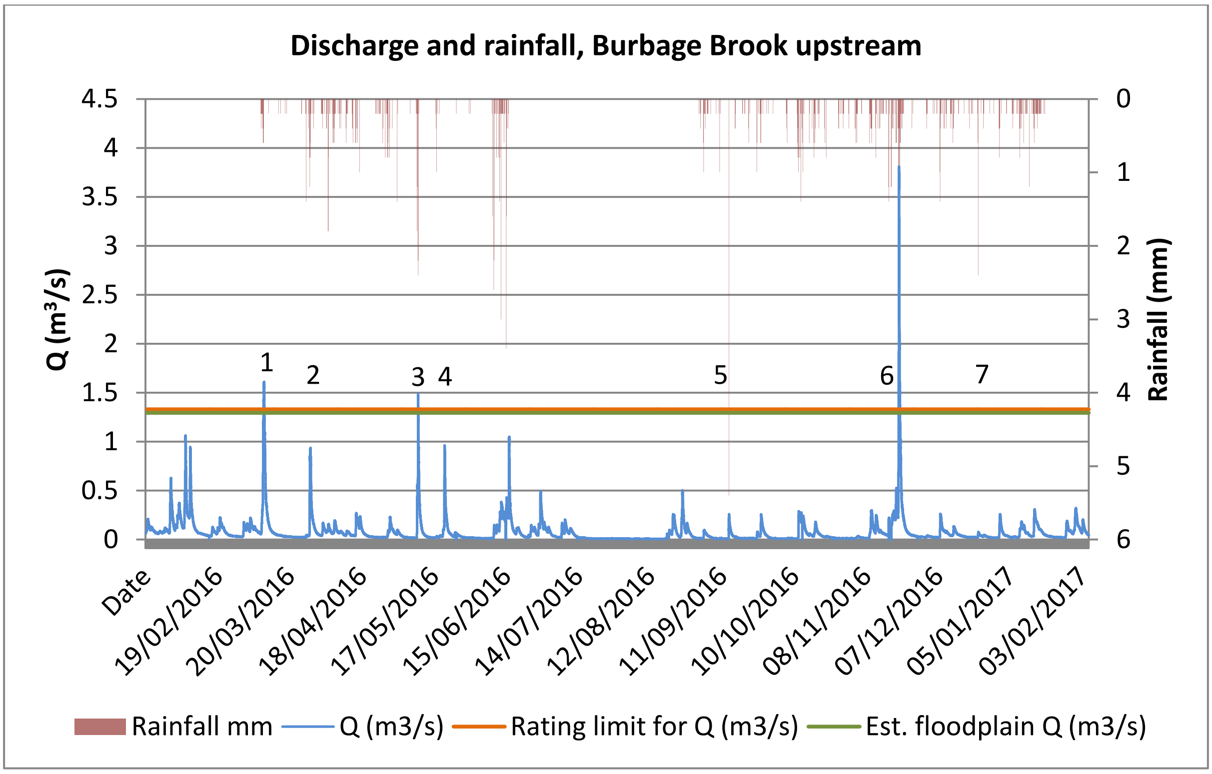

Figure 4.12: Discharge and rainfall data at Burbage Brook upstream. Note the limits of reliable estimations of Q

4.1.7. Limitations of storm data

Peak Q in storms 1 and 3 exceeded the rating limit at both stations. The floodplain limit was exceeded at the upstream (but not the downstream) station. Discharge data have been included from these storms, although they should be treated with caution.

Peak Q in storm 6 (21/11/2016) significantly exceeded limits of both the rating relationship and the floodplain height at both monitoring stations. Discharge data have therefore been disregarded for this storm. However, it was a major hydrological event, and is therefore of value in the record. Hydrograph metrics relating to timings have therefore been included in analyses.

4.1.8. Storm hydrograph assessment

In order to facilitate direct comparison of hydrological data from the two monitoring stations, discharge values were standardised by dividing by catchment area (km^2) to produce discharge values that could be compared regardless of the different catchment sizes (m^3/s/km^2).

4.1.8.1. Hydrograph metrics

Following the methodology in Allott *et al.* (2015), the following metrics were extracted from the selected storm events:

Lag-time

Lag time was derived from the time interval (in minutes) between maximum rainfall intensity and peak storm discharge (Figure 4.13

Figure 4.13: A typical storm hydrograph (from Allott *et al.*, 2015). a) indicates the time interval between maximum rainfall intensity and peak storm discharge used to determine lag-time; (b) indicates the magnitude of peak storm discharge, when the baseflow component has been deducted.; (c) the pale grey shaded area represents total storm discharge; (d) the dark grey shaded area represents total rainfall/precipitationa). Lag time gives an indication of the rate at which precipitation runs off the landscape and enters the channel, with longer lag times indicating that water is being released more slowly.

Peak storm discharge

Peak storm discharge (Peak Q_s; m^3/s/km^2) is the difference between the maximum recorded discharge, and the coincident baseflow component (Figure 4.13b). During and immediately following storm events baseflow becomes elevated. To account for this, the ‘constant slope’ method (McCuen, 1998) was used to separate the storm-flow component of the hydrograph from the baseflow component. This method assumes that baseflow increases linearly throughout the storm event (Figure 4.13).

Hydrograph Shape Index (H.S.I.)

The H.S.I. is defined as the ratio of peak storm discharge (m^3/s/km^2) to total storm discharge (m^3/s/km^2) (Figure 4.13b and c). This index provides a simple measure of overall hydrograph shape; relatively high ratios represent more ‘flashy’ hydrographs which are highly reactive to rainfall and runoff generation, while relatively low ratios indicate more attenuated hydrographs with lower peak flows relative to the size of the discharge event.

Percentage runoff

Percentage runoff is the proportion of storm rainfall that reaches the stream channel to become discharge within the storm event. Low percentage runoff values indicate substantial within-storm storage of water in the catchment, whereas high percentage runoff values indicate that most of the rainfall generates storm-flow. The parameter is derived from total storm rainfall and total storm discharge (Figure 4.13c and d).

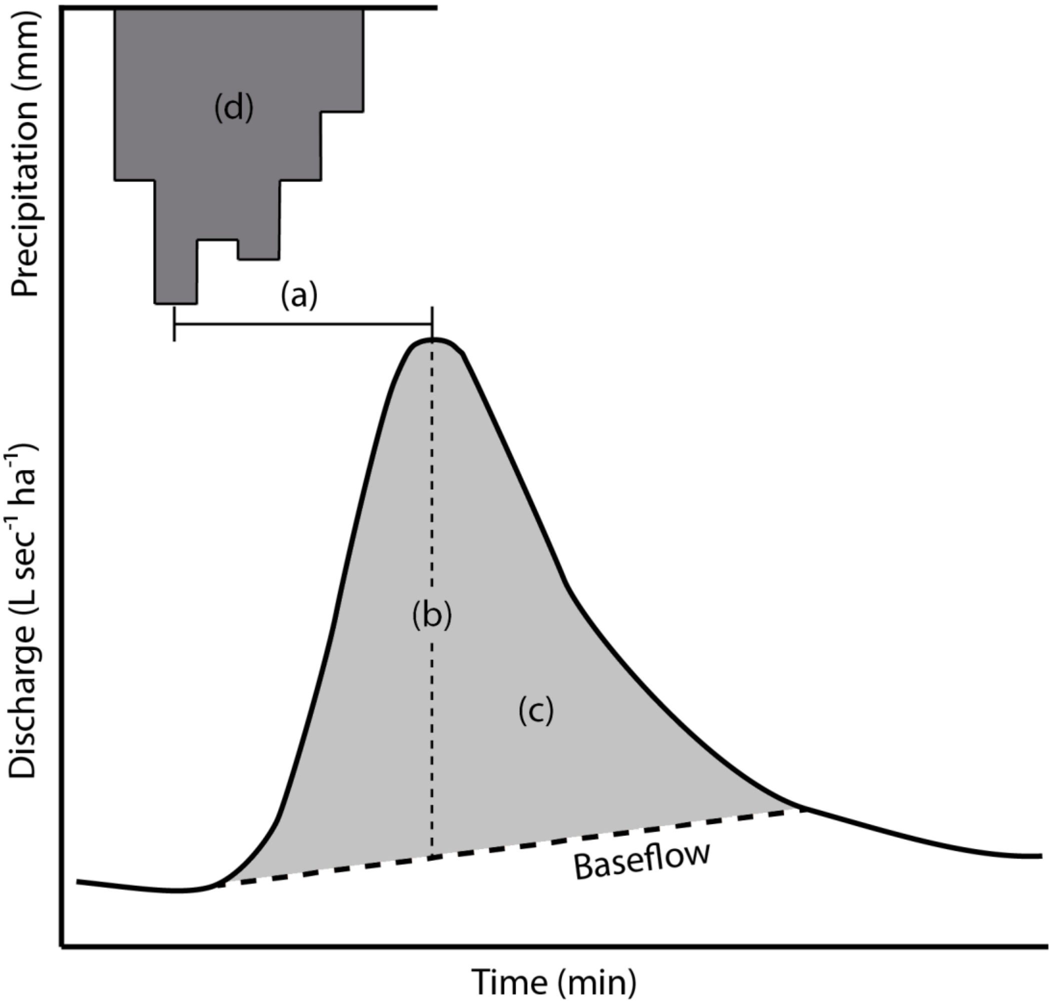

Figure 4.13: A typical storm hydrograph (from Allott *et al.*, 2015). a) indicates the time interval between maximum rainfall intensity and peak storm discharge used to determine lag-time; (b) indicates the magnitude of peak storm discharge, when the baseflow component has been deducted.; (c) the pale grey shaded area represents total storm discharge; (d) the dark grey shaded area represents total rainfall/precipitation

4.2. Rainfall monitoring

Rainfall data were collected using a HOBO RG3 rain gauge located nearby on Burbage Moor (SK 26624 82762). This logger recorded 10-minute period rainfall totals using a tipping bucket, enabling the calculation of rainfall total estimates for the catchment, at the same sampling frequency as the flow data available from the river stage loggers.

4.3. Results

Storm hydrograph metrics were extracted from the data from the selected storms, and are presented in Table 4.3. Difference between the datasets from the downstream and upstream was tested for significance using the Related-Samples Wilcoxon Signed Rank Test (see Table 4.4). Distributions of values within each dataset for each hydrograph metric are presented in Figure 4.14, Figure 4.15, Figure 4.16 and Figure 4.17.

Storm Hydrograph Metric (Standardised)	**Description**	**Burbage Brook u/s**	**Burbage Brook d/s**	**Difference as % of BB u/s**
Total rain (mm)	Total storm rainfall at gauge	18.2	18.2	0.0
Lag time (hh:mm)	Time between midpoint of peak rain intensity and peak Q	08:55	06:35	26.2
Peak Q ($m^3/s/km^2$)	Peak discharge (including baseflow)	0.287	0.251	12.5
Peak Q_s ($m^3/s/km^2$)	Peak stormflow discharge	0.271	0.210	22.5
H.S.I.	Ratio of peak storm Q to total storm Q	0.000019	0.000023	21.1
% runoff	Stormflow as a % of rainfall	53.6	30.7	42.7

Table 4.3: Median values of key hydrograph metrics from six selected post-works storms at Burbage Brook downstream and upstream. Red = downstream < upstream; green = downstream > upstream

Storm Hydrograph Metric	**n pairs**	**Test statistic**	**Standard Error**	**Asymptotic significance (2-sided test)**
Lag time	5	12	3.708	0.225
Peak Q_s	5	4	1.871	0.593
H.S.I.	6	20	4.77	0.046
% runoff	6	3	4.77	0.116

Table 4.4: Results of statistical testing for significance of difference between hydrograph metrics from six selected post-works storms at Burbage Brook downstream and upstream, using the Related-Samples Wilcoxon Signed Rank Test. Blue = not significant difference at 95% confidence; orange = significant difference at 95% confidence

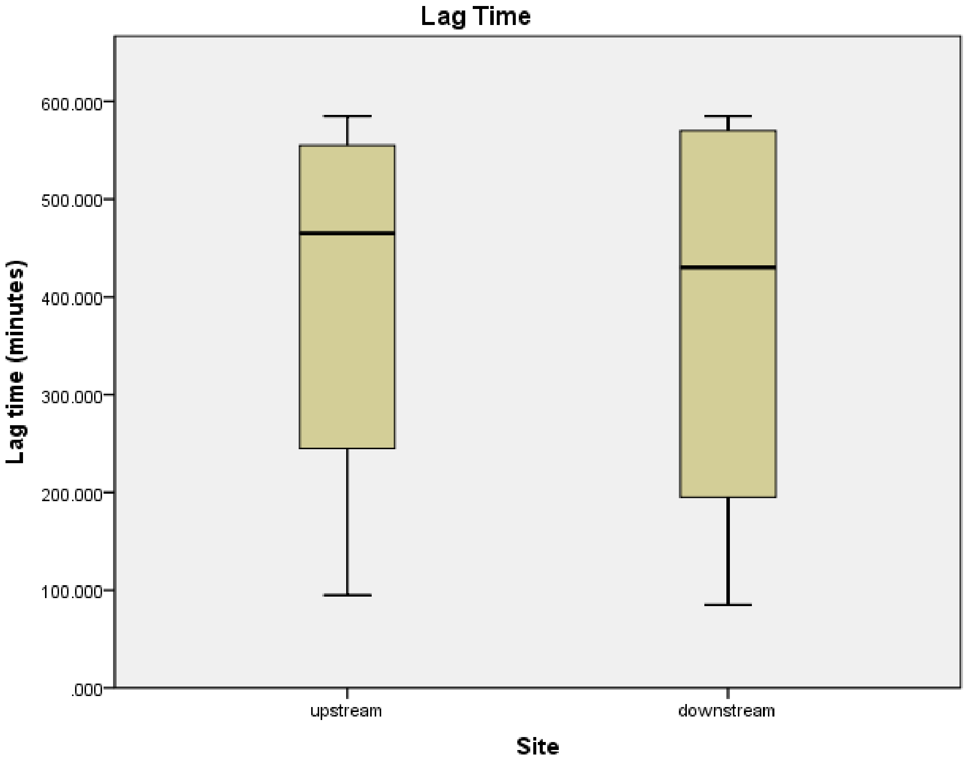

Figure 4.14: Distribution of lag time, six storms in 2016

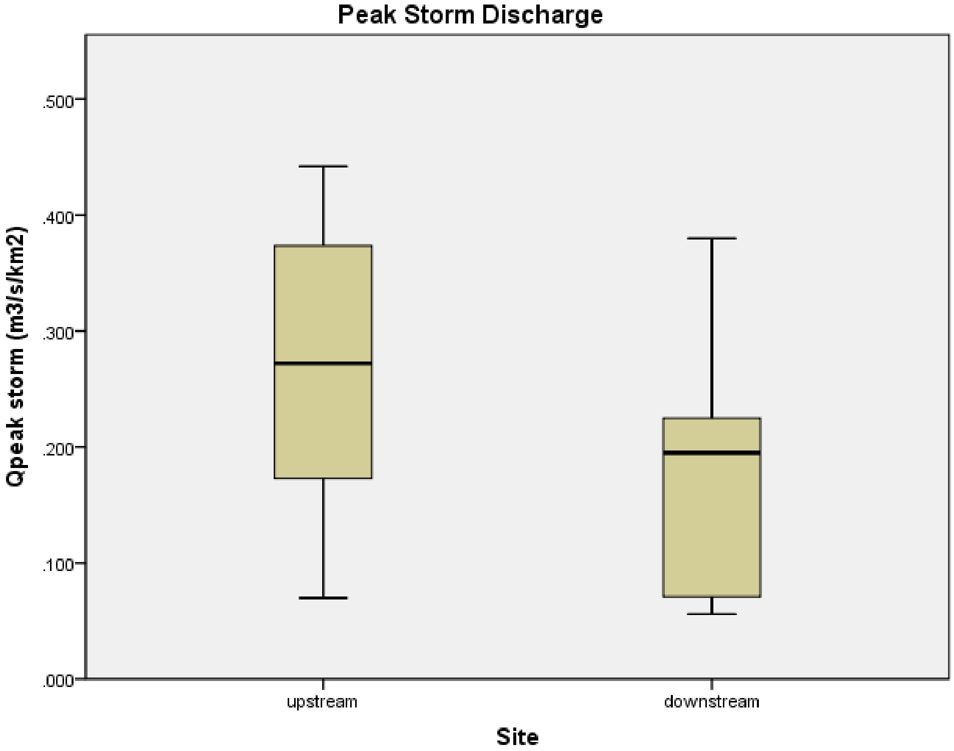

Figure 4.15: Distribution of peak storm discharge, six storms in 2016

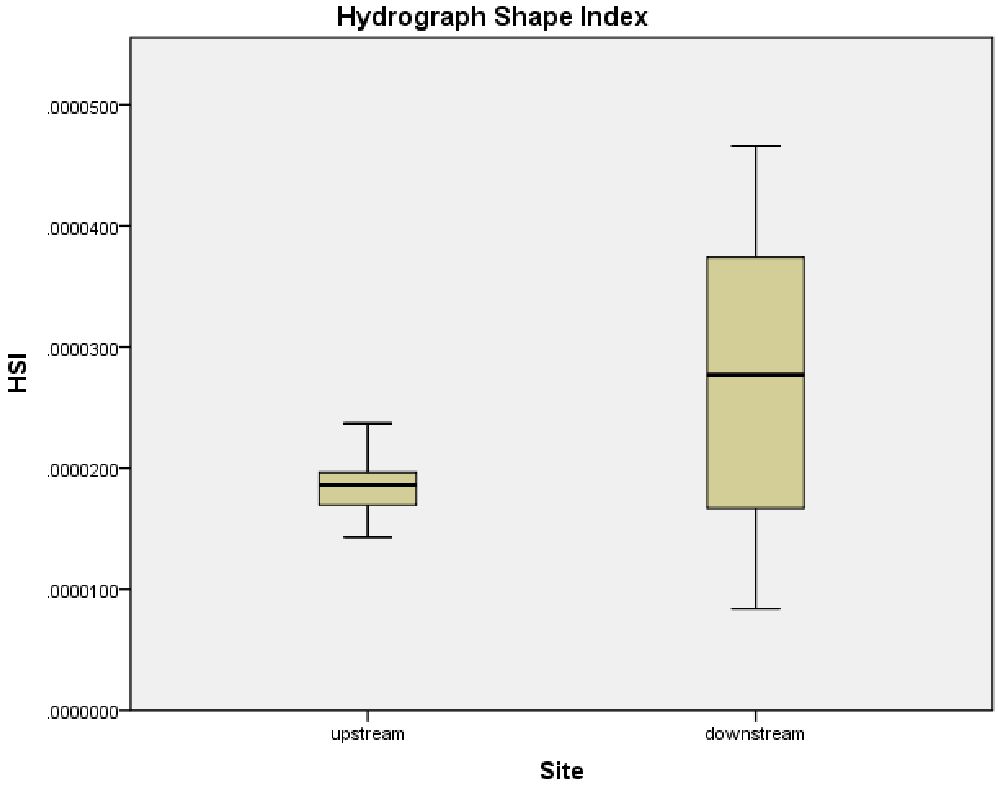

Figure 4.16: Distribution of HSI, six storms in 2016

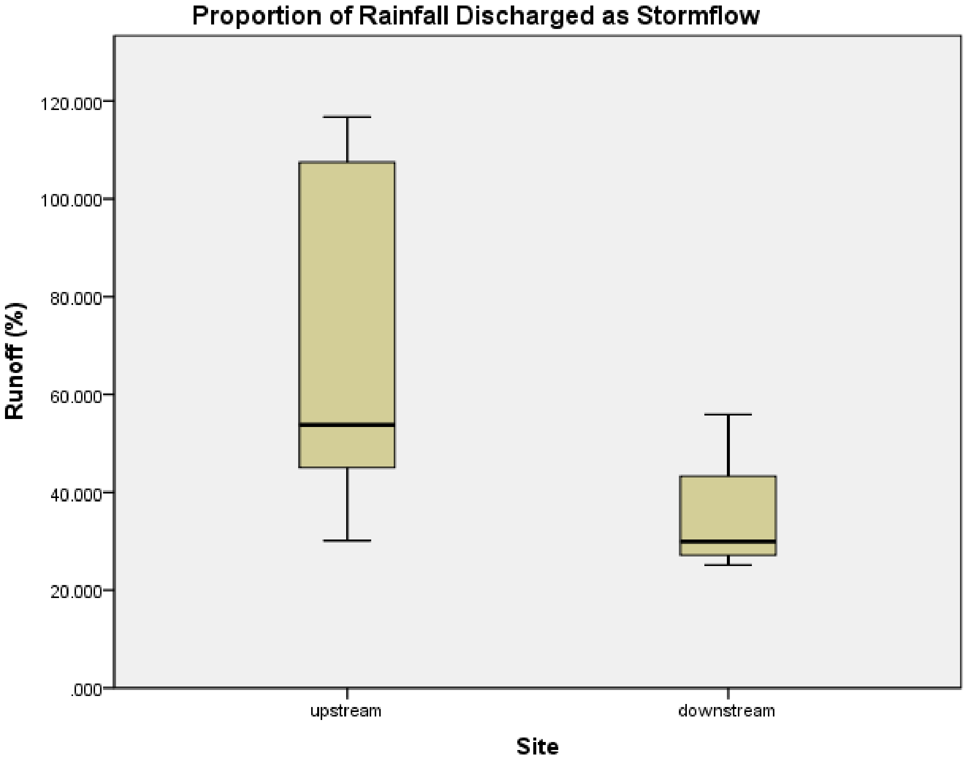

Figure 4.17: Distribution of the proportion of rainfall discharged as stormflow, six storms in 2016

4.3.1. Comparison with pre-works baseline data

Peak flow data were available for five pre-works storms from WHS (2015), enabling comparison between pre- and post-works data, as presented in Table 4.5 and Figure 4.18. Whereas median standardised peak Q was 3.1% lower at Burbage Brook downstream (0.433 $m^3/s/km^2$) than Burbage Brook upstream ($0.447 m^3/s/km^2$) before the felling of the conifer plantation, this difference increased to 12.5% in the dataset of the current study. This increase in the difference between downstream and upstream peak Q was not statistically significant according to the Mann-Whitney U-Test ($n_{pre\text{-}works} = 4$, $n_{post\text{-}works} = 6$, U=12, p=1). It should be noted that peak Q in all five pre-works storms exceeded the rating limit at the downstream station, and three out of five exceeded the rating limit at the upstream location. Data from the most extreme storm were excluded; the other four storms were included, but these results should be treated with caution.

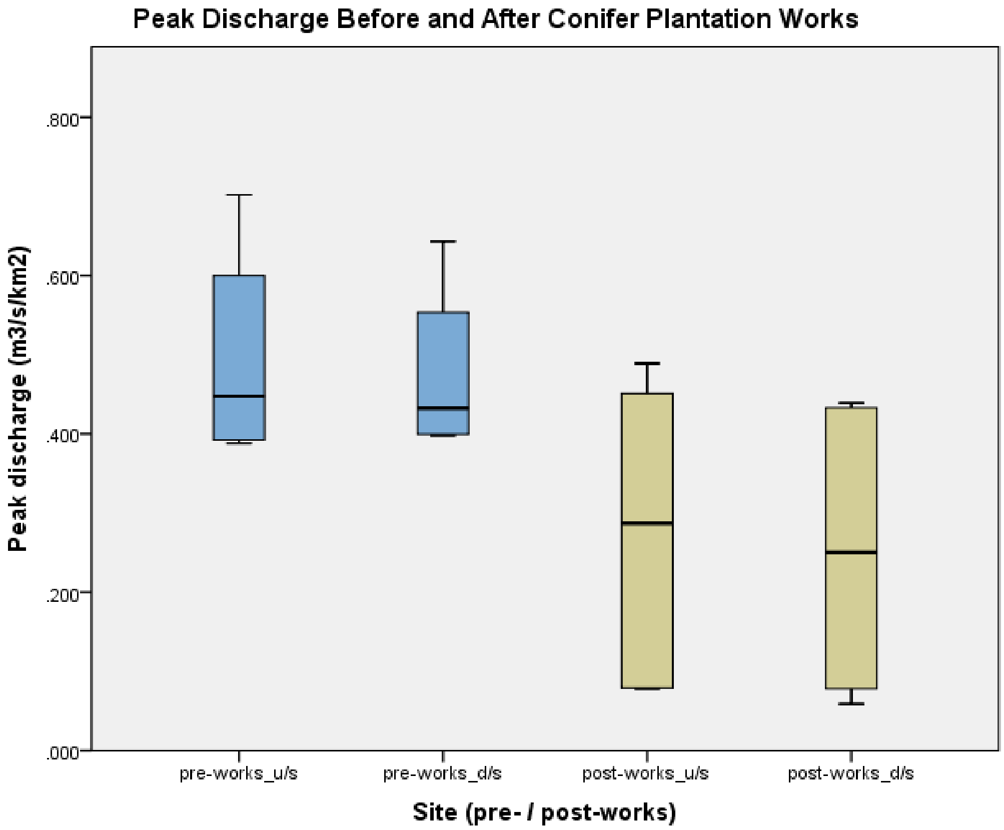

Figure 4.18: Distribution of peak discharge at upstream and downstream stations, pre- and post-works

Storm Hydrograph Metric (Standardised)	Burbage Brook u/s	Burbage Brook d/s	Difference as % of BB u/s
Median Peak Q Pre-works ($m^3/s/km^2$)	0.447	0.433	3.1
Median Peak Q Post-works ($m^3/s/km^2$)	0.287	0.251	12.5

Table 4.5: Comparison of pre- and post-works median peak Q data at Burbage Brook downstream and upstream. Red = downstream < upstream; green = downstream > upstream

Storm Hydrograph Metric	n_{pre}	n_{post}	Test statistic	Standard Error	Asymptotic significance (2-sided test)
Change in peak storm Q difference (upstream/downstream) between pre- and post-works datasets	4	6	12	4.69	1

Table 4.6: Results of statistical testing for significance of change in peak storm Q difference (Burbage Brook upstream/downstream) between pre- and post-works datasets, using the Mann-Whitney U-Test. Blue = not significant difference at 95% confidence; orange = significant difference at 95% confidence

4.4. Discussion

Hydrograph metrics other than peak discharge for five storms were not available for pre-works data. Raw data from the upstream and downstream loggers were available, but the calibration data were not, meaning that discharge data could not be calculated. If these calibration data become available in the future, hydrograph metrics relating to peak stormflow discharge and H.S.I. could be extracted from the pre-works data, allowing direct comparison of pre- and post-works conditions. Rainfall data were also not available. It is believed that these were not collected during the pre-works study, meaning that lag times and percentage runoff data cannot be calculated for pre-works storms. It was considered that, due to the localised nature of precipitation in the Peak District National Park, it would be inaccurate to use rainfall data from another location to calculate either volumes or timings of precipitation. The data presented in this study are therefore considered primarily as baseline data, for comparison to data collected by future monitoring. Comparisons may be made between data from the monitoring stations upstream and downstream of the conifer plantation works area. However, these do not necessarily represent the impacts of the works themselves, as they may reflect differences between hydrological regimes of the two catchments which are more dominant than any impacts of the works.

The area of conifer plantation felled constituted less than 20% of the total downstream catchment, so any impacts of clear-felling on water flow response to rainfall may well have been counterbalanced by other factors (remaining standing woodland, differences in soil types/vegetation types and associated water table heights).

Additional discussion of individual hydrograph metrics is presented below; the above comments apply to all of these metrics.

4.4.1. Lag time

Median lag time from peak rainfall intensity to peak discharge was shorter at the downstream station than at the upstream station, although the difference was not significant. This potential difference could be a result of loss of woodland canopy causing denudation of the ground surface, a reduction in interception rates and higher velocities of overland flow. However, it should be noted that in all but one storm (Storm 1), lag times were either very similar (difference<25 minutes) or longer at the downstream station than at the upstream station. The difference in median values is strongly affected by a shorter observed lag time at the downstream station than the upstream station in Storm 1.

As the newly planted broadleaf woodland matures, lag times may increase in the downstream catchment, as the travel time of rainfall from landing in the catchment to arriving in the stream channel increases due to increased interception rates and surface roughness.

4.4.2. Peak storm discharge

Median standardised peak storm discharge was lower at the downstream station than at the upstream station, although the difference was not significant. This potential difference could indicate a lower proportion of rainfall input being discharged as stormflow (and therefore a higher proportion being discharged after the storm, as baseflow). This could be a result of a lower water table (and therefore a greater water storage capacity) in the downstream catchment (moorland headwater catchments such as that of the upstream catchment tend to have higher water tables) resulting in higher infiltration rates and reduced production of stormflow.

4.4.3. H.S.I.

Median H.S.I. was significantly higher at the downstream station than at the upstream station (n (pairs)=6, Z=20, $p<0.05$). This difference could indicate that, of the total stormflow produced, a higher proportion was discharged as peak discharge at the downstream than the upstream station. This suggests a ‘flashier’ hydrological regime within the stormflow element of discharge. This could be a result of reduced surface roughness through the clear-felling of the conifer plantation leading to higher overland flow velocities. As the newly planted broadleaf woodland matures, surface roughness will likely increase, with associated reductions in overland flow velocities and attenuation of storm hydrographs.

4.4.4. Percentage runoff

The percentage of rainfall discharged as stormflow was lower in the downstream catchment than in the upstream catchment, although the difference was not significant. This suggests a potentially greater water storage capacity in the downstream catchment than in the upstream catchment, due to higher water tables in the upstream catchment, as would be expected in a moorland headwater catchment.

4.4.5. Comparison with pre-works data

As discussed above, these data should be treated with caution. Standardised peak discharge was lower at the downstream station than at the upstream station in both the pre- and post-works datasets, and the difference was greater in the post-works dataset. This could suggest that storm hydrographs have attenuated as a result of the works in the conifer plantation. It might reasonably have been expected that the hydrological regime in the downstream catchment would, instead, have become 'flashier' as a result of the clear-felling. However, if these data are reliable, then the remedial works such as installation of debris dams and windrowing of brash may have negated the impacts of the loss of canopy and surface roughness due to clear-felling.

4.5. Conclusions

Future data are required to establish year-on-year trajectories of change as a result of the works between the downstream and upstream catchments. Comparison of the available pre-works data with data from the current study suggest that the clear-felling works in the conifer plantation may not have resulted in increased flood risk in the short term.

While statistical analyses of datasets from the upstream and downstream monitoring stations show no significant differences in most hydrograph metrics, there are some indications suggesting a potentially flashier stormflow response to rainfall in the downstream catchment than in the upstream catchment (shorter lag times and significantly higher H.S.I.), although peak storm discharge and percentage runoff were both observed to be lower in the downstream catchment than the upstream catchment, suggesting greater water storage capacity in the downstream catchment.

It is recommended that further efforts are made to obtain the calibration data for the pre-works river stage sensor datasets. This would allow the calculation of continuous discharge data for the pre-works period of study, and therefore the direct comparison of additional storm hydrograph metrics (H.S.I. and peak storm Q) from pre- and post-works storms, providing highly valuable baseline data to assess the initial impacts of the works in the conifer plantation.

It is also recommended that, despite previous concerns, Burbage Brook downstream is continued as a monitoring station, as the rating relationship has remained stable, and floodplain stage height was only exceeded in one storm during the current period of study. By contrast, the suggested alternative monitoring location (Burbage Brook weir) appears to produce an unstable rating relationship over time, due to the susceptibility of the river bed to localised sediment deposition during large storm events. Further monitoring is required to assess the longer-term viability of the weir as a monitoring station.

5. Water quality monitoring

5.1.1. Water Framework Directive

The Water Framework Directive (WFD) establishes a legal framework to protect and restore clean water across Europe and ensure its long-term, sustainable use. Under the directive, water management is based on river basins, and specific deadlines are set for Member States to protect aquatic ecosystems. The directive applies to inland surface waters, transitional waters, coastal waters and groundwater (European Commission, 2016).

Table 8.2 lists the WFD threshold values for the determinands included in this report. For full details of WFD requirements see *The River Basin Districts Typology, Standards and Groundwater threshold values* (WFD, 2010).

5.1.2. Drinking Water Inspectorate

The Drinking Water Inspectorate (DWI) was formed in 1990 to provide independent reassurance that public water supplies in England and Wales are safe and drinking water quality is acceptable to consumers and meets the standards set down in law. The legal standards for drinking water are set down in national regulations and come directly from European law. The health based standards are based on expert global opinion and World Health Organisation guidelines (DWI, 2017).

Table 8.3 lists the Drinking Water Standards (DWS) for the determinands included in this report. For full details of the DWS see *The Water Supply (Water Quality) Regulations 2000* (Water Supply Regulations, 2000).

5.2. Methodology

Water quality was monitored every four weeks at the Burbage Brook upstream, downstream and weir monitoring stations, to assess any impacts as a result of the works at the conifer plantation. Monitoring started in February 2016 and is ongoing at the time of writing. Data from samples collected until January 2017 are included in the analyses of this study. Stream water samples were collected using sterile 1000 ml storage bottles that are pre-rinsed with stream water three times. Samples were refrigerated within seven hours of collection and collected by Scientific Analysis Laboratories (SAL) Ltd. within 5 days of sampling. SAL has a maximum turnaround time of 10 days; therefore, samples were analysed within 16 days (as recommended by SAL) for Dissolved Organic Carbon (DOC), Particulate Organic Carbon (POC) and Total Organic Carbon (TOC). Samples were also analysed for ammonia, nitrate, nitrite, orthophosphates, phosphorous, colour, pH and a suite of heavy metals.

Monitoring started in February 2016, a year after the conifer plantation felling works were completed. For the purposes of this report, water quality data from the monitoring station downstream of the plantation are compared to data from the monitoring station upstream of the plantation and the station further downstream at the weir. It is assumed that, if the works had caused a chemical input to the river, this would result in higher concentrations at the downstream station than at the upstream station, but that concentration would have reduced at the weir station, due to dilution. However, due to the size of the plantation relative to the size of the catchment (less than 20%), it is likely that any effects on water quality of the felling works would be counterbalanced by other factors such as area of remaining standing woodland and differences in soil type and vegetation type/cover (WHS 2014).

5.3. Results

Results are presented here as annual median values for each determinand at each monitoring station. Datasets for each determinand at the downstream and weir stations were tested for difference as compared to the equivalent dataset from the upstream station, using the Related-Samples Wilcoxon Signed Rank Test.

Results of tests regarding determinands of particular interest (identified within the aims of this report and/or as potential negative impacts of the conifer plantation clear-felling works) and/or where statistically significant differences were observed are presented in this section; full results are presented in appendix 8.1.

5.3.1. Carbon and water colour

Median concentrations of dissolved, particulate and total organic carbon (DOC, POC, TOC) were observed to be lower at the downstream station than at the upstream station, and lower again at the weir station. The same was observed for water colour. Difference in median concentrations between upstream and downstream stations was significant for DOC, TOC and water colour (see Table 5.1). Difference in concentrations between upstream and weir stations was significant for all four determinands (see Table 5.2). These patterns are what might be expected in an upland peatland catchment: carbon concentrations and water colour are highest at the headwaters where tributaries are fed by areas of blanket peat; this effect is increasingly diluted further down the valley as increasingly high proportions of the catchment are fed by non-peat soils.

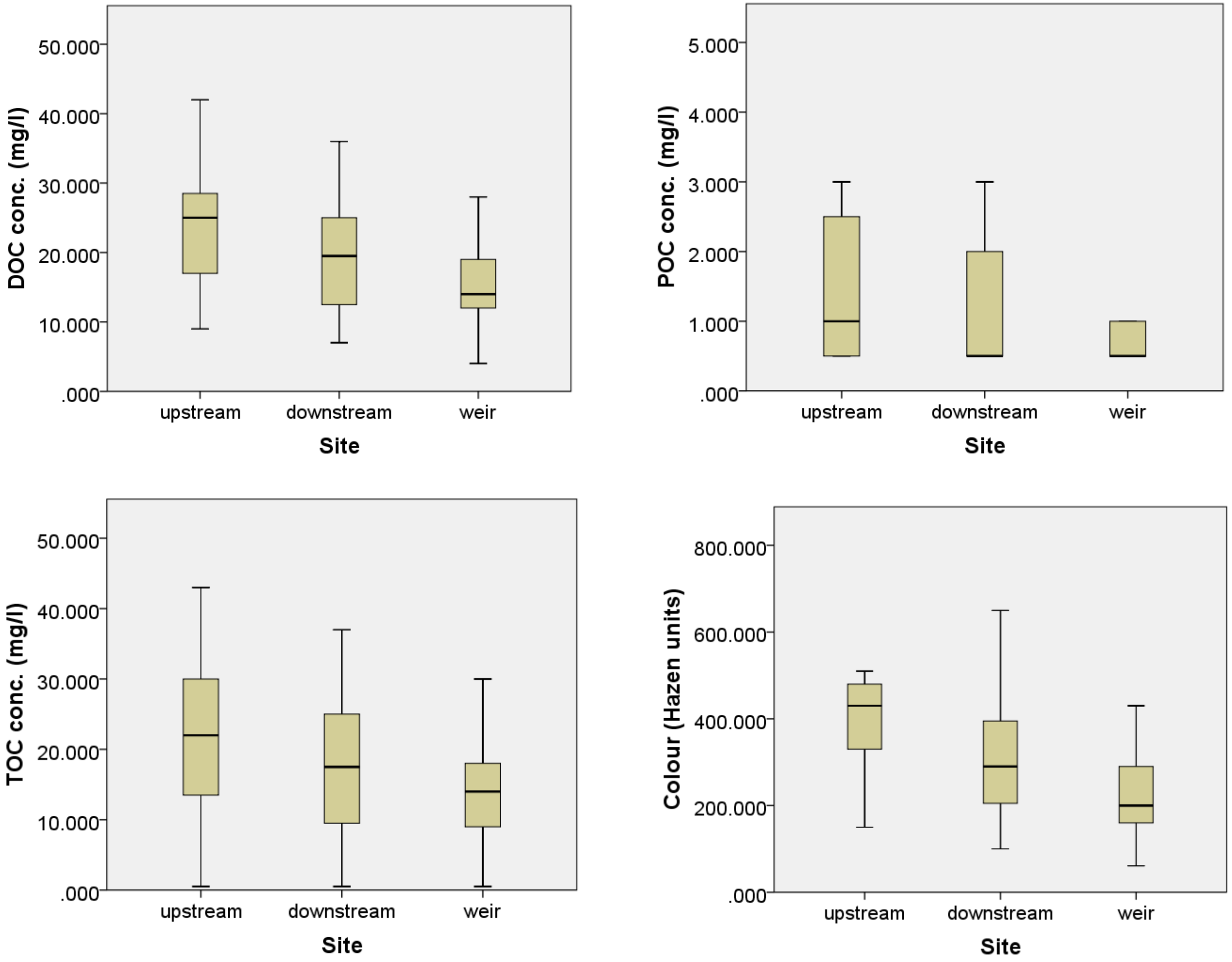

Figure 5.1: Distribution of concentration of carbon (dissolved, particulate and total) and water colour at the upstream, downstream and weir stations (February 2016 – January 2017)

Determinand	n pairs	Test statistic	Standard Error	Asymptotic significance (2-sided test)
DOC	12	66	11.214	0.03
POC	11	17	4.717	0.168
TOC	11	54	9.792	0.007
Colour	11	66	11.219	0.003

Table 5.1: Results of statistical testing for significance of difference between concentrations of DOC, POC and TOC, and water colour at Burbage Brook upstream and Burbage Brook downstream (February 2016 – January 2017), using the Related-Samples Wilcoxon Signed Rank Test. Blue = not significant difference at 95% confidence; orange = significant difference at 95% confidence

Determinand	n pairs	Test statistic	Standard Error	Asymptotic significance (2-sided test)
DOC	11	0.000	11.231	0.003
POC	11	0.000	4.757	0.027
TOC	11	0.000	8.434	0.008
Colour	11	0.000	11.236	0.003

Table 5.2: Results of statistical testing for significance of difference between concentrations of DOC, POC and TOC, and water colour at Burbage Brook upstream and Burbage Brook weir (February 2016 – January 2017), using the Related-Samples Wilcoxon Signed Rank Test. Blue = not significant difference at 95% confidence; orange = significant difference at 95% confidence

5.3.2. Orthophosphate

Median concentrations of orthophospate, measured using a Discrete Analyser, were observed to be 2.8mg/l lower at the downstream station than at the upstream station (difference was insignificant), and 7.5mg/l lower at the weir than at the upstream station (difference was significant: Z=0, $p<0.05$).

5.3.3. Nitrate

Increasing nitrate concentrations were highlighted as a potential issue post-felling by WHS (2014). Results from the current study show that median nitrate concentrations, measured using a Discrete Analyser were the same at the upstream and downstream stations; an insignificant increase was observed at the weir.

5.3.4. Acidity

Increases in nitrate concentration can be accompanied by increased acidity; this was raised as a potential concern by WHS (2014). No significant difference in pH was observed between the monitoring stations.

5.3.5. Aluminium

Increases in nitrate concentration can also be accompanied by increased aluminium concentrations (WHS, 2014). Concentrations in the current study, measured using ICP/OES (filtered), were observed to be lower at the downstream and weir stations than at the upstream station. Difference was not significant at the downstream station; difference was significant at the weir station (Z=0, $p<0.05$).

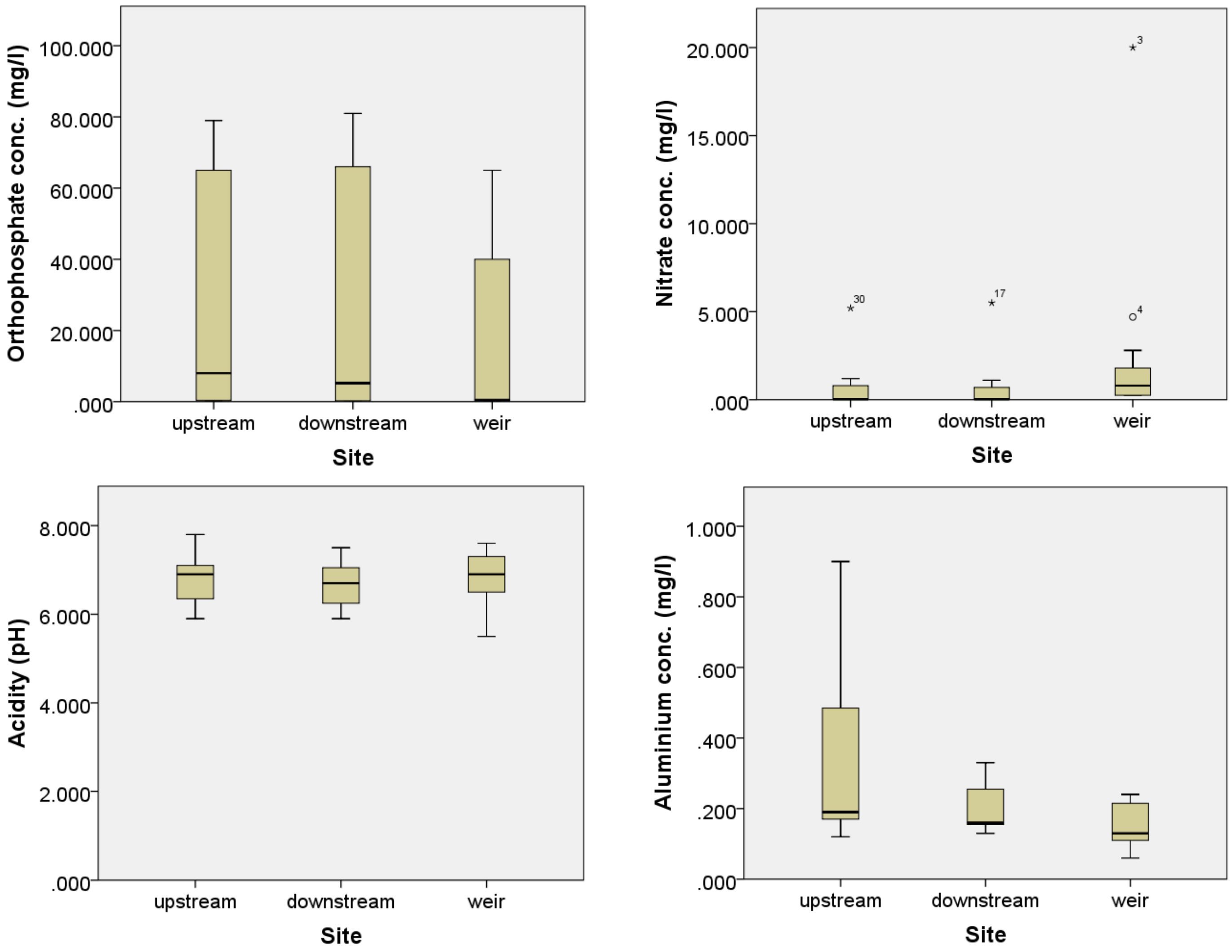

Figure 5.2: Distribution of concentrations of orthophosphate, nitrate, acidity and aluminium at the upstream, downstream and weir monitoring stations (February2016 – January 2017)

Determinand	n pairs	Test statistic	Standard Error	Asymptotic significance (2-sided test)
Orthophosphate	11	18	4.77	0.116
Nitrate	10	4.5	2.716	0.854
Acidity	11	30	8.352	0.369
Aluminium (ICP/OES)	7	22	5.895	0.175

Table 5.3: Results of statistical testing for significance of difference between concentrations of orthophosphate, nitrate and aluminium, and pH at Burbage Brook upstream and Burbage Brook downstream (February 2016 – January 2017), using the Related-Samples Wilcoxon Signed Rank Test. Blue = not significant difference at 95% confidence; orange = significant difference at 95% confidence

Determinand	n pairs	Test statistic	Standard Error	Asymptotic significance (2-sided test)
Orthophosphate	11	0	5.916	0.018
Nitrate	10	44	9.747	0.09
Acidity	11	38	9.772	0.283
Aluminium (ICP/OES)	7	0	4.757	0.027

Table 5.4: Results of statistical testing for significance of difference between concentrations of orthophosphate, nitrate and aluminium, and pH at Burbage Brook upstream and Burbage Brook weir (February 2016 – January 2017), using the Related-Samples Wilcoxon Signed Rank Test. Blue = not significant difference at 95% confidence; orange = significant difference at 95% confidence

5.3.6. Zinc

Zinc concentrations, as measured by ICP/OES, were lower at both the downstream and weir stations than at the upstream station. Difference was not quite significant at the downstream station ($Z=10$, $p=0.066$); difference was significant at the weir station ($Z=0$, $p<0.05$).

5.3.7. Nickel

Nickel concentrations, as measured by ICP/MS, were higher at the downstream and weir stations than at the upstream station. Both increases were significant (downstream: $Z=0$, $p<0.01$; weir: $Z=36$, $p<0.01$), although the effect size was small (1µg/l).

5.3.8. Barium

Barium concentrations, as measured by ICP/MS, were higher at the downstream station than at the upstream station, and higher again at the weir station. Difference to upstream concentrations were significant at both downstream ($Z=5$, $p<0.05$) and weir ($Z=36$, $p<0.05$) stations.

Determinand	n pairs	Test statistic	Standard Error	Asymptotic significance (2-sided test)
Zinc (ICP/OES)	7	10	2.716	0.066
Nickel (ICP/MS)	10	0	8.17	0.006
Barium (ICP/MS)	10	5	8.441	0.038

Table 5.5: Results of statistical testing for significance of difference between concentrations of zinc, nickel and barium at Burbage Brook upstream and Burbage Brook downstream (February 2016 – January 2017), using the Related-Samples Wilcoxon Signed Rank Test. Blue = not significant difference at 95% confidence; orange = significant difference at 95% confidence

Determinand	n pairs	Test statistic	Standard Error	Asymptotic significance (2-sided test)
Zinc (ICP/OES)	7	0	4.717	0.026
Nickel (ICP/MS)	10	36	2.636	0.008
Barium (ICP/MS)	10	36	7.141	0.012

Table 5.6: Results of statistical testing for significance of difference between concentrations of zinc, nickel and barium at Burbage Brook upstream and Burbage Brook weir (February 2016 – January 2017), using the Related-Samples Wilcoxon Signed Rank Test. Blue = not significant difference at 95% confidence; orange = significant difference at 95% confidence

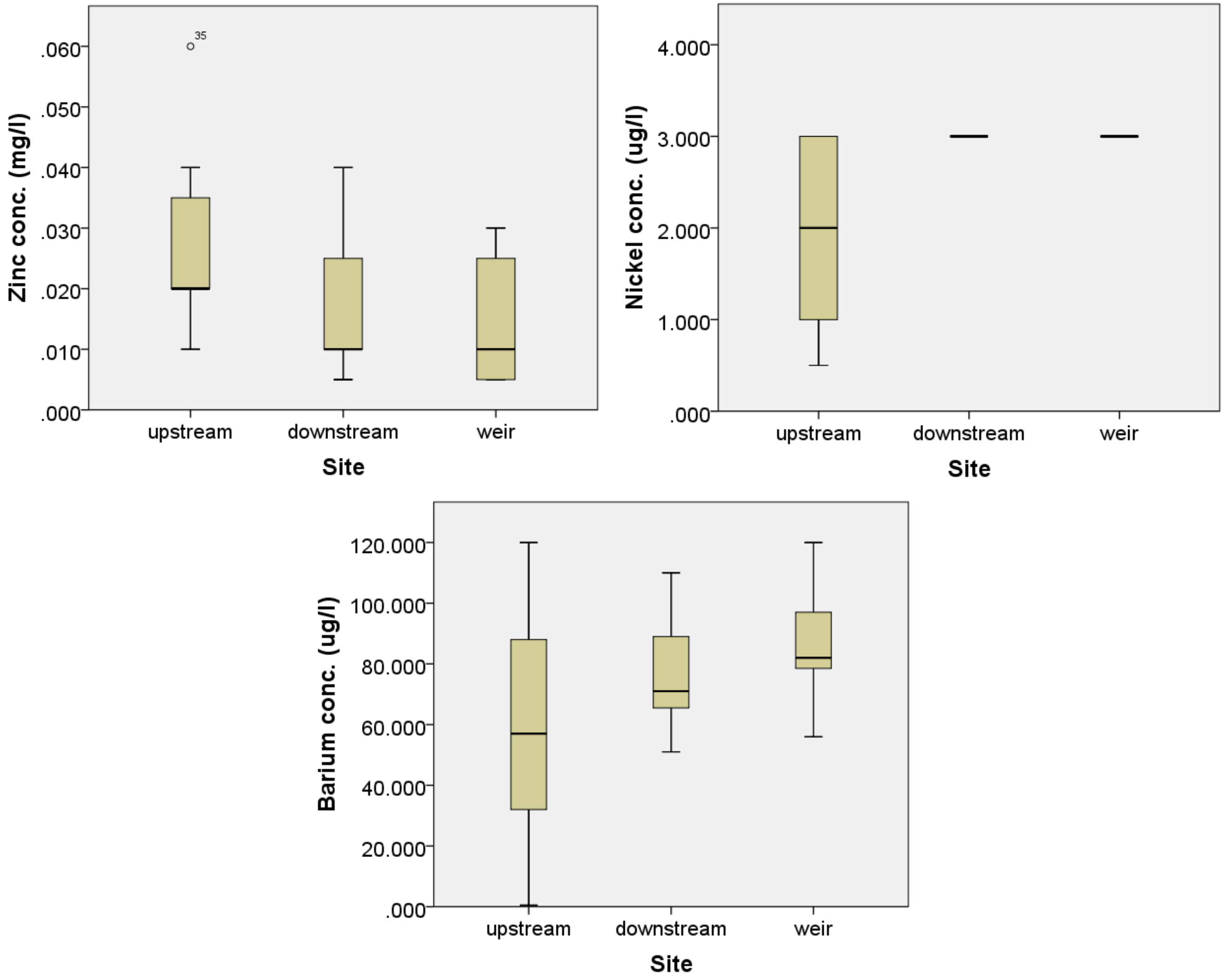

Figure 5.3: Distribution of concentrations of zinc, nickel and barium at the upstream, downstream and weir monitoring stations (February2016 – January 2017)

5.3.9. Other determinands

No significant differences were observed between values at the upstream station and either the downstream or weir locations for any other determinands.

5.4. Discussion

No water quality data were available from before the works were carried out in the conifer plantation. Therefore, while data from the downstream station have been compared to equivalent data from the upstream catchment to assess for any major differences which could be as a result of the works, these are essentially all baseline data. The area of conifer plantation felled constituted less than 20% of the total downstream catchment, so any impacts of clear-felling on water quality are likely to have been counterbalanced by other factors (remaining standing woodland, differences in soil/vegetation types).

Future monitoring may be able to establish trajectories of change in water quality as a result of these works.

No statistically significant increases in median values for determinands highlighted as potential issues by WHS (2014) were observed at the downstream station as compared to the upstream station. Concentrations of nickel were significantly higher at both the downstream and weir stations as compared to the upstream station, although it should be noted that the effect size was small (1µg/l) and concentrations were well below the limit for both WFD and DWS targets (see Table 8.2 and Table 8.3). Concentrations of barium were also significantly higher at the downstream station than at the upstream station. However, it was observed that concentrations were higher again at the weir station, suggesting that the cause of the increase is unlikely to be the works in the conifer plantation. Barium is not controlled under the WFD or DWS regulations.

Annual mean concentrations of cadmium, copper, iron and zinc were all above the limits set under the WFD. However, concentrations were either the same or lower at the downstream and weir stations than at the upstream station. It is therefore suggested that the cause of these high concentrations was not the works in the conifer plantation.

Annual mean water colour and pH were both above DWS limits. However, pH was within WFD targets; water colour was typical of a peatland headwater catchment and was lower at the downstream station than at the upstream station and lower again at the weir station, suggesting that the works in the conifer plantation may not have increased water colour.

As discussed above, it cannot be known whether water quality has improved or deteriorated as a result of the works in the conifer plantation, as pre-works data are not available. The current study does not suggest any major causes for concern, and the data presented will provide a robust description of baseline conditions against which future changes in water quality may be assessed, as the newly planted broadleaf woodland matures.

6. Project end and decommissioning of monitoring locations

No further funding has been secured to continue this Project. Therefore, all water level and barometric loggers were downloaded and removed from the three monitoring locations on the 14th September 2017. All infrastructure, including stilling well, steel dexion structure and ruler for measuring stage height, was also removed from Burbage Brook weir on this date. Currently, the infrastructure installed by WHS remains in place at the Burbage Brook upstream and downstream monitoring locations (see Figure 4.1 and Figure 4.2).

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8. Appendices

8.1. Water quality monitoring

Category/ method	Determinand/ unit	Upstream (median)	Downstream (median)	Weir (median)
Carbon	DOC/ mg/l	25	19.5	14
	POC/ mg/l	1	0.5	0.5
	TOC/ mg/l	22	17.5	14
Water Colour	Hazen	430	290	200
Absorbance	254nm	1.1995	0.892	0.616
	400nm	0.2195	0.156	0.105
	465nm	0.0985	0.068	0.047
	665nm	0.0165	0.012	0.006
DOC qualities	(E4:E6; Abs465/Abs665)	6.502924	6.467532	6.214286
	(Colour:carbon; Abs400/DOC)	0.0096	0.00838	0.008077
	(SUVA; Abs254/DOC)	0.054241	0.050195	0.047385
Acidity	pH	6.9	6.7	6.9
ICP/MS (Filtered)	As (D)/ µg/l	2.5	1.7	1.2
	Ba (D)/ µg/l	57	71	82
	Be (D)/ µg/l	0.025	0.05	0.0375
	Cd (D)/ µg/l	0.08	0.1	0.095
	Cr (D)/ µg/l	0.5	0.5	0.5
	Cu (D)/ µg/l	1.55	1.7	1.4
	Pb (D)/ µg/l	3.85	2.9	2.25
	Hg (D)/ µg/l	0.025	0.025	0.025
	Ni (D)/ µg/l	2	3	3
	Se (D)/ µg/l	0.025	0.025	0.25
	V (D)/ µg/l	1	1	1
	Zn (D)/ µg/l	15	13	12
ICP/MS (Total)	As (T)/ µg/l	3	1.85	1.5
	Ba (T)/ µg/l	33	63	77.5
	Be (T)/ µg/l	0.05	0.065	0.065
	Cd (T)/ µg/l	0.08	0.115	0.105
	Cr (T)/ µg/l	1	0.75	0.75
	Cu (T)/ µg/l	2.6	2.35	2.2
	Pb (T)/ µg/l	9.2	7	6.5
	Hg (T)/ µg/l	0.025	0.025	0.025
	Se (T)/ µg/l	0.25	0.025	0.25
	V (T)/ µg/l	1	1	1
	Zn (T)/ µg/l	19	18.5	16.5
ICP-OES	Al (D)/ mg/l	0.19	0.16	0.13

(Filtered)	As (D)/ mg/l	0.01	0.01	0.01
	Ba (D)/ mg/l	0.07	0.09	0.09
	Be (D)/ mg/l	0.005	0.005	0.005
	B (D)/ mg/l	0.04	0.04	0.03
	Cd (D)/ mg/l	0.005	0.005	0.005
	Cr (D)/ mg/l	0.005	0.005	0.005
	Cu (D)/ mg/l	0.01	0.005	0.005
	Fe (D)/ mg/l	2.2	2.1	1.3
	Pb (D)/ mg/l	0.015	0.015	0.015
	Hg (D)/ mg/l	0.005	0.005	0.005
	Ni (D)/ mg/l	0.005	0.005	0.005
	Se (D)/ mg/l	0.02	0.02	0.02
	V (D)/ mg/l	0.005	0.005	0.005
	Zn (D)/ mg/l	0.02	0.01	0.01
ICP/OES	Phosphorous/ mg/l	0.5	0.5	0.5
	Total hardness/ mg/l	20.5	22.5	29
Discrete Analyser	Ammonia/ mg/l	0.24	0.11	0.08
	Nitrate/ mg/l	0.025	0.025	0.8
	Nitrite/ mg/l	0.8	0.075	0.05
	Orthophosphates/ mg/l	8	5.2	0.5

Table 8.1: Annual median values (2016) for all determinands analysed at upstream, downstream and weir monitoring stations

Category/ method	Determinand/ unit	WFD target (mean)	Upstream (mean)	Downstream (mean)	Weir (mean)
Acidity	pH	6-9	6.5	6.5	6.8
ICP/MS (Filtered)	As (D)/ µg/l	50	2.23	1.664	1.267
	Cd (D)/ µg/l	0.08	0.087	0.095	0.093
	Cr (D)/ µg/l	3.4	0.8	0.682	0.667
	Cu (D)/ µg/l	1	1.44	1.655	1.446
	Pb (D)/ µg/l	7.2	5.325	4.618	3.425
	Hg (D)/ µg/l	0.05	0.033	0.031	0.030
	Ni (D)/ µg/l	20	1.95	3.091	3
	Zn (D)/ µg/l	8	14.7	14.273	11.75
	Fe (T)/ mg/l	1	2.314	2.286	1.256

Table 8.2: Comparison of annual mean values (2016) to Water Framework Directive targets for relevant determinands at upstream, downstream and weir monitoring stations. Green = below/within WFD limit; red = exceeding WFD limit

Category/ method	Determinand/ unit	DWS	Upstream (mean)	Downstream (mean)	Weir (mean)
Colour/ Colorimtery	Hazen units	20	404	305	226
Acidity	pH	5.2	6.5	6.5	6.8
ICP/MS (Filtered)	As (D)/ µg/l	10	2.23	1.664	1.267
	Cd (D)/ µg/l	5	0.087	0.095	0.093
	Cr (D)/ µg/l	50	0.8	0.682	0.667
	Cu (D)/ µg/l	2	1.44	1.655	1.446
	Pb (D)/ µg/l	25	5.325	4.618	3.425
	Hg (D)/ µg/l	1	0.033	0.031	0.030
	Ni (D)/ µg/l	20	1.95	3.091	3
	Se (D)/ µg/l	0.5	0.025	0.025	0.25
ICP/OES (Filtered)	Al (T) mg/l	200	0.36	0.29	0.229
	B (T) mg/l	1	0.041	0.032	0.03
	Fe (T)/ mg/l	200	2.314	2.286	1.256

Table 8.3: Comparison of annual mean values (2016) to Drinking Water Standards targets for relevant determinands at upstream, downstream and weir monitoring stations. Green = below DWS limit; red = exceeding DWS limit