Final Report: Skell Catchment Scale Monitoring

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Authors: Brown, H., Keevil, G., and Hodgson, D.M.
Reviewed by: Iain Mann – Nidderdale National Landscape, Gabby Crisp – National Trust
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Non-technical Summary

River catchments are complicated systems with interrelated natural, social, and technical considerations. Natural flood management (NFM) interventions are a means to manage predicted future increases in climate-related hazards is by improving the resilience of river catchments. A series of NFM interventions were installed in the River Skell catchment with the aim of reducing sediment load and river level, particularly during flood events. To understand the benefits, a long-term monitoring campaign of the river was initiated. This campaign combined in-river measurements of river level and turbidity, and water sampling by volunteers to measure several parameters at a series of upstream to downstream locations, including within the Fountains Abbey and Studley Royal site.

Establishing a long-term monitoring programme at a catchment-scale is an important step to demonstrating, and quantifying, the effectiveness of NFM. Currently, long-term monitoring programmes that focus on river level, sediment load, and water quality to assess NFM benefits are rare. Therefore, there have been several learnings that can be translated to other systems. A cost effective and data-rich in-river monitoring programme has been developed that has characterised the catchment system. In particular, the very short response time between heavy rainfall events and increase in river level and sediment load has been documented for the first time. This means that the Skell is characterised as a 'flashy' catchment, and that a successful outcome of NFM will be to reduce its flashiness, but that preventing flooding is not a realistic aspiration. The volunteer sampling has shown that water quality is poor, and increasingly poor through the catchment. Some parameters have complex temporal and spatial patterns, which has a stronger relationship to seasons, river stage (rising or falling), and timing with respect to storm events.

In summary, the catchment-scale monitoring of the River Skell has resulted in a major advance in characterising the behaviour of the system to rainfall events and provides a basis for demonstrating the importance of NFM interventions to reduce flood risk and sedimentation in the Fountains Abbey and Studley Royal site. The longer the monitoring time series the more reliable the correlations between river behaviour and these parameters will be. This can be used to be more confident in assessing the benefits of NFM installations, and in managing the wider catchment.

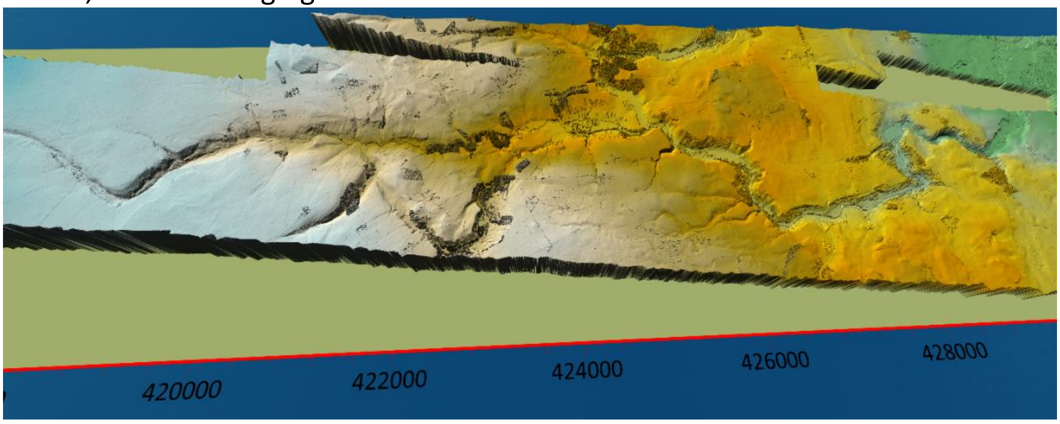


Figure 1.1 – *Perspective view of the River Skell catchment. Note the steep margins and tributary channels to the main river course, which mean this system has a 'flashy' character.*

Contents

1 Executive Summary

The long-term monitoring of catchment dynamics and water quality before, during, and after NFM interventions in the River Skell have led to several important, and exportable, learnings. An overarching learning is that even a small catchment, like the Skell, has so many interacting parameters, and such natural variability, that identification of impacts attributable to NFM requires decadal time series of monitoring information.

Determining a baseline from which to assess NFM benefits is strongly recommended, although this remains a rare step in many programmes. A key learning from this catchment-scale monitoring programme, however, is that establishing a baseline is non-trivial. Indeed, the annual and seasonal variability in rainfall patterns in a responsive (flashy) catchment like the Skell means that a baseline is unlikely to exist. Nonetheless, characterising the catchment dynamics prior to installation of interventions is an essential step if there is an aspiration to understand NFM benefits. Characterisation of the catchment prior to NFM installation provides a crucial understanding of the system behaviour from which to compare future responses to pattern weather events.

An important outcome from this programme has been the iterative development of a monitoring procedure that balanced value for money and useful data acquisition, which can be rolled out to other catchments. The key results of the catchment-scale monitoring demonstrated that the Skell system is highly responsive to rainfall events above a threshold; that there is a close relationship of river level and turbidity; that most of the sediment is transported during large rainfall events; and that during these events much of the particulate material is transferred through the system. In addition, some water quality parameters have a simple downstream increase in properties, whereas other parameters have a complex temporal pattern that are related to seasonal change (land-use), river stage (falling or rising levels), and timing in relation to storms. The statistical correlation of these relationships will benefit from a longer time series of data. Therefore, another outcome is that this unusually long monitoring period is insufficient to fully characterise the complex responses of the catchment systems. Several important sediment source areas have been identified, including within the Fountains Abbey and Studley Royal site, that could be a focus for additional NFM approaches.

The results also suggest that preventing flooding is not a realistic aspiration, but that with sufficient NFM measures in place the flood peak will be lengthened and lowered, and that management of water levels in the Fountains Abbey and Studley Royal site can help reduce flood risk. Significant reduction in sediment load is likely to rely on longer term changes in land and river management. The Skell is unusual in having a series of online ponds and lakes that are a substantial sediment reservoir. These features further complicate the understanding of sediment flux and result in a very long sediment retention time-scale. However, targeting sediment source ‘hotspots’ will have major short-term benefits.

In summary, the long-term catchment-scale monitoring programme has revealed many key insights into the way this system functions and provides a solid foundation and comprehensive dataset from which to quantify the benefits of NFM into the future if monitoring is maintained.

2 Introduction

The UK is impacted by hydrological extremes (floods and droughts), which affect homes, businesses, food security and energy supplies, and our heritage landscapes. These hazards are set to intensify (in magnitude, frequency and duration) due to the influence of climate change. One way to manage future impacts from increased exposure to climate-related hazards is by improving river catchment resilience through natural flood management (NFM) interventions. Therefore, understanding the interplay and responses of different parameters is crucial to improve the resilience of a river catchment.

The Nidderdale National Landscapes and the National Trust are the lead organisations delivering the Skell Valley Project, which aims to increase the resilience of the landscape, help nature to thrive, empower people, and celebrate the heritage of the catchment. As part of this work, Natural Flood Management (NFM) is being installed to reduce the risk of flooding at Fountains Abbey and downstream in Ripon. The NFM installations also aim to reduce the amount of sediment entering the river system, and to reduce the amount of dredging of the lakes at the Fountains Abbey and Studley Royal site. The role of the University of Leeds (the Yorkshire Integrated Catchment Solutions Programme (iCASP) and the Sediment, Soil and Pollutant Analysis Laboratory (SSPAL)) is to monitor the impact of the NFM interventions on both changes in flow and sediment.

This report summarises the monitoring of the Skell Valley river catchment before, during, and after installation of a range of NFM intervention and Nature Based Solutions (NBS). The River Skell is a flashy system. That is, there is a rapid response in river character (level and sediment load) to precipitation events. This short response time means downstream sites, including Fountains Abbey and Studley Royal, are vulnerable to flooding events. One major storm, Storm Barbet, impacted the catchment during the monitoring programme, which allowed assessment of a large precipitation event on river and catchment function. The data presented in this report represents an unusually long duration monitoring programme, which links meteorological, hydrodynamic, and sediment data, alongside a comprehensive water quality dataset that was achieved through a sampling programme by volunteers. These resulting large dataset allows deeper understanding of the dynamics of the River Skell, and establishes a reference framework to assess the impacts, and benefits, of NFM and NBS installations over a long monitoring period.

3 Skell catchment context

3.1 Study Location

The geology in the Skell River comprises intercalated Carboniferous sandstone and mudstone units in the upstream catchment, with an unconformity overlain by dolomitic (carbonate) Permian rocks in lower catchment around the Studley Royal lakes. The changes between harder sandstones and softer mudstones locally influences the river gradient and control the location of spring lines. The increased conductivity seen around Site 4 could be attributed to the exhumed band of Cayton Gill Shell Bed (that also defines the base of the Brimham Grit at Brimham Rocks), which might cause an increase in salinity at this point.

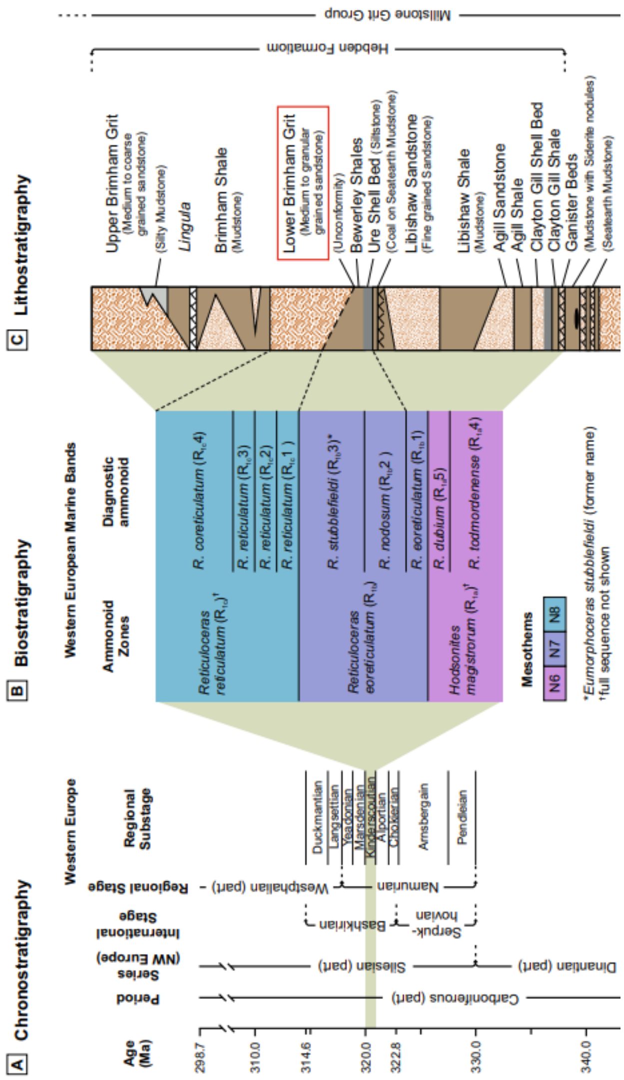


Figure 3.1 - *Summary of exhumed Carboniferous rocks in upstream Skell Valley chronostratigraphy (A), biostratigraphy (B) and lithostratigraphy (C) associated with the Lower Brimham Grit. The Kinderscoutian interval is shaded green (modified in part after Dunham & Wilson, 1985; British Geological Survey, 2008; Davydov et al., 2010; Waters, 2011; Waters et al., 2011a; Waters & Condon, 2012). Figure from Soltan (2018).*

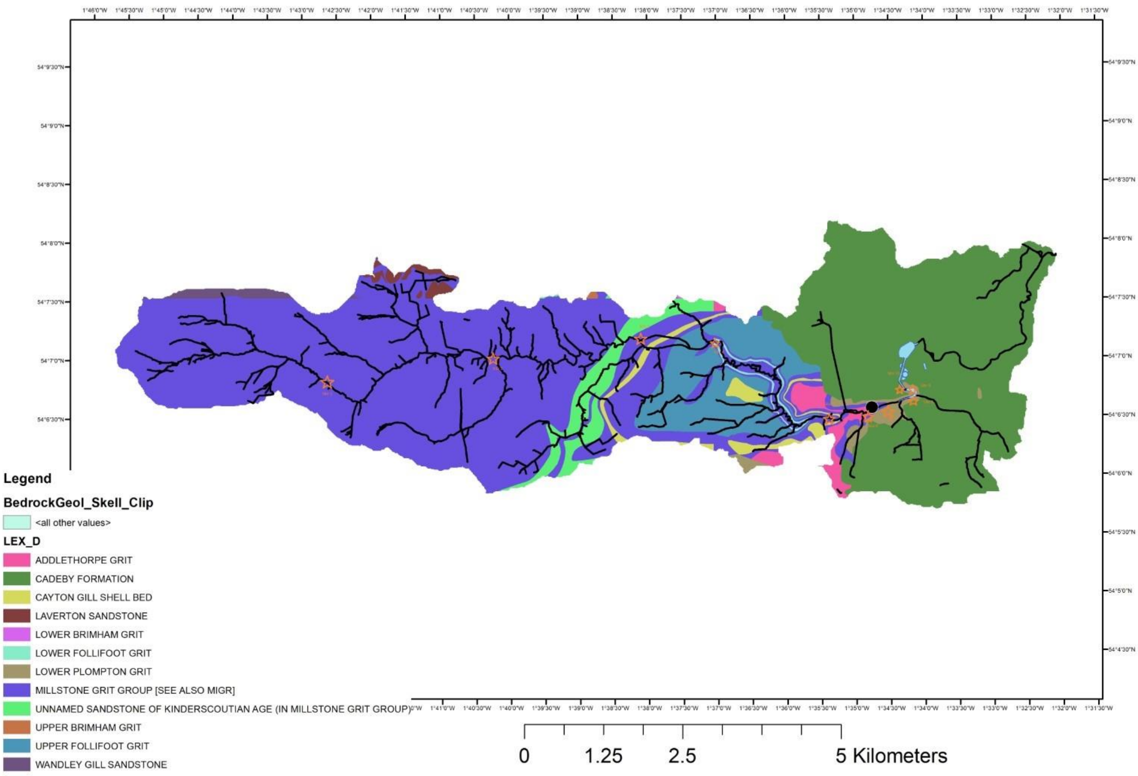


Figure 3.2 – *Geology map of the River Skell Catchment with the volunteer baseline sampling locations marked with orange stars.*

3.2 Establishing a Baseline

Establishing a baseline in a catchment is recommended prior to installation of NFM and NBS interventions in order to compare, and ideally quantify, the benefits to river level (lowering flood peaks) and sedimentation (reduced particulate load). Here, the monitoring overlapped with the installation of NFM in parts of the catchment. Nonetheless, there was a phase of monitoring aimed at establishing baseline conditions. However, it became apparent that baseline conditions in a complex and flashy catchment like the Skell are a chimera.

The flow conditions within the River Skell are completely dependent on the local rainfall. The Environment Agency have a rainfall sensor at Lumley Moor near Low Grantley, a few kilometres north of the River Skell (Fig. 3.3-3.4). This sensor has an almost complete record of rainfall from 1989-to-present. The rainfall data (Fig. 3.3) shows a series of high daily peaks each associated with large rainfall events, these large rainfall events occur all year round (Fig. 3.3b), the largest single event occurred in June 2007. There is a weak trend of the annual rainfall totals increasing with time since 1989 (Fig. 3.3c). Within the monitoring period (mid 2023-early 2025), 2023 was an average year in terms of rainfall (Fig. 3.4a & b). The winter of 2024 was noticeably wet, with the largest rainfall total since 1989, and the spring of 2024 was also very wet.

There is only a single Environment Agency sensor on the River Skell at Alma Weir, which is downstream of the confluence with the River Laver, east of Ripon. This site has an almost complete daily record of discharge since 1989, although no data have been published since August 2024 (Fig. 3.3 & 3.4). Figure 3.3 shows a highly season pattern of flow within the river Skell, with higher flows in the winter months. Figure 3.4b shows that much of the first half of 2023 was characterised by noticeably low flow conditions, whereas the flow was noticeably high in the winter and spring of 2024. The total discharge for winter 2024 was the highest recorded at Alma Weir. The total discharge for 2024 was the 3rd highest recorded at Alma Weir (the data from the autumn has not been published by the Environment Agency).

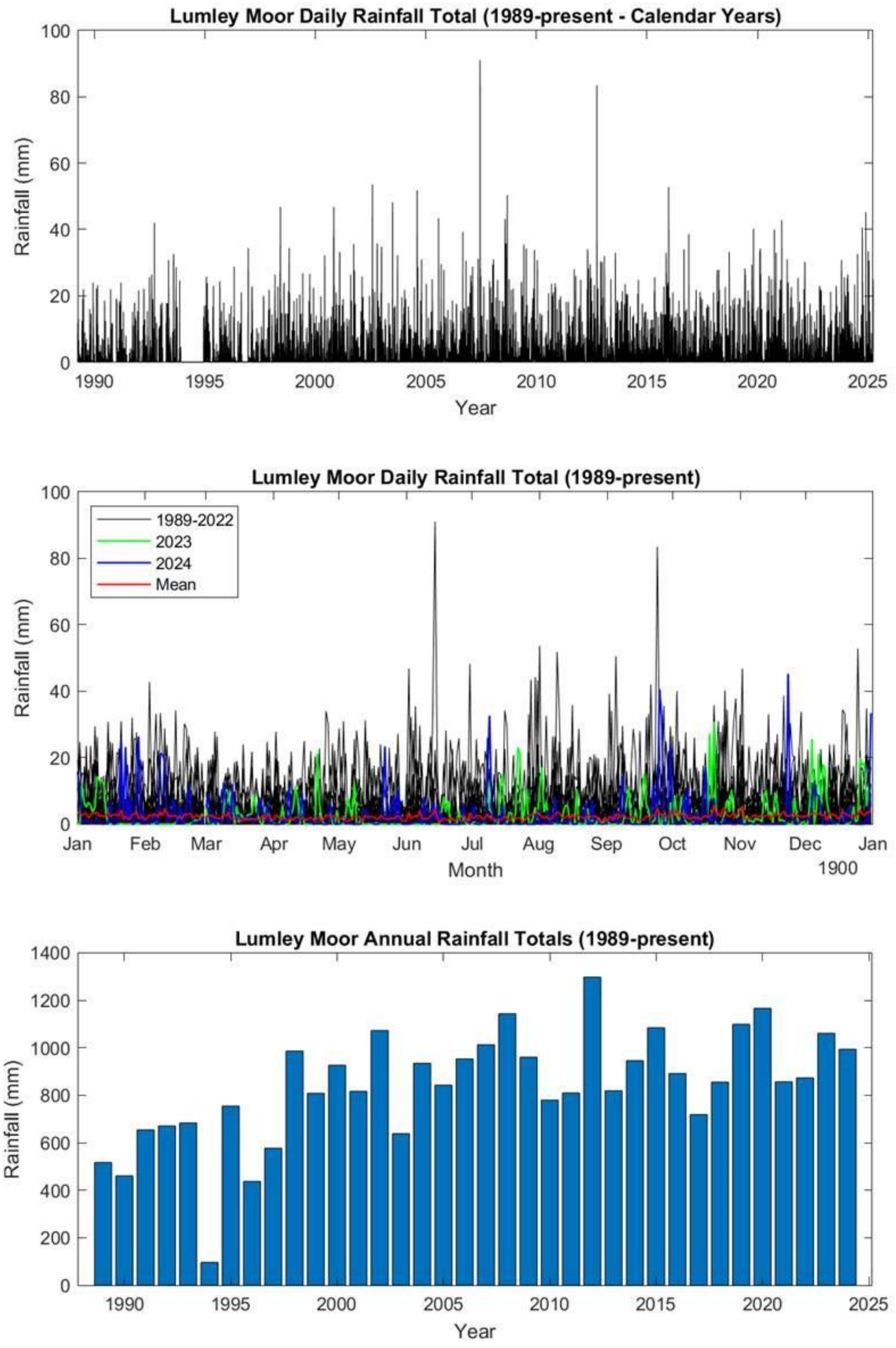
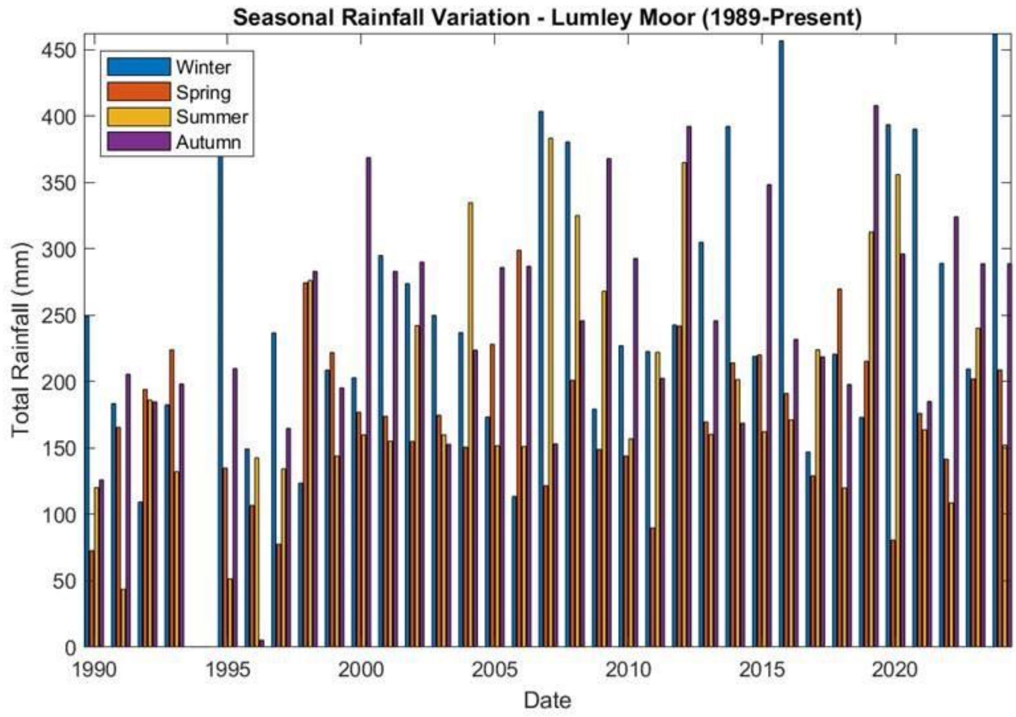


Figure 3.3 - *Rainfall data from the sensor at Lumley Moor. A. Complete plot of all data since 1989. B. The complete data set plotted on an annual axis to highlighting the lack of seasonality. C. Annual (calendar year) rainfall total. (Data Environment Agency)*



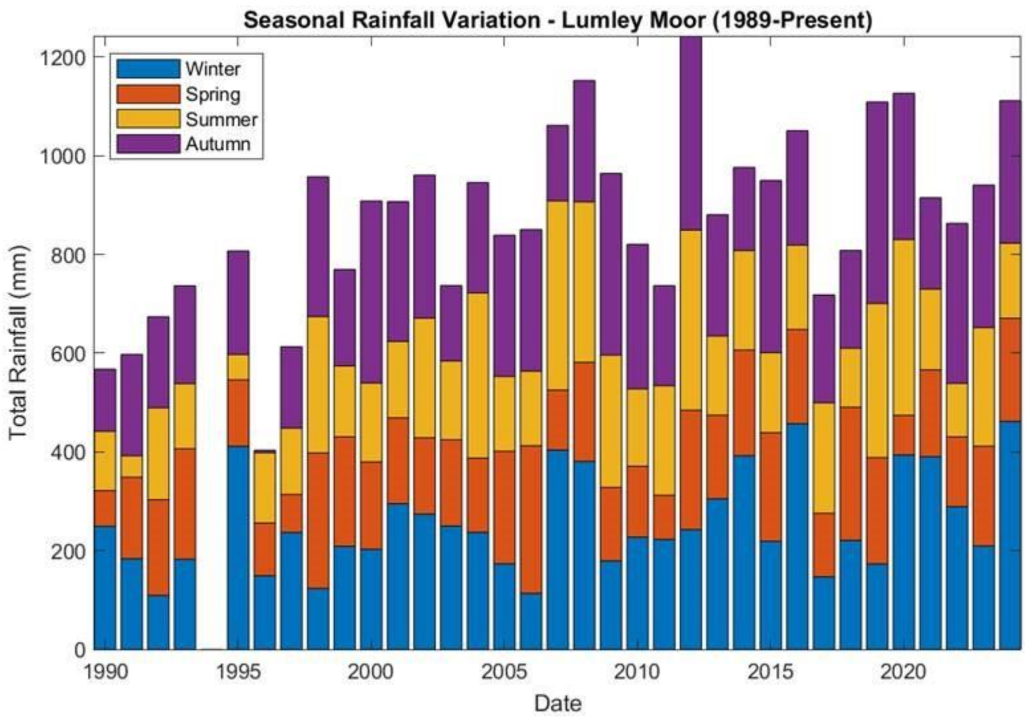
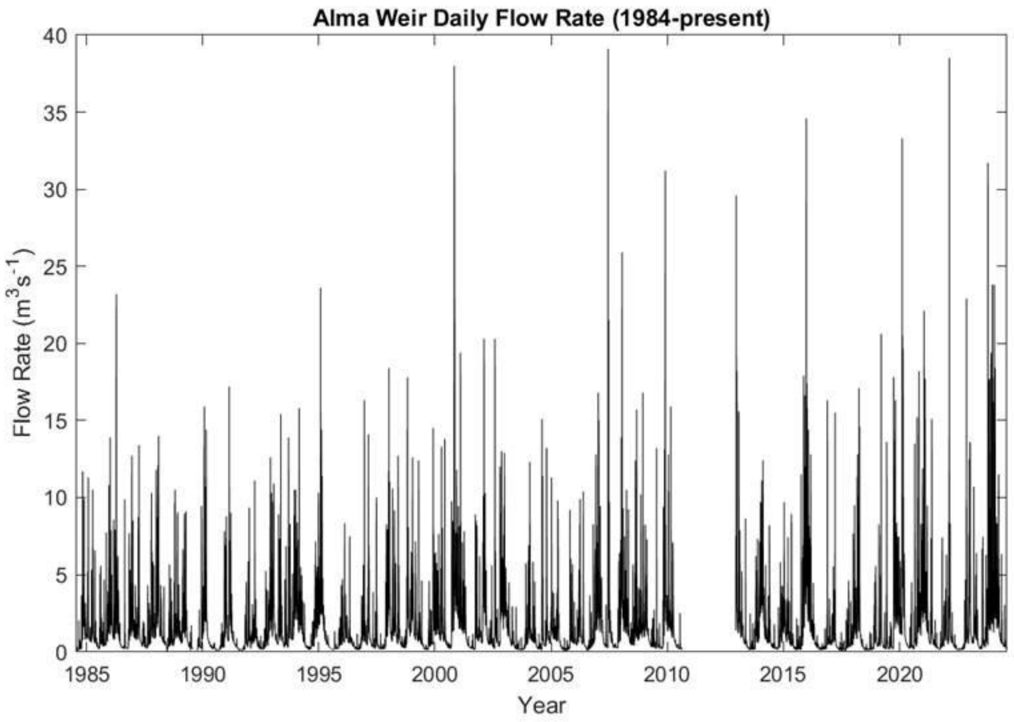


Figure 3.4 - *Rainfall data from the sensor at Lumley Moor. A. Seasonal rainfall totals plotted for each year (Meteorological seasons). B. Cumulative seasonal rainfall totals for each year from 1989 (Data Environment Agency).*



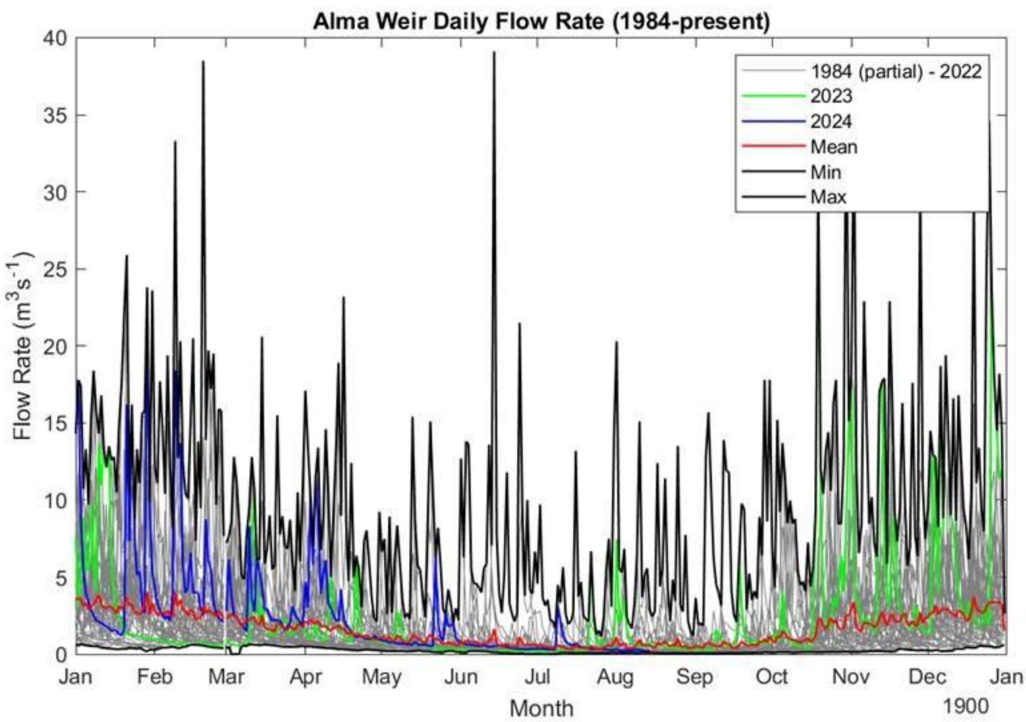
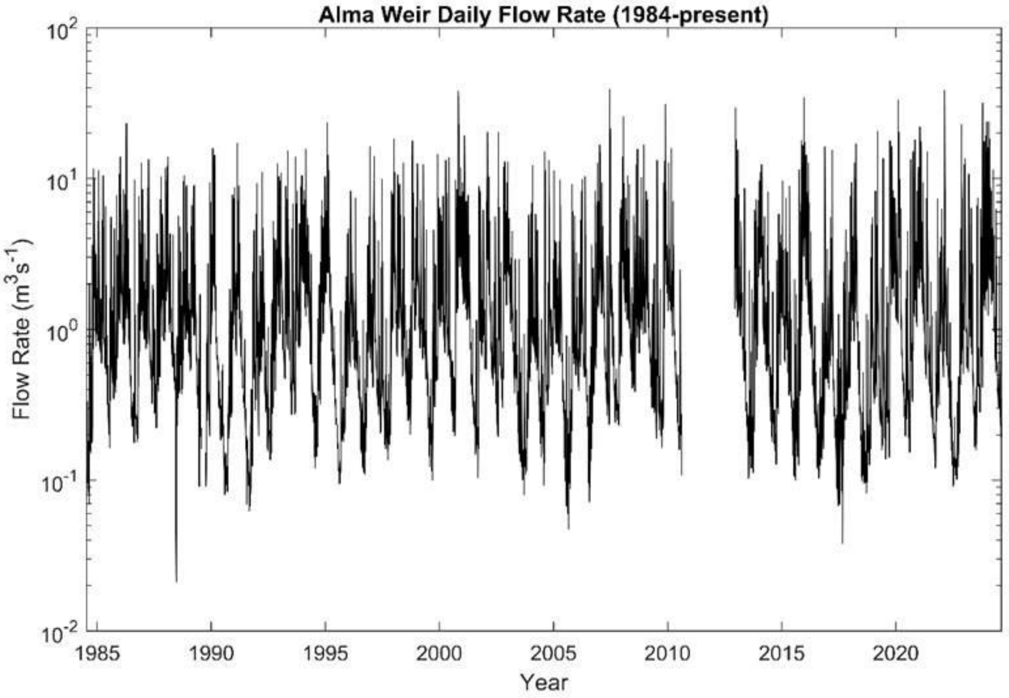


Figure 3.5 - *Flow data from Alma Weir. A. All daily data from 1985-Aug 2024. B. The same data plotted on seasonal axis to show seasonality (Data Environment Agency).*



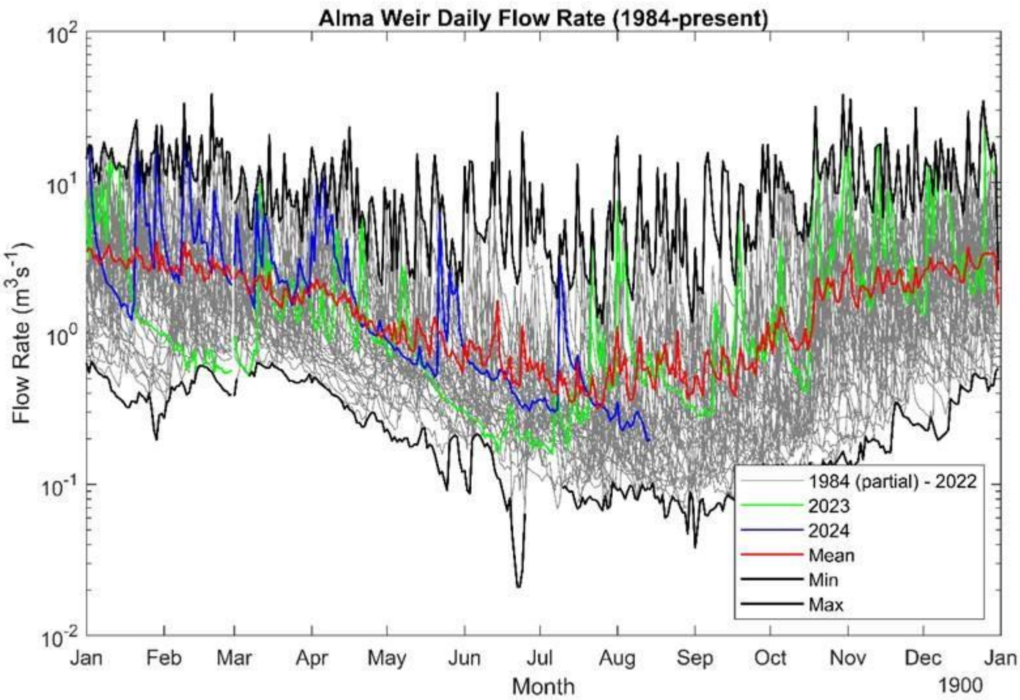
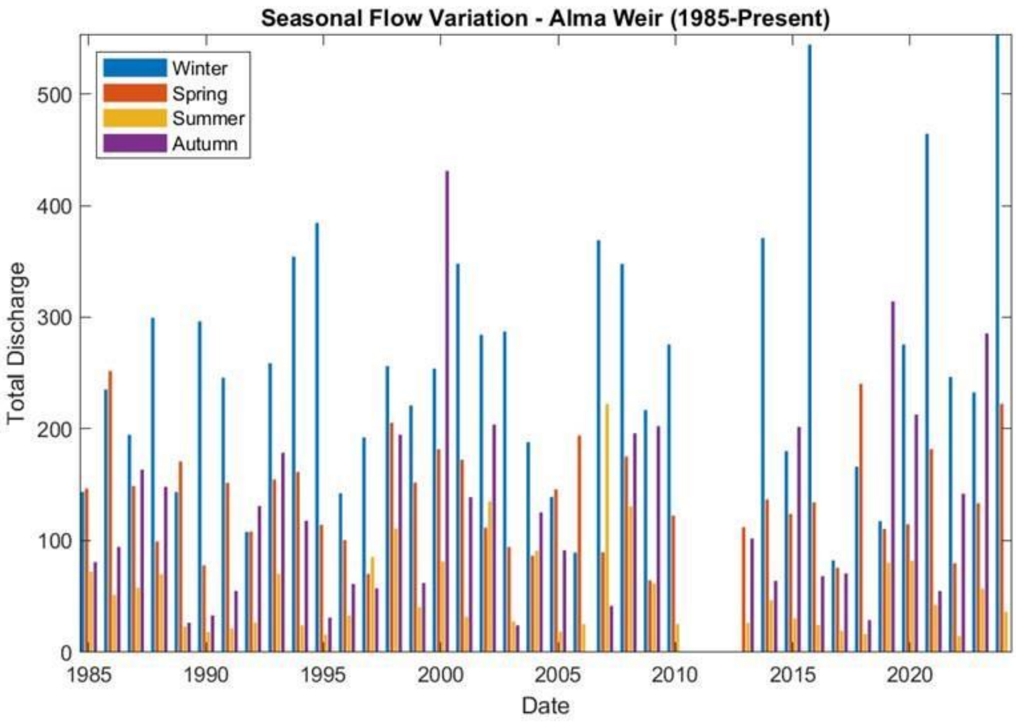


Figure 3.6 - *Flow data from Alma Weir. A. Daily data from 1985-Aug 2024, plotted on a semi log axis to highlight low flow data. B. The same data plotted on seasonal axis to show seasonality, plotted on a semi log axis to highlight low flow data (Data Environment Agency).*



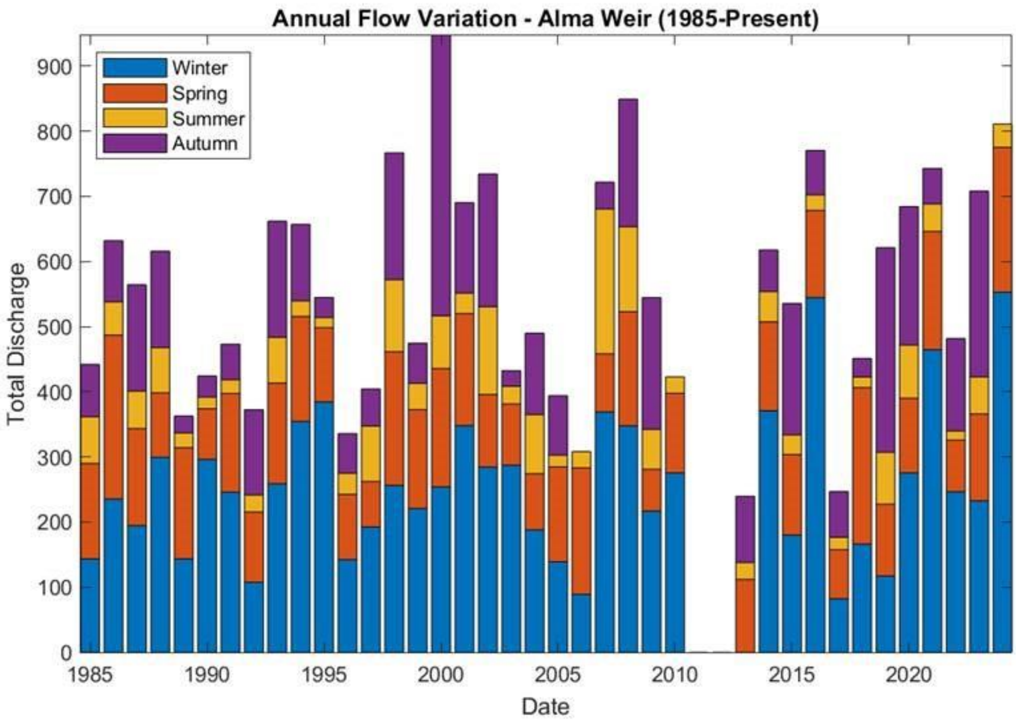


Figure 3.7 - *Flow data from Alma Weir. A. Seasonal discharge totals plotted for each year (Meteorological seasons). B. Cumulative seasonal discharge totals for each year from 1989 (Data Environment Agency).*

The River Skell is clearly seasonally dependent and extremely flashy (Figs. 3.3-3.7). Figure 3.3a hints at some underlying increase in both the intensity and number of large flow events. Further analysis has been undertaken to try to quantify any such change. Figure 3.7 shows the daily discharge data for both the River Skell at Alma Weir, the River Laver just upstream of Ripon, and the differenced result from these two flow stations. The Alma Weir data includes both the Rivers Skell and Laver, the Laver component can be isolated from its separate record, which is only recorded a couple of kilometres upstream, the remainer thus represents the contribution of the River Skell without the component from the River Laver. All three data sets show a similar flashy pattern.

The daily discharge timeseries has been further analysed to quantify both the Flashiness Intensity and the Flashiness Index. The Flashiness Intensity is calculated by summing all the occasions in a year that the daily flow exceeds the total mean flow plus 5 standard deviations. This calculation effectively counts all the large flow events within a single year.

The Flashiness Index is quantified by the ratio of absolute day-to-day fluctuations of streamflow relative to total flow in a year (Baker et al., 2004):

$$FI_y = \frac{\sum_{i=1}^{n} |q_i - q_{i-1}|}{\sum_{i=1}^{n} q_i}$$

Where FI is the Flashiness Index, q is the mean daily discharge, i is day, n = 365 (366) and y indicates the year of estimation. FI is a dimensionless measure that ranges between 0 and 2. Zero represents a constant flow.

At Alma Weir both the Flashiness Intensity and the Flashiness Index show an increasing trend with time. The same increase is seen in the Flashiness Intensity on the River Laver, but there is no clear trend in the Flashiness Index. The River Skell data shows a very strong trend in both the Flashiness Intensity and Flashiness Index. This suggests that the River Skell has seen an increase in both the number and intensity of large flow events, and that this trend continues to increase.

Figure 3.12 shows the same methodology applied to the EA rainfall data from Lumley Moor. The same trend of increasing flashiness intensity and frequency is not present within the rainfall data. There is some evidence of increasing rainfall intensity, but not frequency and this trend is not as obvious as it is for the discharge data. This suggests that the long-term trends observed within the Skell catchment are not solely the product of changing rainfall pattern, but that this is likely to be a land use change that is driving the increase in flashiness intensity and frequency.

In summary, although there are some trends in the flashiness of the catchment, this character and the ‘natural’ seasonal and annual variations in precipitation mean that no clear baseline conditions can be established. There is the opportunity to use big data approaches to identify and characterise meteorological ‘types’ – periods with similar conditions – against which differences in flow and sediment load could be compared to assess the impacts of NFM.

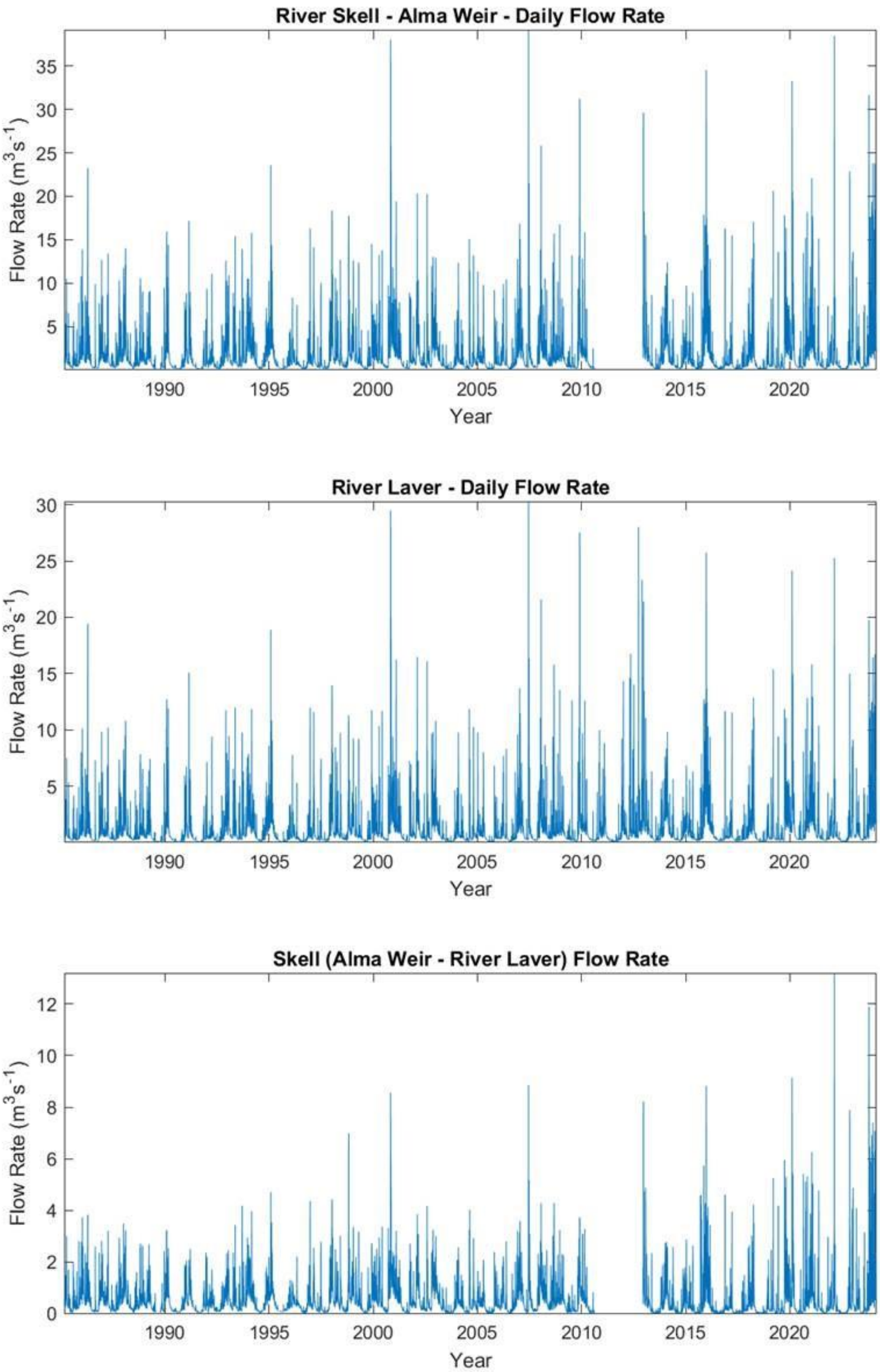


Figure 3.8 - *Flow data from Alma Weir. A. All daily data from 1985-Aug 2024. B. All daily flow data from the River Laver at Ripon. C. Alma Weir – Laver, the remainder between the two records estimating the daily flow within just the River Skell (Data Environment Agency).*

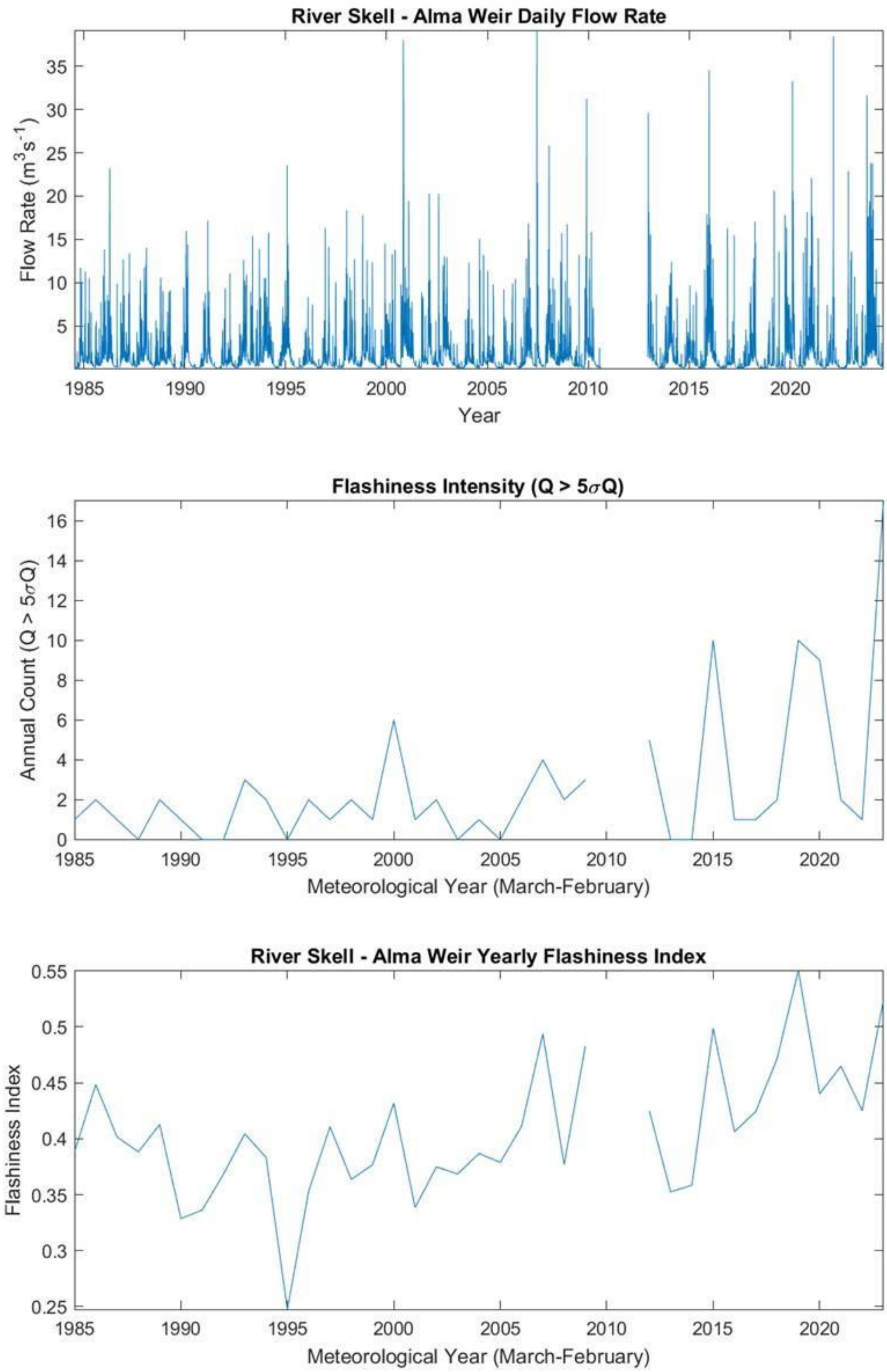


Figure 3.9 - *Flow data from Alma Weir. A. All daily data from 1985-Aug 2024. B. The Annual Flashiness Intensity (the sum of all the days where the flow exceeds the mean plus 5 standard deviations). C. The Annual Flashiness Index, the ratio of absolute day-to-day fluctuations of streamflow relative to the total flow in a year (Data Environment Agency).*

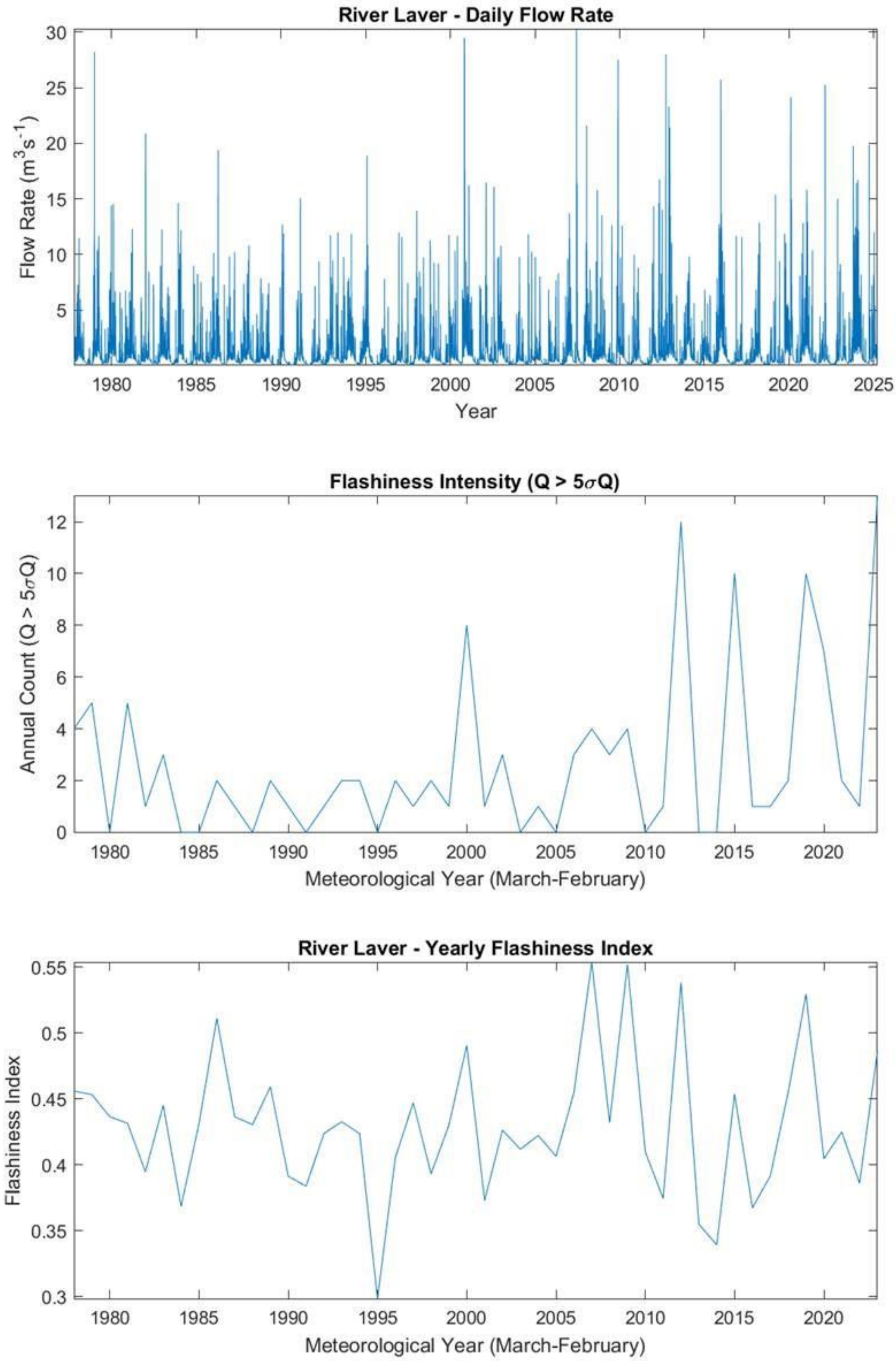


Figure 3.10 - *Flow data from River Laver. A. All daily data from 1985-Aug 2024. B. The Annual Flashiness Intensity (the sum of all the days where the flow exceeds the mean plus 5 standard deviations). C. The Annual Flashiness Index, the ratio of absolute day-to-day fluctuations of streamflow relative to the total flow in a year (Data Environment Agency).*

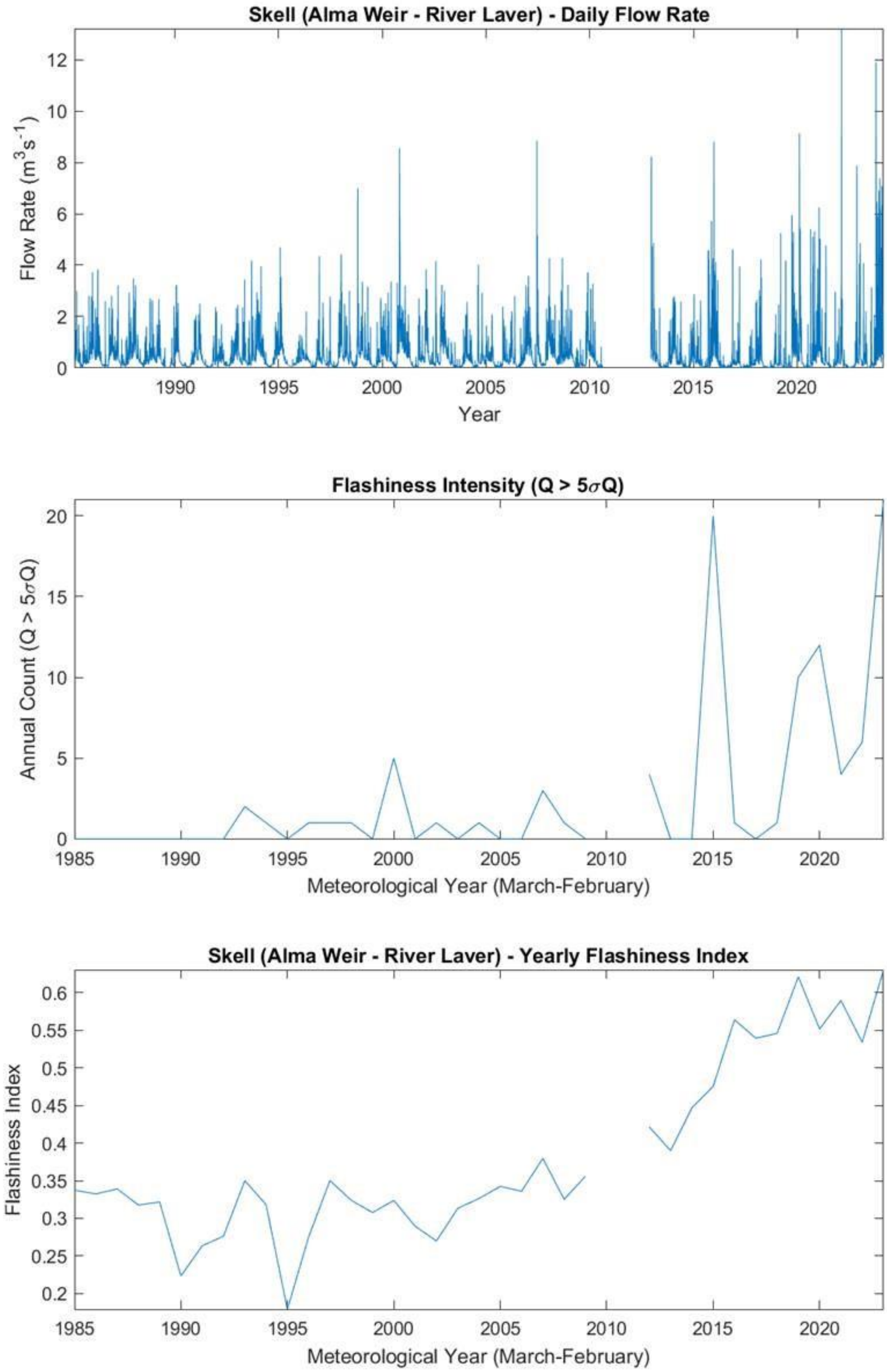


Figure 3.11 - *Flow data for Alma Weir – River Laver – base Skell flow. A. All daily data from 1985-Aug 2024. B. The Annual Flashiness Intensity (the sum of all the days where the flow exceeds the mean plus 5 standard deviations). C. The Annual Flashiness Index, the ratio of absolute day-to-day fluctuations of streamflow relative to the total flow in a year (Data Environment Agency).*

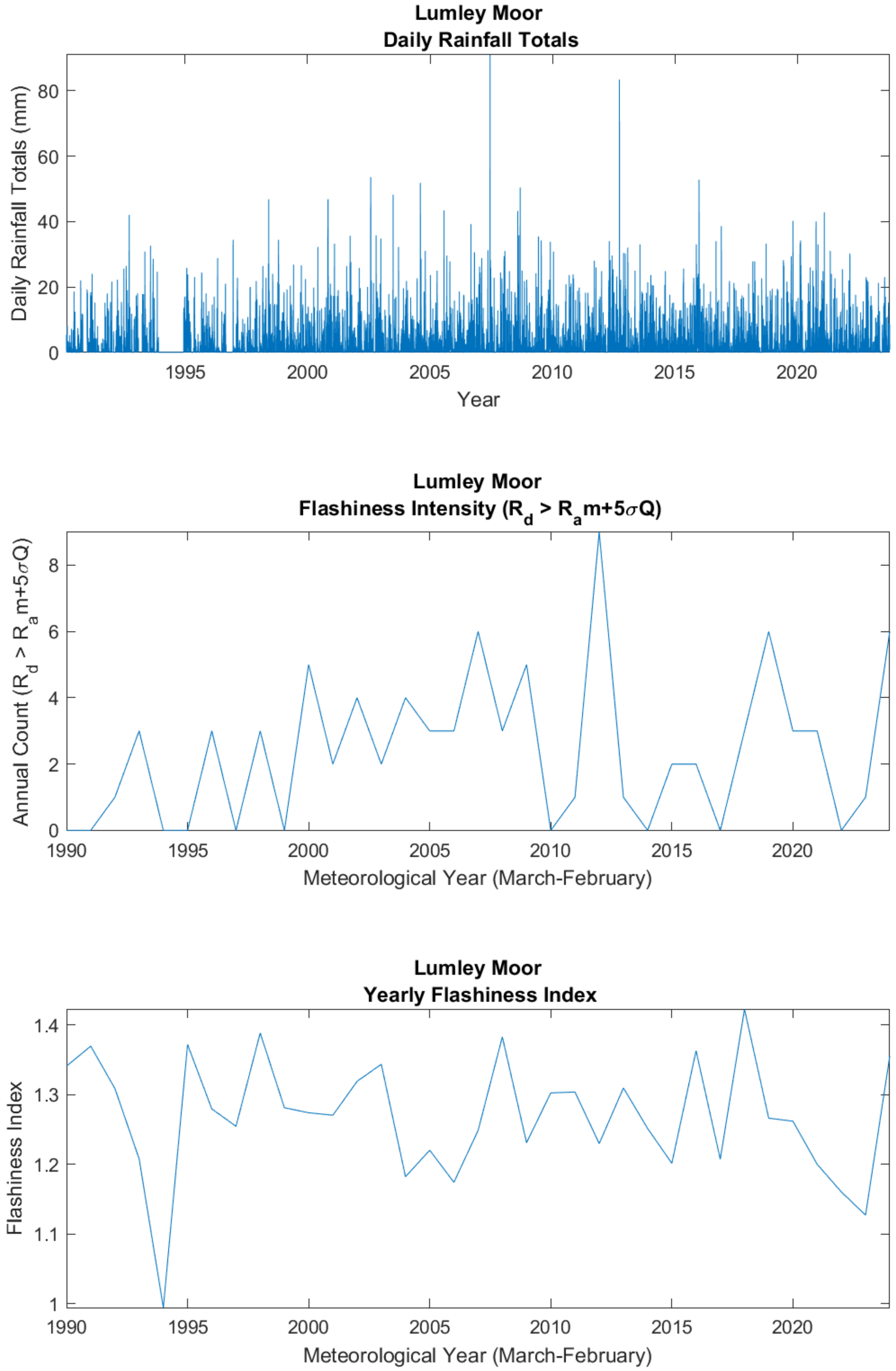


Figure 3.12 - *Daily Rainfall data from Lumley Moor. A. All daily data from 1990. B. The Annual Flashiness Intensity (the sum of all the days where the rainfall total exceeds the mean plus 5 standard deviations). C. The Annual Flashiness Index, the ratio of absolute day-to-day fluctuations of rainfall relative to the total rainfall in a year (Data Environment Agency).*

3.3 Site Selection

3.3.1 Volunteer Baseline Samples

The volunteer baseline sampling locations were selected to ensure that:

1. They were located on public rights of way
2. They were easy to access and could be sampled safely from the bank/bridge
3. They were spread throughout the catchment to analyse changes caused by variations in land use and geology.

This resulted in 10 locations being chosen, 5 upstream of the Fountains Abbey and Studley Royal site and 5 within the site. These sites spanned the length of the catchment and had sample points above and below tributary inputs and land use change.

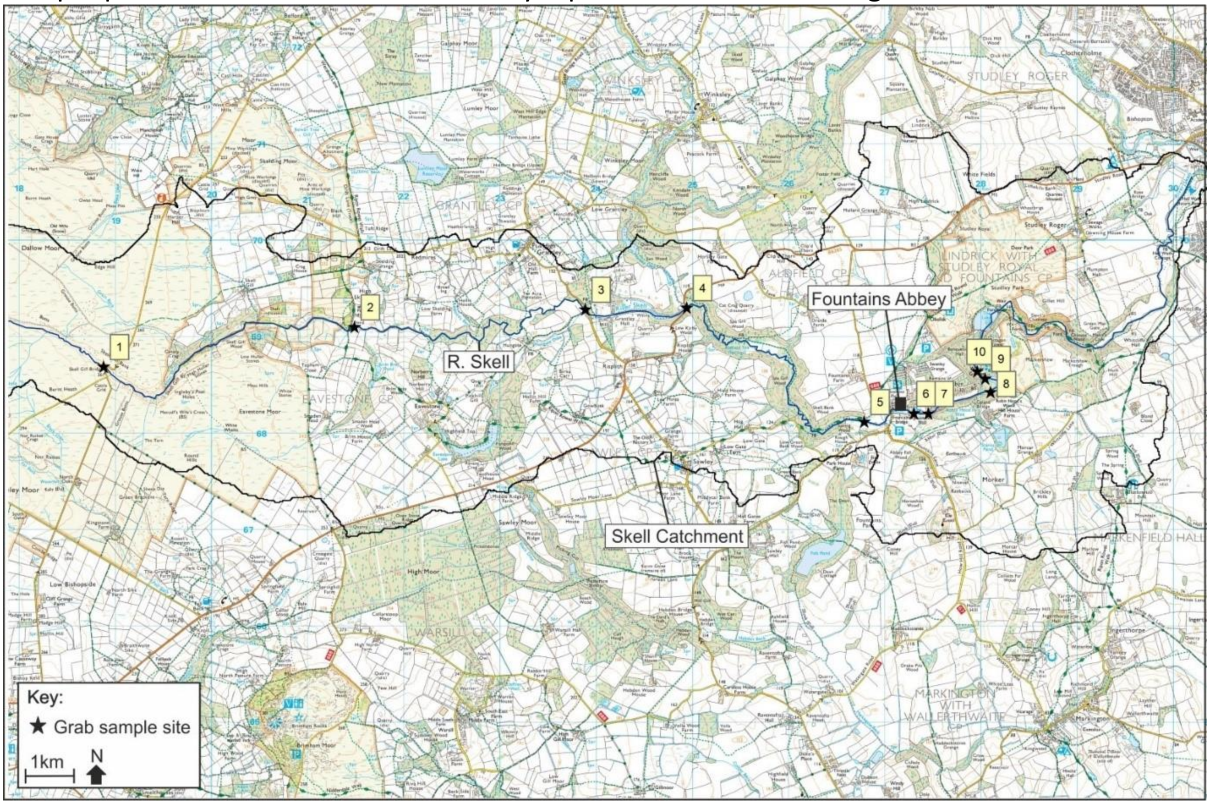


Figure 3.13 – *Location of volunteer sample sites.*

3.3.2 In-river Monitoring Equipment Deployed

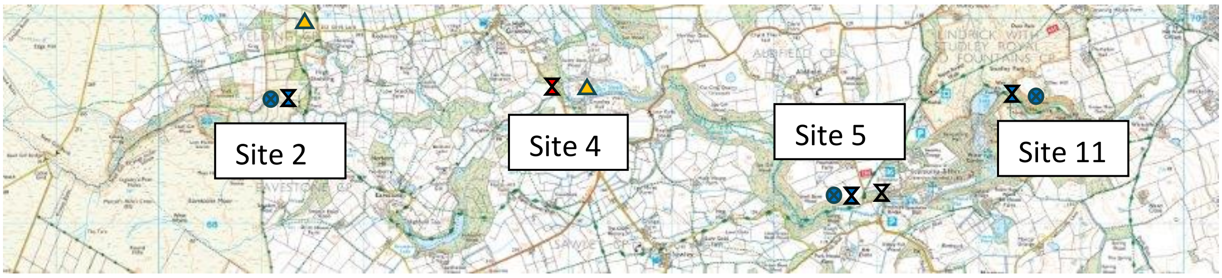


Figure 3.14 – *Location of in-river monitoring equipment: Calibration pressure sensor (atmospheric), Logging Depth Pressure sensor deployment, Real Time Depth Pressure sensor deployment, Turbidity sensor deployment, Weather Stations.*

The in-river monitoring equipment has been deployed across the four sites (Fig. 3.14). Site 5 has the longest running record for level and turbidity (Fig. 4.4), and all four sites were deployed from September 2024 to December 2024. There were several large leaky dams installed in the Spa Gill area, upstream of Site 4. The location in the catchment has the potential to provide useful information on the impact of these interventions. However, there was very limited access for monitoring during the project, and their influence remains poorly constrained.

4 Results

4.1 Weather Conditions

Initially this project recorded data at a single weather station located at Grantley Hall in the middle of the catchment. This station started collecting data in January 2023 (Fig. 4.1). A second weather station was added by the University of Leeds in November 2023, located at High Skelding, not far from Site 2 (Fig. 4.2). Neither station is ideally located, the Grantley Hall site was chosen as there is access to reliable mobile data and the site is very secure. However, the actual site is partially shaded by a Yew tree. The High Skelding site provides a record at a higher topographic level, however this site is over exposed, and the rainfall record is likely affected by high speeds.

The High Skelding sensor location is a much more exposed site, characterised by the substantially higher recorded wind speeds. The constant Wind Speed and the Gust Speed are higher on the High Skelding sensor. The High Grantley Station records lower winter nighttime temperatures, this sensor is in a local ‘frost pocket’. Conversely, the summer temperature data recordings are generally lower at the High Skelding site, again highlighting the effects of topography.

The rainfall records recorded by the two sensors are generally very similar with both stations showing the same trends (Fig. 4.3). The record from High Skelding shows the effects of topographic enhancement, as some of the recorded high intensity rainfall events are larger. The variations recorded between these two sites highlight that neither Station is located within a ’perfect’ site, however this does not subtract from the usefulness of the data. Variation between the sites due to topographic enhancement at High Skelding seems more likely than shadowing effects at Grantley Hall.

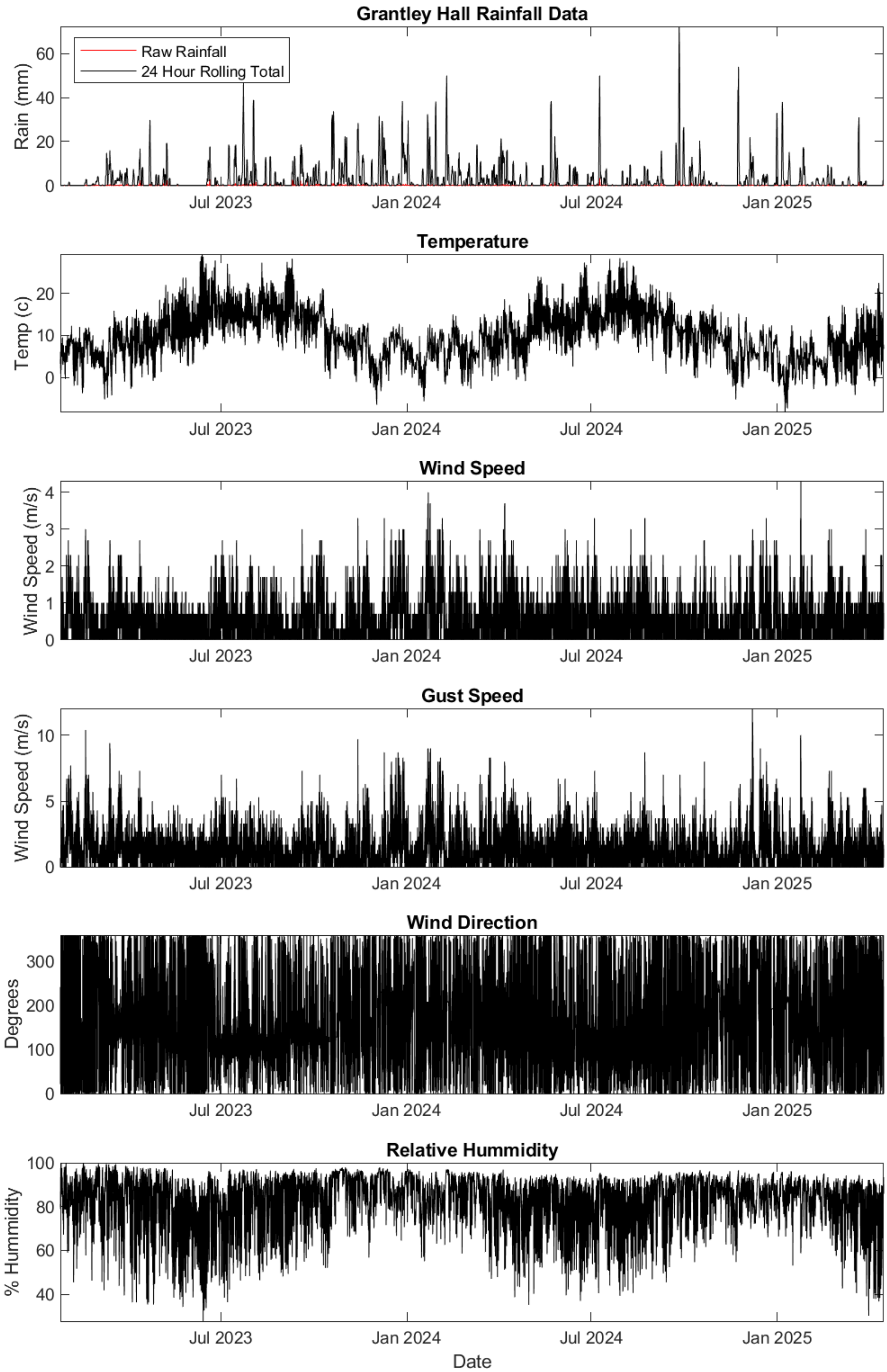


Figure 4.1 – *The entire weather record from the Grantley Hall sensor, showing rainfall data, temperature, windspeed, gust speed, wind direction and relative humidity.*

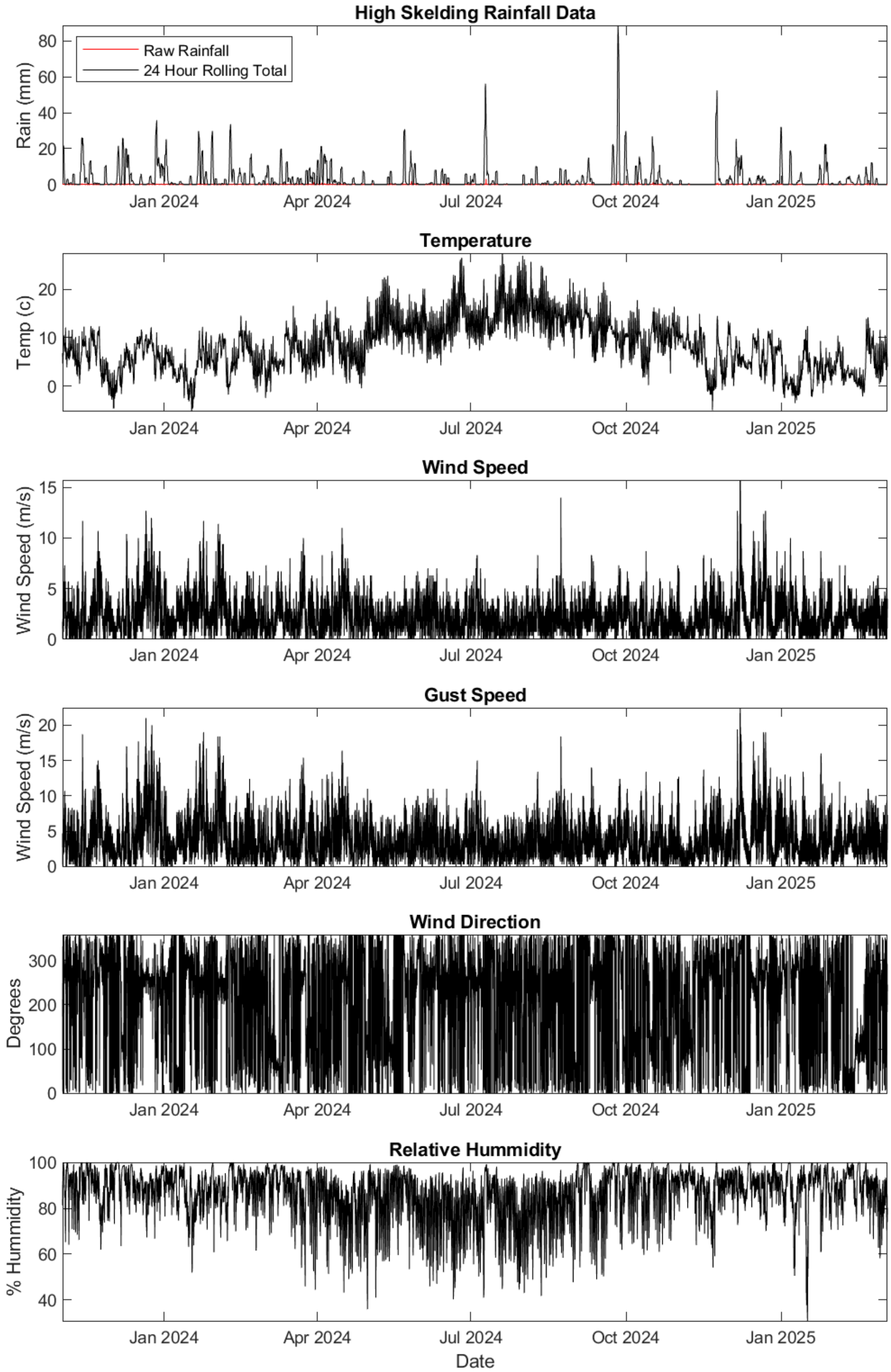
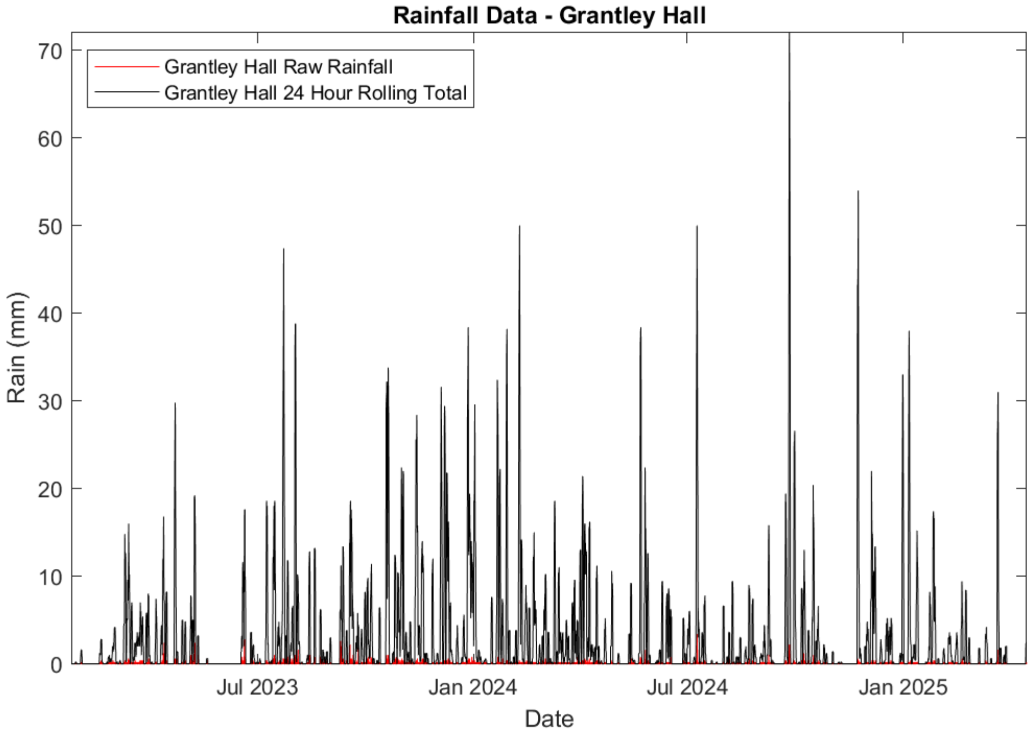


Figure 4.2 – *The entire weather record from the High Skelding sensor, showing rainfall data, temperature, windspeed, gust speed, wind direction and relative humidity.*



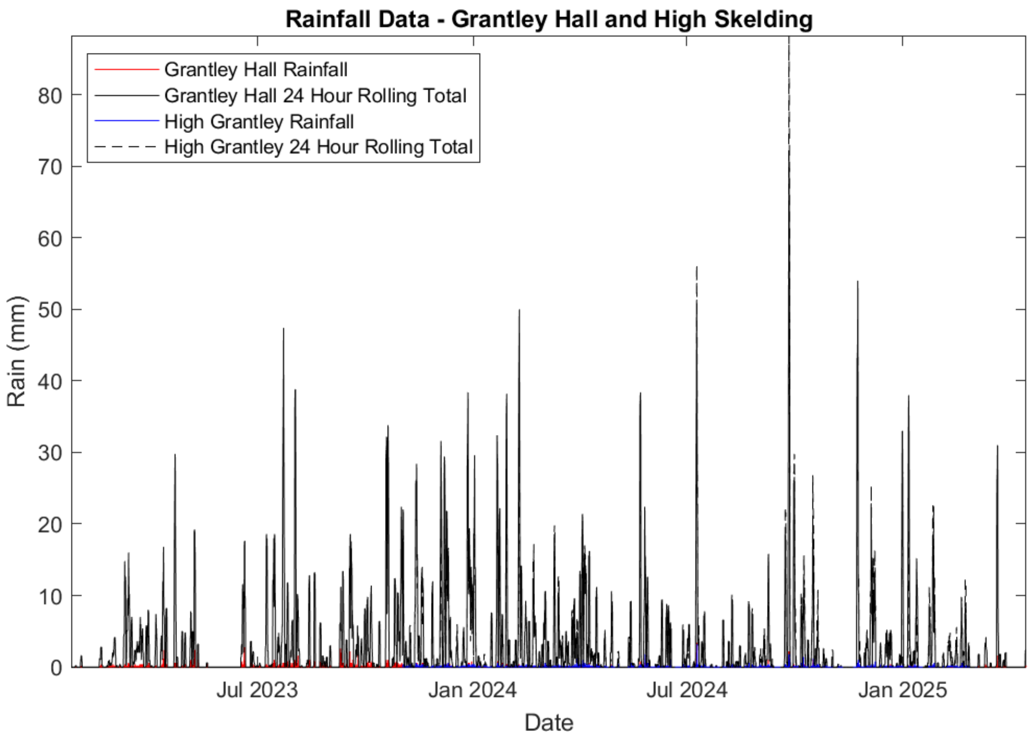


Figure 4.3 – *Comparison of rainfall data between Grantley Hall and High Skelding sensors. Mostly the two records track very closely, but the High Skelding record clearly shows the effect of topographic enhancement leading to higher daily rainfall totals during some rainfall events.*

4.2 Flow Height and In-river Turbidity

4.2.1 Instrumentation Data – Water Level Data

An evolving strategy of instrumentation was deployed in this project. Initially, two pressure sensors and a single turbidity sensor were deployed within the river Skell and another pressure sensor to monitor the atmospheric pressure. Atmospheric pressure has been monitored for the duration of the project at West Gate on the Fountains Site. These data are required to convert the raw pressure data to water depth. This conversion is sensitive to the effects of atmospheric pressure. The remaining pressure sensor was kept as a spare to cover any failure or equipment loss and was eventually deployed at Site 11. Later, the University of Leeds supplied several measurement systems to supplement the instrumentation purchased at the start of the project (Table 4.1). These included a stand-alone water depth pressure sensor with remote telemetry, an additional weather station that was deployed at High Skelding and three additional turbidity sensors. The deployment history of all the instrumentation used to monitor the Skell catchment is outlined in Figure 4.4.

Table 4.1 - *Summary of kit bought for the Skell valley Project and supplemented by University of Leeds during the project.*

Item	Number	Bought by?
Weather station with telemetry	1	Project
Pressure sensor	4	Project
Pump sampler	2	Project
Teledyne Acoustic Doppler Current Profiler	1	Project
Grab sampler	1	Project
Aqualogger turbidity sensor with wiper	1	Project
Wolman pebble count	1	Project
Aqulogger turbidity sensor with wiper	3	UoLeeds
Weather station with telemetry	1	UoLeeds
Pressure sensor with telemetry	1	UoLeeds

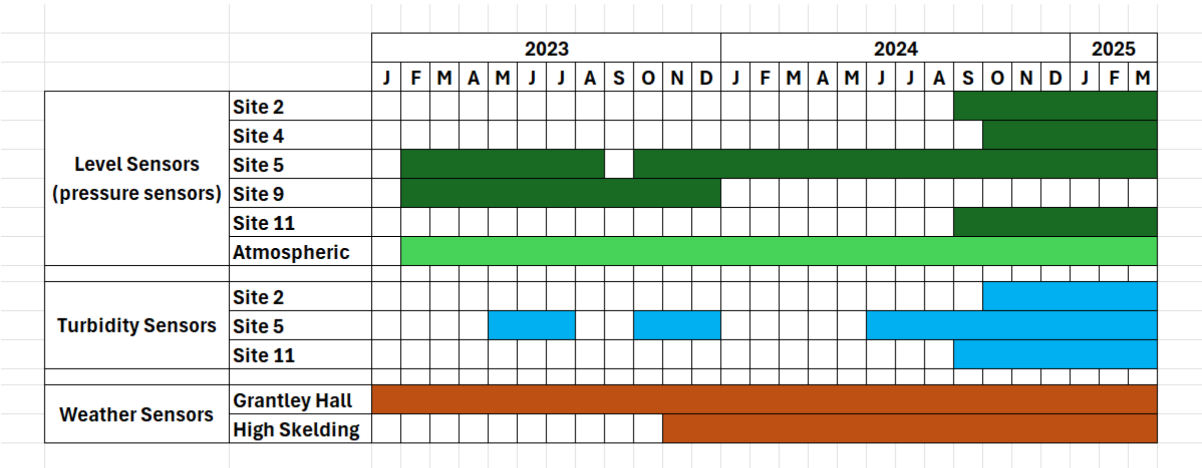


Figure 4.4 – *Summary of monitoring equipment deployed from 2023-2025.*

Initially depth data was recorded at two locations (Figs. 4.5 and 4.6). The first located ~200 m upstream of the West Gate Entrance of the Fountains Site (Site 5) and at a second location at the downstream end of Half-moon Lake (Site 9) proximal to the outlet. Data were collected at Site 5 for nearly the entire duration of the project, although data collection was suspended from August to October 2023 due to difficulties in accessing the site. Data collection at Site 9 was suspended when the pressure sensor was removed from the lake at the end of 2023. It had become clear that data collected at this location were difficult to interpret. This difficulty was attributed to the level of the Lake being controlled by the NT Gardening staff, who lower the levels to enable maintenance work and ahead of forecasted rainfall, to try and limit any potential flooding of the garden.

The location upstream of the West Gate entrance (Site 5) has proven to be highly suitable for collecting water depth data. The depth data collected at Site 5 shows that the early part of 2023 was noticeable dry with only a few major flow events. The winter of 2023-24 was noticeably wet and was characterised by a string of large flow events at occurred at very regular intervals. The winter of 2024-25 has seen fewer large flow events. The largest event recorded at Site 5 was a depth of 1.67 on the 20th October 2023, which was associated with Storm Babet. A similar size peak was also recorded during Storm Babet at Site 9.

Access to additional pressure sensors (purchased by the University of Leeds) allowed a more complex measurement strategy to be deployed in the Autumn of 2024. The Site 5 location was retained, and three addition Sites were identified. These sites were picked to allow expanded data acquisition to enhance the volunteer sampling data. The new sites were located at High Skelding (Site 2 – common with the volunteer sampling location), upstream of Grantley Hall Hotel (adjacent to Site 4), Site 5 and downstream of Studley Lake on the Fountains site, a new location Site 11. Three of the sites (Site 2, 5 and 11) used logging type pressure sensors, where the data must be downloaded from each unit every 150 days. A fourth pressure sensor was deployed at the West Gate to log a barometric atmospheric pressure. A stand-alone depth sensor with integrated modem was deployed at Site 4; this unit uploads data in real time to a web server.

The simultaneous logging of depth at four sites allows detailed examination of the hydrology of the Skell catchment (Figs 4.7, 4.8, 4.9 and 4.10). It is possible to examine the timing of flood hydrographs through the catchment. For example, two large flow events occurred on the 1st and 14th January 2025. The event on the 1st was the result of single rainfall event, the second event on the 14th of January was the result of snow melt. The timing of the arrival of the peaks is different between the two events. It is difficult to make any substantial conclusions from these two events about the detailed hydrodynamics of the catchment.

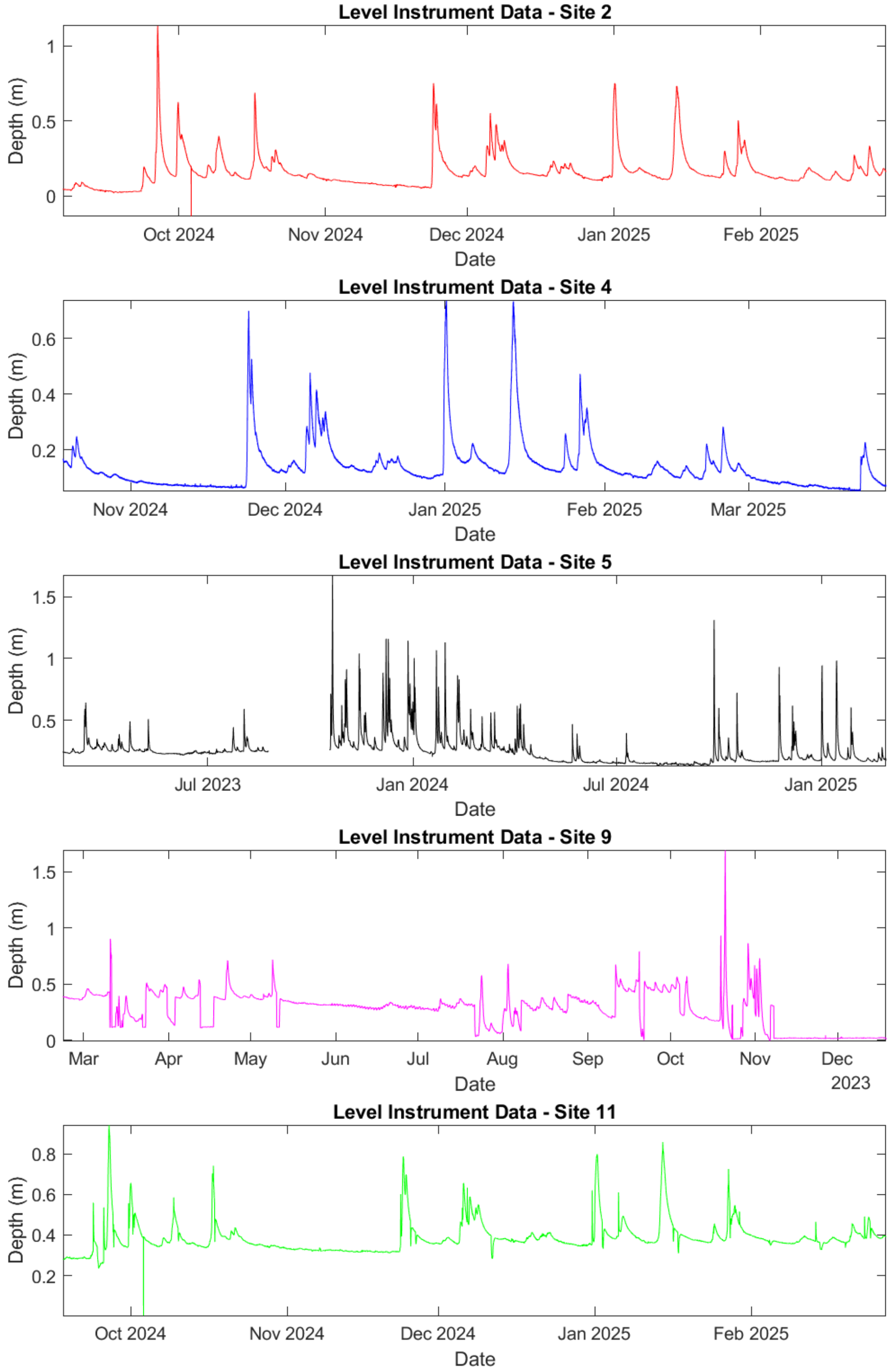


Figure 4.5 – *Overview of all the water depth data collected during the project*

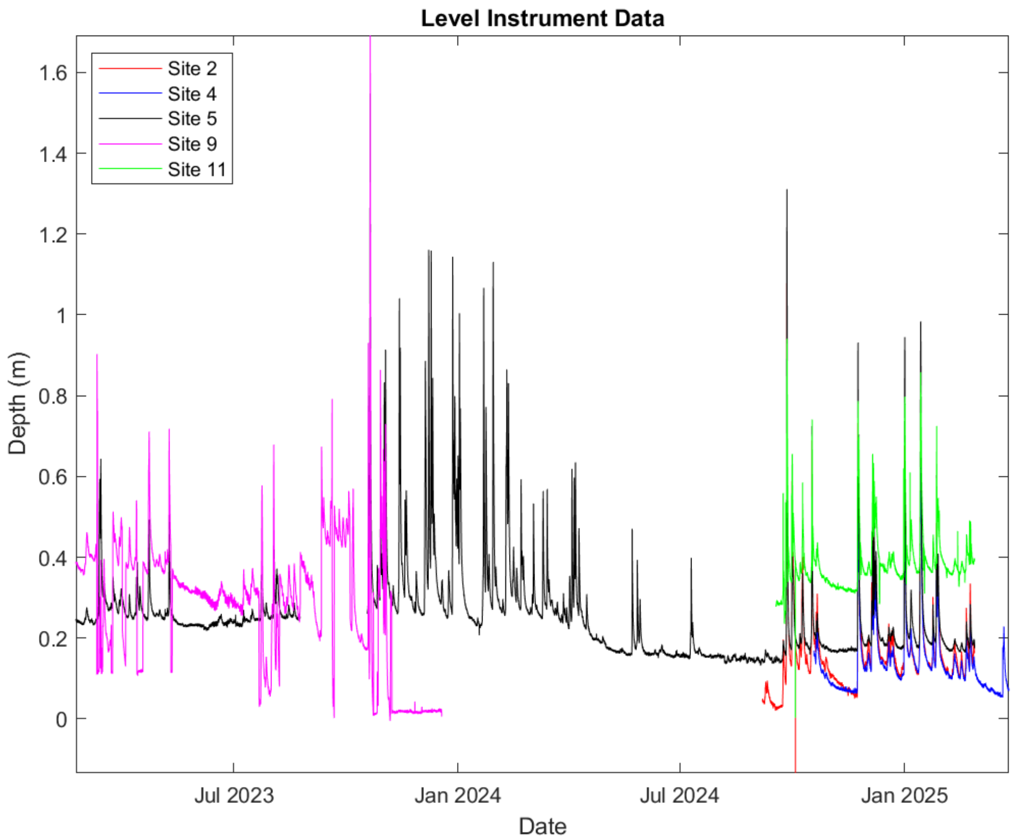


Figure 4.6 – *Overview of all the water depth data collected during the project*

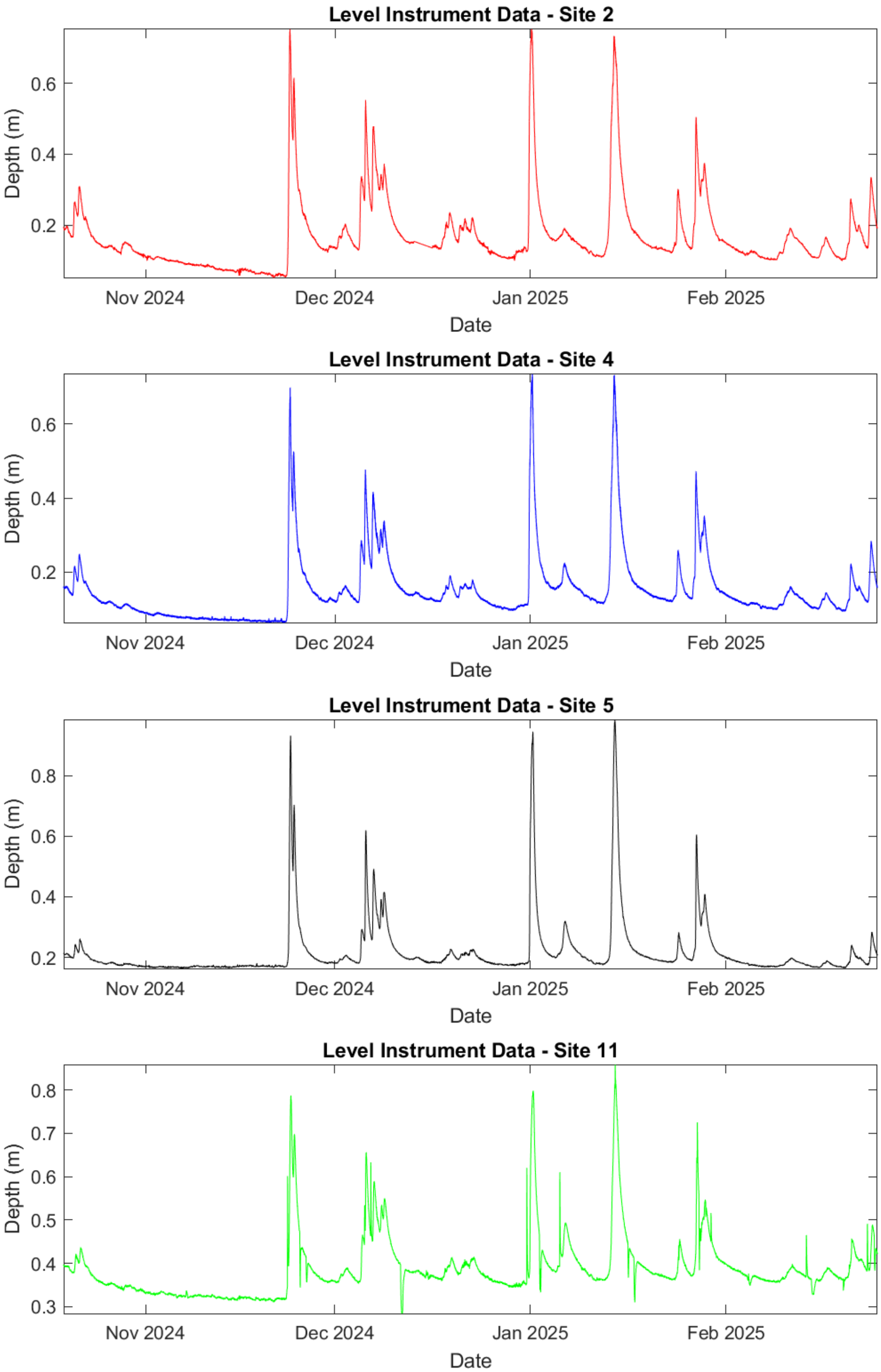


Figure 4.7 – *Overview of all synchronous water depth data collected from four locations between October 2024 and March 2025.*

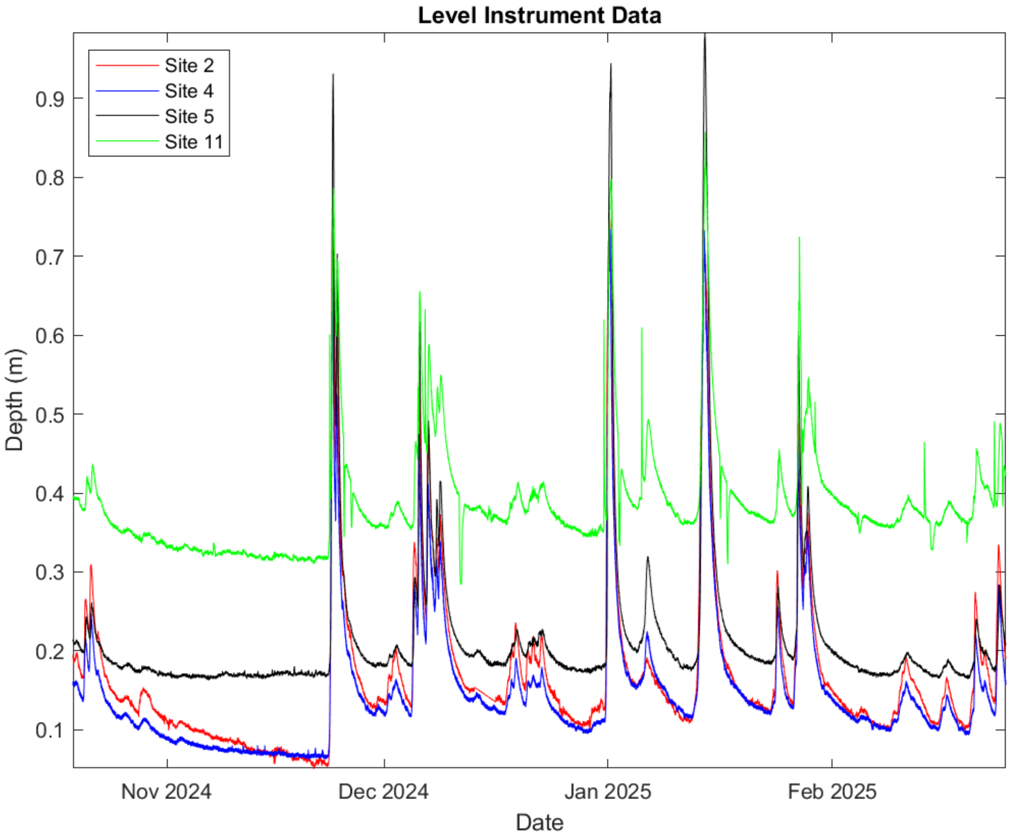


Figure 4.8 – *Overview of all synchronous water depth data collected from four locations between October 2024 and March 2025.*

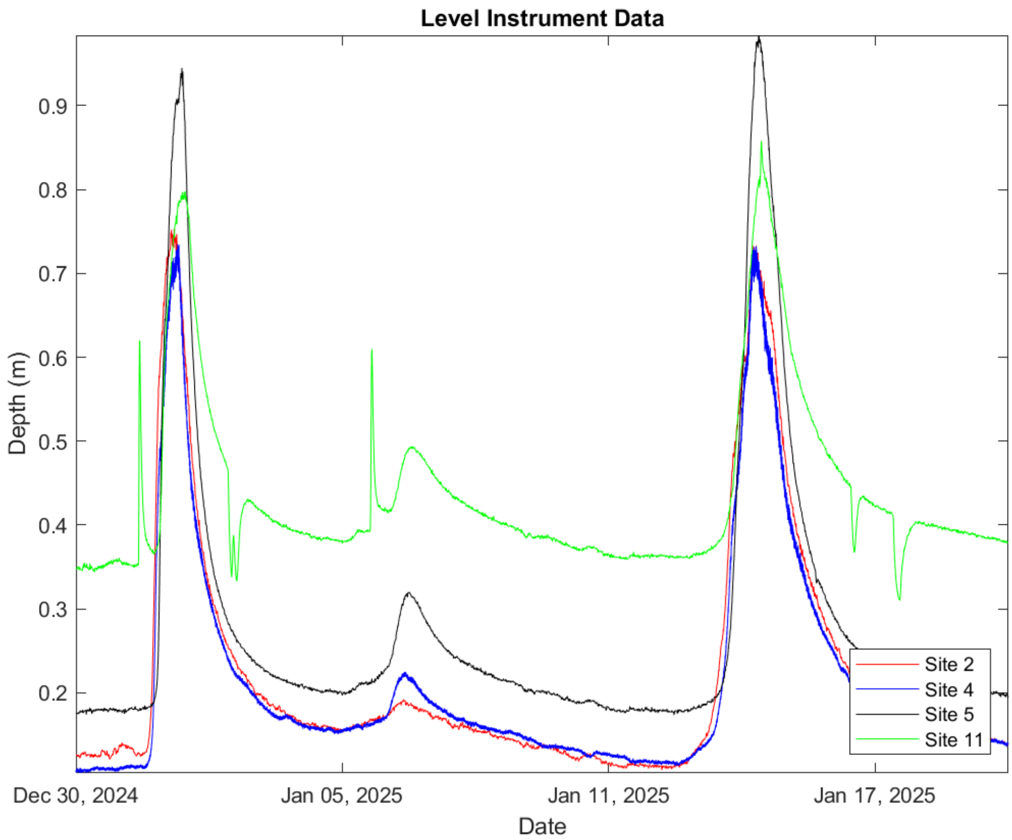


Figure 4.9 – *Overview of all synchronous water depth data collected from four locations between the 30th December 2024 and 20th January 2025.*

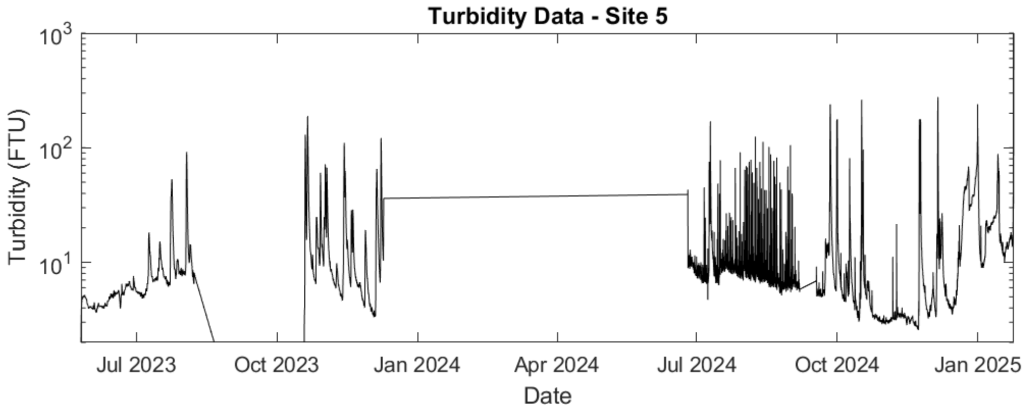
Figure 4.10 – *Approximate timing of peak arrival at Site 2, 4, 5 and 11 for the events on the 1st and 14th of January.*

1st January Event		
Location	TIme of Peak	Time from previous location
Site 2	4.56 am	NA
Site 4	5.46 am	50 mins
Site 5	8.26 am	100 mins
Site 11	10.01 am	95 mins
14th January Event		
Location	TIme of Peak	Time from previous location
Site 2	7.43 am	NA
Site 4	8.36 am	53 mins
Site 5	9.26 am	50 mins
Site 11	11.31 am	125 mins

4.2.2 Instrumentation Data – Turbidity Data

At the start of the project, a single optical turbidity probe was purchased and deployed in parallel with a depth probe at Site 5 (Fig. 4.11). The instrument can log data for up to 8 weeks and then requires a change of batteries when the data can be downloaded. Every three months the instrument requires a service and a clean. The system was deployed in the summer of 2023, and again for two months at the end of 2023. The system was then redeployed in late June 2024 and has been run continuously (with maintenance breaks) for the remaining duration of the project.

Additional turbidity sensors were purchased by the University of Leeds. These were deployed at Sites 2, 4, 5 and 11 to complement water depth sensors at the same locations. The sensor deployed at Site 4 failed on installation and no data were collected at this location. Sensors were successfully deployed at Sites 2, 5 and 11 (Figs 4.11 & 4.12). The sensor at Site 2 was buried by sandy sediment within a few days of deployment in early October and no useful data were collected between October and mid-December. All the sensors were reset in mid-December (batteries changed and data downloaded). After the reset, the wiper unit on the sensor at Site 5 failed, resulting in contamination of the sensor head. The data collected at this Site are not representative of the flow conditions, and no useful data were collected between mid-December and late February. The sensor deployed at Site 11 was smothered in vegetation (from Half-moon and Studley lake), no useful data were collected between mid-December and late February. In summary, the simultaneous data collection yielded useful datasets at Sites 5 and 11 between October and mid-December and at Site 2 from mid-December and late-February.



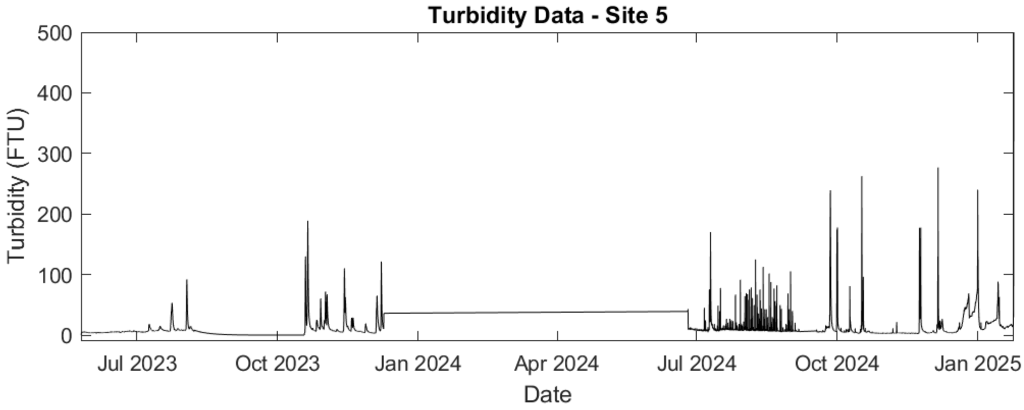


Figure 4.11 – *All turbidity data collected at Site 5 2023-25.*

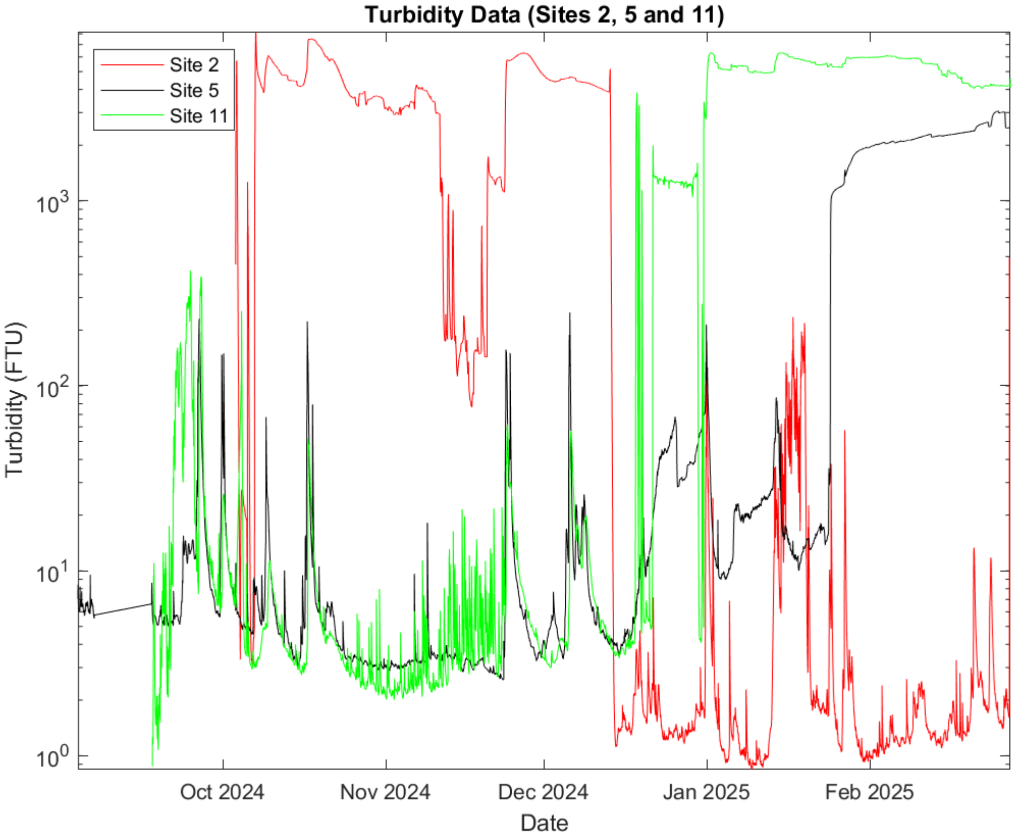


Figure 4.12 – *All turbidity data collected at Site 5 2023-25*

4.2.3 Instrumentation Data – Combined Level and Turbidity Data

Combining the level data and turbidity data provides insights about the timing and magnitude of sediment movements within the river Skell catchment. Figure 4.13 clearly shows a strong correlation between the level and turbidity data (when the turbidity sensors are working properly).

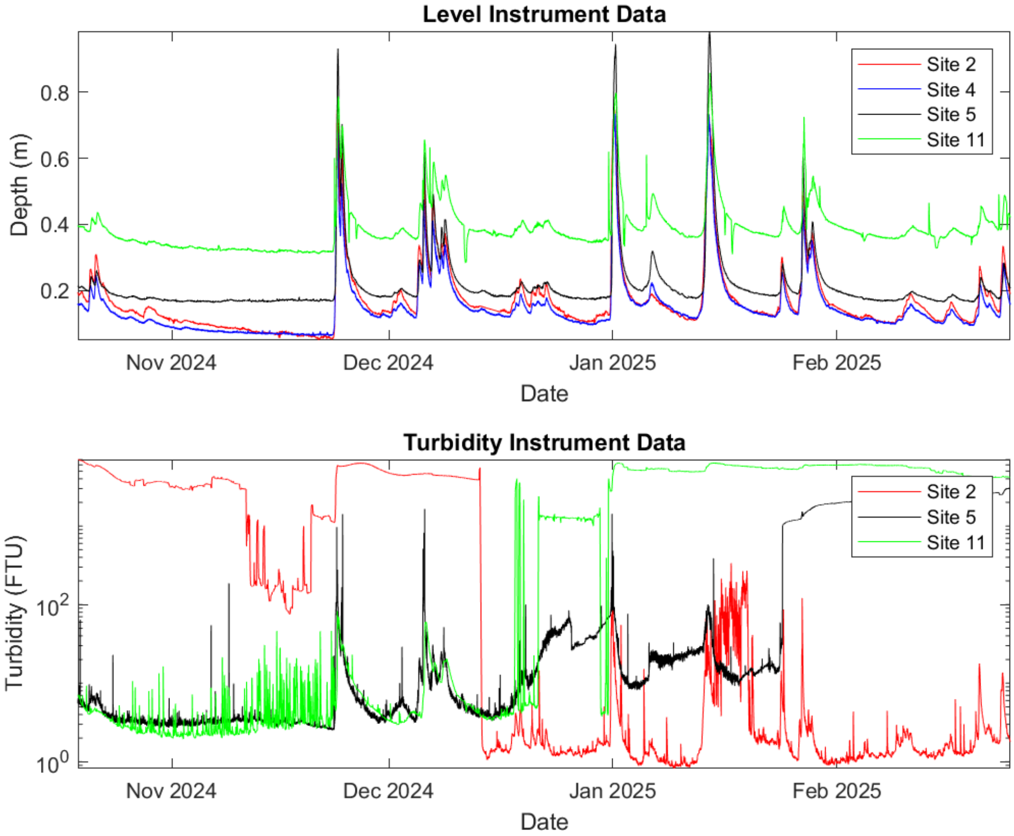


Figure 4.13 – *Synchronous level data from Sites 2, 4, 5 and 11. Matching synchronous turbidity data from Sites 2, 5 and 11.*

Two high flow events occurred between 20th November 2024 and 12th December 2024. The four level sensors show a very similar flow distribution (Fig. 4.14). Sites 2, 4 and 5 all show similar magnitudes and generally very close agreement. Site 11 shows a similar pattern of large peaks but the data from this Site shows several other peaks both positive and negative. Site 11 is located downstream of Studley Royal Lake, just upstream of where the river Skell runs into a solution fissure and is diverted into a cave for approximately 1 km (Maurice et al. 2024). This complex hydrological location makes interpreting the level data difficult. During periods of high flow some of the flow is diverted into the above ground channel. There are likely to be complex suction effects that are responsible for the low flow peaks. The high flow peaks that do not correlate with the other level sensors are likely to be result of Half-Moon Lake being partially drained by the gardening staff either for maintenance or ahead of forecasted storm events.

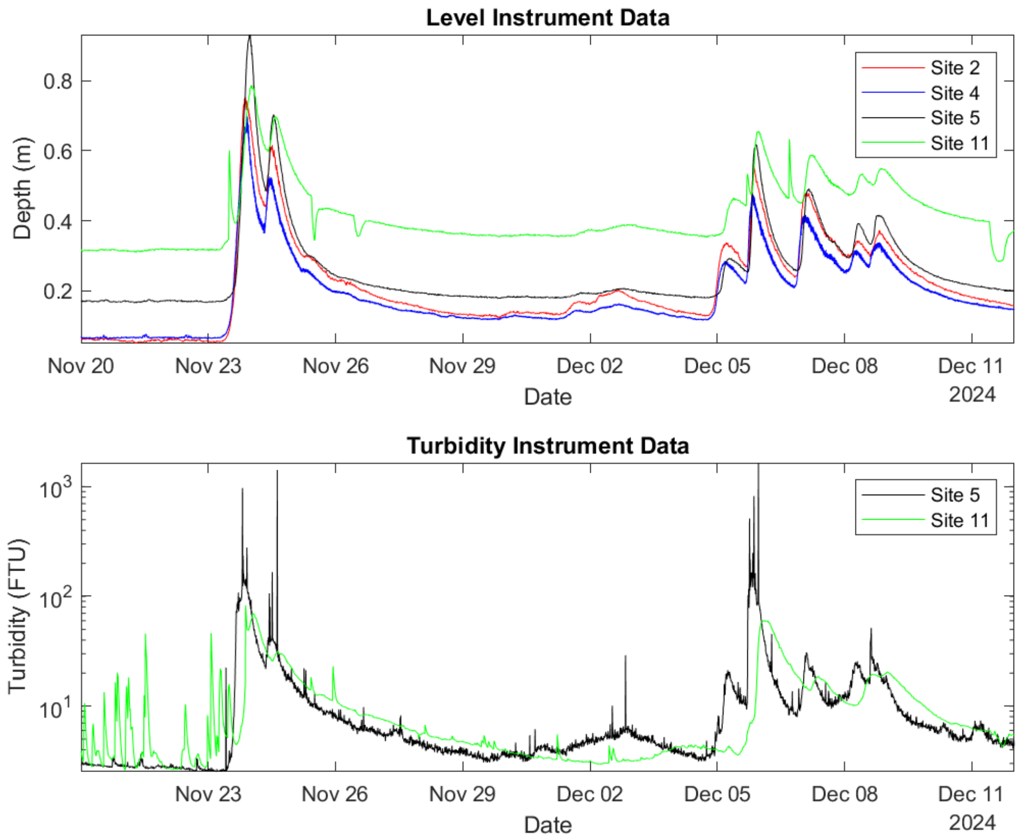


Figure 4.14 – *Synchronous level data from Sites 2, 4, 5 and 11. Matching synchronous turbidity data from Sites 2, 5 and 11, Data from 20th November – 12 December 2024.*

The turbidity data shows strong agreement between the data recorded at Sites 5 and 11 for both flow events between the 20th November – 12th December 2024. The magnitude of the peak turbidity at Site 5 is very similar to that recorded at Site 11. This suggests the Fountains Site is acting as a conduit of suspended sediment, and it does not appear that substantial amounts of suspended sediment are being retained in either Half-Moon Lake or Studley Lake.

Two similar high flow events occurred between the 30 December 2024 and 20th January 2025. The first event was the result of a single large rainfall event, the second event was caused by snow melt. All the level data show very similar distribution for both events. The first rainfall induced flow peak is slightly narrower and a little steeper. The turbidity data from Site 2 show a marked difference; the turbidity peak is approximately twice as high in the first event. These may suggest that sediment movement is highly dependent on the rate of a flow event, or it may suggest the first event flushed much of the mobile sediment in the system, so less was available for the second event.

4.2.4 Storm Babet

Storm Babet was a large storm named by the UK Meteorological Office (19-21st October 2023), the rainfall resulted in a large flood event in the river Skell. The impact of Storm Babet can clearly be seen in the rainfall data (Fig. 4.15), with two rainfall events of 30 mm per 24 hours occurring approximately 30 hours apart. This level of rainfall resulted in a marked increase in the depth of the River Skell at Site 5 (Fig. 4.15). The first event resulted in a maximum depth of 0.7 m and the second in a maximum depth of 1.67 m. The first event effectively saturated the catchment resulting in a much larger peak for the second event. The turbidity data shows a similar pattern with a large peak associated with the first rainfall event and second larger peak following later (Fig. 4.15). However, the disparity between the two peaks is much smaller in the turbidity data. Figure 4.16 shows both the level data and turbidity data for Storm Babet colour coded by date (yellow earliest, blue latest). When plotted on a scatter plot (Fig. 4.16) the first rainfall event of Storm Babet resulted in a near instantaneous increase in turbidity, where the rise in turbidity was faster than the rise in river level. The second rainfall event resulted in a much slower rise in the turbidity even though both events had a similar magnitude. Both rainfall events showed a similar degree of hysteresis (the dependence of the state of a system on its history), where the turbidity rises much faster than it falls and the decay rate for both was very similar. The reason for the disparity in the turbidity data between the two rainfall events is not clear. The extremely rapid initial rise associated with the first rainfall event maybe the result of unknown upstream processes (i.e. a bank collapse, small debris flow).

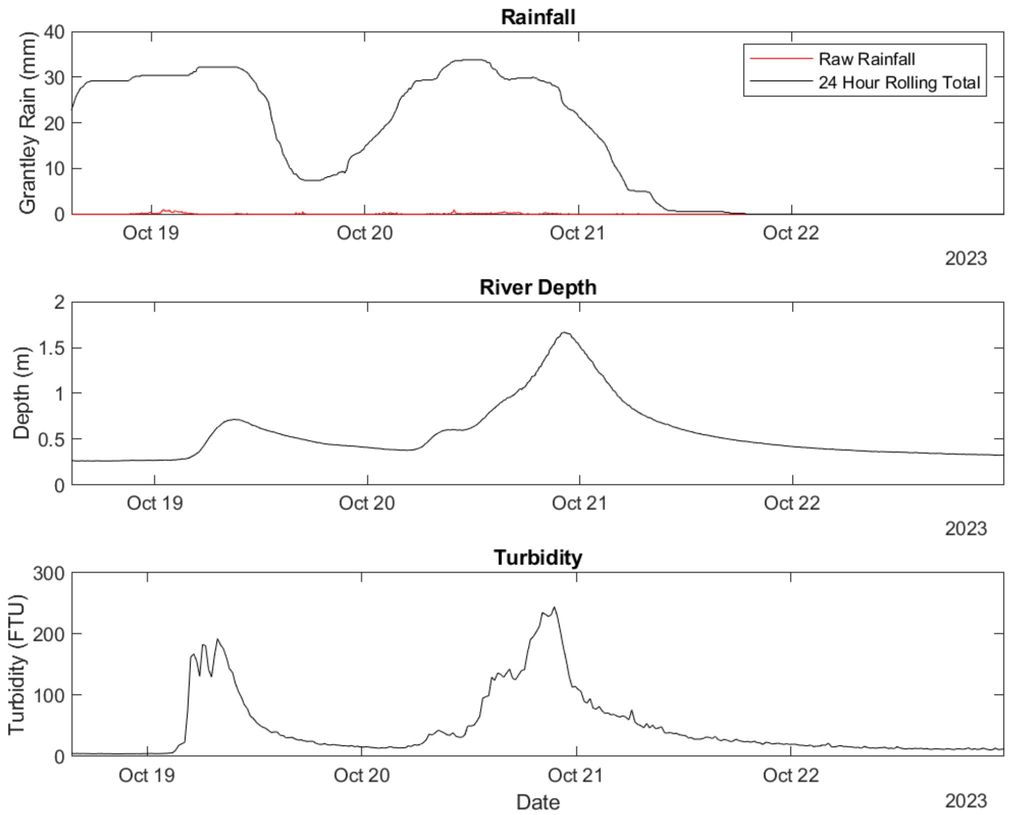


Figure 4.15 – *The first plot shows rainfall data from Grantley Hall for the 19th to 26th October 2023 showing the rainfall associated with storm Babet. Storm Babet resulted in two rainfall events which both resulted in ~ 30 mm of rainfall in 24 hours approximately 30 hours apart. The next plot shows the level of the River Skell at Site 5 for the same time as the rainfall data, showing the double peak associated with the two rainfall events. The final plot shows*

turbidity sensor data also from Site 5 showing the double peak associated with the two rainfall events.

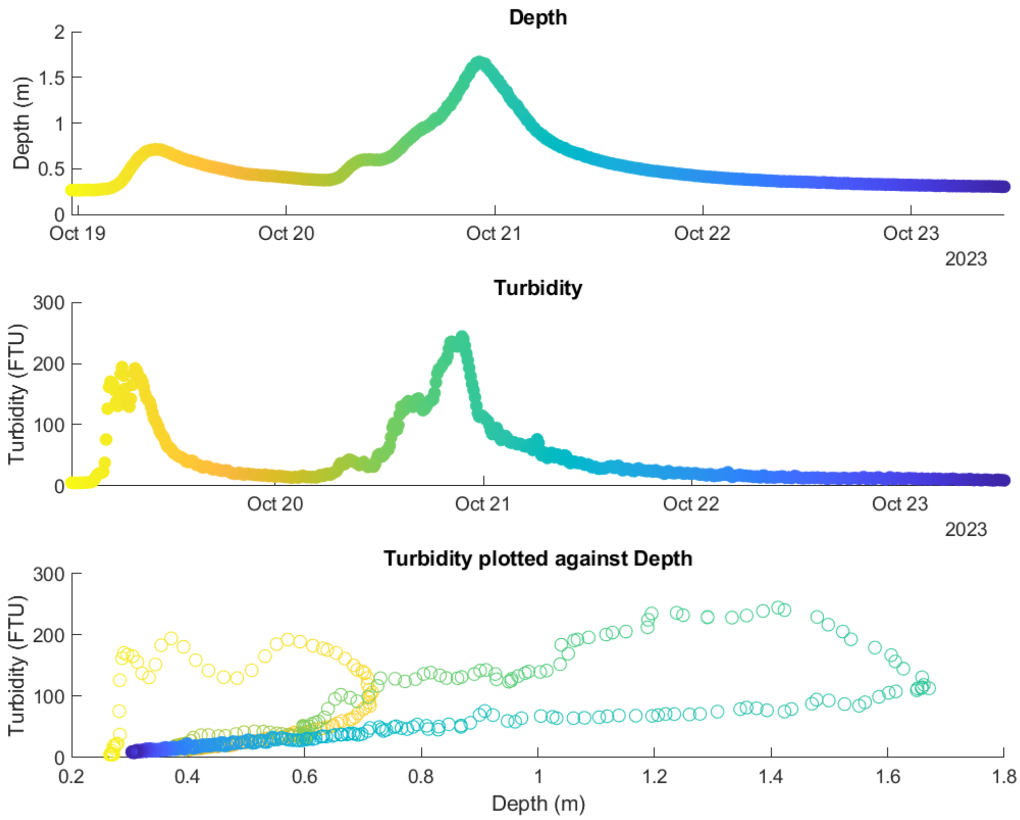


Figure 4.16 – *The same Depth and Turbidity data as shown in the previous figure, the data are plotted in a colour range yellow to blue, this colour indicated the relative age of the data. The third plot is a scatter plot of the same turbidity and depth data plotted against each other.*

4.3 Volunteer samples

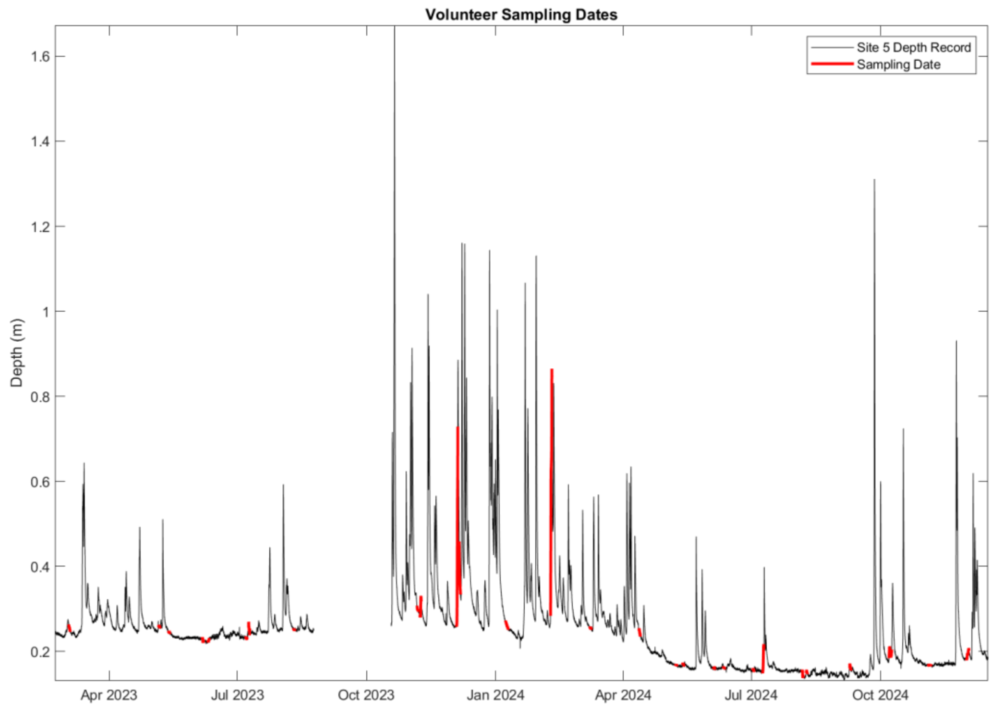


Figure 4.17 – *Record of depth (m) at site 5 with the dates of volunteer sampling highlighted in red.*

The volunteers took samples in a wide range of flow conditions and heights, which has allowed for a good baseline to be collected, and some trends identified. However, the volunteers were asked not to undertake sampling during periods of high or exceptionally high flow to ensure the safety of the persons collecting the samples (Figures 4.17 and 4.18).

Figure 4.18 – *The month of each volunteer sampling trip and the height, flow and season on the day (s) of collection. Where there was more than one sampling day, the height was averaged. There were no sampling months where the flow or height were markedly different on each of the sampling days.*

Month	Height	Flow	Season
September 2022	Low	Rising	Autumn
January 2023	Medium	Falling	Winter
March 2023	Medium	Rising	Spring
May 2023	Medium	Base	Spring
June 2023	Low	Base	Summer
July 2023	Medium	Falling	Summer
August 2023	Medium	Peak	Summer
September 2023	Medium	Base	Autumn
October 2023	Medium	Falling	Autumn

November 2023	High	Falling	Autumn
December 2023	High	Rising	Winter
January 2024	High	Falling	Winter
February 2024	High	Peak	Winter
March 2024	Medium	Falling	Spring
April 2024	High	Falling	Spring
May 2024	Medium	Base	Spring
June 2024	Medium	Base	Summer
July 2024	Medium	Rising	Summer
August 2024	Medium	Base	Summer
September 2024	Medium	Base	Autumn
October 2024	Medium	Falling	Autumn
November 2024	Medium	Falling	Autumn
December 2024	Medium	Base	Winter

4.3.1 Nitrate Concentration

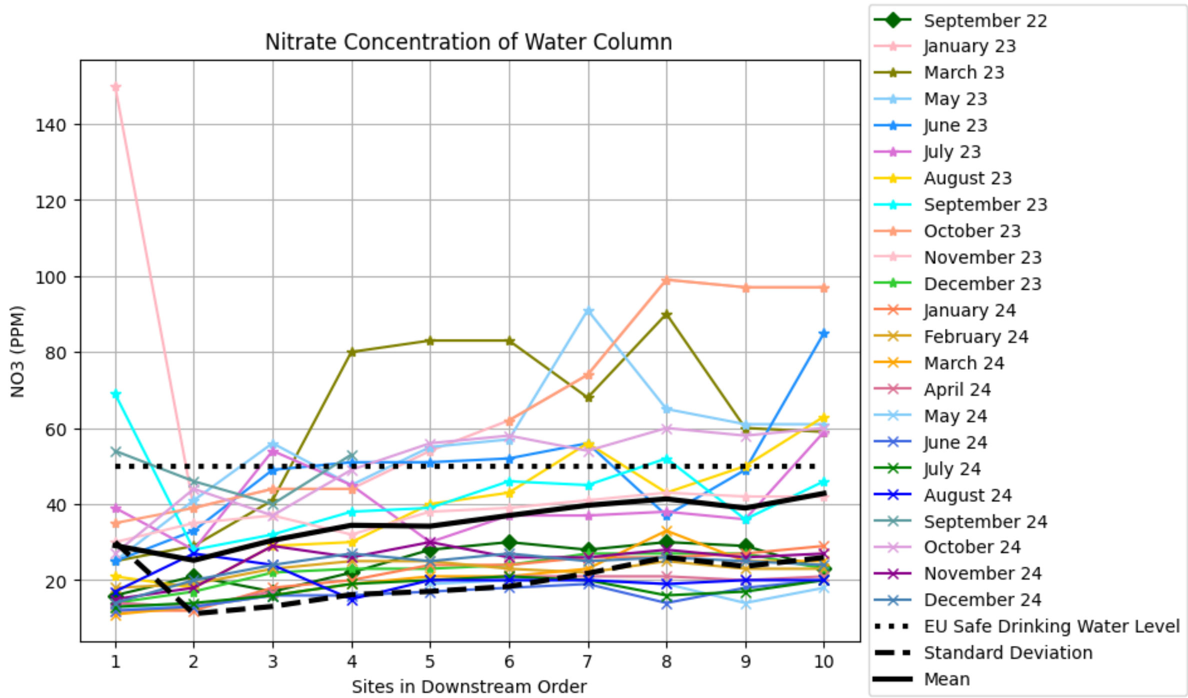


Figure 4.19 - *Nitrates (ppm) in water column from September 2022 to December 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits.*

A very large amount of data has been collected. At first inspection these data appear to be very noisy, with few visible trends (Fig 4.19). Grouping the data by the conditions on the day of sample collection helps in the identification of trends (Fig 4.18 and 4.20-4.37).

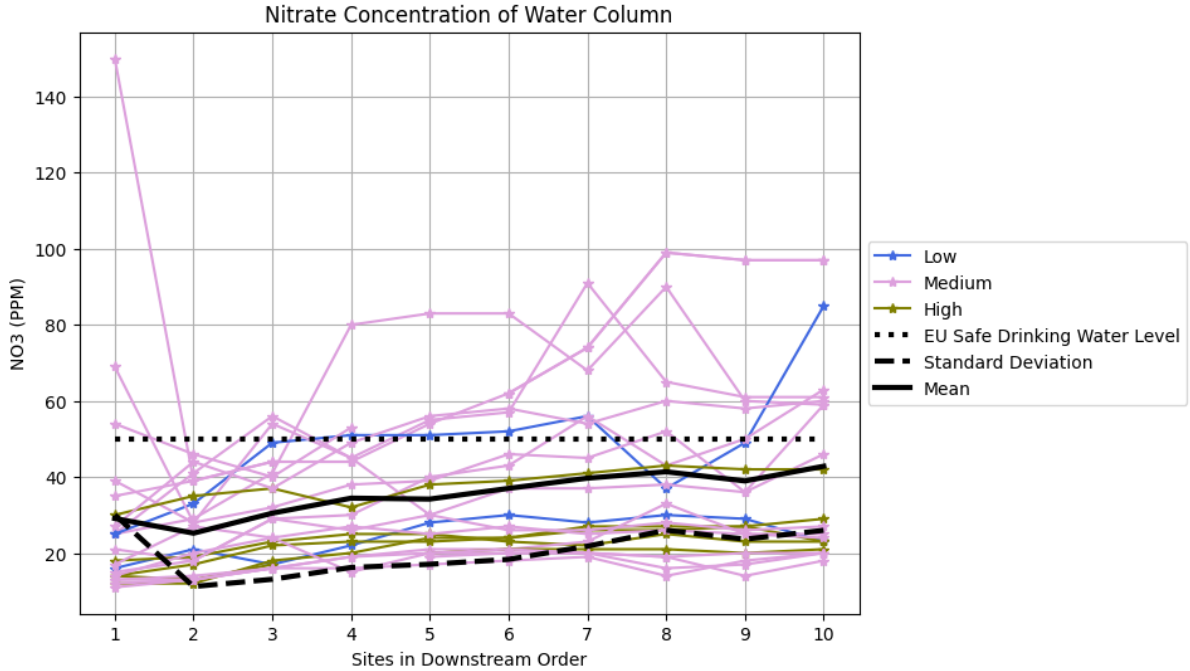


Figure 4.20 - *Nitrates (ppm) in water column from September 2022 to December 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits. The months have been grouped by the river height at Alma Weir on the day of sampling to low (n=2), medium (n=15) and high (n=5).*

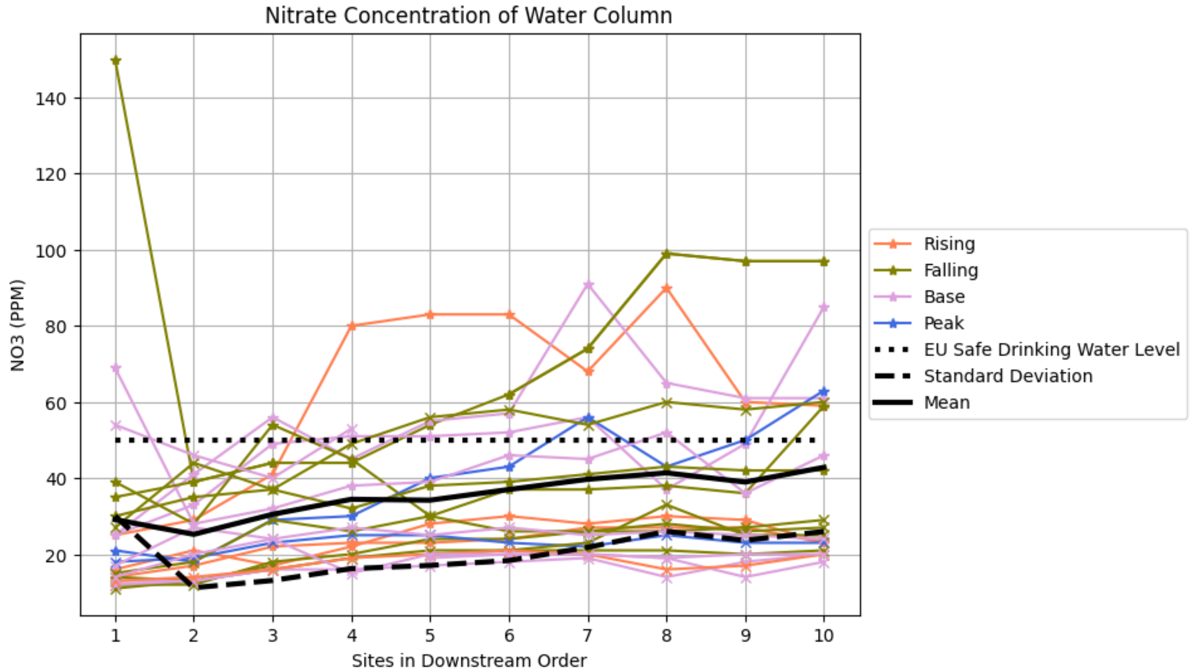


Figure 4.21 – *Nitrates (ppm) in water column from September 2022 to December 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits. The months have been grouped by the*

river stage at Alma Weir on the day of sampling to rising (n=4), falling (n=9), peak (n=2) and base (n=8).

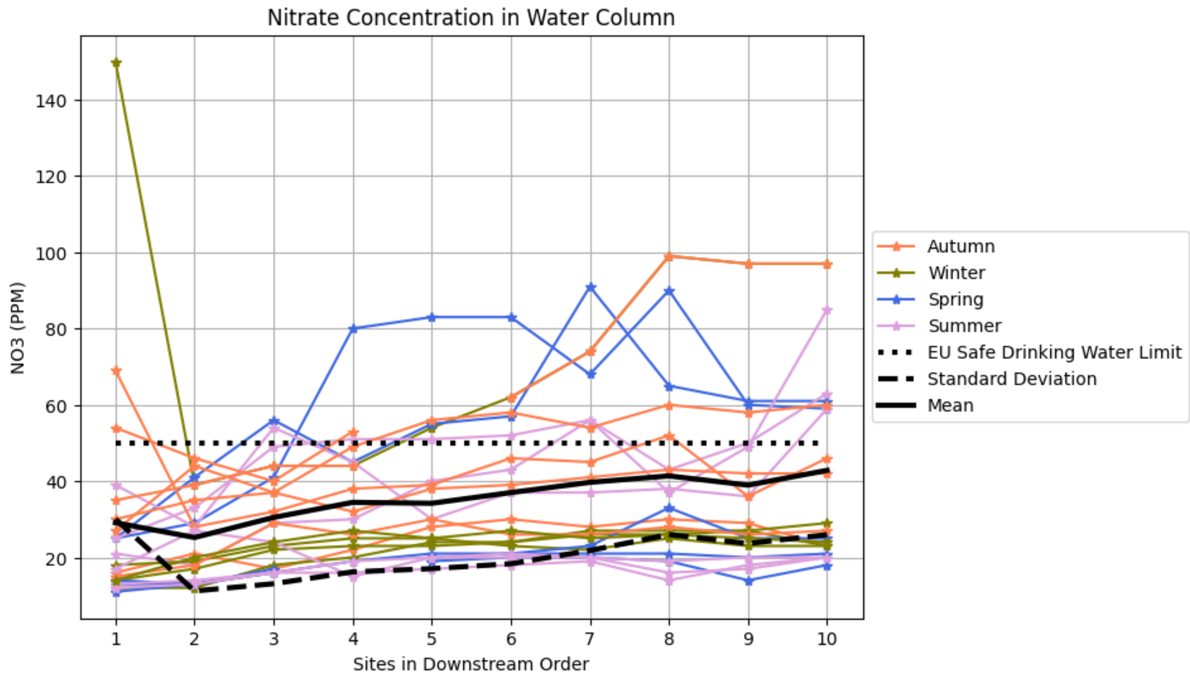


Figure 4.22 – *Nitrates (ppm) in water column from September 2022 to December 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits. The months have been grouped by the season on the day of sampling to Autumn (n=7), Winter (n=5), Spring (n=5) and Summer (n=6).*

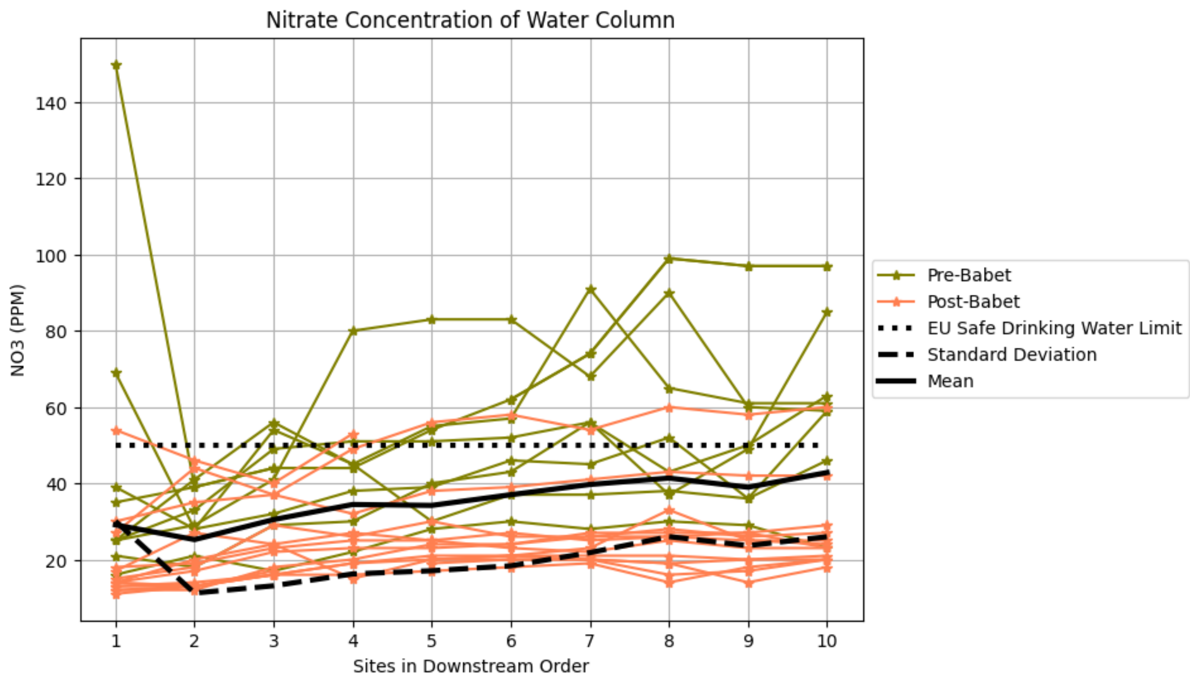


Figure 4.23 – *Nitrates (ppm) in water column from September 2022 to December 2024 in downstream order. The standard deviation and mean have been calculated for each site to*

demonstrate the variation between sampling visits. The months have been grouped by the months of sampling before (n= 9) and after (n=14) Storm Babet (18th -21st October 2023).

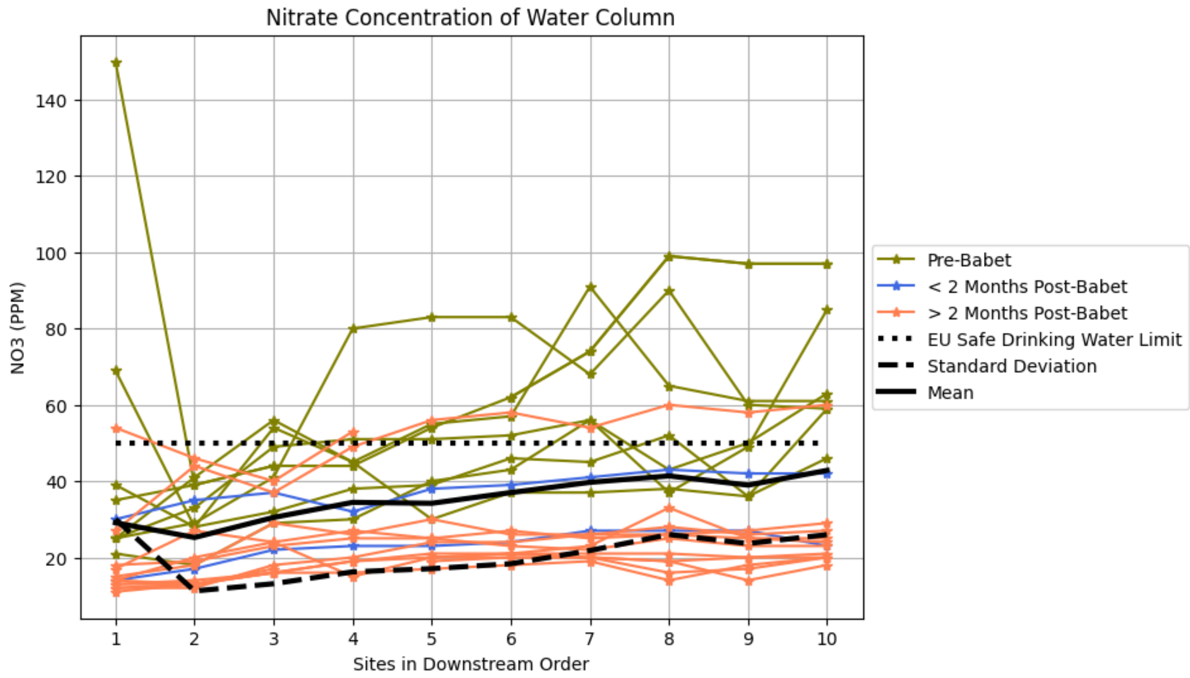


Figure 4.24 – *Nitrates (ppm) in water column from September 2022 to December 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits. The months have been grouped by the months of sampling before (n= 9), less than 2 months after Storm Babet (n=2) and more than 2 months after (n=12) Storm Babet (18th -21st October 2023).*

There is a general increase in concentration from upstream to downstream and the most variability is at site 1. The spring and autumn months have Nitrate levels above the mean, whereas winter is predominantly below the mean (Fig 4.24). When the river is high at Alma Weir the nitrate levels are mostly equal to the mean or below. When the river is at its peak or rising the nitrate levels are equal to or below the mean, and when the river is falling it is over the mean and the base values are variable. There is a noticeable difference between the results pre and post Storm Babet. Pre-storm values are much higher and mostly above the mean while those post-Babet are much lower and below the mean.

4.3.2 pH

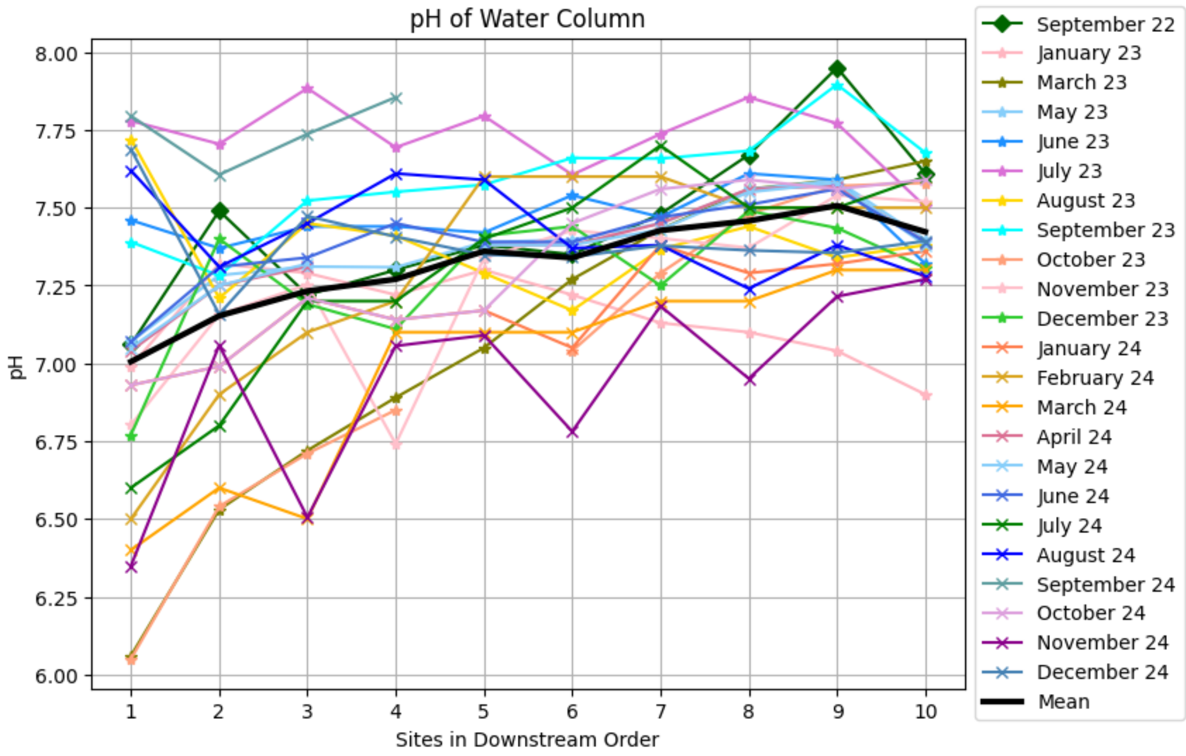


Figure 4.25 – *pH of water column from September 2022 to November 2024 in downstream order. The mean has been calculated for each site to demonstrate the variation between sampling visits.*

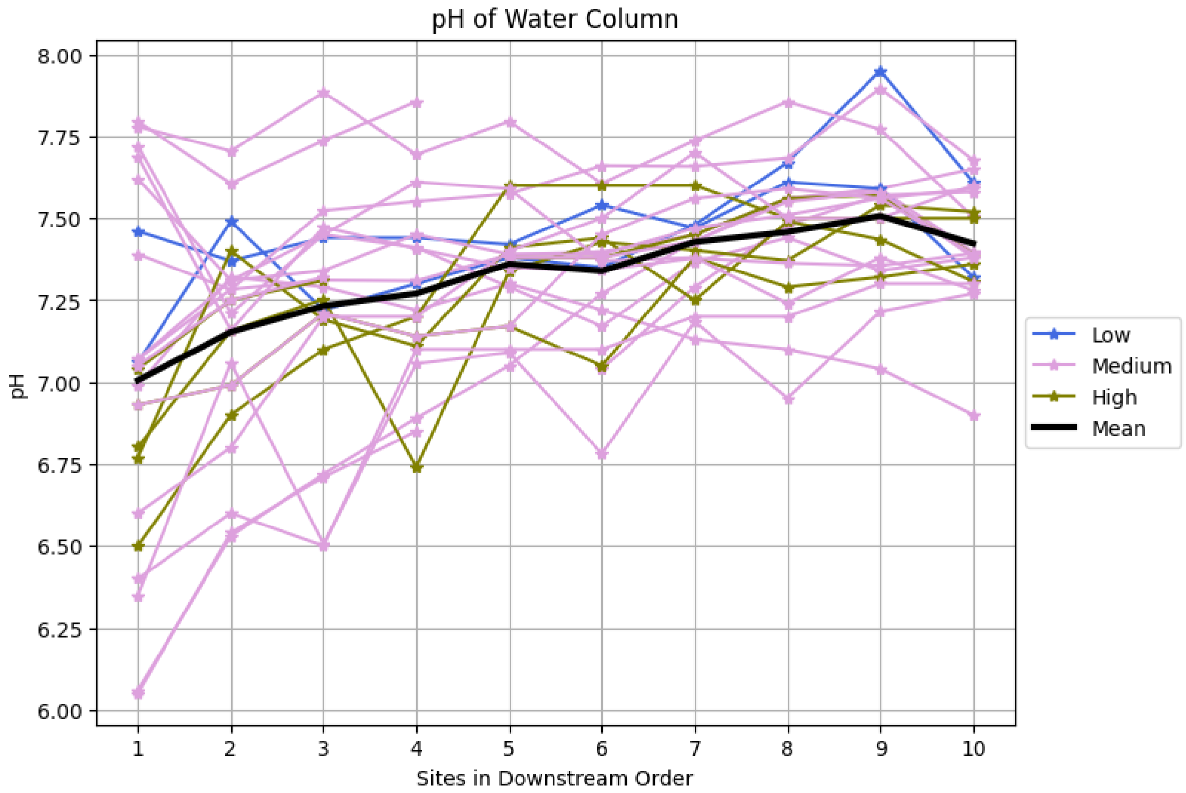


Figure 4.26 – *pH of water column from September 2022 to November 2024 in downstream order. The mean has been calculated for each site to demonstrate the variation between sampling visits. The months have been grouped by the river height at Alma Weir on the day of sampling to low (n=2), medium (n=15) and high (n=5).*

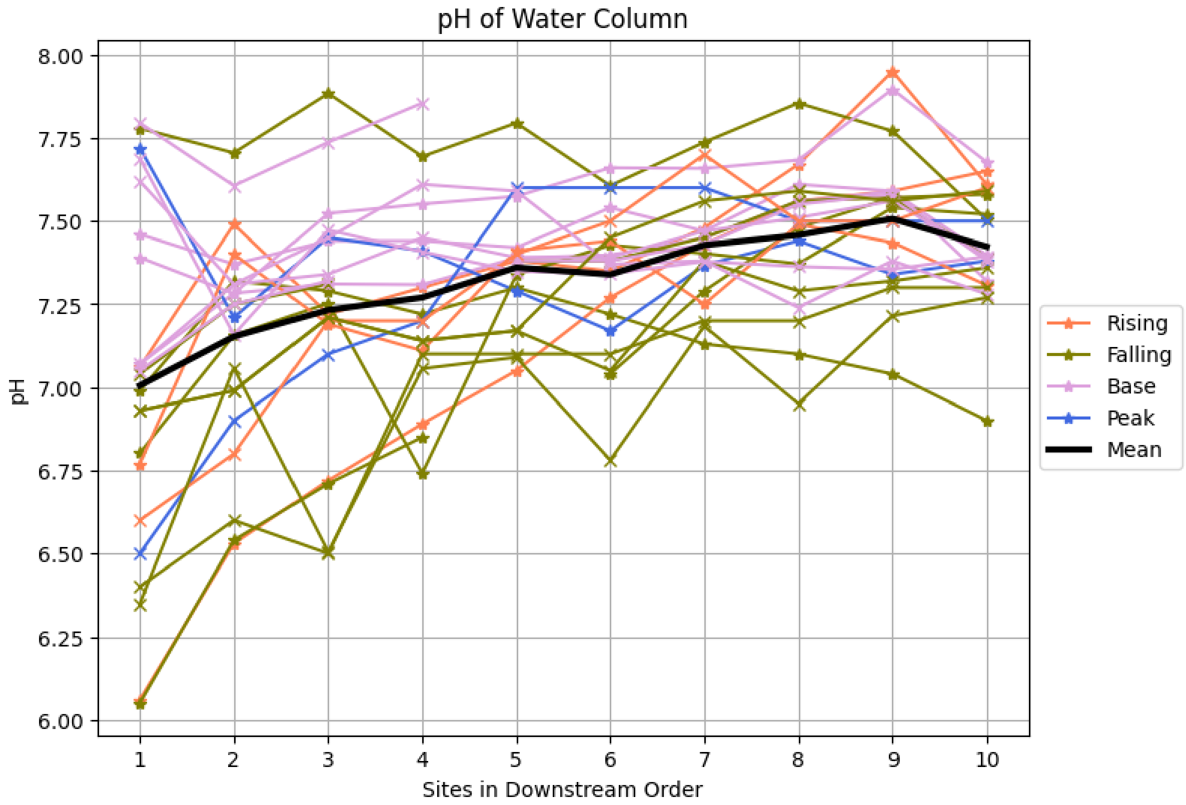


Figure 4.27 – *pH of water column from September 2022 to November 2024 in downstream order. The mean has been calculated for each site to demonstrate the variation between sampling visits. The months have been grouped by the river stage at Alma Weir on the day of sampling to rising (n=4), falling (n=9), peak (n=2) and base (n=8).*

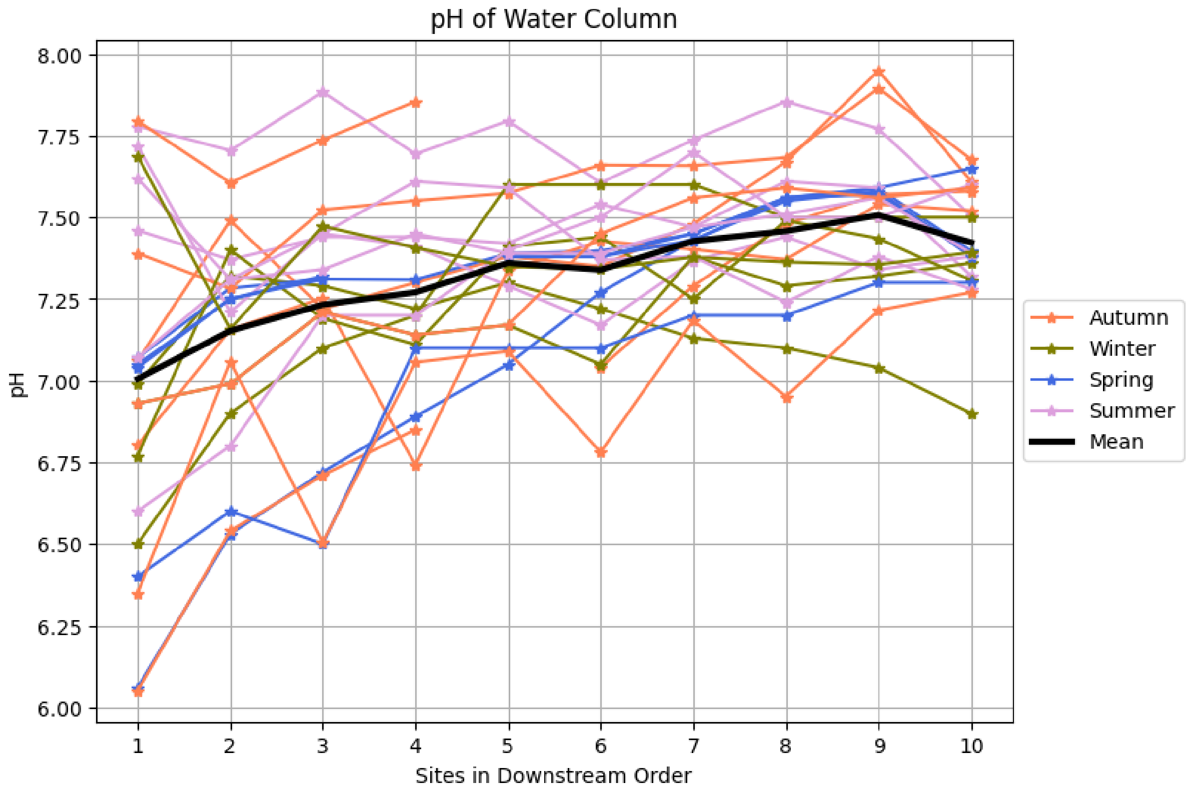


Figure 4.28 – *pH of water column from September 2022 to November 2024 in downstream order. The mean has been calculated for each site to demonstrate the variation between sampling visits. The months have been grouped by the season on the day of sampling to Autumn (n=7), Winter (n=5), Spring (n=5) and Summer (n=6).*

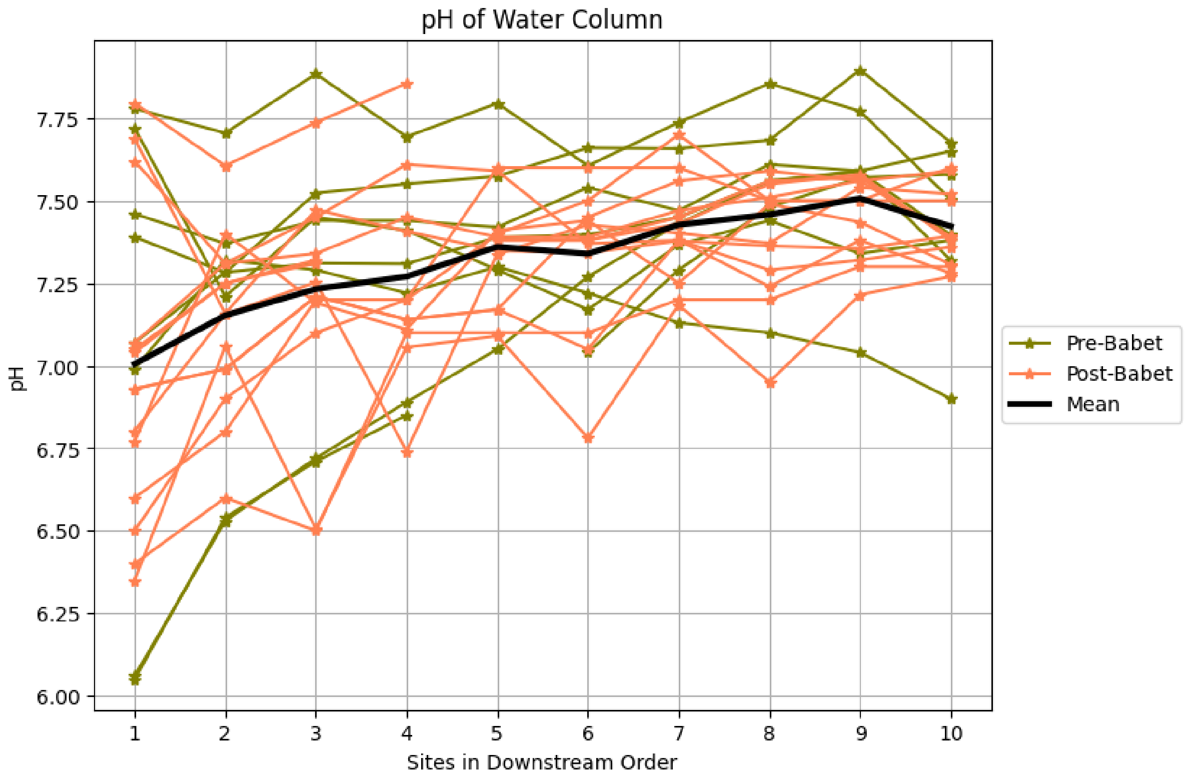


Figure 4.29 – *pH of water column from September 2022 to November 2024 in downstream order. The mean has been calculated for each site to demonstrate the variation between sampling visits. The months have been grouped by the months of sampling before (n= 9) and after (n=14) Storm Babet (18th -21st October 2023).*

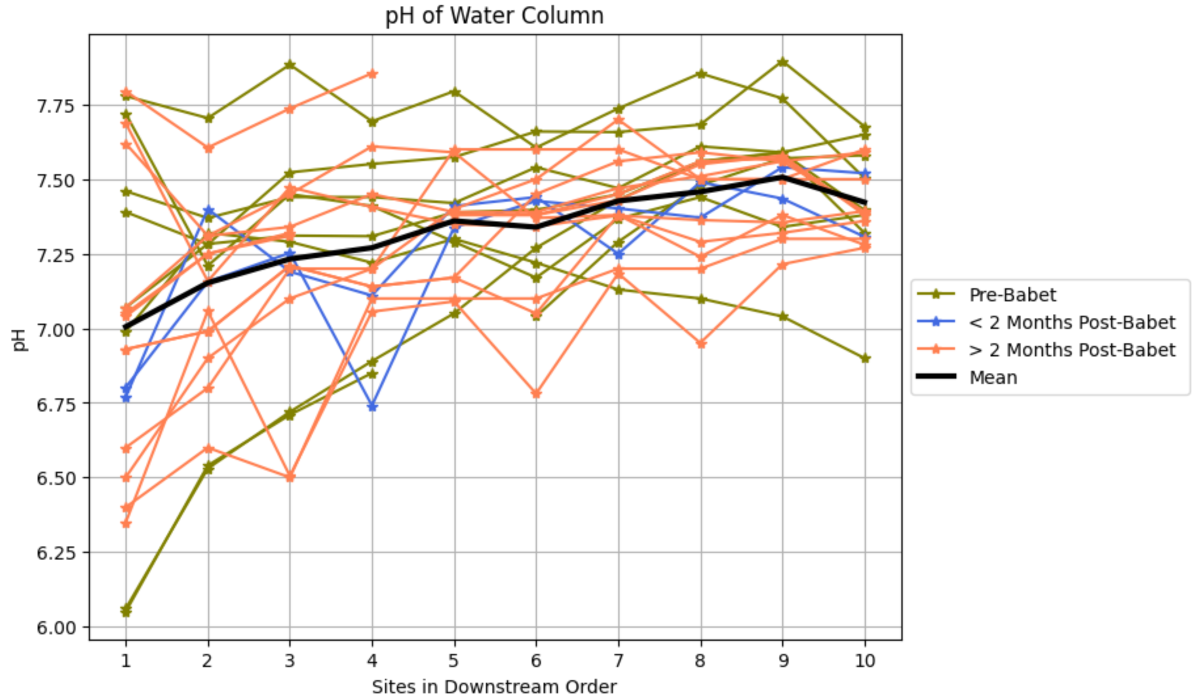


Figure 4.30 – *pH of water column from September 2022 to November 2024 in downstream order. The mean has been calculated for each site to demonstrate the variation between sampling visits. The months have been grouped by the months of sampling before (n= 9), less than 2 months after Storm Babet (n=2) and more than 2 months after (n=12) Storm Babet (18th -21st October 2023).*

pH shows a variety of responses (Figures 4.25-4.30). Overall, the pH levels increase downstream, and this seems to be a very robust trend. When the river level is high at Alma Weir the pH is typically equal to or below the mean pH. When the river level is low then the pH is above the mean in most samples. When the river stage is falling most samples are below the mean value. This trend is amplified progressively with distance downstream. When the river is at base level, the measured values are mostly above the mean and there is less variation downstream. Both rising and peak flow follow the mean. The pH level does not seem to change seasonally. Spring is mostly below the mean and summer mostly above the mean value but this could be a coincidence of the timings of high/low flow events (Fig 4.28). Site 1 has the most variance, this is likely due to the influence of acidic moorland run-off during high flow events.

4.3.3 Conductivity

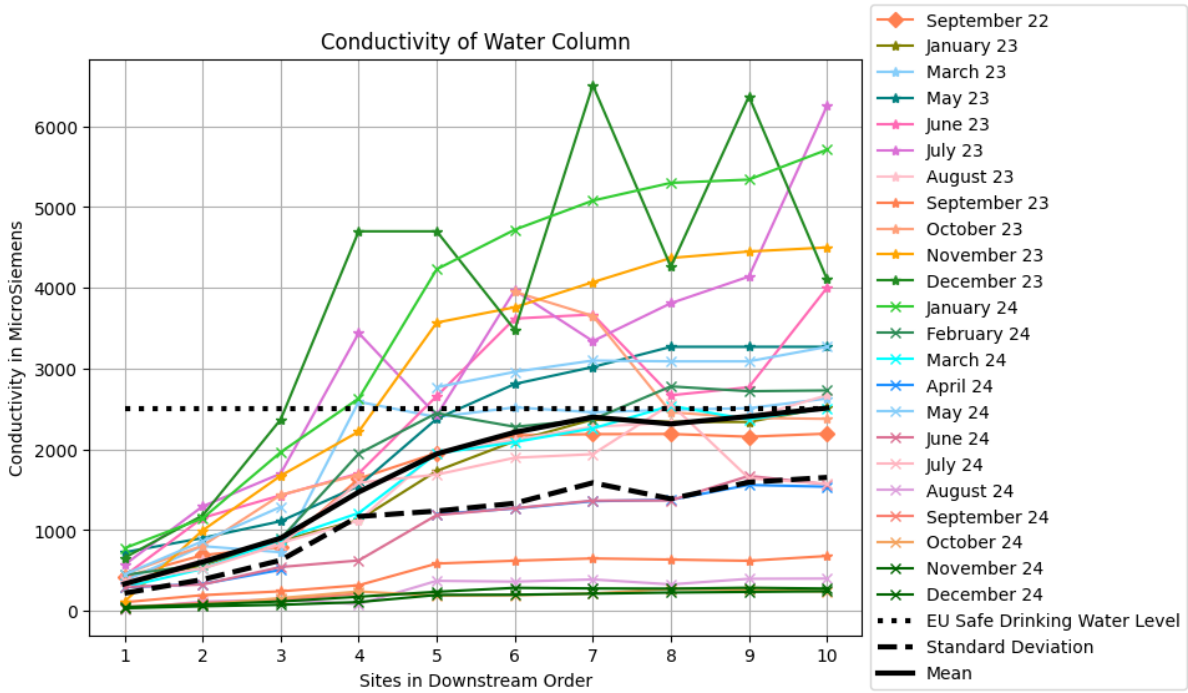


Figure 4.31– Conductivity (microSiemens) of Water Column from September 2022 to December 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits.

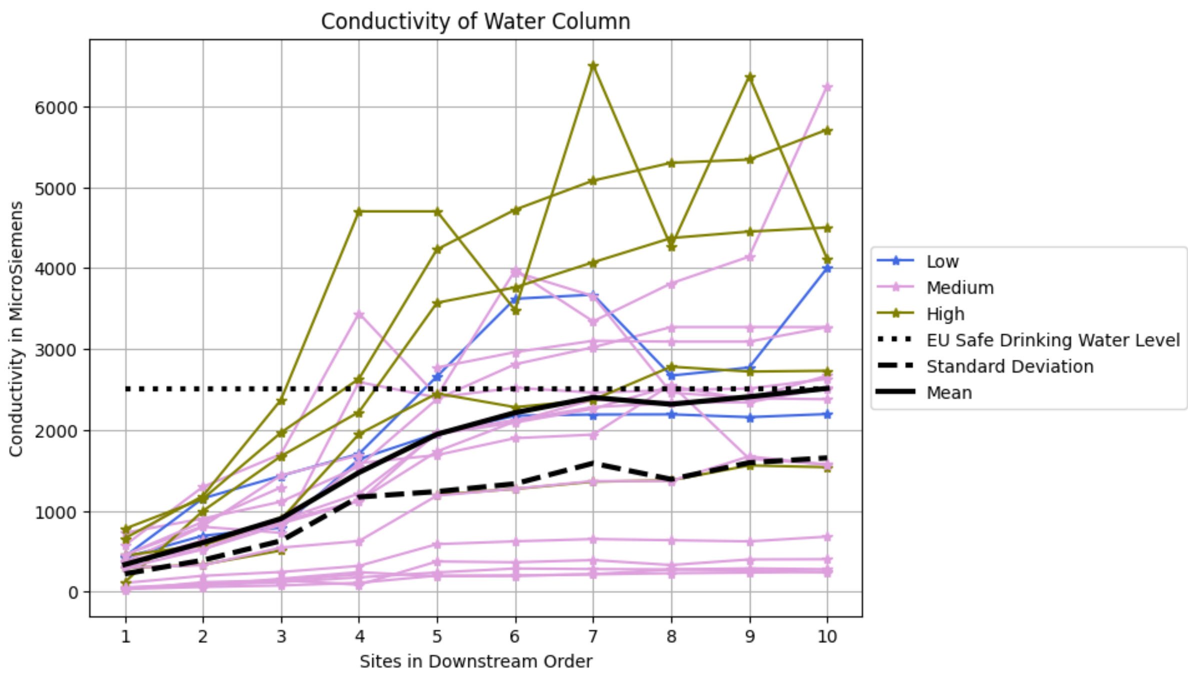


Figure 4.32 – *Conductivity (microSiemens) of Water Column from September 2022 to December 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits. The months have been grouped by the river height at Alma Weir on the day of sampling to low (n=2), medium (n=15) and high (n=5).*

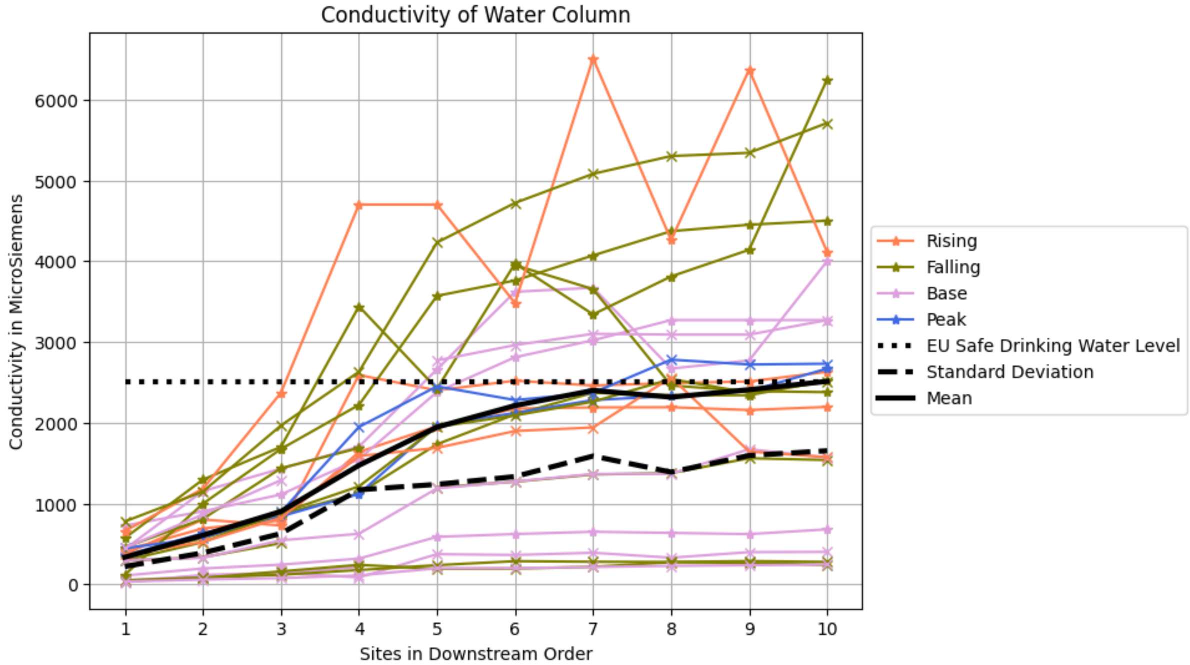


Figure 4.33 – *Conductivity (microSiemens) of Water Column from September 2022 to December 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits. The months have been grouped by the river stage at Alma Weir on the day of sampling to rising (n=4), falling (n=9), peak (n=2) and base (n=8).*

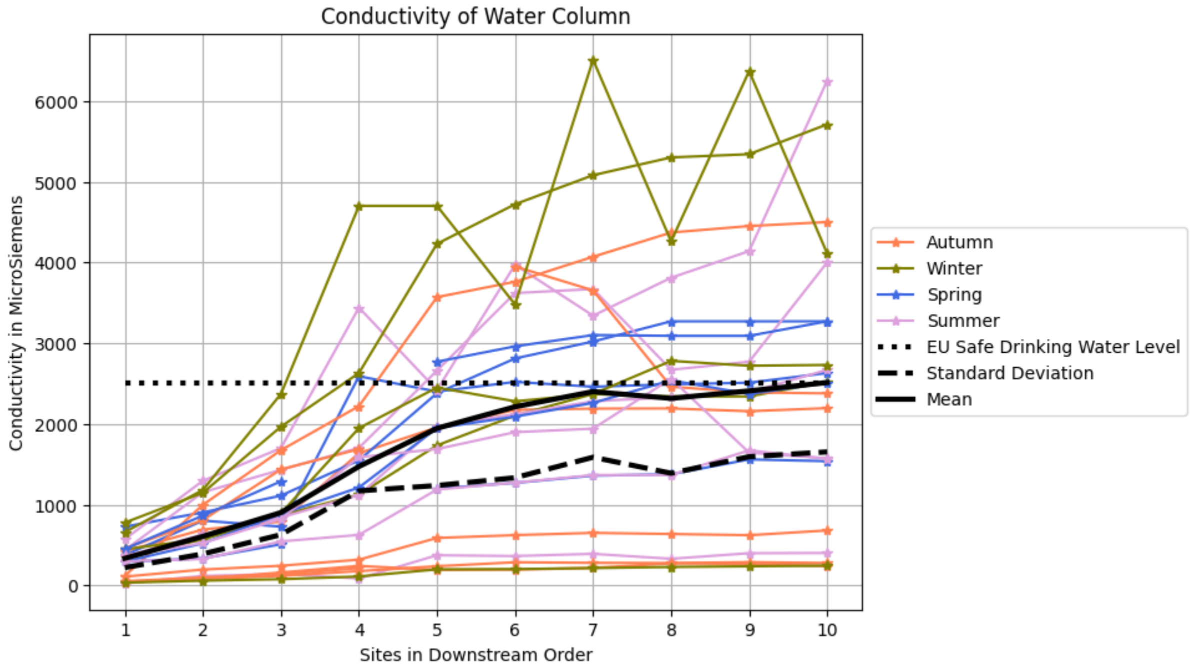


Figure 4.34 – *Conductivity (microSiemens) of Water Column from September 2022 to December 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits. The months have been grouped by the season on the day of sampling to Autumn (n=7), Winter (n=5), Spring (n=5) and Summer (n=6).*

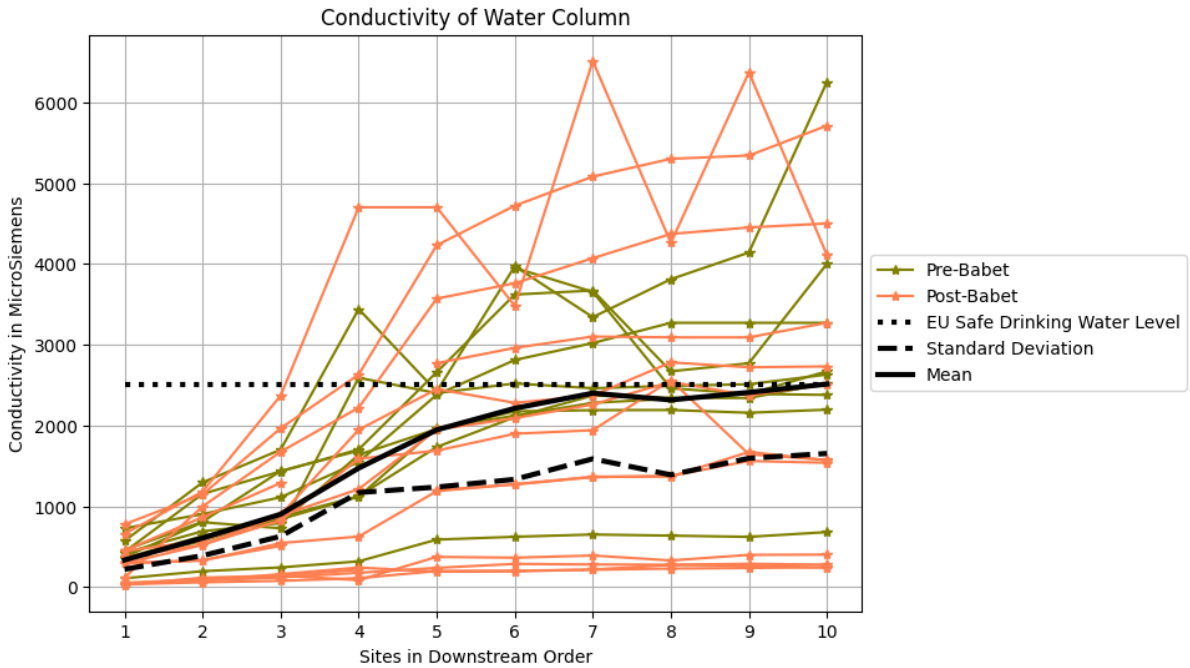


Figure 4.35 – *Conductivity (microSiemens) of Water Column from September 2022 to December 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits. The months have been grouped by the months of sampling before (n= 9) and after (n=14) Storm Babet (18th -21st October 2023).*

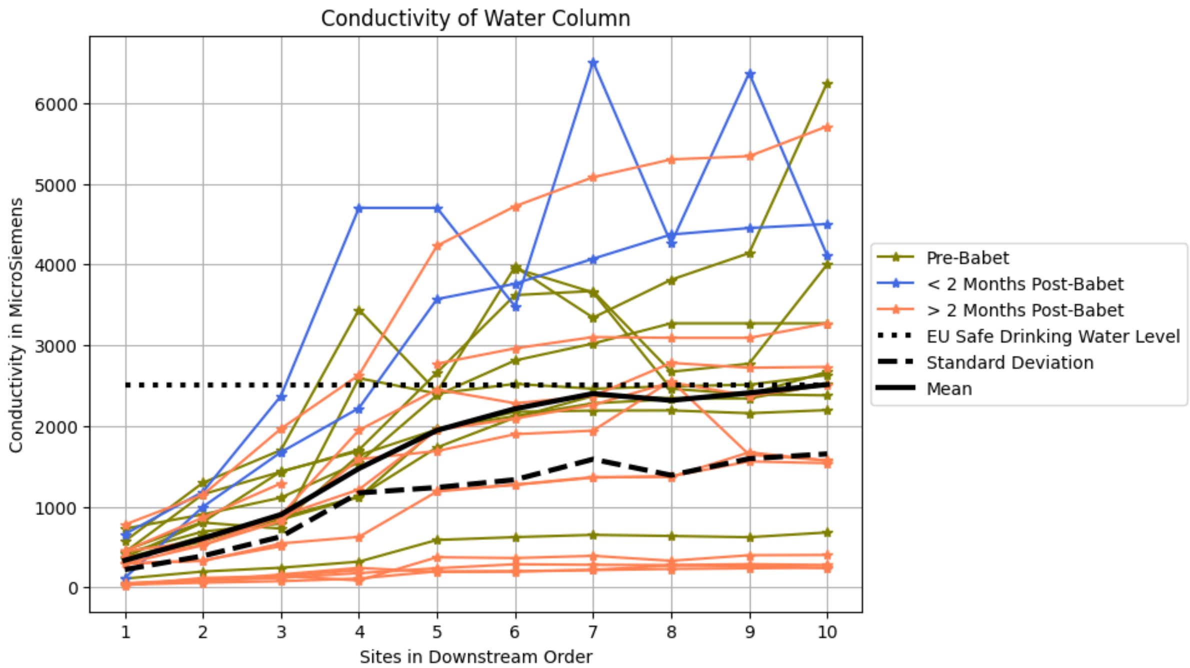


Figure 4.36 – *Conductivity (microSiemens) of Water Column from September 2022 to December 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits. The months have been grouped by the months of sampling before (n= 9), less than 2 months after Storm Babet (n=2) and more than 2 months after (n=12) Storm Babet (18th-21st October 2023).*

The measured conductivity shows a strong increase downstream (Figures 4.31-4.36). The standard deviation of conductivity also increased downstream, which means that the variance of the results from the mean increases downstream. The increased conductivity seen around Site 4 could be attributed to the exhumed band of Cayton Gill Shell Bed (that also defines the base of the Brimham Grit at Brimham Rocks), which might cause an increase in salinity at this point. When the river is high or low at Alma Weir, most samples are above the mean. When the river stage is falling most samples are above the mean, the peak flow samples follow the mean, the base samples are at or below the mean, as are the rising limb samples excluding one taken in December 2023. Winter has the highest conductivity values. This is likely a consequence of road salt being washed into the river. Spring has very little variation in samples and all results are close to or above the mean. Summer has the most variation. Storm Babet has minimal influence on the results. The two high values in the 2 months after Storm Babet are likely due to them being collected in winter and increased levels of road salt in the river. Sites 3-10 have some samples which are above the EU safe water drinking limit for conductivity. Overall, conductivity appears to be high in the river Skell, but no obvious reason for this has been identified within this study.

4.3.4 Turbidity

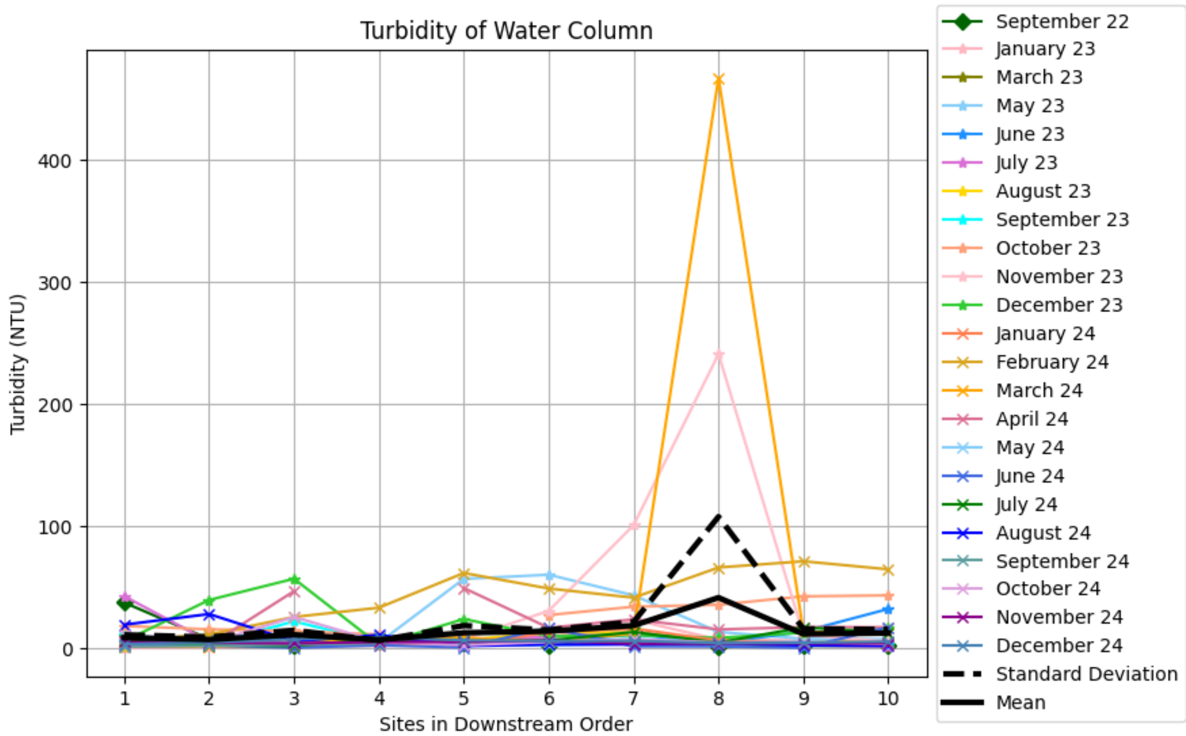


Figure 4.37 – *Turbidity (Nephelometric Turbidity Units) in water column from September 2022 to December 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits.*

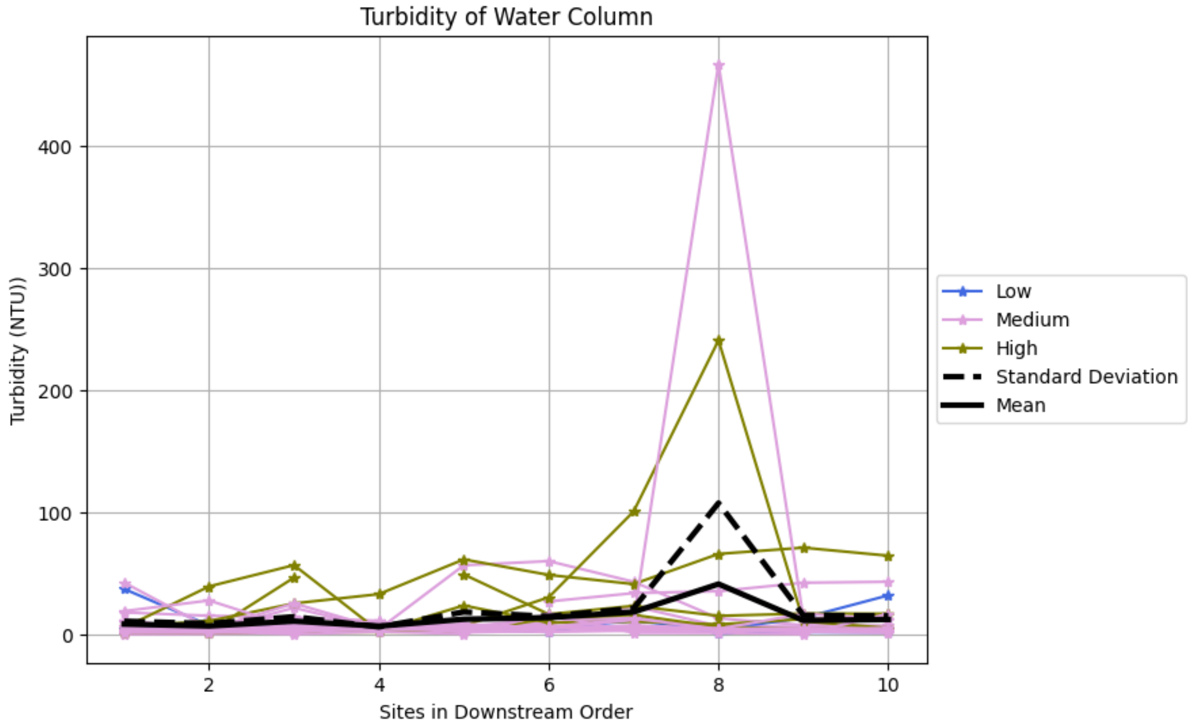


Figure 4.38 – *Turbidity (Nephelometric Turbidity Units) in water column from September 2022 to December 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits. The months have been grouped by the river height at Alma Weir on the day of sampling to low (n=2), medium (n=15) and high (n=5).*

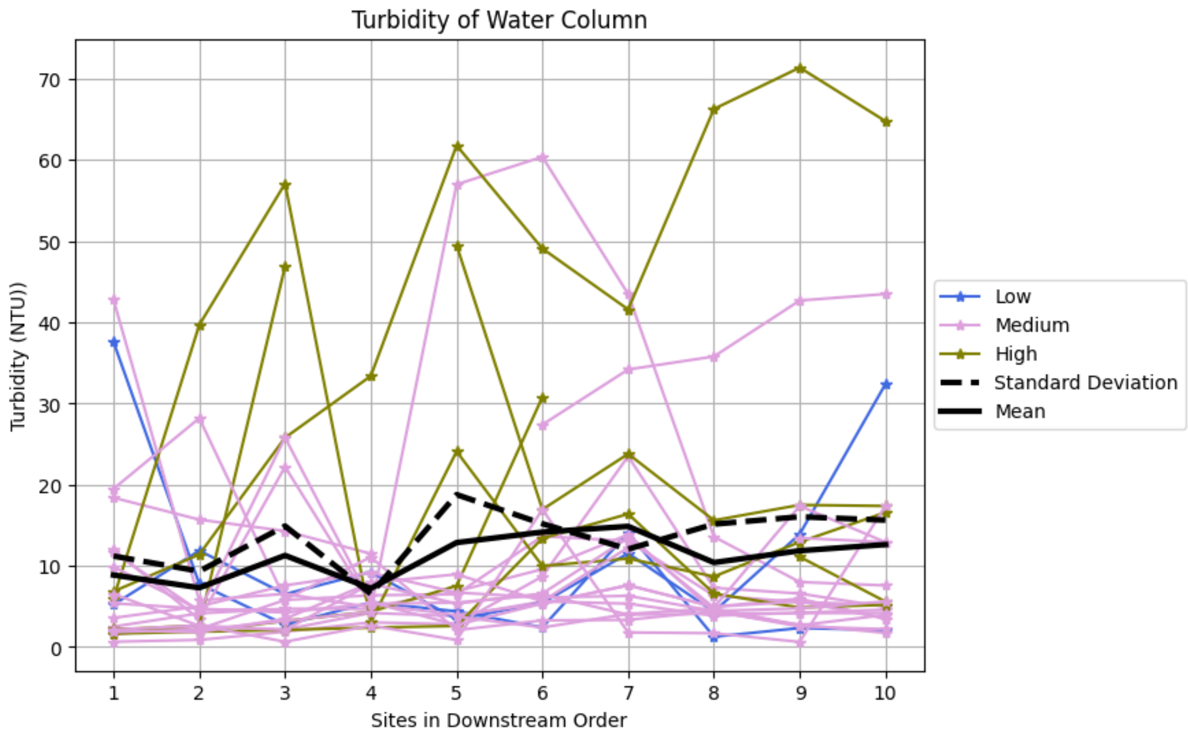


Figure 4.39 – *Turbidity (Nephelometric Turbidity Units) in water column from September 2022 to December 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits. The data have been filtered to exclude points greater than two standard deviations away from the mean to remove outliers and improve trend visualisation. The months have been grouped by the river height at Alma Weir on the day of sampling to low (n=2), medium (n=15) and high (n=5).*

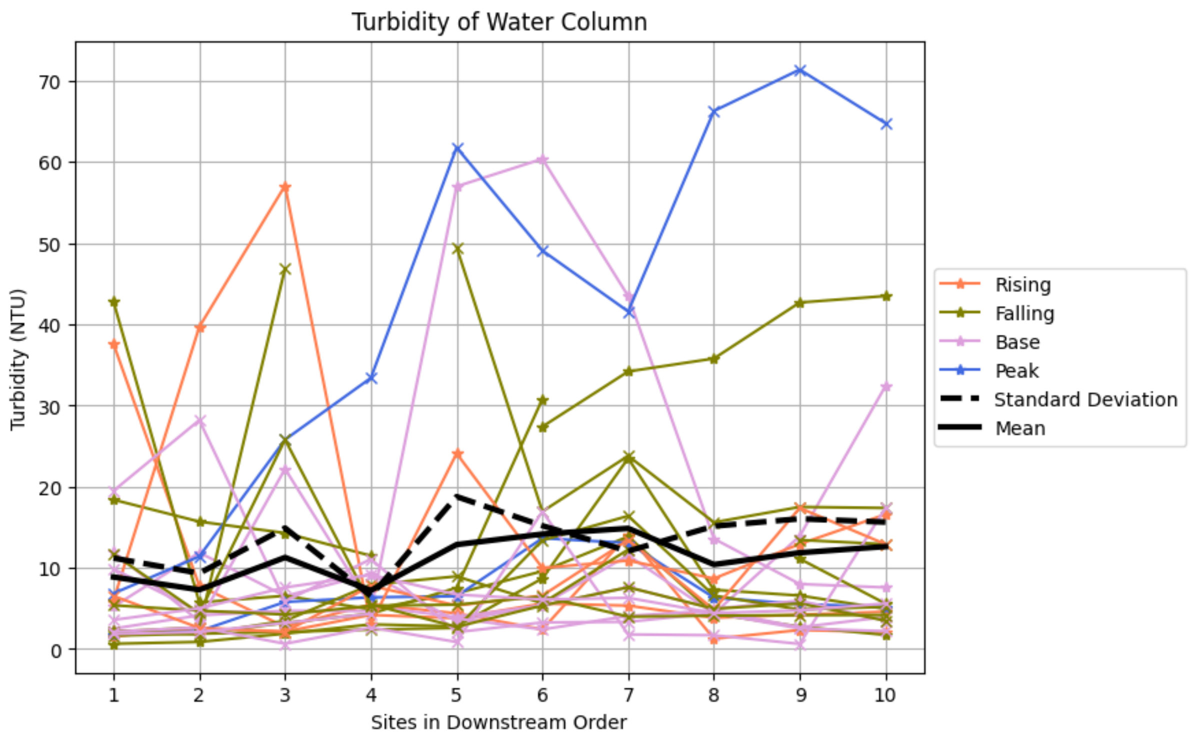


Figure 4.40 – *Turbidity (Nephelometric Turbidity Units) in water column from September 2022 to December 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits. The data have been filtered to exclude points greater than two standard deviations away from the mean to remove outliers and improve trend visualisation. The months have been grouped by the river stage at Alma Weir on the day of sampling to rising (n=4), falling (n=9), peak (n=2) and base (n=8).*

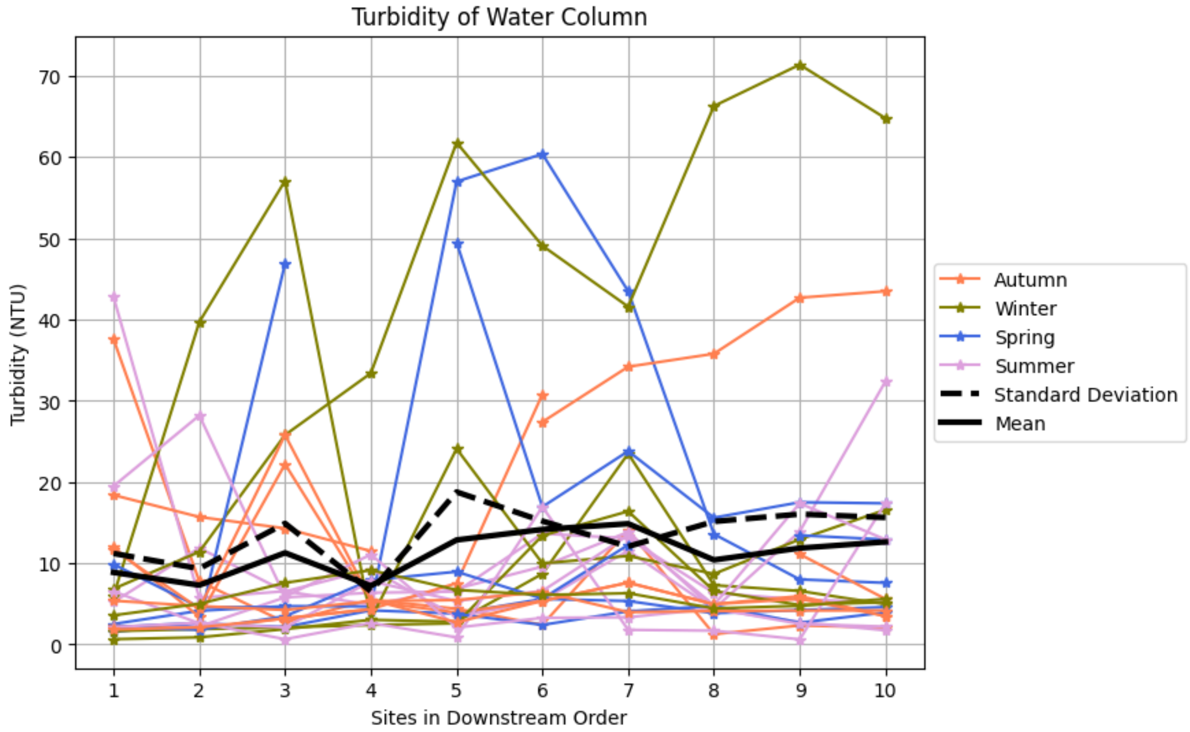


Figure 4.41 – *Turbidity (Nephelometric Turbidity Units) in water column from September 2022 to December 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits. The data have been filtered to exclude points greater than two standard deviations away from the mean to remove outliers and improve trend visualisation. The months have been grouped by the season on the day of sampling to Autumn (n=7), Winter (n=5), Spring (n=5) and Summer (n=6).*

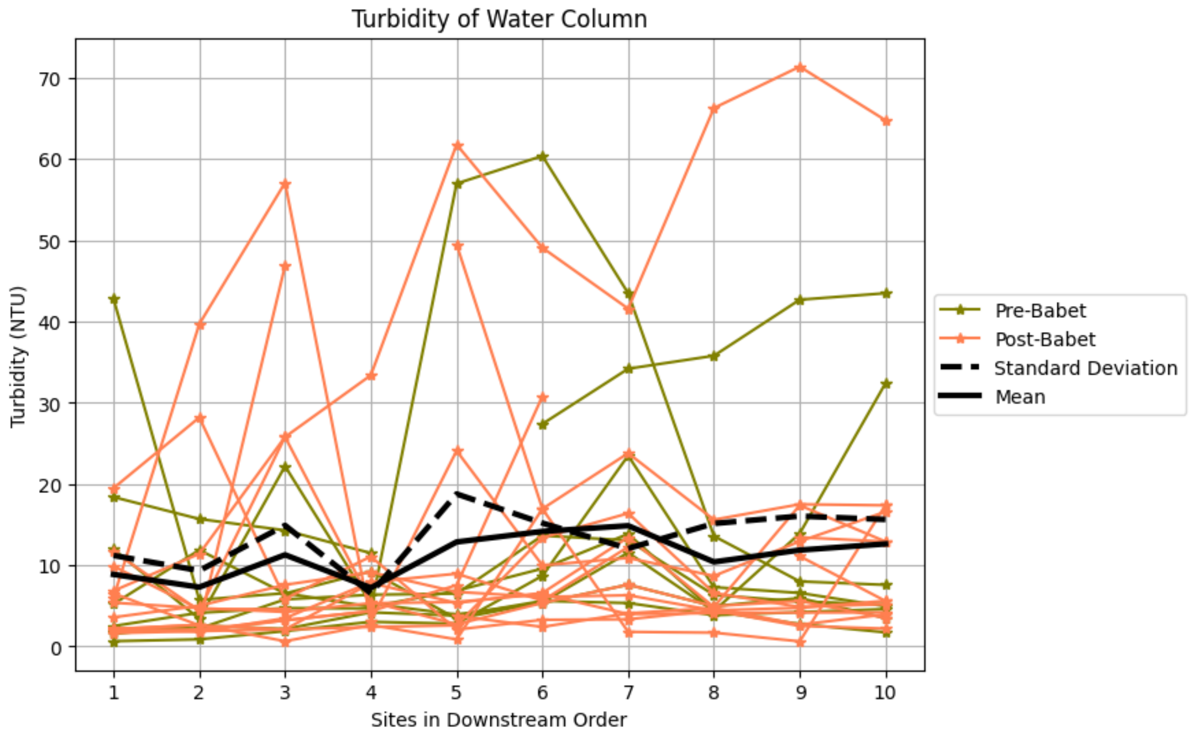


Figure 4.42 – *Turbidity (Nephelometric Turbidity Units) in water column from September 2022 to December 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits. The data have been filtered to exclude points greater than two standard deviations away from the mean to remove outliers and improve trend visualisation. The months have been grouped by the months of sampling before (n= 9) and after (n=14) Storm Babet (18th -21st October 2023).*

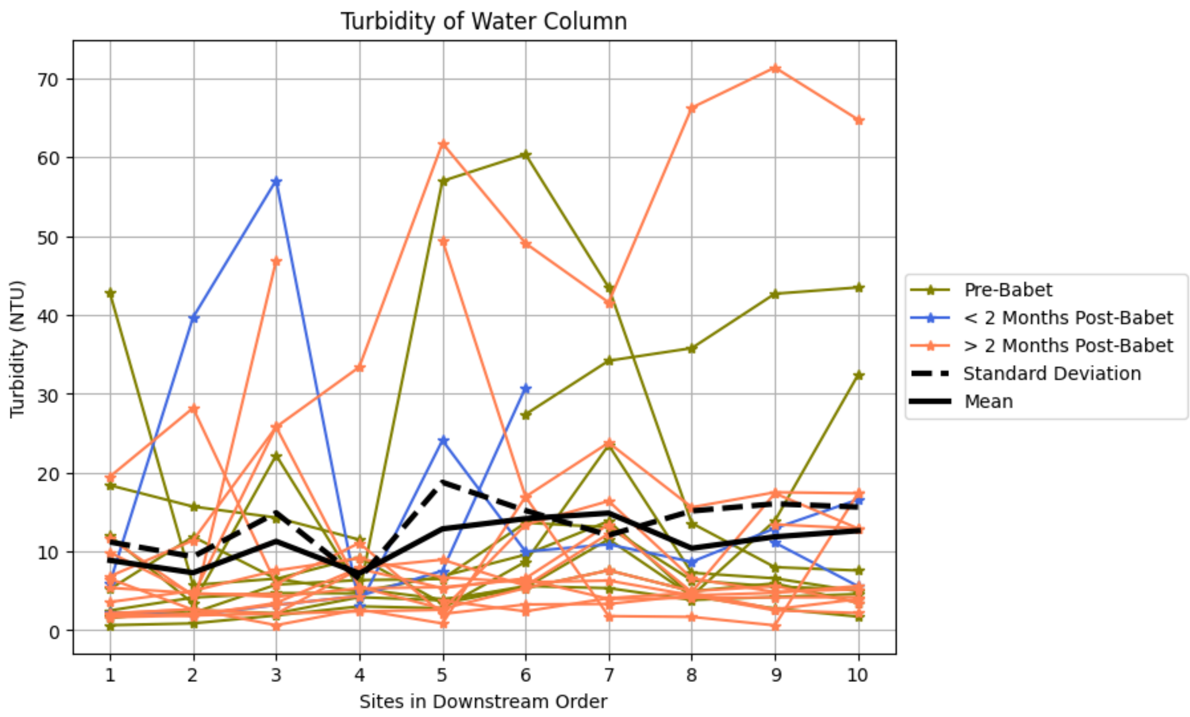


Figure 4.43 – *Turbidity (Nephelometric Turbidity Units) in water column from September 2022 to December 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits. The data have been filtered to exclude points greater than two standard deviations away from the mean to remove outliers and improve trend visualisation. The months have been grouped by the months of sampling before (n= 9), less than 2 months after Storm Babet (n=2) and more than 2 months after (n=12) Storm Babet (18th -21st October 2023).*
4.37-4.43

The turbidity data contains a couple of outlying values (Figs 4.37 & 4.38). The outlying turbidity peaks were present at Site 8 in the unfiltered samples collected in January 2023 and March 2024. Both months were collected during a falling limb when the river was at a medium height at Alma Weir. In March, a 'muddy sample' note was recorded during analysis, which could be due to the sample being collected after there had been an input of sediment into Half Moon Lake that had not settled. Whether this input came from upstream or from within the Fountains Abbey and Studley Royal site is not possible to resolve. It is unlikely to be from a sampling error, such as scouring the river bed during sampling, as the river is canalised at that point and the base flow is maintained by a weir at the outlet into the Main Lake. Therefore, the river depth would not become so low that this would be likely.

When the river is high at Alma Weir, the turbidity is mostly above the mean. When it is low, the turbidity is mostly low except for some spikes at Sites 1 and 10 (Figs 4.37-4.43). These spikes could be due to sampling error. However, the river is quite deep in this location, so Site 1 is likely caused by dissolved organic carbon in the river from moorland run-off. Site 10 could be due to remobilisation of sediment, which had settled into Half-Moon Lake or other locations on the Fountains Estate. Across all samples there is a trend for high turbidity measurements at Site 3 and then Sites 5-10 through the Fountains Estate. This suggests there is a source of sediment at, or upstream of, these sites.

4.3.5 Concentration of Dry Solids

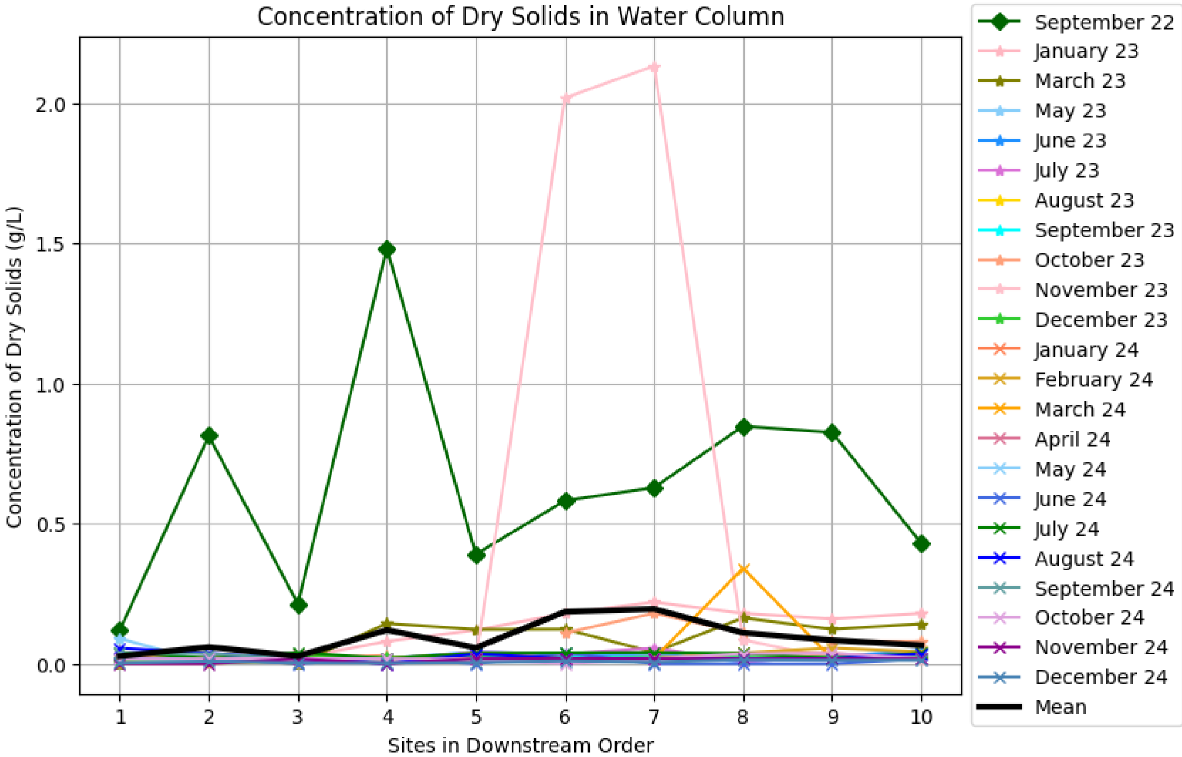


Figure 4.44 – *Concentration (g/L) of Dry Solids in Water Column from September 2022 to December 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits.*

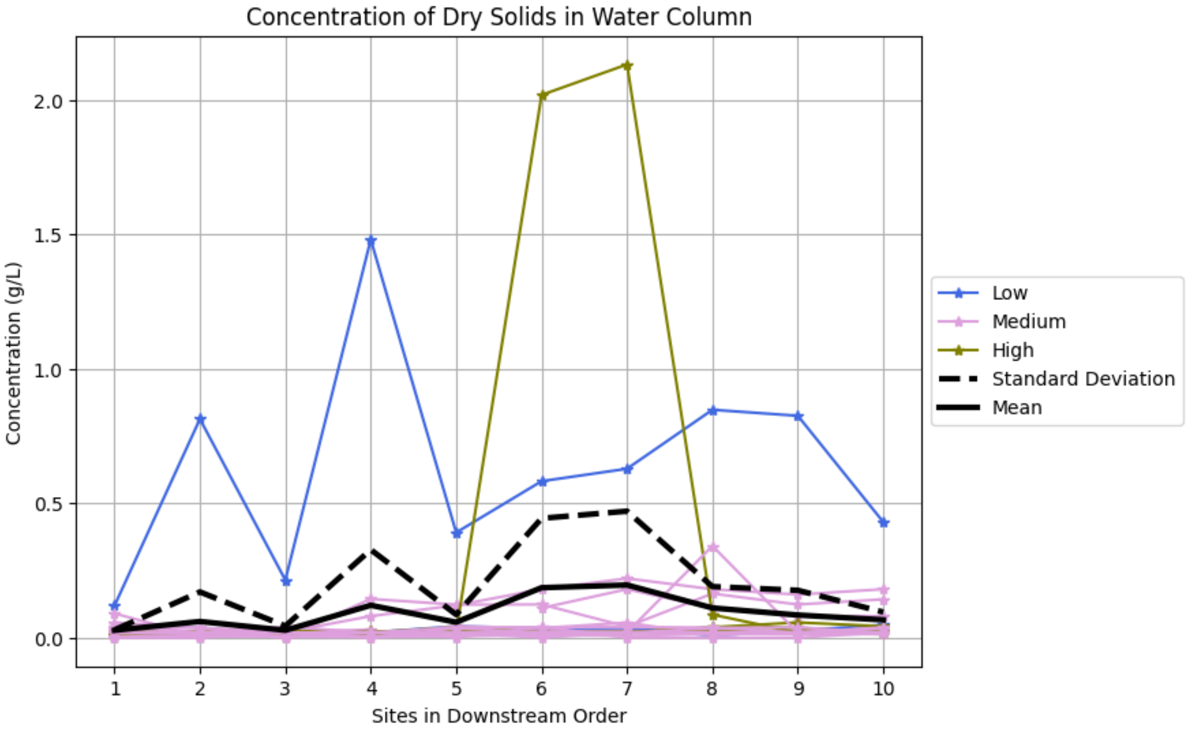


Figure 4.45 – *Concentration (g/L) of Dry Solids in Water Column from September 2022 to December 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits. The months have been grouped by the river height at Alma Weir on the day of sampling to low (n=2), medium (n=15) and high (n=5).*

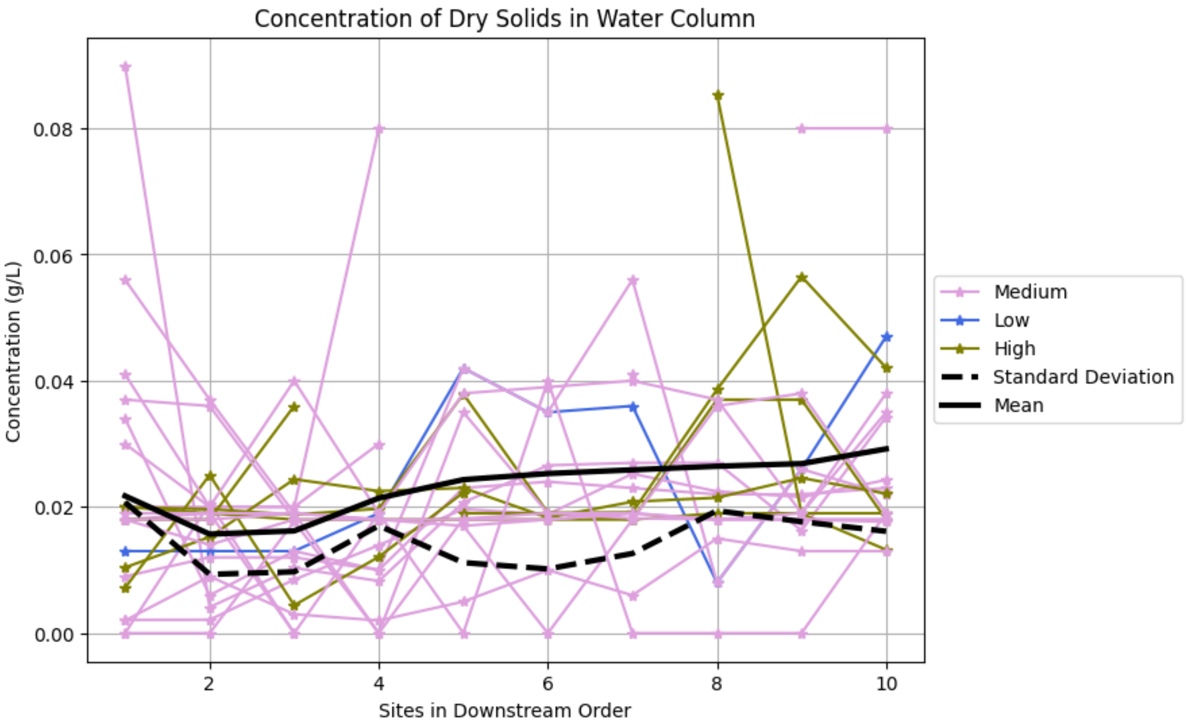


Figure 4.46 – *Concentration (g/L) of Dry Solids in Water Column from September 2022 to December 2024 in downstream order. The standard deviation and mean have been*

calculated for each site to demonstrate the variation between sampling visits. The data have been filtered to exclude points greater than one standard deviation away from the mean to remove outliers and improve trend visualisation. The months have been grouped by the river height at Alma Weir on the day of sampling to low (n=2), medium (n=15) and high (n=5).

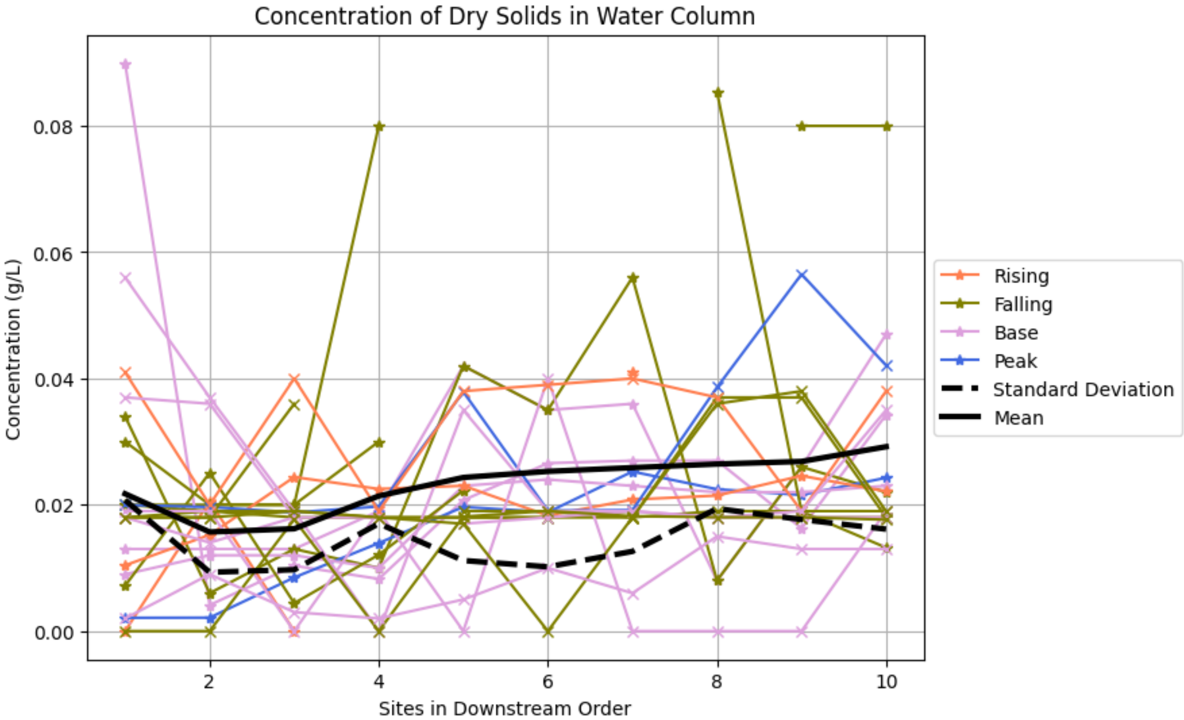


Figure 4.47 – *Concentration (g/L) of Dry Solids in Water Column from September 2022 to December 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits. The data have been filtered to exclude points greater than one standard deviation away from the mean to remove outliers and improve trend visualisation. The months have been grouped by the river stage at Alma Weir on the day of sampling to rising (n=4), falling (n=9), peak (n=2) and base (n=8).*

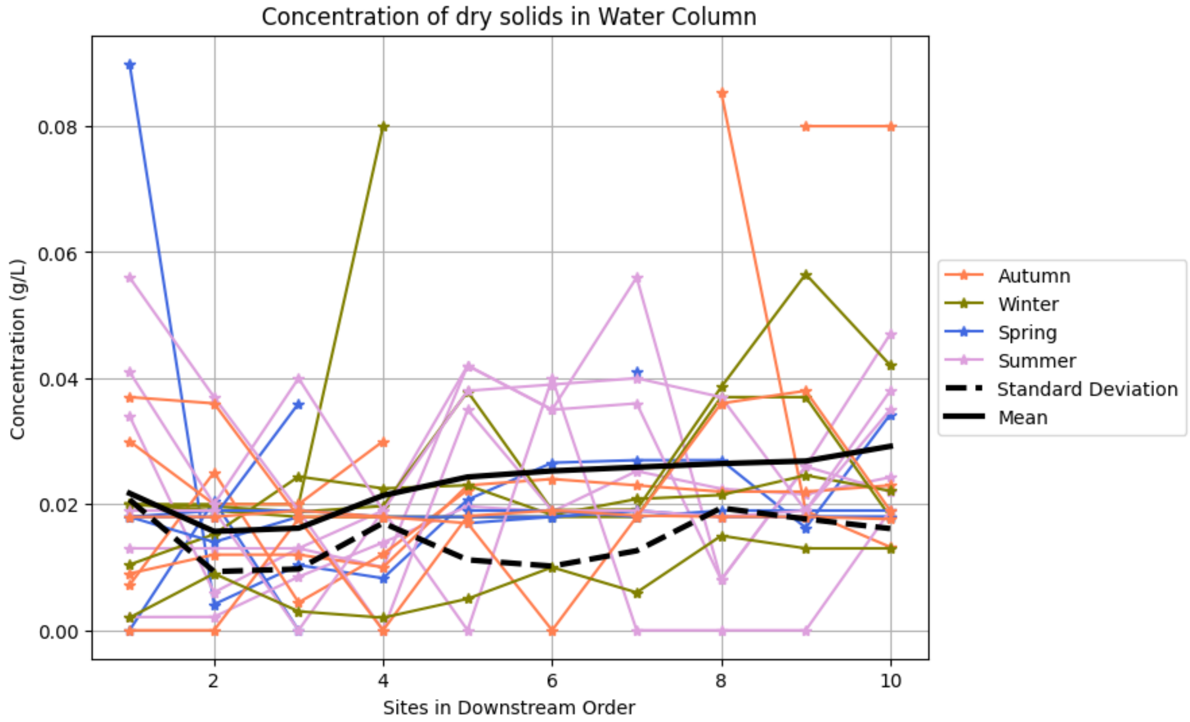


Figure 4.48 – *Concentration (g/L) of Dry Solids in Water Column from September 2022 to December 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits. The months have been grouped by the season on the day of sampling to Autumn (n=7), Winter (n=5), Spring (n=5) and Summer (n=6).*

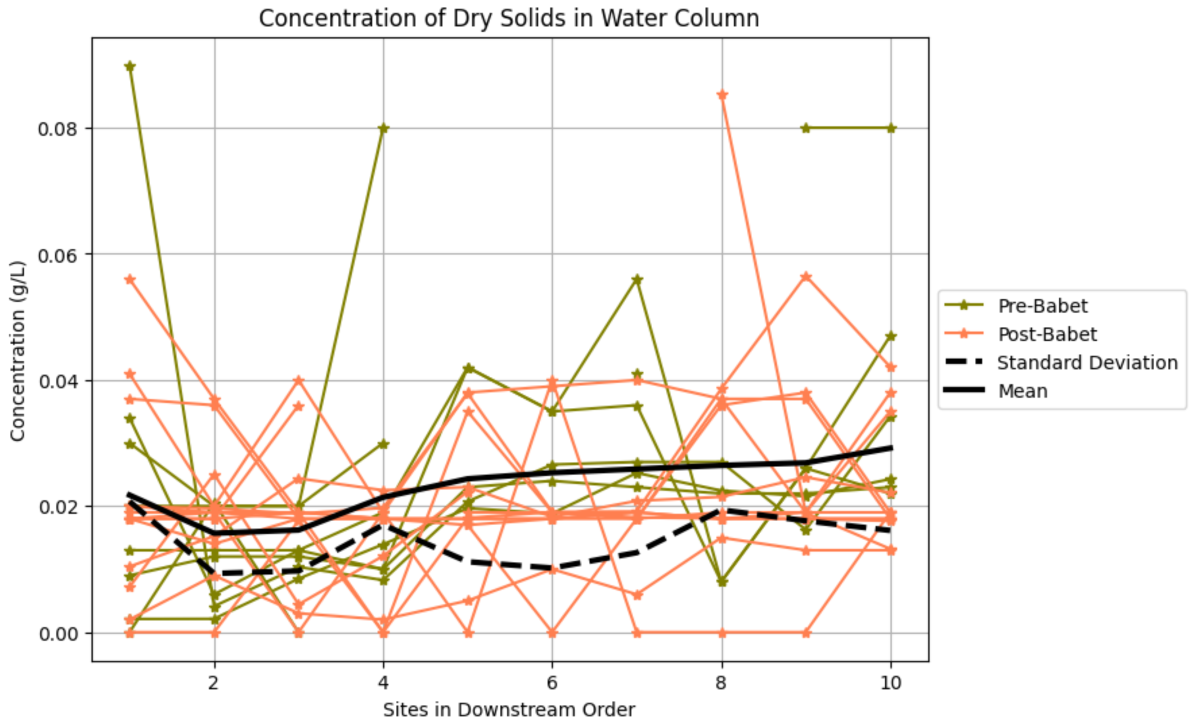


Figure 4.49 – *Concentration (g/L) of Dry Solids in Water Column from September 2022 to December 2024 in downstream order. The standard deviation and mean have been*

calculated for each site to demonstrate the variation between sampling visits. The data have been filtered to exclude points greater than one standard deviation away from the mean to remove outliers and improve trend visualisation. The months have been grouped by the months of sampling before (n= 9) and after (n=14) Storm Babet (18th -21st October 2023).

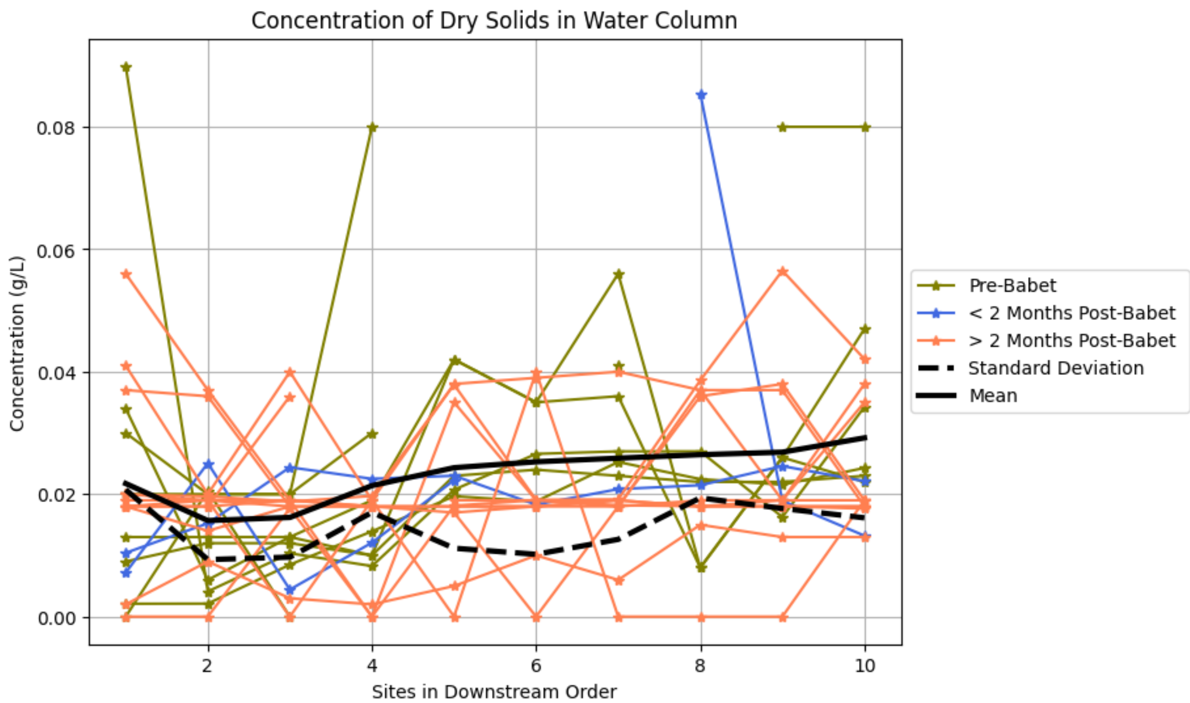


Figure 4.50 – *Concentration (g/L) of Dry Solids in Water Column from September 2022 to December 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits. The data have been filtered to exclude points greater than one standard deviation away from the mean to remove outliers and improve trend visualisation. The months have been grouped by the months of sampling before (n= 9), less than 2 months after Storm Babet (n=2) and more than 2 months after (n=12) Storm Babet (18th -21st October 2023).*

There is a complex pattern of dry solid measurements through the catchment, with a weak increase in the mean value moving downstream (Figures 4.44-4.50). Sites 1 and 4 have the highest standard deviation, and so the largest variation in samples from the mean. The river height at Alma Weir has few trends for the filtered data. Sites 1, 4 and 8 have the most variation, and Sites 2 and 3 have the least amount of variation. When the river stage is rising, most samples were above the mean value. When the river is in peak flow, the top of the catchment is below the mean, but the bottom of the catchment is above the mean. This suggests that there are several sediment sources and/or sinks in the lower catchment. The season has some impart on the concentration of suspended sediment in the samples (Fig 4.48). The summer samples at Sites 5-8 are above the mean value. This could be due to vegetation in the river. In general, Autumn is below the mean except for outliers. This is likely due to most high flow events taking place in winter or summer. Storm Babet had some impact on the concentration of dry solids. Most high values are pre storm Babet, particularly at Sites 4-8, and most samples from post-Babet are below the mean. This suggests that sediment tends to accumulate in the Skell during periods of low and normal flow. During extremely high flow sediment is remobilised. This is evidence that most sediment movement occurs during a very short period. Indeed, it is possible that most of the sediment transport in a season or a year takes place in a few hours within the peak of a storm event. This makes monitoring sedimentation extremely difficult, because if most of the sediment transport occurs during extreme flow events the monitoring has to be activated during the event, which is technically challenging.

4.3.6 Grainsize of Suspended Sediment

4.3.6.1 D10

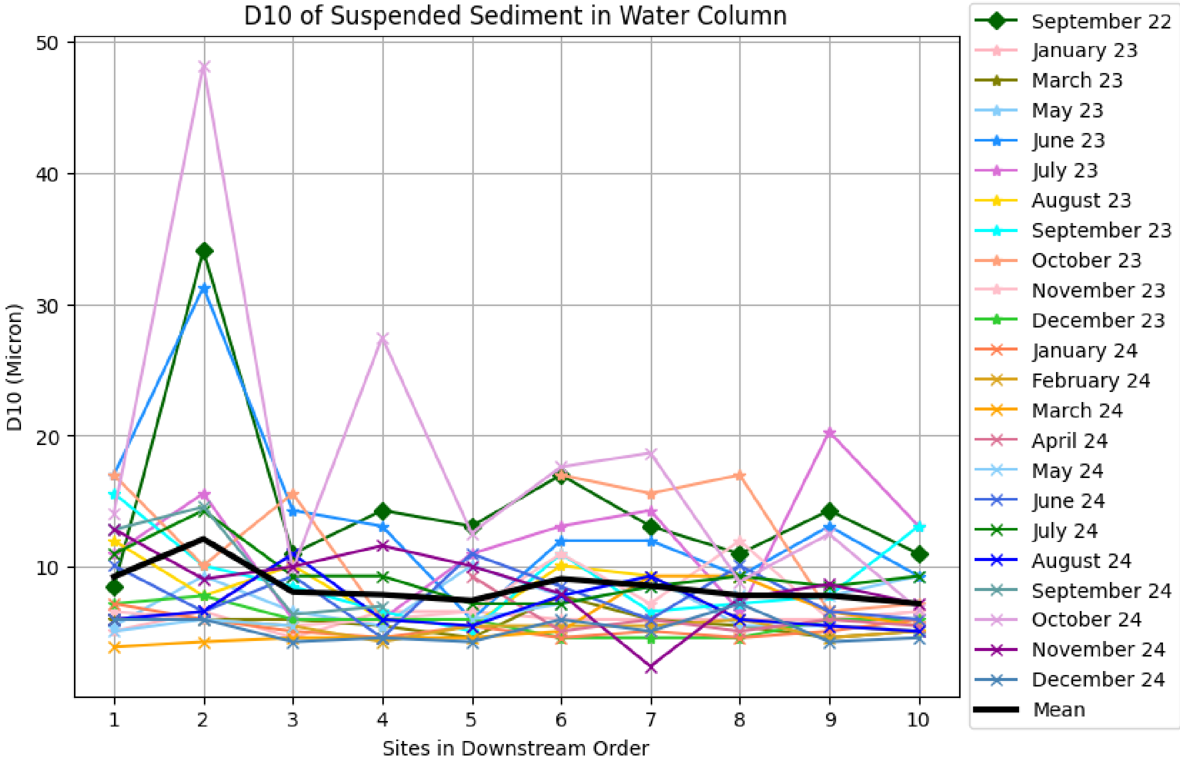


Figure 4.51 – *D10* (micron) of suspended sediment from September 2022 to November 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits.*

*The D10 represents the size class of the 10th percentile of grain size, the upper size boundary for the finest 10th of the suspended sediment. The D50 represents the upper limit of the size class for the median of the suspended sediment, or the mean value. The D90 is the size class of the 90th percentile of grain size. Size class is another name for the boundaries the grain size data is organised into (e.g., 1-2mm, 2-3mm, 3-4mm, etc), the particle sizer then calculates the volume of the total sample which falls into each size class.

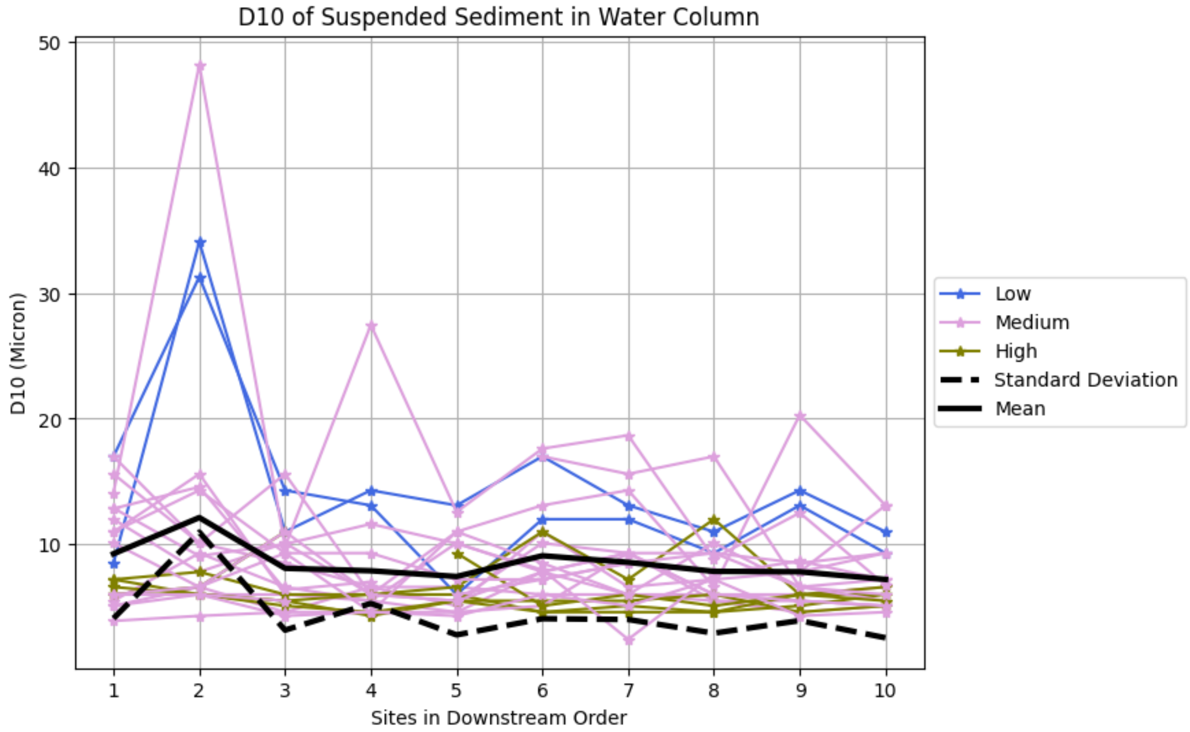


Figure 4.52 – *D10* (micron) of suspended sediment from September 2022 to November 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits. The months have been grouped by the river height at Alma Weir on the day of sampling to low (n=2), medium (n=15) and high (n=5).*

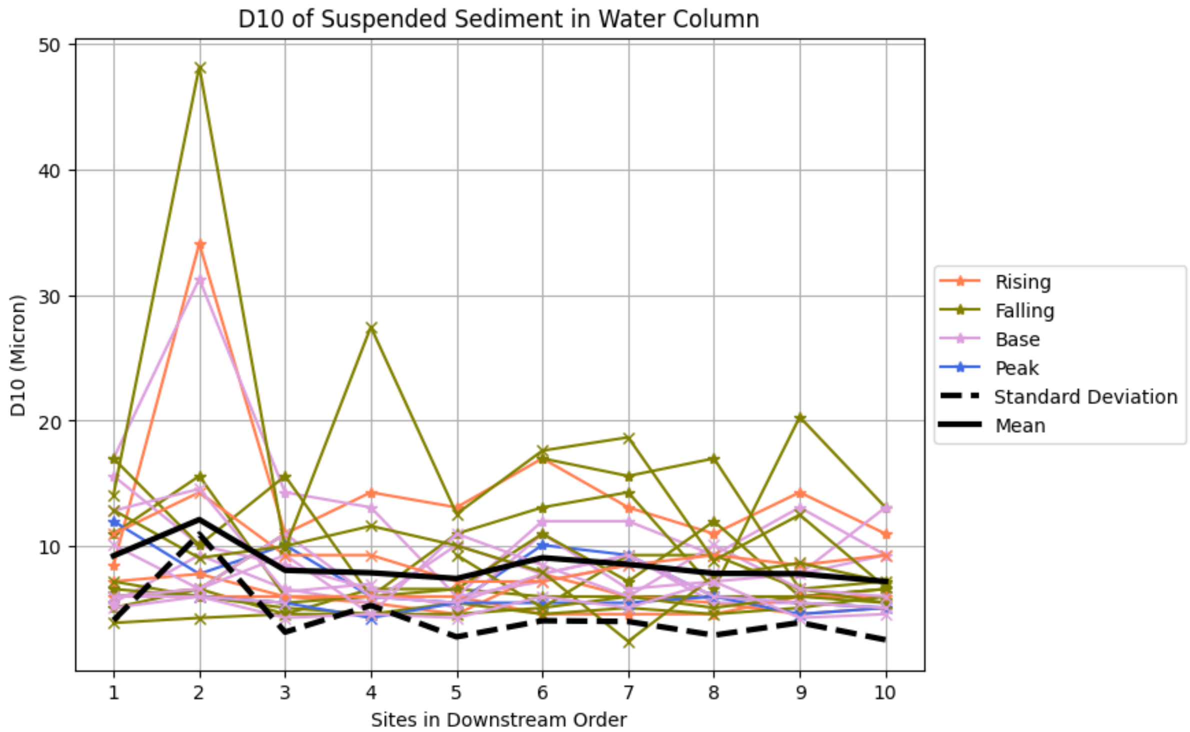


Figure 4.53 – *D10* (micron) of suspended sediment from September 2022 to November 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits. The months have been grouped by the river stage at Alma Weir on the day of sampling to rising (n=4), falling (n=9), peak (n=2) and base (n=8).*

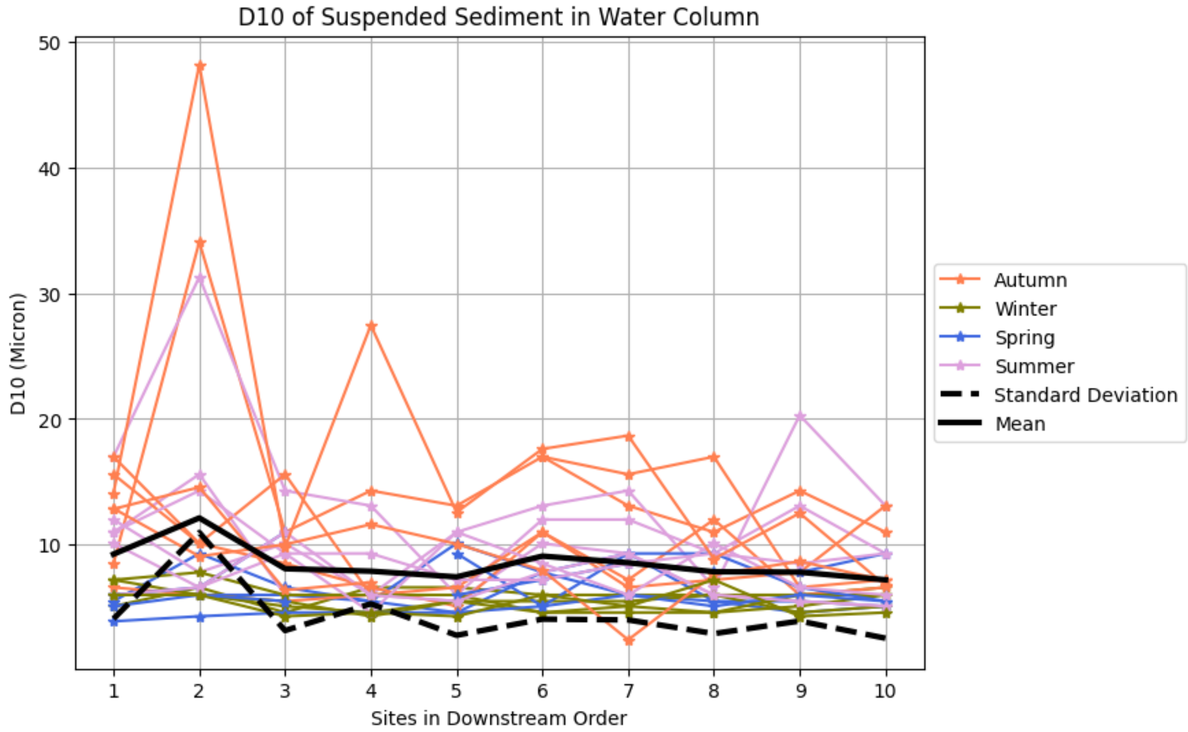


Figure 4.54 – *D10* (micron) of suspended sediment from September 2022 to November 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits. The months have been grouped by the season on the day of sampling to Autumn (n=7), Winter (n=5), Spring (n=5) and Summer (n=6).*

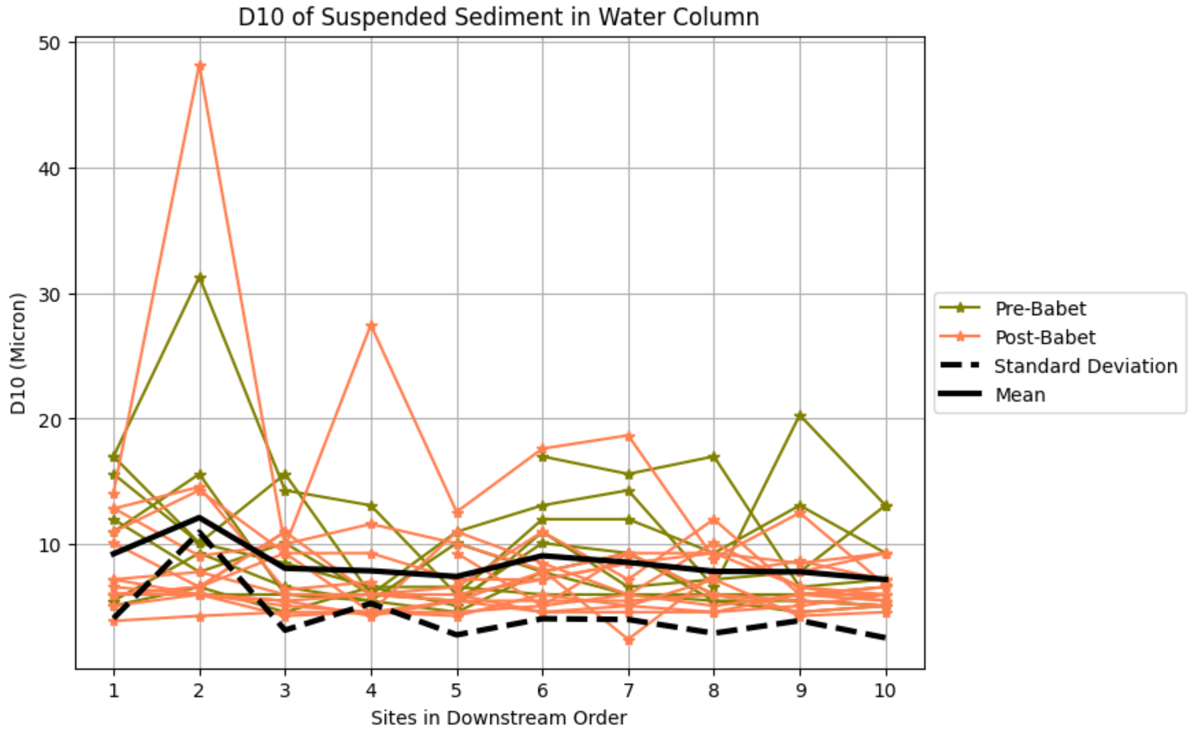


Figure 4.55 – *D10* (micron) of suspended sediment from September 2022 to November 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits. The months have been grouped by the months of sampling before (n= 9) and after (n=14) Storm Babet (18th -21st October 2023).*

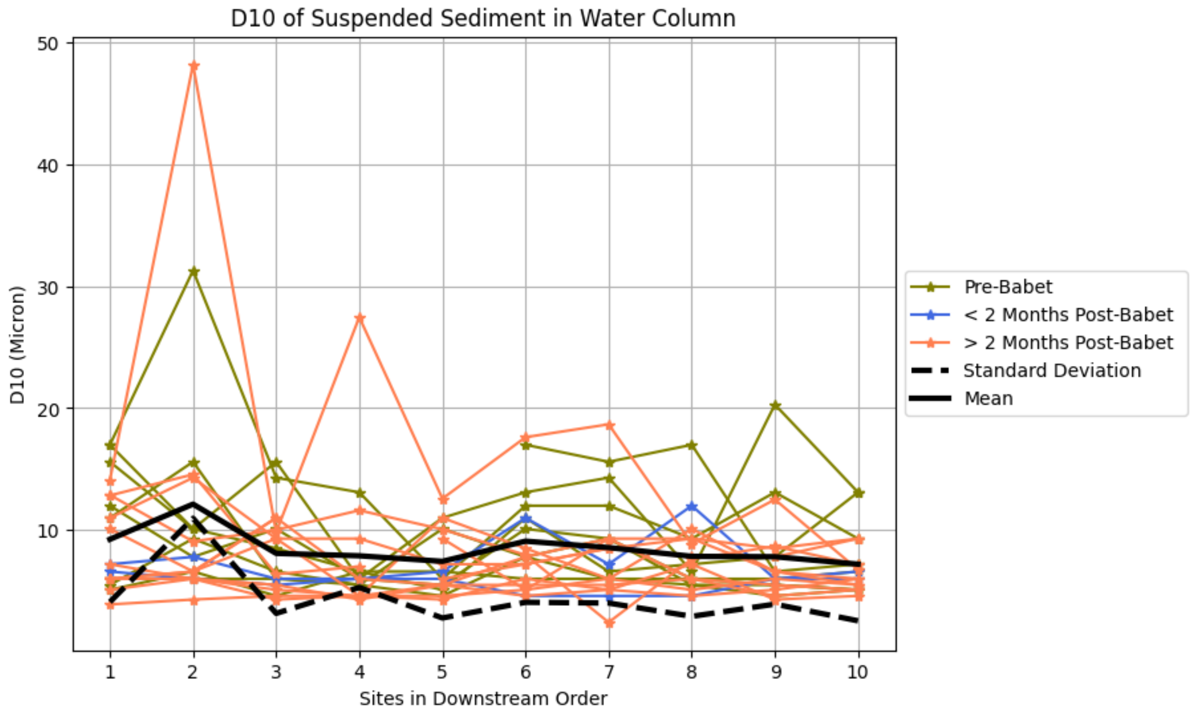


Figure 4.56 – *D10* (micron) of suspended sediment from September 2022 to November 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits. The months have been grouped by*

the months of sampling before (n= 9), less than 2 months after Storm Babet (n=2) and more than 2 months after (n=12) Storm Babet (18th -21st October 2023).

There is a weak trend of fining of the D10 of suspended sediment downstream (Figures 4.51-4.56). The most variation is at Site 2, but all samples are within the silt class (3.9 – 62.5 micron). High flows impact the D10 sediments. When the river Skell is high at Alma Weir, most samples are below the mean size. When the river is low the samples are below the mean size. The stage of the river does not support any obvious trends. The seasonality does produce some trends. There are generally larger D10 values in autumn and summer months. Winter and Spring are usually below mean. This could be due to land-use practices that cause greater entrainment of fine particulate matter (e.g. bare soil over winter, increased use of shoot tracks) during these months, or the increased rainfall causing scouring of settled material throughout the catchment. Storm Babet seems to have impacted the results, most of the months which coarser D10 samples are pre-Babet and most months post-Babet are finer.

4.3.6.2 D50

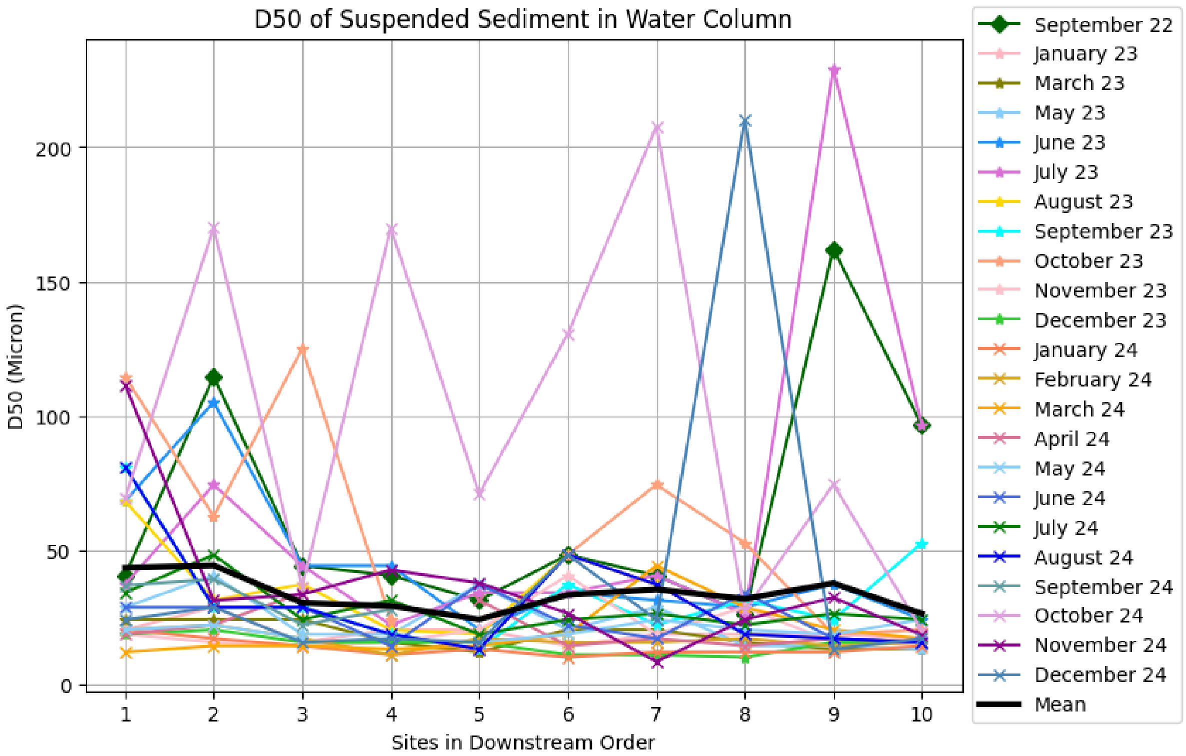


Figure 4.57 – *D50* (micron) of suspended sediment from September 2022 to November 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits.*

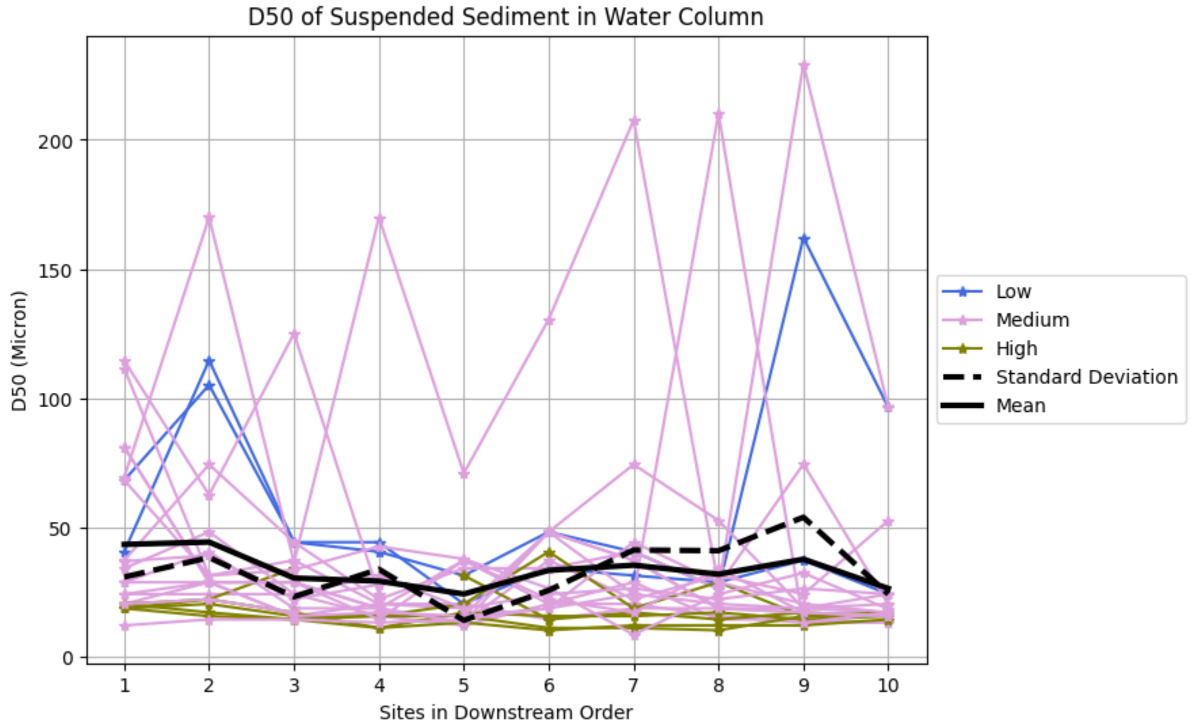


Figure 4.58 – *D50* (micron) of suspended sediment from September 2022 to November 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits. The months have been grouped by the river height at Alma Weir on the day of sampling to low (n=2), medium (n=15) and high (n=5).*

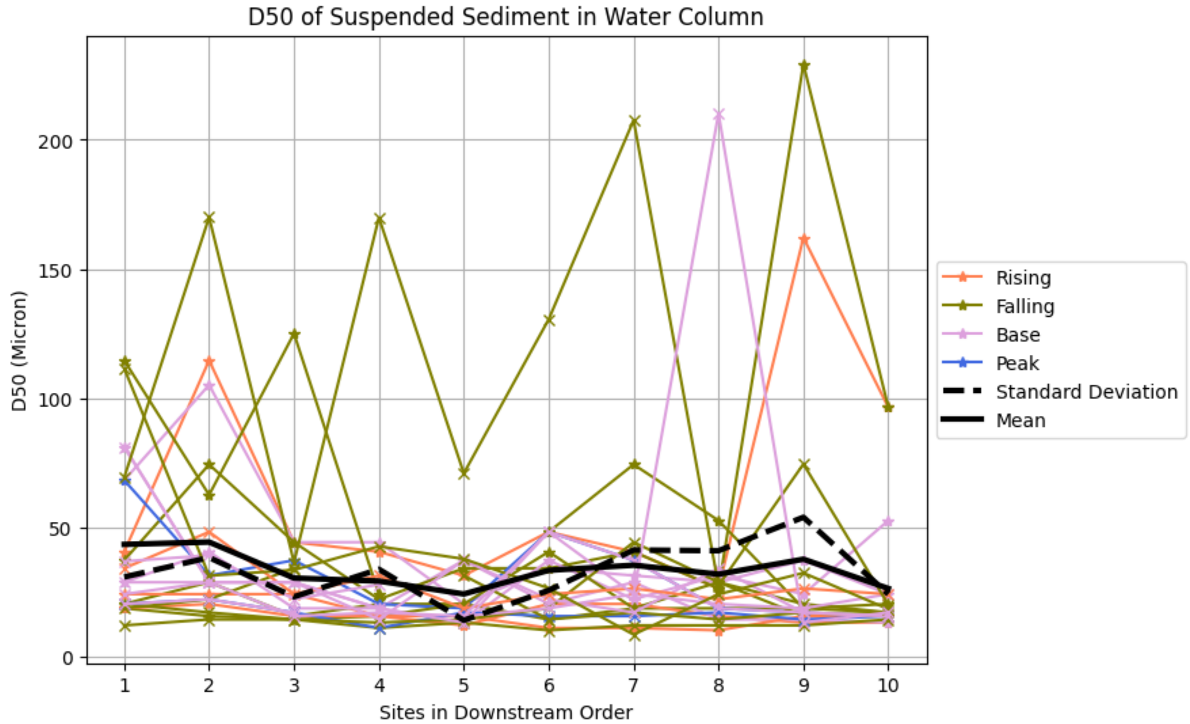


Figure 4.59 – *D50* (micron) of suspended sediment from September 2022 to November 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits. The months have been grouped by the*

river stage at Alma Weir on the day of sampling to rising (n=4), falling (n=9), peak (n=2) and base (n=8).

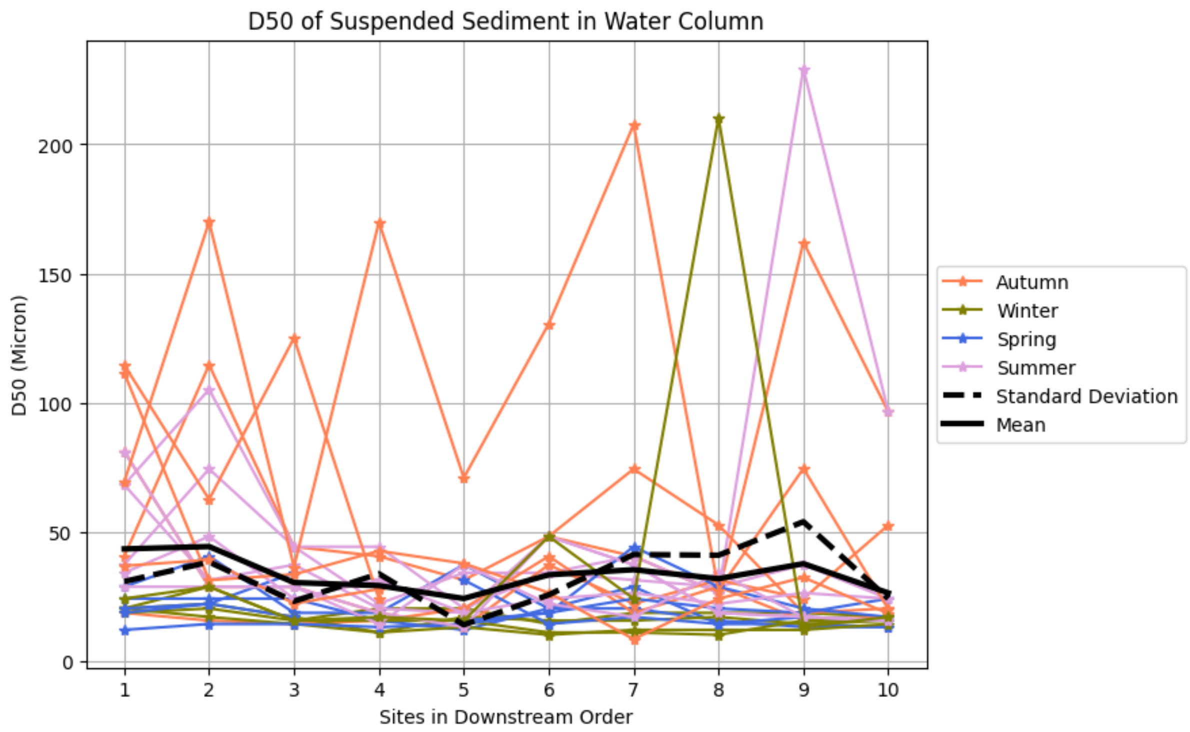


Figure 4.60 – *D50* (micron) of suspended sediment from September 2022 to November 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits. The months have been grouped by the season on the day of sampling to Autumn (n=7), Winter (n=5), Spring (n=5) and Summer (n=6).*

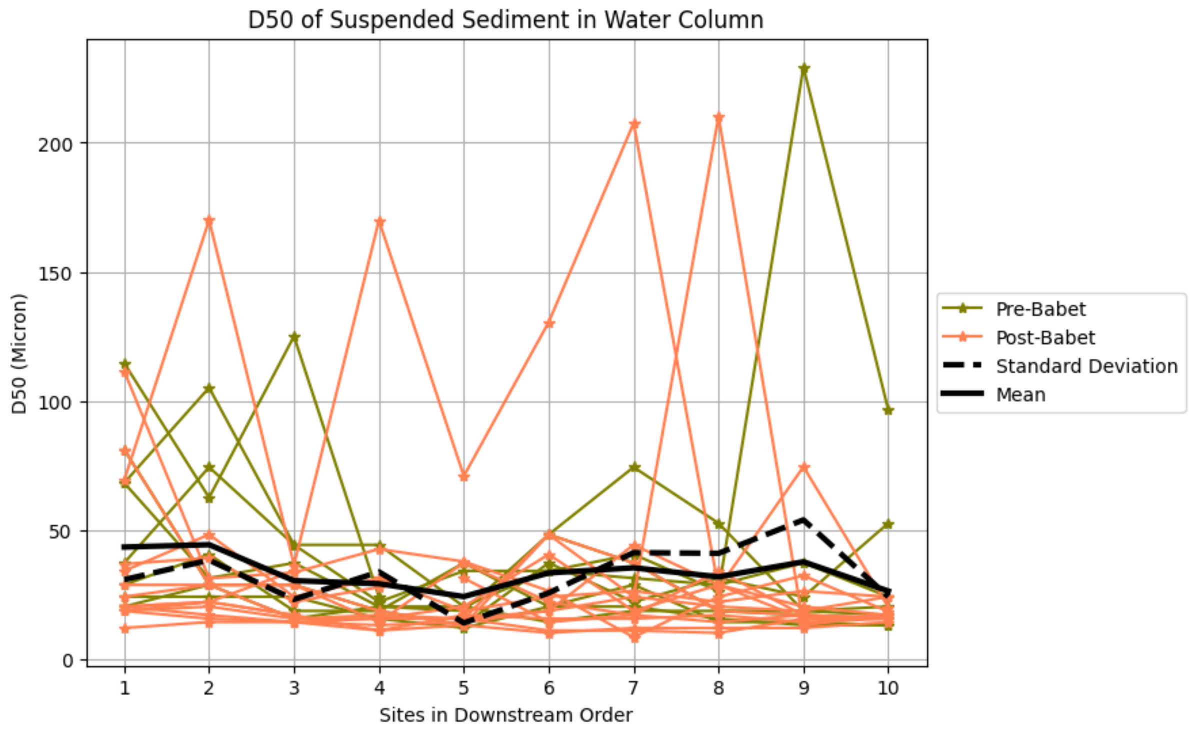


Figure 4.61 – *D50* (micron) of suspended sediment from September 2022 to November 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits. The months have been grouped by the months of sampling before (n= 9) and after (n=14) Storm Babet (18th -21st October 2023).*

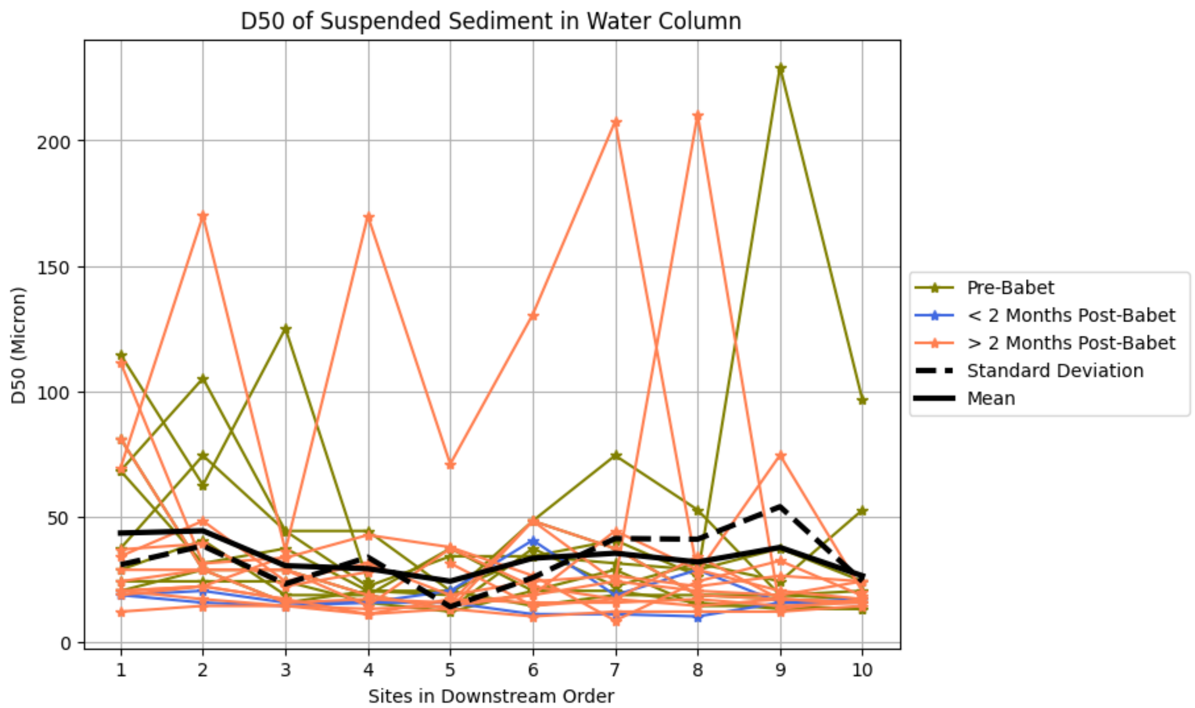


Figure 4.62 – *D50* (micron) of suspended sediment from September 2022 to November 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits. The months have been grouped by the months of sampling before (n= 9), less than 2 months after Storm Babet (n=2) and more than 2 months after (n=12) Storm Babet (18th -21st October 2023).*

The D10 value show that most of the sites are still within the silt classification (3.9 micron - 62.5 micron), however some of the higher spikes from sites 1, 2, 3 and 9 fall into the very fine (62.5micron – 125 micron) and fine (62.5micron – 250 microns) sand classification (Figures 4.57-4.62). Sites 1 and 2 are slightly coarser than downstream sites and have more spikes than the other sites. The standard deviation from the mean is highest at Site 9, this is due to most samples being below the mean and a few outliers which are much greater than the mean. The D50 mirrors the trends shown by D10, the height has the biggest influence on trends. Low flows give larger median particle sizes and high flow are finer. Seasonality also follows the same trends as D10. Spring and winter and below the mean, autumn is above the mean and has the most outliers.

4.3.6.3 D90

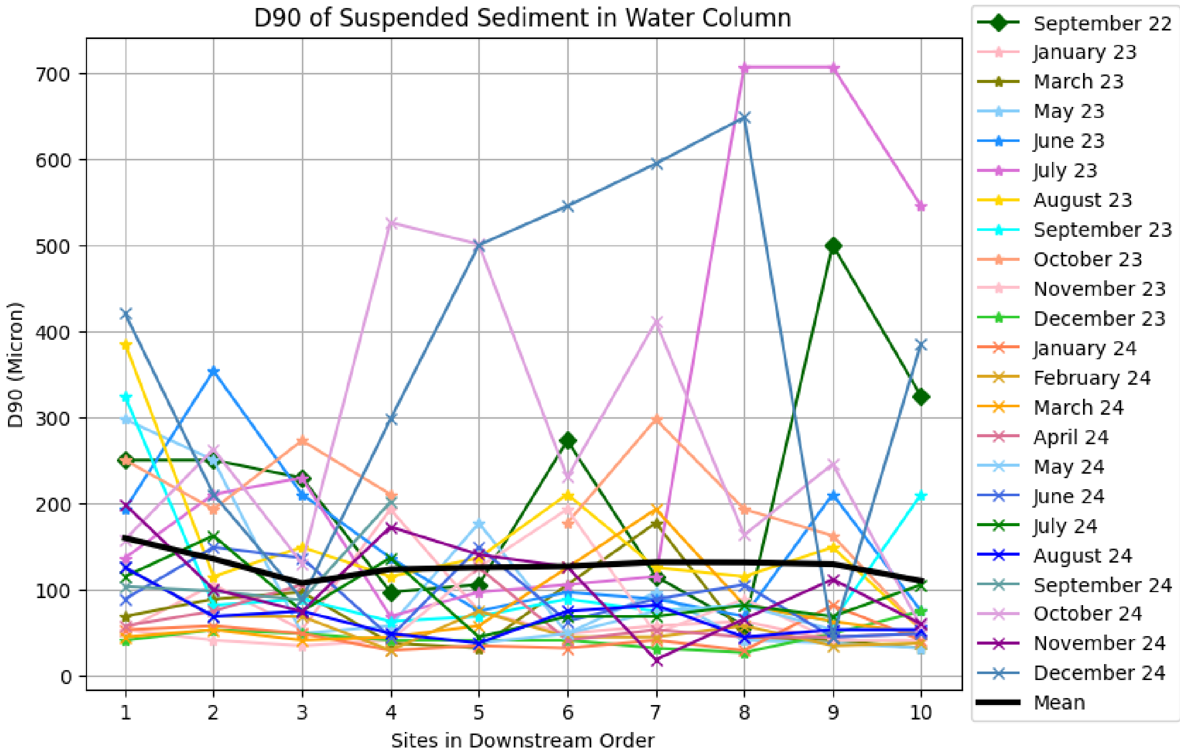


Figure 4.63 – *D90* (micron) of suspended sediment from September 2022 to November 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits.*

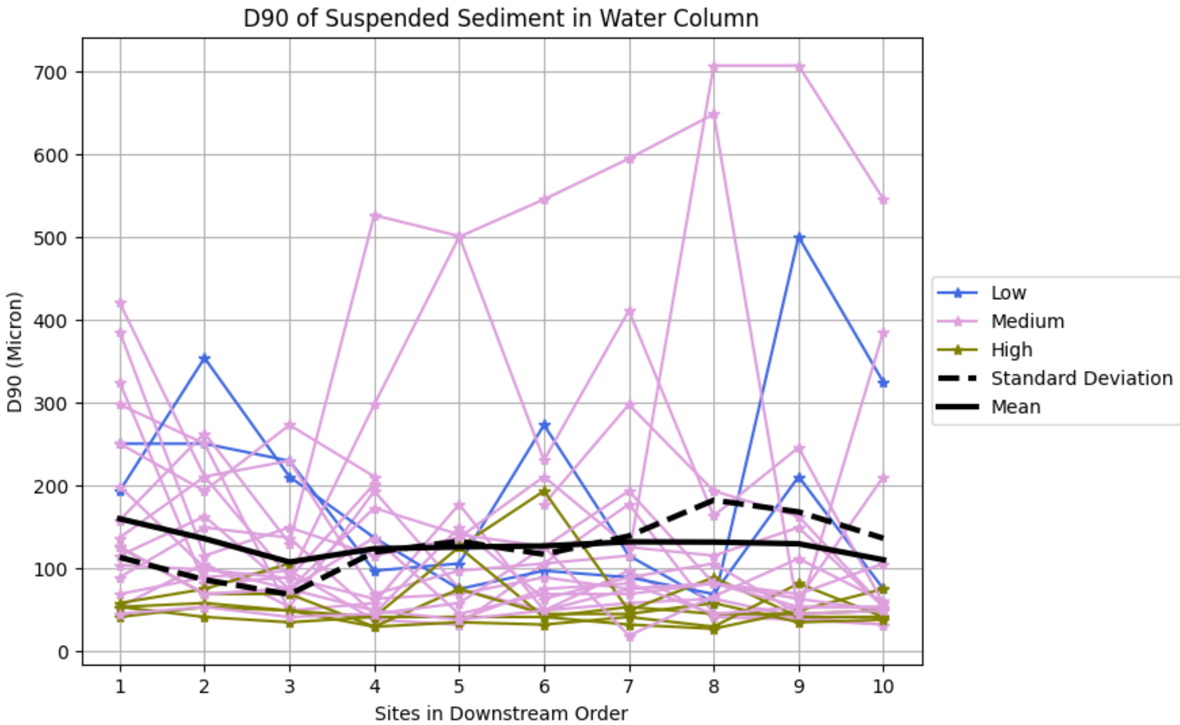


Figure 4.64 – *D90* (micron) of suspended sediment from September 2022 to November 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits. The months have been grouped by*

the river height at Alma Weir on the day of sampling to low (n=2), medium (n=15) and high (n=5).

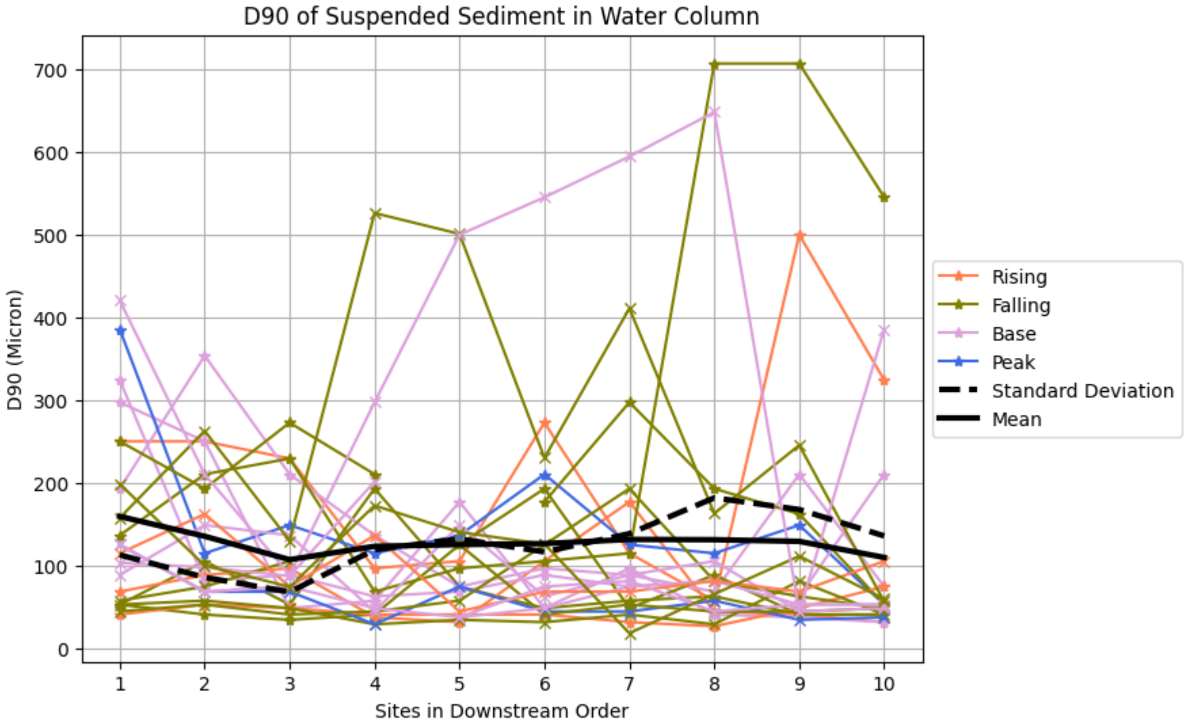


Figure 4.65 – *D90* (micron) of suspended sediment from September 2022 to November 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits. The months have been grouped by the season on the day of sampling to Autumn (n=7), Winter (n=5), Spring (n=5) and Summer (n=6). The months have been grouped by the river stage at Alma Weir on the day of sampling to rising (n=4), falling (n=9), peak (n=2) and base (n=8).*

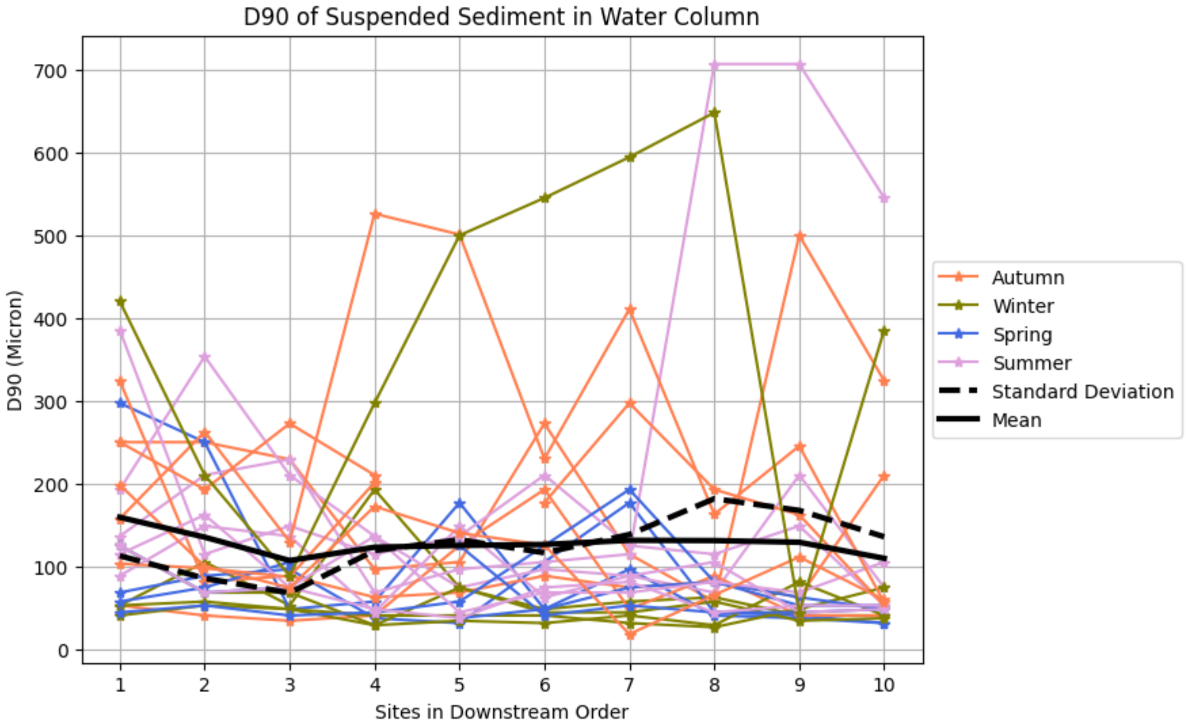


Figure 4.66 – *D90* (micron) of suspended sediment from September 2022 to November 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits. The months have been grouped by the season on the day of sampling to Autumn (n=7), Winter (n=5), Spring (n=5) and Summer (n=6).*

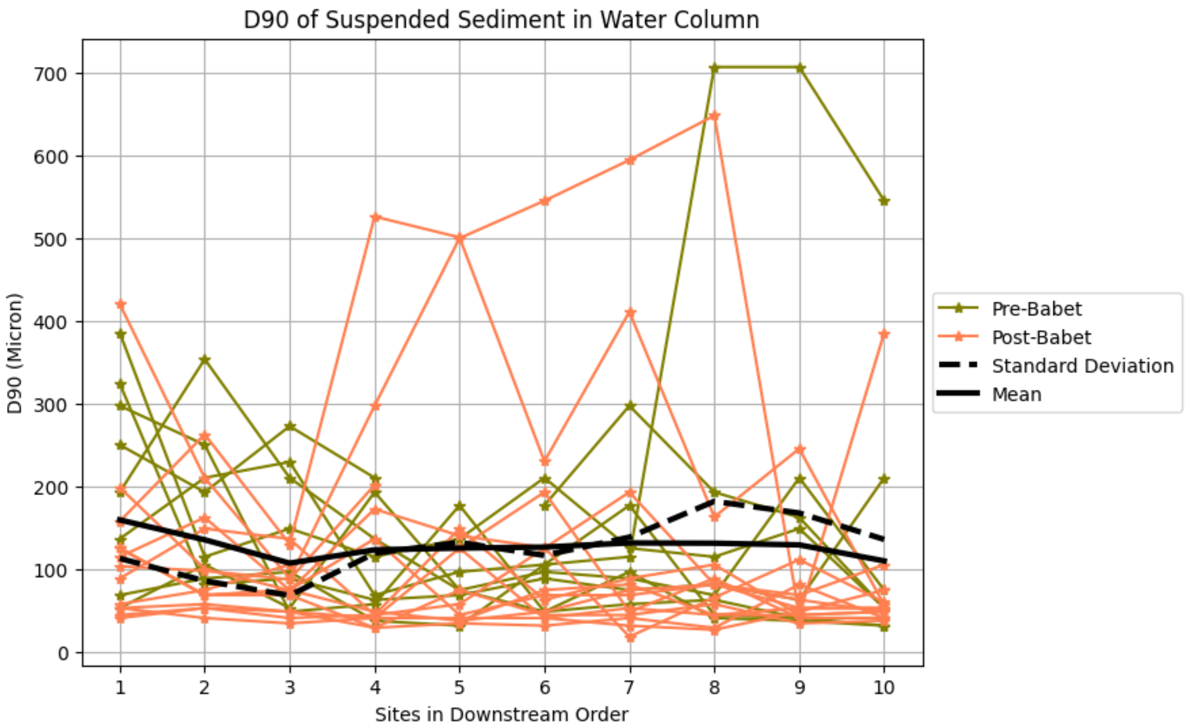


Figure 4.67 – *D90* (micron) of suspended sediment from September 2022 to November 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits. The months have been grouped by the months of sampling before (n= 9) and after (n=14) Storm Babet (18th -21st October 2023).*

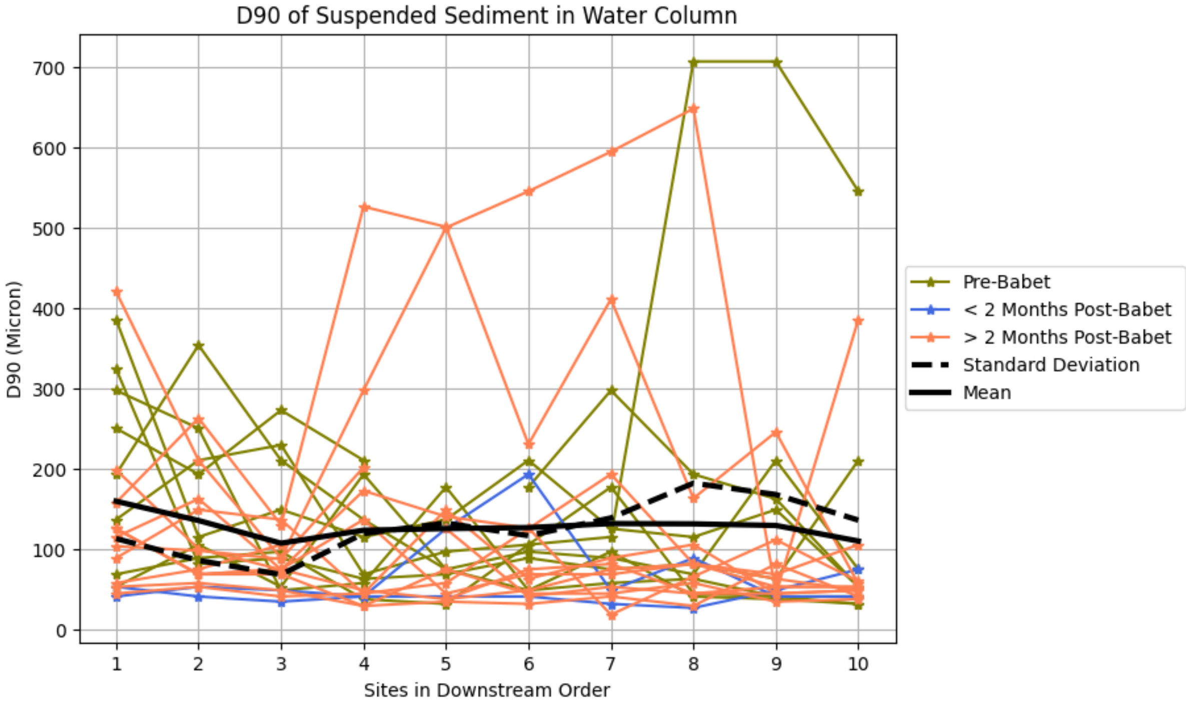


Figure 4.68 – *D90* (micron) of suspended sediment from September 2022 to November 2024 in downstream order. The standard deviation and mean have been calculated for each site to demonstrate the variation between sampling visits. The months have been grouped by the months of sampling before (n= 9), less than 2 months after Storm Babet (n=2) and more than 2 months after (n=12) Storm Babet (18th -21st October 2023).*

Figures 4.63-4.68 show that most of the sites are within the very fine sand (62.5micron – 125 micron) and fine sand (62.5micron – 250 microns) classification with some of the larger samples in the medium sand (250 micron – 500 micron) and coarse sand (500 micron – 1mm) classifications. Sites 1-4 have the most variation. Sites 4-10 have the most outliers, but most of the samples are at or below the mean. The height of the river at Alma Weir impacts the results in the same way as D10 and D50. When the river is high, most samples are less than 100 microns. When the flow is medium height, the range is the greatest. When the river is low, there are more peaks and outliers, specifically at Sites 2 and 9. The trends in D10, D50, and D90 downstream through the catchment show a weak, albeit segmented, decrease in mean values. The season has similar impacts on size – autumn is mostly above the mean and spring is mostly below the mean.

None of the coarse size samples were from the months with high flow. They were predominantly from July, September, October and December with 'normal' flow height.

4.3.7 Bedload

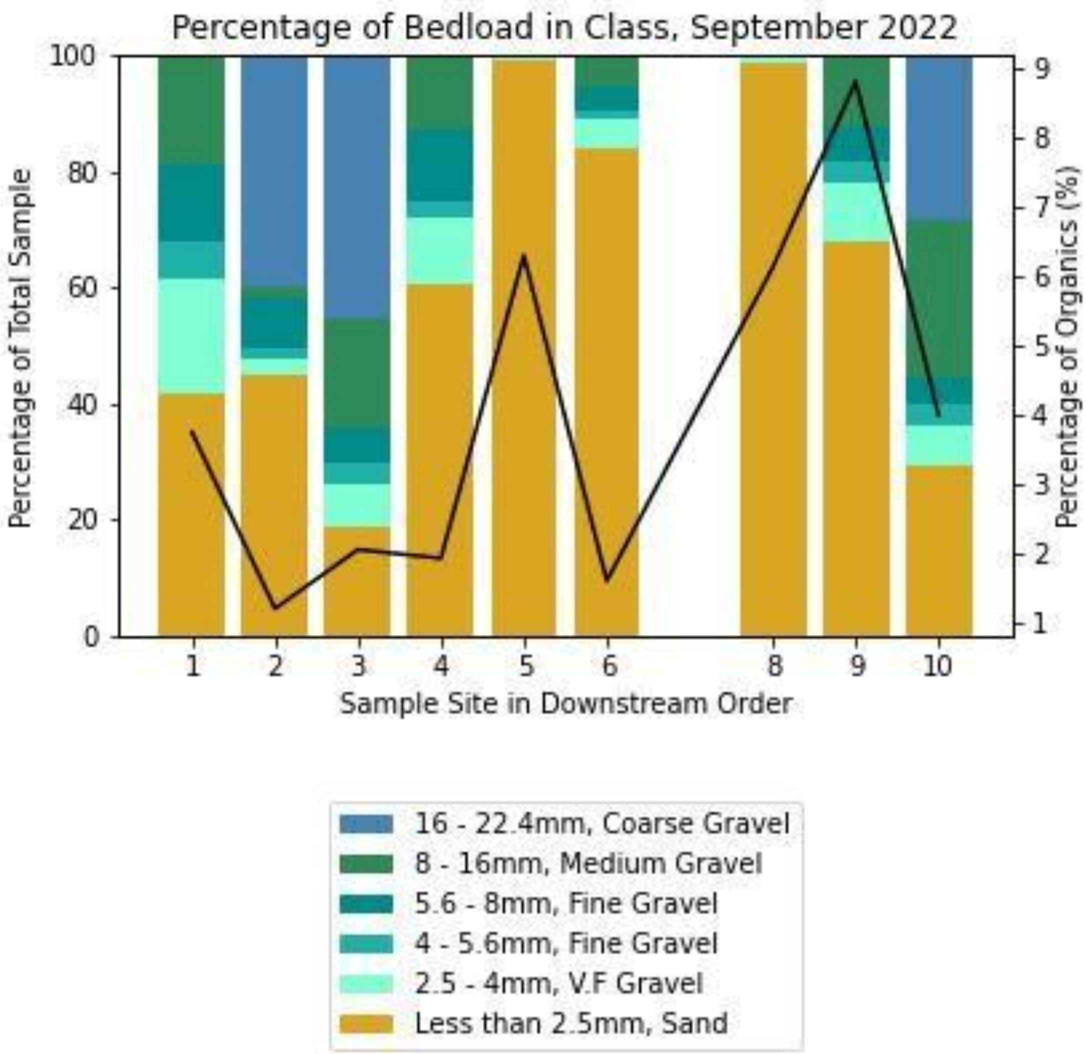


Figure 4.69 – *The percentage by mass of bedload with organics retained on each sieve (2.5, 4, 5.6, 8, 16 and 22.4mm) from the September 2022 visit in downstream order. On the second Y axis there is the percentage of organics (loss on ignition methodology) present in each sample collected in September 2022, also in downstream order.*

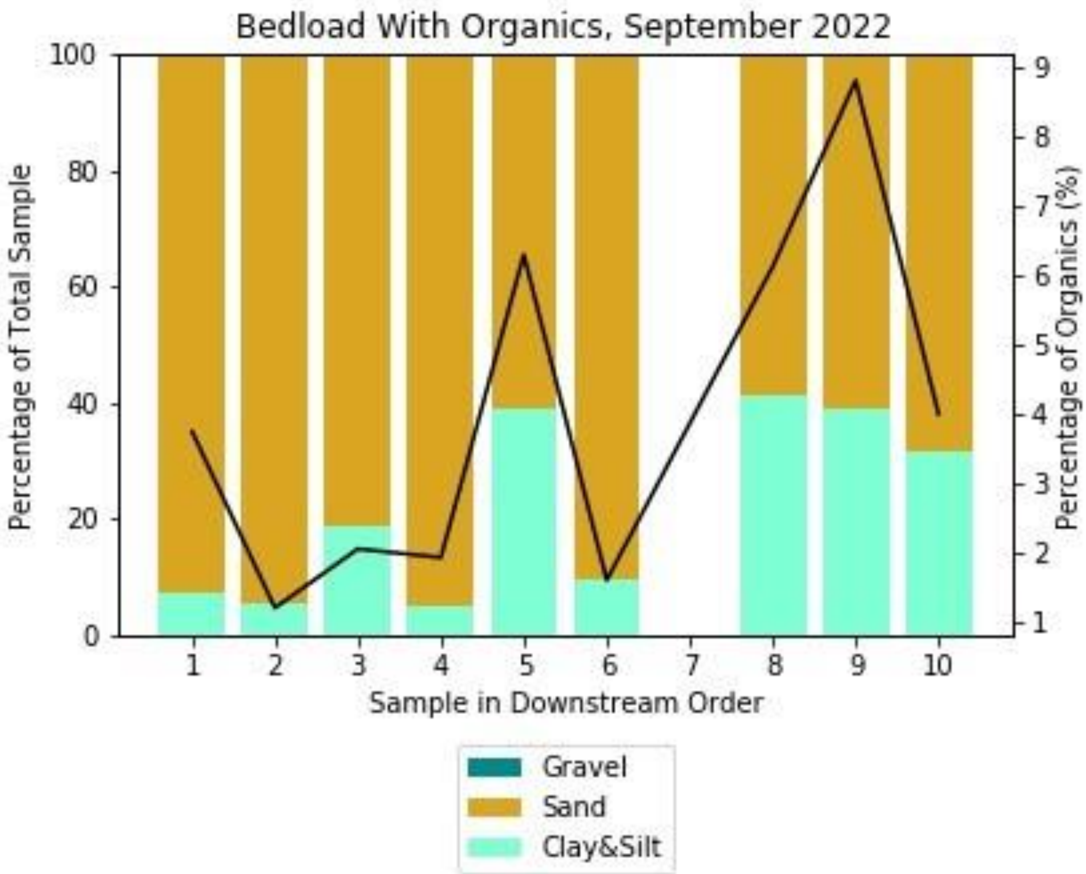


Figure 4.70 – *The percentage of the total bedload sample collected in September 2022, analysed using the Retsch Camsizer which falls into clay and silt (0.98 -3.9 micron and 3.9 – 62.5 micron respectively), sand (62.5 micron – 2mm) and gravel (2 - 4mm) classes on the Krumbian Phi scale. This is the sample prior to the removal of organics using loss on ignition technique. The line denotes the percentage of the total sample which is organic which was calculated using the loss on ignition method.*

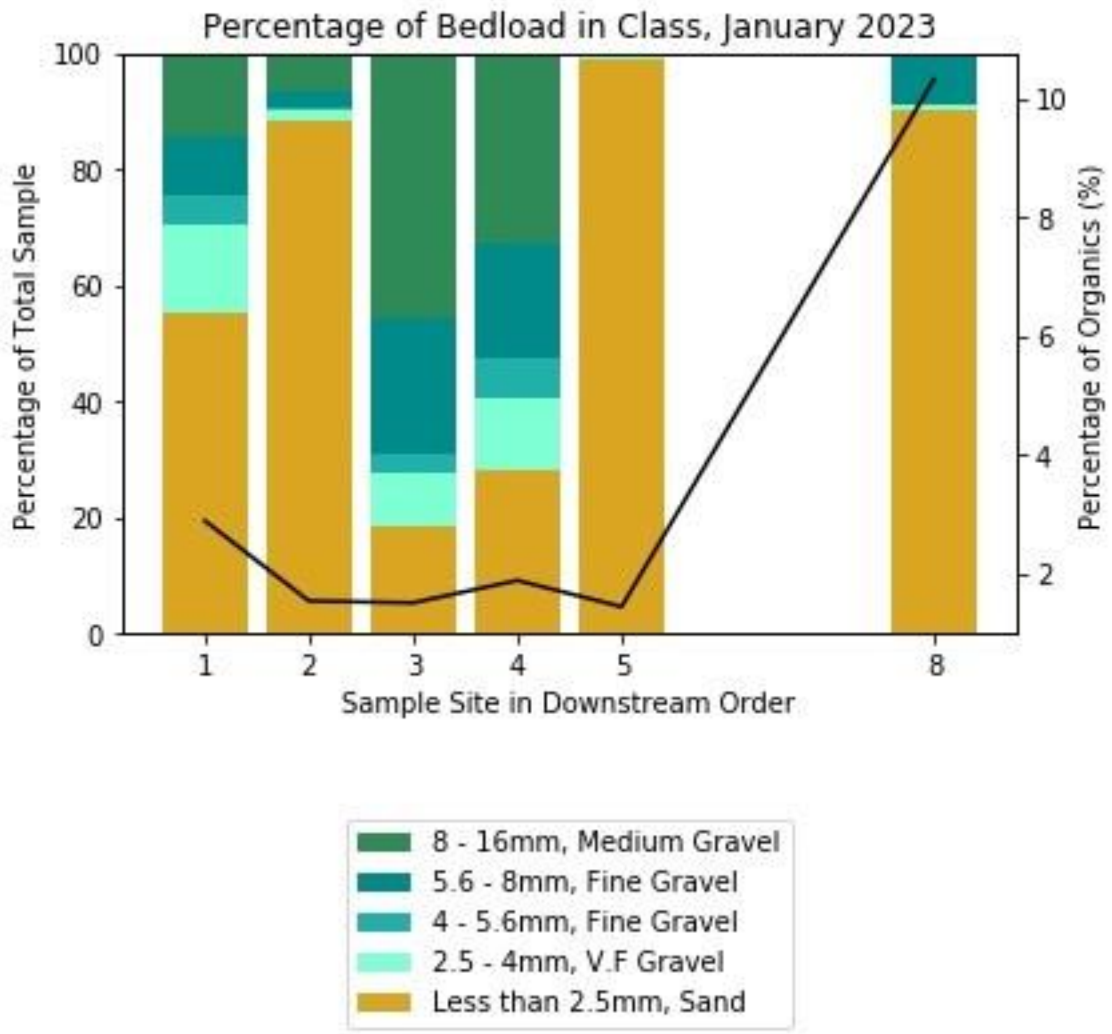


Figure 4.71 – *The percentage by mass of bedload with organics retained on each sieve (2.5, 4, 5.6, 8, 16 and 22.4mm) from the January 2023 visit in downstream order. On the second Y axis there is the percentage of organics (loss on ignition methodology) present in each sample collected in January 2023, also in downstream order.*

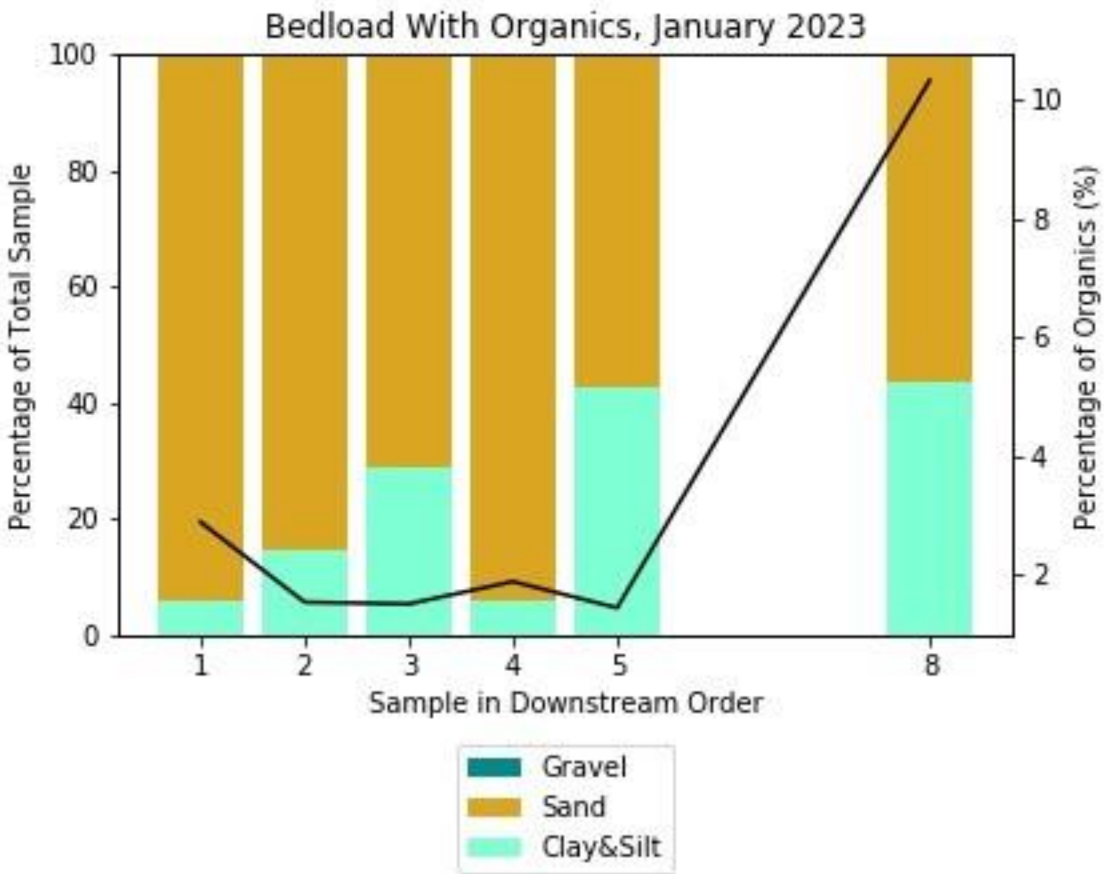


Figure 4.72 –*The percentage of the total bedload sample collected in January 2023, analysed using the Retsch Camsizer which falls into Clay & Silt (0.98 -3.9 micron and 3.9 – 62.5 micron respectively), Sand (62.5 micron – 2mm) and Gravel (2 - 4mm) classes on the Krumbian Phi scale. This is the sample prior to the removal of organics using loss on ignition technique. The line denote the percentage of the total sample which is organic which was calculated using the loss on ignition method.*

The bedload samples collected in September 2022 and January 2023 follow a similar pattern to those found in the volunteer sampling (Figures 4.69-4.72). In September 2022, the Skell at Alma weir was at a low level (height=0.12m) but was rising. The bedload collected had high levels of fine material (Clay (0.98 -3.9 micron) and Silt (3.9 – 62.5 micron) at Sites 5 and 9. At Sites 1-4, the higher proportion of sand present in the bedload coincides with large variation in the D90 of the suspended sediment. Similarly, Site 9 has high percentage of organic material as well as a combination of a low mean in the D90 with numerous outliers.

This suggests that the fine sediment that had previously settled in the ponds on the Grantley Hall and Fountains Abbey estates was being resuspended. These sites also had much higher levels of organic material present in their samples, which suggests this material is a mixture of soil (usually 3-6% organic matter) and organic matter from other anthropogenic sources, such as wastewater treatment plants. In January 2023, the river level was medium (height=0.27m) and was falling after a high flow event. The highest percentage of organic material was found at site 8, and sites 5 and 8 both had bedload with high levels of fine material (Clay (0.98 -3.9 micron) and Silt (3.9 – 62.5 micron). Sites 3 and 4 had much coarser bedload, over 70% of the sample was greater than 2.5mm. It is likely that this is due to most of the finer bedload being flushed from the system during the high flow event and only being present at site 8 as it is in Half Moon Lake.

5 Analysis

5.1 Volunteer samples

To investigate relationships between the different measures from the volunteer sampling programme, simple correlation tests were performed.

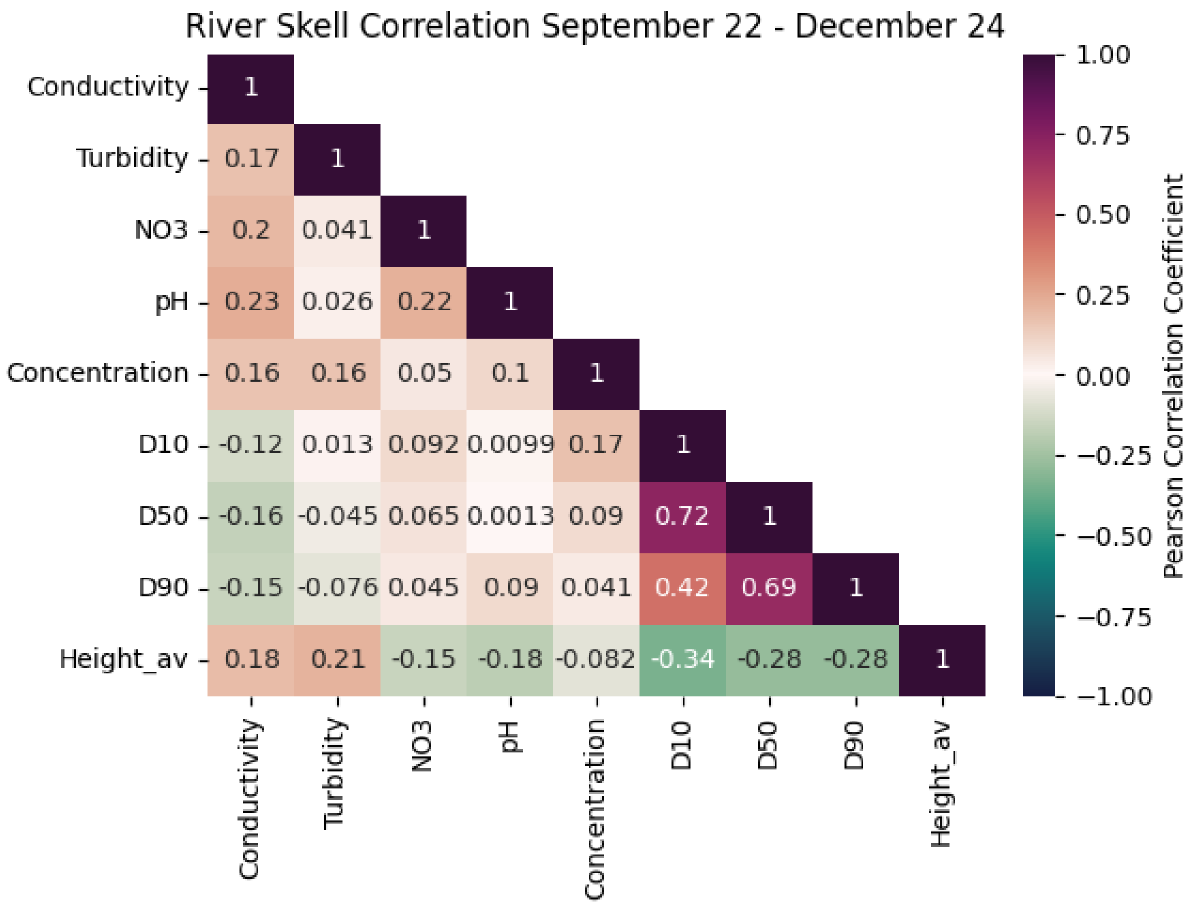


Figure 5.1 – *Pearson correlation coefficients for the unfiltered results of each analysis undertaken for the volunteer samples, plus the average height at Alma Weir over the day(s) the samples were taken. A correlation coefficient of less than 0.05 is deemed to show a statistically insignificant similarity between the variables. A correlation coefficient of 0.4-0.8 is deemed to show moderate correlation between the variables.*

When all the data are analysed using a Pearson correlation test only the grain size variables have moderate correlation (Fig 5.1). As with the results from the volunteer samples, when the results are filtered to only include the samples which are taken when Alma Weir was either low, medium or high, correlation between the variables can be found.

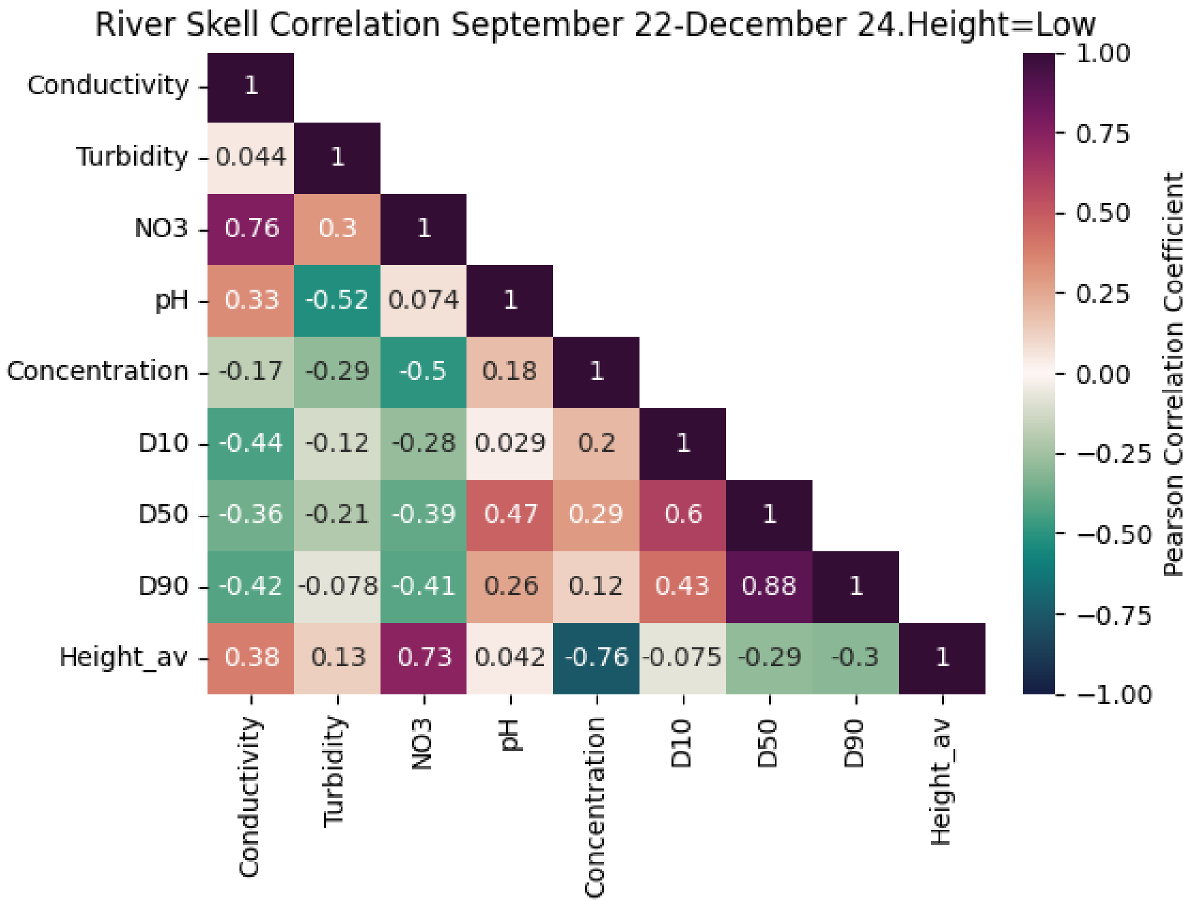


Figure 5.2 – *Pearson correlation coefficients for the results of each analysis undertaken for the volunteer samples, plus the average height at Alma Weir over the day(s) the samples were taken. These data were filtered to only include the results collected when Alma Weir was low. A correlation coefficient of less than 0.05 is deemed to show a statistically insignificant similarity between the variables. A correlation coefficient of 0.4-0.8 is deemed to show moderate correlation between the variables.*

When the data are filtered to only include the results when the river is low there is stronger correlation between variables than the unfiltered data (Fig 5.2). In addition to the correlation between the D10/50/90, there is positive correlation between nitrate concentration and conductivity, nitrate concentration and the height of the river pH and D50 (median) particle size of the suspended sediment. There is negative correlation between conductivity and D10, conductivity and D90, pH and turbidity, nitrate concentration and concentration of dry solids, and nitrate concentration and D90.

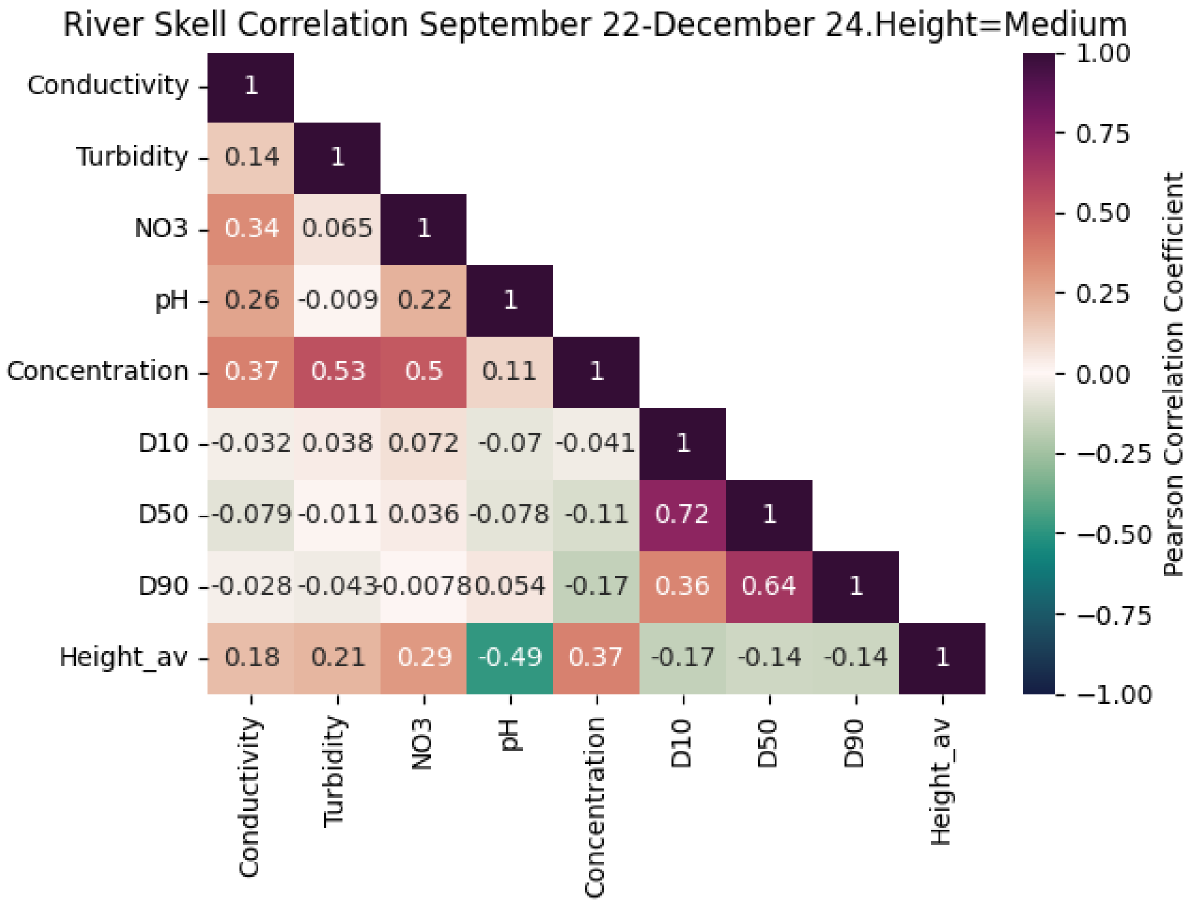


Figure 5.3 – *Pearson correlation coefficients for the results of each analysis undertaken for the volunteer samples, plus the average height at Alma Weir over the day(s) the samples were taken. These data were filtered to only include the results collected when Alma Weir was medium. A correlation coefficient of less than 0.05 is deemed to show a statistically insignificant similarity between the variables. A correlation coefficient of 0.4-0.8 is deemed to show moderate correlation between the variables.*

When the river height at Alma Weir is medium there are fewer variables which have significant correlations than when the river is low (Fig 5.3). There is a positive correlation between the concentration of dry solids and turbidity, and the concentration of dry solids and the concentration of nitrates. This is in addition to the correlation between the particle size results. There is a negative correlation between the pH and the height at Alma Weir on the day of sampling.

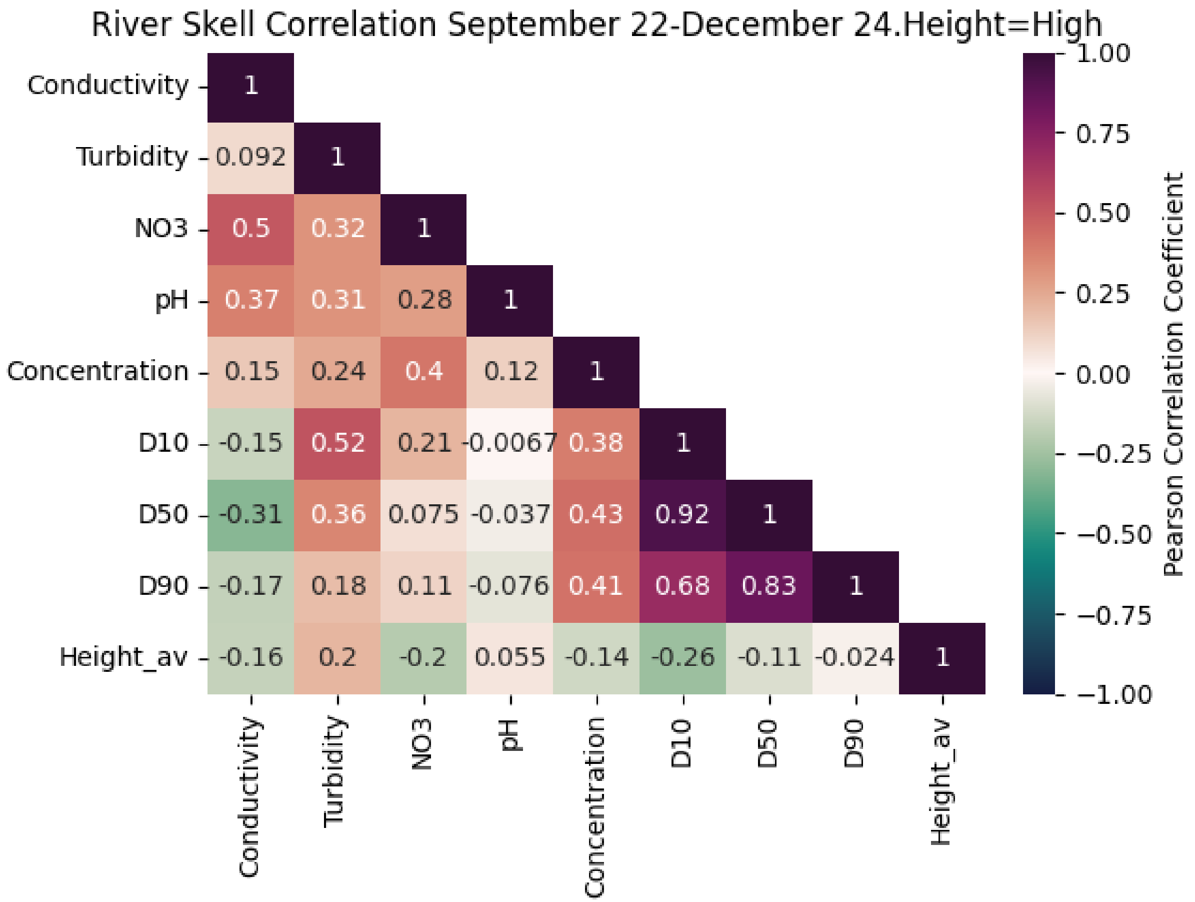


Figure 5.4 – *Pearson correlation coefficients for the results of each analysis undertaken for the volunteer samples, plus the average height at Alma Weir over the day(s) the samples were taken. These data were filtered to only include the results collected when Alma Weir was high. A correlation coefficient of less than 0.05 is deemed to show a statistically insignificant similarity between the variables. A correlation coefficient of 0.4-0.8 is deemed to show moderate correlation between the variables.*

There is a positive correlation between the concentration of nitrates and conductivity, D10 and turbidity, concentration of dry solids and concentration of nitrates, D50 and concentration of dry solids and D90 and concentration of dry solids (Fig 5.4). This is in addition to the correlation between the particle size results.

Figure 5.5 –*Pair plots of the unfiltered results of each analysis undertaken for the volunteer samples. The colours denote the height of Alma Weir on days of sampling and have been split into low (n=2), medium (n=15) and high (n=5). The diagonal plot is a distribution plot of each variable where the x axis is the extent (e.g. size in Micron for D10) and the y axis is the percentage of the total sample that falls into that size, the colours also denote the river height at Alma Weir on days of sampling (blue=low, orange=medium and green=high).*

The diagonal distribution plots highlight how influential the stage height is on the results for most variables (Fig 5.5). For most variables there seems to be a threshold where most results are within a fine range with a few outliers where flow conditions allow.

6 Key Learnings/Outcomes

6.1 Are there persistent downstream changes in water quality?

Nitrate concentration, pH and conductivity increase downstream across all seasons, flow conditions and stages. The increase in Nitrate is likely due to the runoff from farming land as the river moves through the catchment. The increase in pH is due to the acidic moorland water being diluted by runoff, which is more alkaline. The increase in conductivity is likely due to a combination of salt grit run off from roads during winter, and from farmland during the spring and autumn fertilisation periods.

6.2 What are the water quality issues in the catchment?

Conductivity is generally very high across the catchment and even the mean values cross the EU safe drinking water limit at Site 10. There is a high Nitrate concentration too, this likely is due to the land use throughout the catchment – the mixture of arable and livestock farming in the catchment produces large amounts of Nitrates and can increase the conductivity of the water. Additionally, conductivity can increase in winter months when road grit is washed into the river. Conductivity can also be influenced by the geology of the area. There is an exhumed band of Cayton Gill Shell Bed upstream of site 4, which could be the cause of the rapid increase in conductivity at this location.

6.3 What evidence is there that the Skell is flashy?

The Skell is a flashy catchment, with short response times between rainfall events and increase in river level and sediment load. The increase in high flow peaks shown in the river level data without concurrent increase in peaks in rainfall data suggest that the river Skell is flashy and becoming flashier. Both the intensity and frequency of large flow events are increasing in the River Skell since 2012. There is no evidence of increases in large rainfall event frequency and only limited evidence of rainfall intensity increasing. The observed increase in the flashiness of the river Skell is attributed to changes in land use throughout the catchment that have led to reductions in infiltration and storage capacity, and increase in overland flow, and other external drivers which have increased the amount of water draining into the river. Therefore, the installation of NFM interventions is timely.

6.4 Is there a simple flood wave after high precipitation events?

The catchment upstream of Fountains Abbey site mostly has linear flood wave progression during high flow events. The turbidity, both in the volunteer sampling and the in-river monitoring, scales with discharge. There is some evidence that there is a threshold in river height below which there is minimal sediment transport and above which there are large scale transport events. This threshold will be impacted by flow, intensity, historical (e.g. preceding rain/drought conditions in the catchment) and season (e.g. availability of bare soil to entrain into overland flow during winter). This complexity is the result of land use and other external factors. By undertaking long term monitoring, a closer link between preceding conditions, rainfall intensity, and flood response could be constrained.

6.5 Which parameters are spatially and temporally complex?

The concentration of dried solids taken from the volunteer river sampling is particularly complex and would require addition sampling and analysis to resolve. Conductivity, turbidity, and the particle size of the suspended sediment are all stage dependant and display considerable hysteresis. To fully quantify a system that has these complex characteristics would require sampling at a higher frequency and across different river stages (with associated H&S considerations). This is due to the large number of possible inputs of suspended sediment into the river, which all have different thresholds and transport mechanisms. Additionally, the lack of long-term baseline of these parameters before NFM were installed makes it difficult to identify where there are spatial and temporal trends and where there are acute issues, such as sampling errors. It has been generally accepted that establishing a baseline in a catchment is recommended prior to installation of NFM and NBS interventions to compare, and ideally quantify, the benefits to river level (lowering flood peaks) and sedimentation (reduced particulate load). Although monitoring overlapped with the installation of NFM in parts of the catchment there was a phase of monitoring aimed at establishing baseline conditions. However, it became apparent that baseline conditions in a complex and flashy catchment like the Skell are a chimera, and that a more tangible aspiration is to characterise the dynamics, and responses, of a catchment over a sufficient time series to help assess the differences that NFM/NBS approaches might have.

6.6 Does NFM/NBS make a difference?

The Skell Valley is a heterogeneous catchment with complex interlinked parameters. The timescale of this project has established a time series over an unusually long period but has been revealed to be too short to establish and quantify the impact of the NFM/NBS. Most of the NFM in the Skell Valley, especially trees and hedgerows, are not mature enough to provide NFM benefits. On an intervention scale, it has been possible to show positive impacts (see Payment by Results report). However, understanding these benefits on a catchment scale will require a longer period of monitoring. This will help understanding of the role of pre-cursor events and seasonal land use change, and the natural variability in annual weather patterns.

Even when mature, the NFM/NBS will not prevent flooding in the Skell Valley. However, a longer-term monitoring will be able to use similar weather patterns from previous data to demonstrate how the interventions can both reduce and extend the flood peak, and therefore reduce the associated damage to the heritage landscape.

The overland flow and sediment erosion risk maps for the catchment scale monitoring were not ground truthed. When this step was undertaken at a farm scale with the land holder (see Payment by Results report) it was invaluable and ensured that NFM were placed in the most effective possible location. As the models do not include field drains, small springs or elevation under 5m, it can misappropriate flood and erosion risk, resulting in a less effective NFM type being chosen or location used. For example, leaky woody dams are better suited to tributaries rather than main channel locations with steep sided banks.

6.7 What are the main sediment sources?

The peaks in D90 at Sites 1 and 2, and the presence of large amounts of sandy sediment at Site 2 (enough to disrupt the turbidity sensor at this location), point to a source of relatively coarse mobile sediment above Site 2. The D90 data also highlights the presence of coarser sediment at the locations within the Fountains Site. The analysis of the cores retrieved from Half-Moon Lake, and a visual survey of the lake margin showed the presence of large amounts of sand grade sediment. This is likely sourced from the southern margin of Half-Moon Lake. Some of this sediment likely comes from the tributary associated with Garland Bridge. The D10 data has a seasonal signal where sediment is finer during the winter and coarser during the summer, and has been predominantly finer subsequent to Storm Babet in October 2023. The analysis of the cores taken from Half Moon Lake suggests that there is a substantial input of stripped bark and woody debris in the system, which may be from the Fountains site or further upstream. The large number of field drains, weirs, pools and lakes along with river make it difficult to identify the source of the fine scale sediment without employing costly sediment finger printing techniques. It is likely there are several sources throughout the upstream catchment and Fountains Abbey site.

6.8 What makes a good monitoring strategy?

A good monitoring strategy needs to balance up front cost of equipment with on-going cost of maintenance, site visits to download data, data storage, and data analysis by experts. In river, high frequency time series instruments are invaluable for identifying trends. These instruments also allow for continual monitoring, and as such can monitor high flow events without endangering staff, unlike the volunteer sampling protocol. The downside is that their deployment creates large data files over the course of a project and require expertise to install, set up and process the data collected. Nonetheless, we found that pairing river level and turbidity sensors were an ideal way to monitor responses to precipitation, and that multiple pairs can help to track flood waves. Volunteer sampling proved to be a great way to obtain a lot of information about a catchment during ‘normal’ flow conditions. An added benefit is that volunteer sampling helps to engage the local community with the wider aims of the project. The wide range of parameters tested each month allowed for a catchment wide picture which would have been prohibitively expensive to have replicated with in-river probes. These data helped to inform the optimum location of in-river monitoring probes, identifying areas of interest and possible sources of sediment.

7 Recommended next steps

7.1 Continuation of Monitoring

The continuation of in-river monitoring would allow for a longer record to be established and would allow for current and future impact of NFM installations to be identified. This monitoring would comprise of a telemetry enabled level sensor at Site 5 and ideally another one at Site 1 or Site 2, using a relay to overcome the lack of mobile phone signal. A sonde located at Site 5 would give turbidity, conductivity, pH, nitrate and phosphate timeseries data. Employing both monitoring devices would reduce the onsite maintenance required as data would either stream directly to a website or could be downloaded without having to remove the device from the river. University of Leeds staff would continue to process and present the data on a biannual basis. The deployment of a series of level sensors shows that such analysis is possible and that a level sensor deployed high in the catchment with an integrated modem that automatically uploads data to the cloud could provide ~ 90 minutes of warning before a flood peak arrives at the Fountains Site. The river Skell has significant potential for a trial of flood nowcasting.

Installation of a sediment trap in Garland Bridge would quantify the input of sediment during high flow events. Another option for Garland Bridge would be the installation of Dales Land Net probe, set up to monitor water depth. This would provide a very low maintenance option (£500 for probe, £60 per year for data charges). This probe will log flow depth and automatically upload all the data to a website.

7.2 Coring of Half Moon Lake

By conducting a more thorough coring of Half Moon Lake, with possible sediment finger printing approaches, a firmer link between lake sedimentation and its primary source could be identified.

7.3 GPR in lake

By conducting repeat GPR (Ground Penetrating Radar) surveys of Studley Lake the changing volume of sediment within the lake could be calculated. This an approach could enable quantification of changes in sedimentation and the impacts of the NFM. It would also identify whether any of the other inputs into Studley Lake are sources of sediment, such as Nelsons Walk.

8 References

MAURICE, L.D., COOPER, A.H., FARRANT, A.R., MATHEWSON, E., AND MURPHY, P.J., 2024. BGS Karst Report Series: P2. Karst in the southern outcrop of Permian limestones (and associated gypsum). British Geological Survey Open Report, OR/23/057. 124pp.

9 Appendix 1: Methodology

9.1 Laboratory Methodology

Ten sample sites were identified based on a combination of location relative to NFM and accessibility. The same procedure was undertaken at each field site, except for sample sites 2, 3, 4 and 6 where sampling was undertaken from bridges, and a window of the chapel room, rather than the riverbank.

At each site one 250ml sample was obtained: i) to assess the total suspended solids; ii) to assess the suspended particle size; and iii) to assess the nutrient/chemical composition. The person collecting the samples used a bottle float to take a sample of river water from the middle of the river.

In addition to the three river water samples, we obtained bedload samples from sites with appropriate access in September 2022 and January 2023. These samples were taken using a scoop/scoop on wooden pole, depending on accessibility, and placed into a 150ml plastic beaker. Photographs of the upstream and downstream of each sample site were taken and any differences from the month before noted.

The sampling strategy at each site consisted of:

1. Bottle float with 150ml polyethylene bottle was thrown into the centre of the river. Once there were no more bubbles at the surface of the water that indicates the bottle is full and could be brought back to the bank/bridge.
2. This bottle was then decanted into the correct bottle for that sample site.

In low flow months a drill pump was used to avoid disturbing the bedload during sampling. The methodology was the same as the bottle float, except the weighted end of the tube for the pump sampler was lowered into the river and the sample collected by running the drill pump.
All the sampling equipment was sterilised using Distel high level disinfectant before and after each sampling visit to maintain biosecurity. All the water and sediment samples will be disposed of using the University of Leeds 'Offensive' waste disposal procedures, this is an incineration process. All containers are all washed, sterilised, and then reused.

9.2 Laboratory Methodology

All sample analysis was undertaken at the Sediment, Soil and Pollutants Analysis Laboratory (SSPAL) within the School of Earth and Environment, University of Leeds. Three samples were obtained from each field location, a total suspended solids sample, a suspended particle size sample and a bed sediment sample.

9.3 Total suspended solids

Before each concentration sample was placed into the sample pot, each empty pot was weighed using an Ohaus Pioneer precision balance to a precision of 0.001g. Each total suspended solids sample (nominally 50ml) was weighed within the sample container. The concentration samples were then placed in a Genlab E3 drying oven and left for 72 hours at 48°C, the samples were then weighed once dry. The samples were then returned to the oven for a further 24 hours and weighed again. The samples were considered dry if the weight between the two measurements varied by less than 0.001g. The percentage total suspended solid content of each sample was calculated using equation 1.

$$Percentage\ total\ suspended\ solids = \frac{Wet\ Weight\ (g) - Empty\ Container\ (g)}{Dry\ Weight\ (g) - Empty\ Container\ (g)}\ x100$$

Equation 2.1

9.4 Suspended particle size samples

The particle size of the suspended solids was determined using a using a Retsch CamSizer XT image sizer configured with the x-flow module. The Retsch CamSizer is an automated camera system takes a continuous stream of images of the falling particles. The pump speed is optimised by the system software to minimise any potential particle overlap. The CamSizer calculates the particle diameter using an automatic image sizing routine that identifies each particle and calculates the particle diameter. The software also records a series of shape parameters, such as sphericity and elongation ratio. The CamSizer uses a pair of cameras, one wide field and one zoom that allows it to identify particles between 1-5000 µm. The cell is flushed between samples to avoid cross contamination.

9.5 Bedload

The particle size of the suspended solids was determined using a using a Retsch CamSizer XT image sizer configured with the x-fall module. The chute vibration intensity is optimised by the system software to minimise any potential particle overlap.
The feeder chute was filled with a sample and each sample was measured until the entire sample had been measured. This was around 15 minutes or 50 million particles counted. At the end of the measurement the feeder chute was cleaned using compressed air to remove any of the previous sample.

9.6 Chemical and nutrient samples

Four types of chemical and nutrient analysis were undertaken for each sample; NO3, pH, turbidity and conductivity. These analyses were completed as soon as possible after collection to mitigate any degradation of nutrients.

9.7 Nitrates analysis

A record of dissolved Nitrates was included in the analysis because it is a good indicator of water quality. Elevated levels of dissolved Nitrates can impact the ecological balance of a watercourse and frequently come from fertiliser run-off, increases in winter-sown cereals, conversion of grassland to arable production, installation of under-drainage to agricultural soils and leakage from septic tanks (Kay et al, 2012). Elevated levels of Nitrates tend to also increase the conductivity of the water column, cause agglomeration of fine sediment and in turn a decrease in concentration and turbidity as these larger agglomerations of particles fall out of suspension (Howden et al, 2011). 70-80% of Nitrate in English rivers comes from agricultural sources (Ferrier et al., 2001; Defra, 2004; Neal et al., 2006).

The nitrates analysis was completed using a Horiba L'Aquatwin compact water quality meter (LAQUAtwin-no3-11) which had been calibrated for a measurement range of 6 – 9900ppm before use. Each sample pot was agitated to ensure the subsample was homogeneous and a 2mL aliquot was removed using a pipette. The subsample then added until it covered the probe sensor and the light shield closed during measurement. Once the stability icon was displayed the measurement was recorded. DI water was used to clean the probe between samples and then the sensor was gently dried with soft tissue to remove any residue.

9.8 pH

A record of pH was included in the analysis because they indicate how soluble and bioavailable nutrients are within the water, in addition to giving an indication of the underlying geology of the area (Metherall et all, 2021).
The pH analysis was completed using a HACH HQ30d portable meter which had been calibrated for a measurement range of 4.01 – 9.21 before use. The small volume probe was attached to the handset, the probe was then submerged in the sample pot until the stabilisation threshold had been met. The result was recorded. The probe was cleaned between samples using deionised water and dried used a paper towel to remove any residue from the deionised water.

9.9 Turbidity analysis

Turbidity was included in the analysis because it is a record of suspended sediment load. The higher the turbidity, the higher the opacity of the water. By contrasting these results with the conductivity and concentration trends the source of fine grain sediment can be found.
The turbidity analysis was completed using an Oaklon waterproof turbidimeter (T-100) which had been calibrated for a measurement range of 0.02 – 800NTU before use. Each sample pot was agitated to ensure the subsample was homogeneous and a 10mL aliquot was added to the vial. The vial was inverted to coat the inside with the sample, the subsample was then discarded. This step was repeated. The vial was then filled with the sample to the mark indicated on the vial. The vial was wiped with a lint free cloth to remove any residue and a thin film of silicone oil was applied to the outside of the vial. The vial was then inserted into the sample well and the light shield placed over the sample vial. Once the stability threshold had been passed the result was recorded. The sample vial was then cleaned using deionised water and dried with a lint free tissue.

9.10 Conductivity analysis

A record of conductivity was included in the analysis because it is a measure of the ability of the solution to conduct electricity and as such give a measure of the ions present in the sample. These data can be used to identify saline input, whether from marine or bedrock sources, or inorganic pollution.
The conductivity analysis was completed using a HACH HQ30d portable meter which had been calibrated for a measurement range of 0.01uS/cm – 200mS/cm before use. The small volume probe was attached to the handset, the probe was then submerged in the sample pot until the stabilisation threshold had been met. The result was recorded. The probe was cleaned between samples using deionised water and dried used a paper towel to remove any residue from the deionised water.

9.11 Data analysis methodology

9.12 Grain size and shape analysis

Once the suspended sediment had been analysed using the Retsch CamSizer the data were processed using a Python Jupyter Notebook script to extract the D10, D50 and D90 of each sample.