UK Centre for Ecology & Hydrology

River Windrush Turbidity Investigation

Results of water quality catchment surveys (July 2020 to January 2021)

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Date 15/04/2021

Title River Windrush Turbidity Investigation

Client Thames Water

Client reference

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Date 18/04/2021

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1 Introduction

Over recent years the River Windrush has been exhibiting turbidity and colouration issues at a number of sites across the catchment. These visually noticeable effects vary from the water having a general lack of clarity or haziness, to strange blue/grey or green/grey hues, through to a milky opalescence as turbidity increases.

The UK Centre for Ecology & Hydrology was invited by Thames Water to carry out a brief initial monitoring campaign with a view to identify possible causes of these problems.

The campaign, which was undertaken between 7th July 2020 and 5th January 2021, comprised four water quality surveys under a variety of flow conditions in an attempt to determine:

- Whether this turbidity/clarity/colour issue can be quantified;
- The extent of the turbidity issues along the Windrush;
- The possible direct sources of turbidity along the Windrush;
- Whether there are multiple biogeochemical factors that combine to cause colour and turbidity problems;
- What impact Thames Water's Sewage Treatment Works (STWs) have on the clarity and turbidity problems of the Windrush.

2 Methods

2.1 Water quality surveys

2.1.1 Selection of study sites

From initial discussions with Thames Water and the Environment Agency and a review of turbidity-related issues reported across the media, it was agreed that UKCEH's work should focus on the middle and lower Windrush, from Naunton to the confluence with the Thames at Newbridge, and the R. Dickler around Bourton-on-the-Water (see Figure 1, Figure 2, Table 1). The monitoring sites were selected to provide representative spatial coverage and to enable the aforementioned questions to be answered. Site selection was further based on the following rationale:

- To investigate if effluent from STWs was causing high turbidity, sampling was undertaken upstream and downstream of four STWs within the catchment, namely those at Naunton (Win1 & 2), Bourton (Win3, 4 & 5), Burford (Win10 & 11) and Witney (Win11 & 13);
- To compare the influence of urban areas/sources on turbidity with that of STW discharges, sampling was undertaken on the Windrush upstream of Witney (Win11) and on both branches of the river downstream, on the west channel (Win13), downstream of the confluence of Colwell Brook and Witney STW, and on the east channel (Win14), which does not receive STW-derived effluent from the town;
- Colwell Brook also was monitored (Win12). As a large proportion of the flow in this stream is comprised of effluent (including CSOs) from Witney STW, this site provided an opportunity to characterise turbidity-related parameters of STW discharges directly;
- Incoming tributaries to the Windrush (Sherborne Brook and Coombe Brook) were also sampled (Win7 and 9, respectively), to establish if they were a potential source of high clay loadings, algae, nutrients or high alkalinities;
- Sampling of both the Windrush and Thames at Newbridge (TC7 & 6, respectively) was also included, to assess the differing properties of the two rivers.

So that data from sites could be directly compared, it was important to complete each of the four rounds of sampling at all locations within the same day. Ease of access, therefore was one of the key criteria for site selection which meant sampling was mostly undertaken from road bridges. Where possible, sites coincided with Environment Agency monitoring points, as this could increase the potential value of this short-term investigation.

Unfortunately accessibility difficulties that caused bed sediment to be disturbed during sampling resulted in the R. Eye site (Win3) being dropped from the final two rounds of surveys. As it happens, the first two surveys had shown that the River Eye at this location had low turbidity, suspended solids, phosphorus and nitrate concentrations; its exclusion was therefore considered unlikely to have a significant effect on the study's findings.

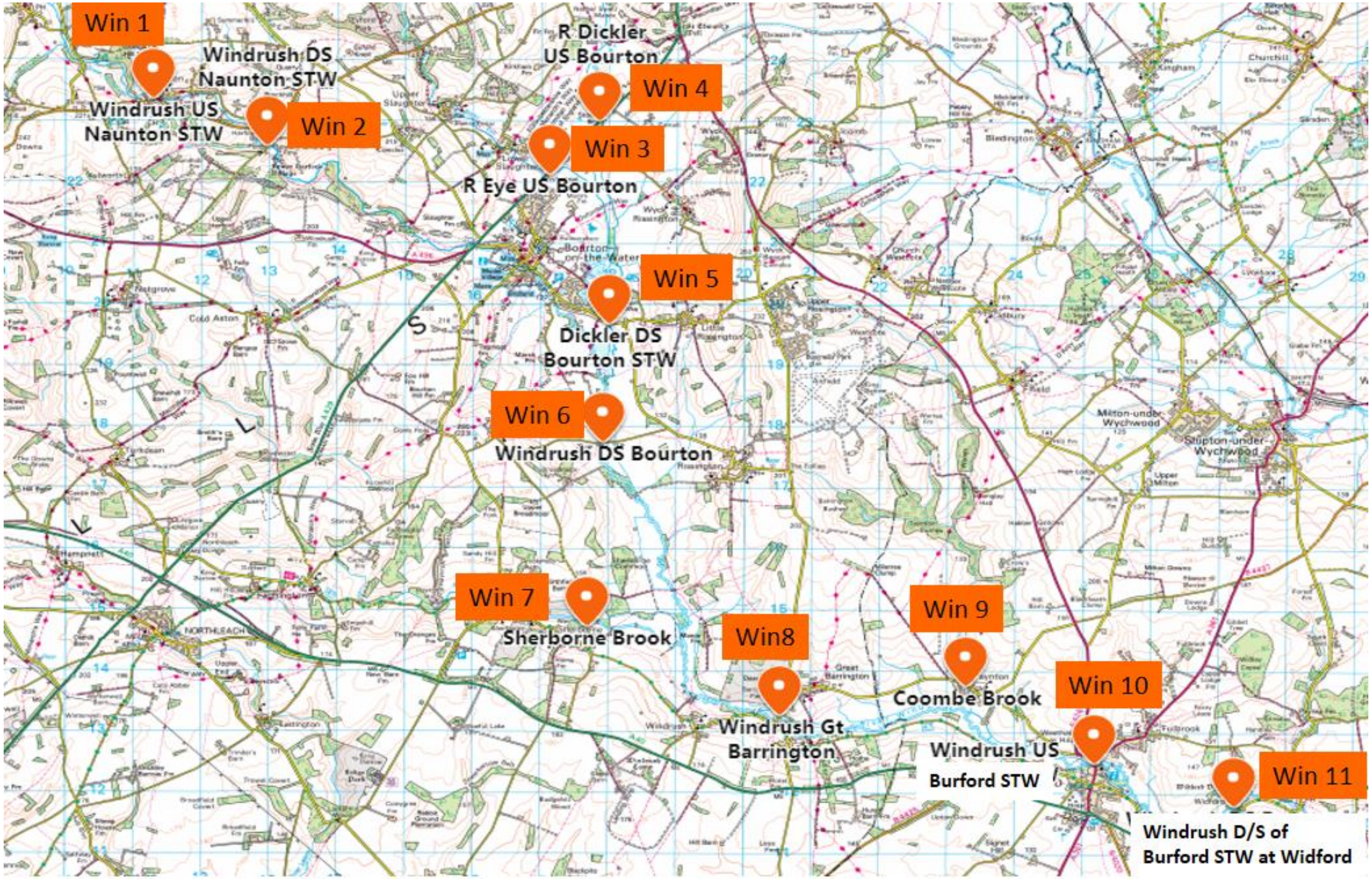

Figure 1. Study site locations in upper and middle Windrush catchment.

Figure 2. Study site loations in the lower Windrush catchment

Table 1. Study site locations

Site code	Site location	Comments
WIN1	Windrush US Naunton	
WIN2	Windrush DS Naunton	Receives Naunton STW effluent
WIN3	Eye at A429	
WIN4	Dickler at A429	
WIN5	Dickler DS Bourton	Receives Bourton STW effluent
WIN6	Windrush DS Bourton	
WIN7	Sherborne Brook	
WIN8	Windrush at Great Barrington	
WIN9	Coombe Brook at Taynton	
WIN10	Windrush US Burford	
WIN11	Windrush at Widford	Receives Burford STW effluent
WIN12	Colwell Brook DS Witney STW	Mainly comprised of Witney STW effluent
WIN13	Windrush DS Witney (W channel)	Receives Witney STW effluent
WIN14	Windrush DS Witney (E channel)	Does not receive Witney STW effluent
TC7	Windrush at Newbridge	
TC6	Thames at Newbridge	

2.1.2 Survey timing

Four rounds of longitudinal surveys were undertaken within this study, each completed from start to finish in a single day. These were timed to capture a wide range of flow conditions: from low flow conditions (July 6th and September 9th, 2020); under increased flow conditions during a persistent rainfall event (November 20th 2020); and during a major flood period when CSOs were triggering (January 5th 2021). The timing of the surveys in relation to the level of the Windrush at Witney is shown in Figure 3.

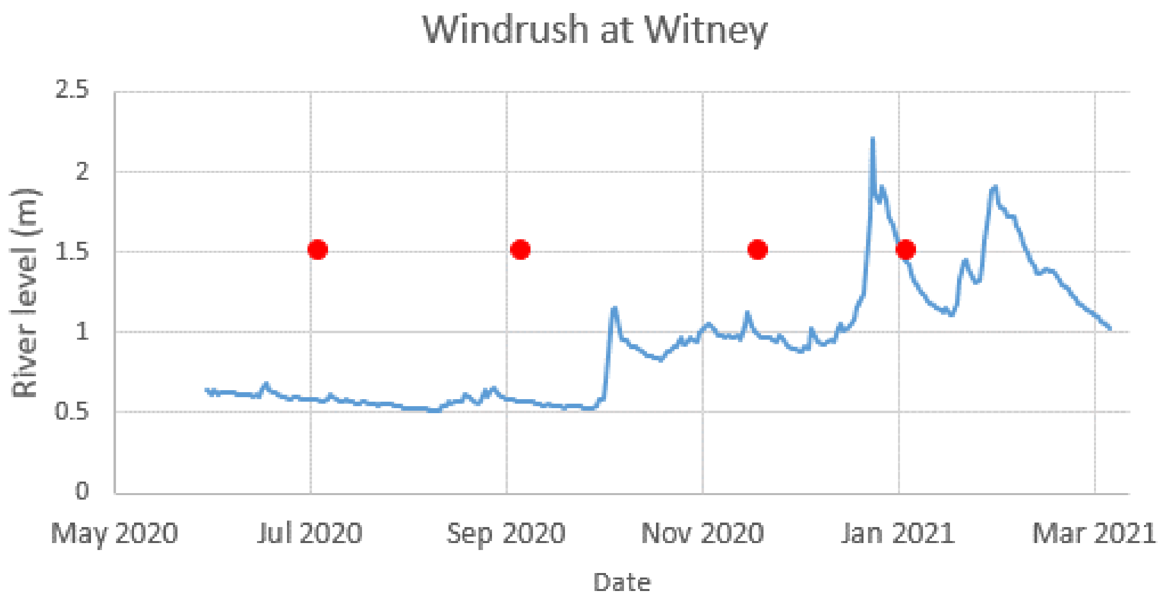

Figure 3.Timing of River Windrush longitudinal surveys (marked by red circles) in relation to river height data (River height data downloaded from RiverLevelsUK website https://riverlevels.uk/windrush-witney#.YFCi7J37Tcs)

2.1.3 Selection of analytical parameters

Analytical determinands were selected based on parameters that could (1) directly quantify the turbidity / colour issues (turbidity, suspended solids quantity, particle size and organic content, chlorophyll, algal cell densities, bacteria), and (2) quantify parameters that could indirectly cause turbidity issues (pH, alkalinity).

Before the third survey was conducted, Thames Water agreed to extend the scope of the study to include full nutrient analysis, to provide a more complete picture of pollution loadings across the catchment, and because soluble phosphorus concentrations are known to have an impact on calcite precipitation reactions, which are a potential cause of milkiness in high-alkalinity rivers. These nutrient analyses were performed on the final two surveys as part of the commissioned work; such sampling had, however, already been undertaken in the first sampling round by UKCEH, on our own volition. For the second survey in September 2020, nutrient analysis was carried out on any remaining samples. Therefore, the total phosphorus data for the second survey is incomplete.

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2.1.4 Sampling methods

Bulk samples were taken from the main flow of each river, using a 10-litre plastic bucket on a rope. The bucket was rinsed twice with the local river water prior to sampling, to avoid cross-contamination between sites. The bulk samples were immediately sub-sampled into two 1-litre bottles for suspended solids and chlorophyll analysis, a 100 ml amber-coloured glass bottle (filled to the brim and sealed to minimise degassing) for pH and alkalinity determinations, and into a 60 ml Nalgene bottle for total phosphorus analysis. A 20 ml sterilin tube was half filled with unfiltered river water for algal and bacterial analyses by flow cytometry, and stored in a cool box until return to the laboratory. Other sub-samples were filtered immediately in the field through a 0.45 μm cellulose nitrate (Whatman WCN grade; Maidstone, UK) membrane filter into 60 ml bottles, for dissolved nutrients and anion analysis. These bottles were acid-washed prior to use. The water temperature of the bulk river water sample was measured in the field using an ATP Multi-Thermo digital thermometer (ATP Instrumentation Ltd. Ashby-de-la-Zouch, UK). Samples were stored in the dark until returned to the laboratory (within eight hours).

The first survey highlighted that despite the perceived high turbidity across the catchment, the quantity of suspended solids was very low, and not sufficient to determine the particle size distribution of the suspended solids load. Therefore, bulk samples (20-litres) were taken from selected sites in future surveys.

2.1.5 Analytical methods

On return to the laboratory, all samples were stored in the dark at 4°C, prior to analysis. The pH was determined using a Radiometer Analytical PHM210 pH meter. The instrument was calibrated prior to use using pH 4, 7, and 10 buffer solutions traceable to National Institute of Standards and Technology (Gaithersburg, USA). Gran alkalinity was determined by acidimetric titration to pH 4 and 3 using 0.5N H_2SO_4. Suspended solids concentrations were determined by filtering a known volume (approximately 1000 ml) of river water through a pre-dried and pre-ashed Whatman GF/C filter paper. The filter paper was then re-dried (16 h at 80°C) and reweighed to determine the mass of solids in the water sample. The filter paper and sediment were then ashed in a muffle furnace at 550°C for three hours, cooled in a desiccator and reweighed, to determine the percentage of the suspended solids that was organic. Chlorophyll concentrations were determined by filtering a known volume of unfiltered river water (approximately 1000 ml) through a Whatman GF/C filter paper. The filter paper was then extracted in 10 ml of 90% v/v acetone/water and refrigerated overnight at 4°C in the dark. Chlorophyll-*a* concentration was determined colorimetrically using a Beckman 750 DU spectrophotometer, using the method of Marker et al. (1980). Chlorophyll analysis was completed within 48 hours of sampling, to avoid errors due to sample stability.

Total phosphorus (TP) was determined by digesting an unfiltered water sample with acidified potassium persulphate in an autoclave at 121°C for 45 min. Acidified ammonium molybdate reagent was then added to the digested samples to produce a molybdenum–phosphorus complex. This intensely blue-coloured compound was then quantified spectrophotometrically at 880 nm (Eisenreich et al. 1975). Soluble reactive phosphorus (SRP) concentrations were determined on a filtered (0.45 μm WCN-grade cellulose nitrate membrane; Whatman, Maidstone, UK) sample, using the phosphomolybdenum-blue colorimetry method of Murphy and Riley (1962), as modified by Neal et al. (2000), using a Seal Auto Analyser 3 (Seal Analytical; Fareham, UK). SRP samples were analysed within 48 h, to minimise errors associated with sample instability. Ammonium concentration was determined using an indophenol-blue colorimetric method (Leeks et al. 1997) using a Seal Auto Analyser 3. Major dissolved anion (fluoride, chloride, bromide, nitrite, nitrate and sulphate) concentrations were determined by ion chromatography (Dionex AS50, Thermo Fisher Scientific; Waltham, USA). Conductivity was measured in the field using a Myron-L Ultrameter. All chemical analyses were analysed alongside internal and external reference standards (LGC Aquacheck, UK).

The algal phytoplankton community was characterised and enumerated by running unfiltered water samples through a Bechman-Coulter Gallios flow cytometer fitted with blue and red lasers, to identify the photosynthetic pigments present in each cell, using the method of Read et al., (2014). This provided cell densities for diatoms, meso- and pico-chlorophytes, cryptophytes and three classes of cyanobacteria. Bacterial cell densities were determined by staining with SYBR-green and running through the Gallios Flow Cytometer using a 488 nm laser.

2.1.6 Turbidity measurements

Turbidity was measured using an Analyte NEP160 (McVan Instruments), in the laboratory. Readings were extremely variable, and the analytical method was gradually refined to try to minimise this variation. Samples were returned to the laboratory, shaken to re-suspend any material, and then a subsample was transferred into a 1-litre HDPE dark bottle (to reduce light interference). The bottle was placed onto a stirrer plate and a magnetic bead used to maintain any solid material in suspension. The bottle was covered with a sheet to further reduce light interference. The turbidity probe was placed at a set depth of 10 cm in the 25 cm high bottle and readings were taken after one minute. Despite these efforts, the turbidity readings remained highly variable, and didn’t appear always to reflect visual observations of turbidity at the sampling sites.

Other methods to measure the turbidity were trialled, including; -

- Transferring the samples into 0.5 m high glass tubes and using photography to try to distinguish turbidity / colour differences between sites.
- Using spectrophotometry at 750 nm and also full wavelength scans to measure obscuration of the light beam by the sample.
- Total particle concentration counts from flow cytometry

None of these methods provided a robust measure of the perceived turbidity, and therefore this study resorted to analysing those determinands that are known to affect, or be affected by, turbidity, such as suspended solids concentration, particle size distribution and organic content, alkalinity, and algal and bacterial concentrations.

2.1.7 Particle size distribution of suspended solids

Bulk water samples (approximately 20 litres) were taken from a variety of sites across the catchment and concentrated by several centrifuging and decanting stages. The concentrated sediment samples were then characterised using a Malvern Mastersizer laser diffraction particle size analyser. Samples were run in triplicate, and then combined as average particle size distributions (PSD).

Smaller samples (5-10 litres) were taken during the first survey in July 2020, which did not yield enough solids sample to produce reliable results (due to the obscuration being too low for the instrument), and therefore these results were rejected. On subsequent surveys, some of the sites had such low suspended sediment concentrations that they also did not produce enough solid material to measure using the Mastersizer technique.

3 Results and discussion

3.1 Water quality surveys

3.1.1 Turbidity

As described above, the turbidity measurements were found to be vary variable for every sample and, accordingly, these results cannot be relied upon fully due to the uncertainty associated with the method and turbidity meter used. However, they do indicate that turbidity values are highest from Burford to the confluence with the River Thames. Sudden increases in turbidity were mainly observed in the River Dickler, downstream of Bourton-on-the-Water (Win5), and in the Windrush downstream of Burford at Widford (Win11). This suggests that the towns' STWs may be contributing to the turbidity signal. However, the river channel passing through Witney that did not receive effluent from Witney STW (the east channel, Win14) also had notable increases in turbidity, and often had higher turbidity values than the west channel that received Witney STW effluent (Win13). Therefore, urban land cover and activities in urban areas appear also to contribute to the turbidity increases. These could include wastewater inputs from domestic misconnections and leaking sewers, road runoff, construction etc. The turbidity in the Colwell Brook (Win12) was relatively low for the first three surveys, indicating that treated effluent from Witney STW was not a major source of turbidity directly. Its contribution to turbidity was highest in the floods during the January 2021 survey, when the Witney STW combined sewer overflow (CSO) was operating and raw sewage was being discharged into the river.

The highest turbidity value, of 34 NTU (Nephelometric Turbidity Units), was observed in the September 2020 survey, on the Windrush at Newbridge (TC7; Figure 2), resulting in a clear difference in colour and turbidity between the Thames (TC6) (3.5 NTU) and the Windrush at the confluence. This shows that turbidity was an effective method of detecting the milky turbidities seen in the lower catchment.

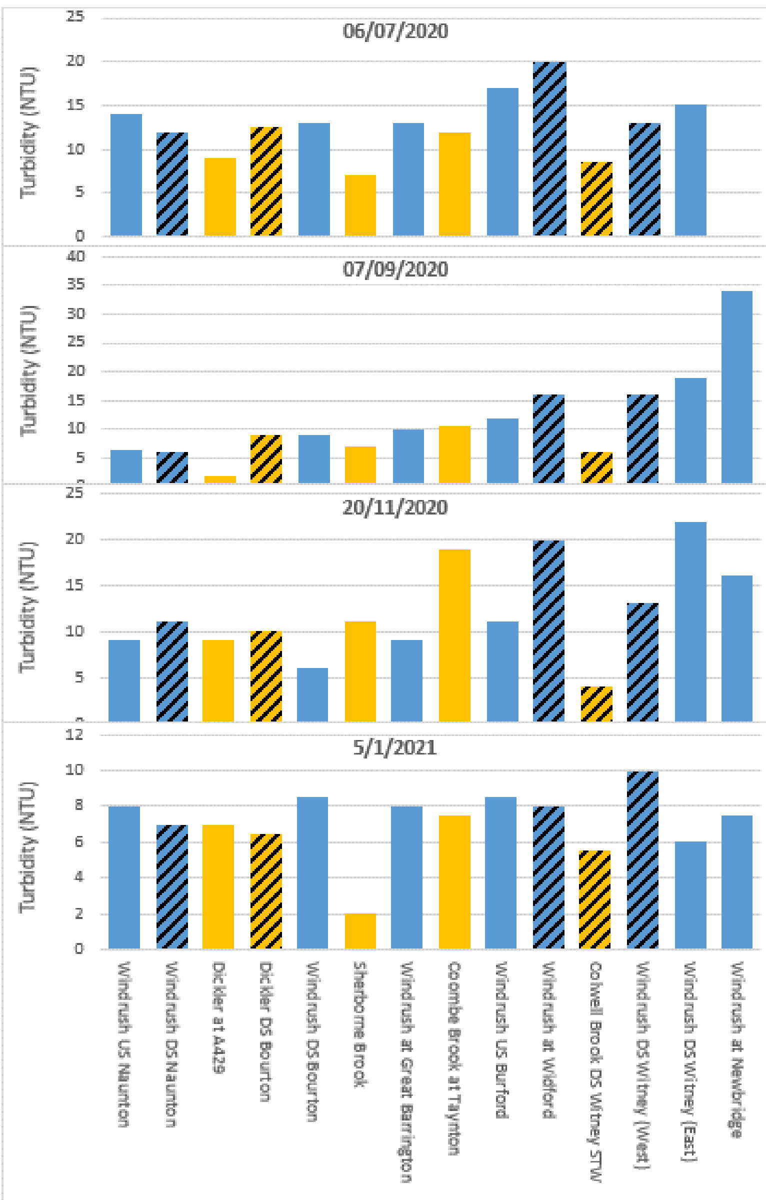

Figure 4. Turbidity data from longitudinal surveys
(Blue = Windrush site. Orange = Tributary. Diagonal shading = immediately downstream of STW)[1]

Due to the uncertainty in the turbidity meter measurements, UKCEH also made a visual assessment at each site, categorising each site as clear, hazy, turbid or very turbid. These subjective assessments are presented in **Error! Reference source not found.**.

There was a general decrease in clarity (and an increase in turbidity) along the river from upstream to downstream under all flow conditions. Turbidity was also observed, by measurement and by-eye, to increase during high flow periods. The high turbidities during the January 2021 flood survey were very brown and probably

[1] All water quality survey graphs in this report are presented in the same format, for ease of interpretation. The graphs are also presented in the Appendix section with the same y-axis values, so that differences between surveys can be more-clearly seen.

related to suspended solids and organic material from soil leachate. During the earlier three surveys, many sites had a milky appearance and, often, with a blue/grey or green/grey colouration. Sites particularly affected by this milkiness and colouration were the R. Dickler, downstream of Bourton (Win5), the Windrush downstream of Burford at Widford (Win10) and the two channels of the Windrush downstream of Witney (photos of turbid sites from each survey provided in Appendix). The turbidity/colour issues tend to be more visually apparent at sites where the river is deep and the water is shaded. This highlights the need to find an instrumental method for measuring the clarity and colour that reflects what people are observing.

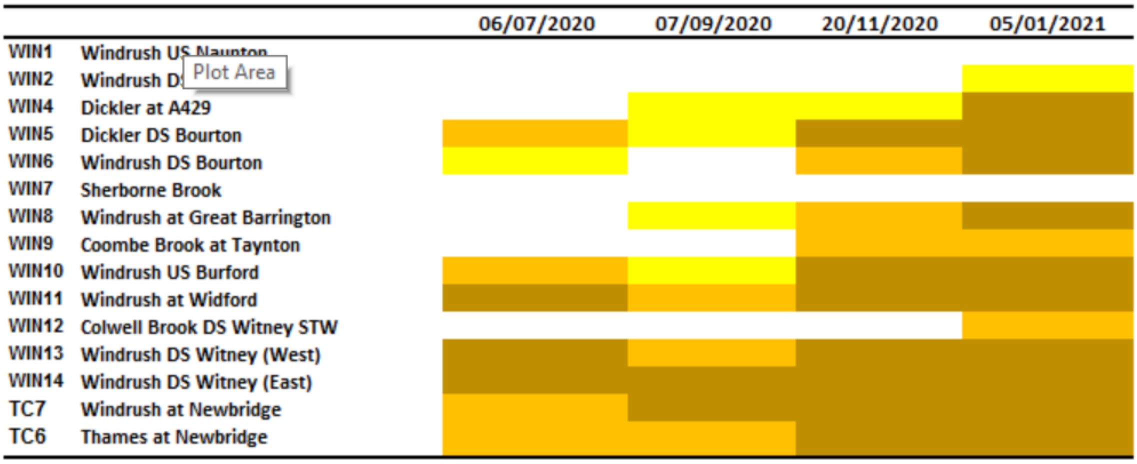

Figure 5. Visual assessment of turbidity
White = clear. Yellow = hazy. Orange = turbid. Brown = very turbid.

3.1.2 Suspended solids

There was an increasing trend in suspended solids (SS) concentrations in the downstream direction during the July, September and November 2020 sampling rounds. The sites at Widford (Win11) and sites downstream of Witney (Win13, 14 & TC 7) tended to have the highest SS concentrations during these surveys.

The two low-flow sampling rounds, in July and September 2020, had similar patterns, with increases in SS as the river passed through the towns of Bourton-on-the-Water and Burford, and also Witney in the September survey. Some of this solids load is likely to be coming from the STW effluent discharges. However, the river channel that passes through Witney (Win14) that does not receive any effluent from Witney STW was found to have similar (usually slightly higher) SS concentrations. This suggests that urban sources (other than STWs) also contribute to SS increases as the river passes through towns. The largest increase in SS and highest concentration (41 mg/l) occurred in September 2020 in the Windrush at Newbridge. This coincided with the highest turbidity in the study and the only appearance of major milkiness observed in these surveys. This shows that SS is an effective monitoring method for detecting such incidents, and also that the cause of the lack of clarity is due to a suspended solid, rather than a dissolved coloured compound.

During the high-flow survey in January 2021, the increasing downstream pattern broke down, and river SS concentrations were actually reduced as they passed through the towns. The highest SS concentrations were observed in the mid-Windrush around Win8 (Windrush at Great Barrington) to Win10 (upstream of Burford), which suggests loss of sediment and soil from fields, and possibly river-bank and river-bed erosion contributes significantly to SS in periods of high flow.

The smaller tributaries tended to have lower SS concentrations than the Windrush, and so were not causing the increased sediment load. Highest tributary concentrations were observed in the Coombe Brook and River Dickler. The sewage-effluent-dominated Colwell Brook had relatively low SS concentrations, particularly during the January 2021 high-flow survey, despite the triggering of the combined sewer overflow at the time.

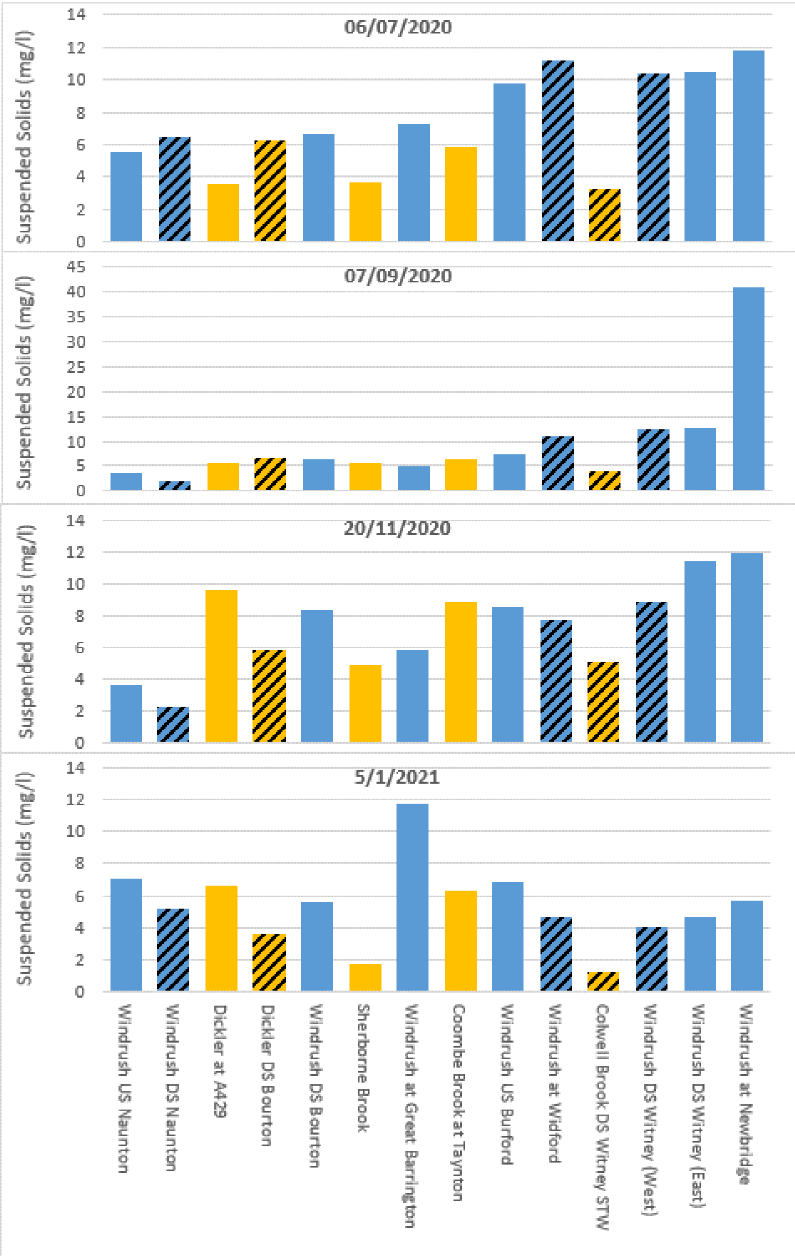

Figure 6. Suspended solids concentration data from longitudinal surveys
(Blue = Windrush site. Orange = Tributary. Diagonal shading = immediately downstream of STW)

3.1.3 Suspended solids organic content

The organic content of the suspended solids load was highest in the July survey (Figure 7), due to high biological activity resulting in high algal and bacterial cell densities, plant debris and other particulate organic material. Organic content tended to be highest in the upper Windrush and R. Dickler. No clear pattern emerged in the percentage organic content as the river passed the towns and STWs. However, data from the Colwell Brook (receiving Witney STW effluent) shows that this STW can discharge organic-rich material into the river system, especially during the flood of January 2021 when Witney CSO was triggered.

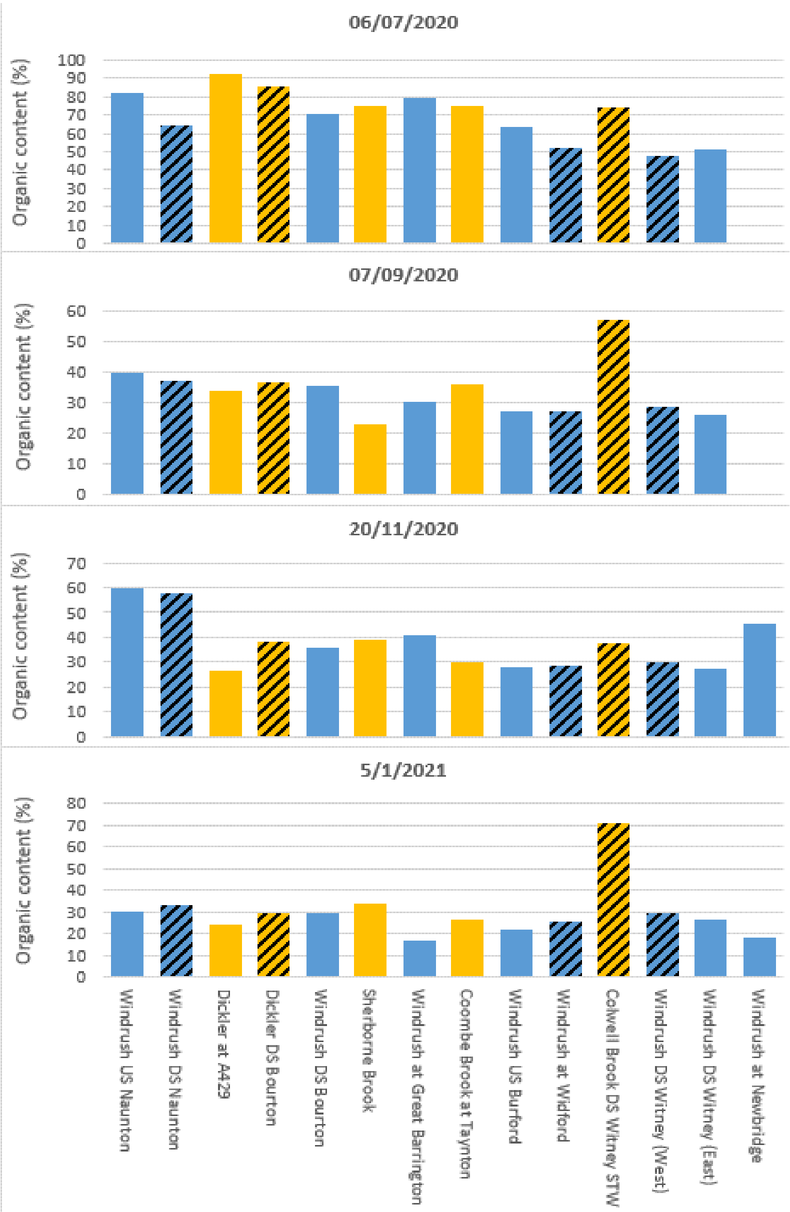

Figure 7. Percentage organic content of suspended solids load from longitudinal surveys
(Blue = Windrush site. Orange = Tributary. Diagonal shading = immediately downstream of STW)

3.1.4 Particle size distribution of suspended solids

Bulk samples were taken from 8-10 sites during each campaign. These sites varied between surveys, and were selected on the day based on previous results and assessment of turbidity by the fieldworker at the time. For some sites, the quantity of suspended sediment was insufficient to produce particle size data. The initial survey did not produce any usable data for this reason, and subsequent surveys took larger samples to avoid this.

September 2020 survey

There was a marked decrease in peak particle size along the river catchment, with the upper Windrush downstream of Naunton (Win2) and Dickler upstream of Bourton-on-the-Water (Win4) having peaks at 89 and 40 nm respectively. The Windrush sites further downstream (Win10, 11 and Win13), which were visually more turbid, all had peak particle sizes of only approximately 10 nm. Sites Win10 to Win13 also had secondary peaks at 400-500 nm.

There was a major difference between the Particle Size Distributions (PSD) in the Windrush and Thames at Newbridge, with the Windrush having coarser particles in the 60 to 220 nm range that were virtually absent in the River Thames (Figure 8; lower graph). The Windrush at Newbridge also had a secondary peak of coarser material ranging from 400 to 600 nm that was again absent in the Thames. There was a clear difference in turbidity at this time of sampling, with the Windrush at Newbridge appearing extremely milky and turbid (discussed more fully in Section 0). It is postulated that the presence of coarser material in the Windrush could be causing light scattering that is causing the colour and turbidity issues. The PSD of the sewage-impacted Colwell Brook (Win12) also had a similar double-peak distribution, and therefore STW effluent could be one of the sources of this coarser material. Within-stream precipitation could also contribute to this coarser suspended material.

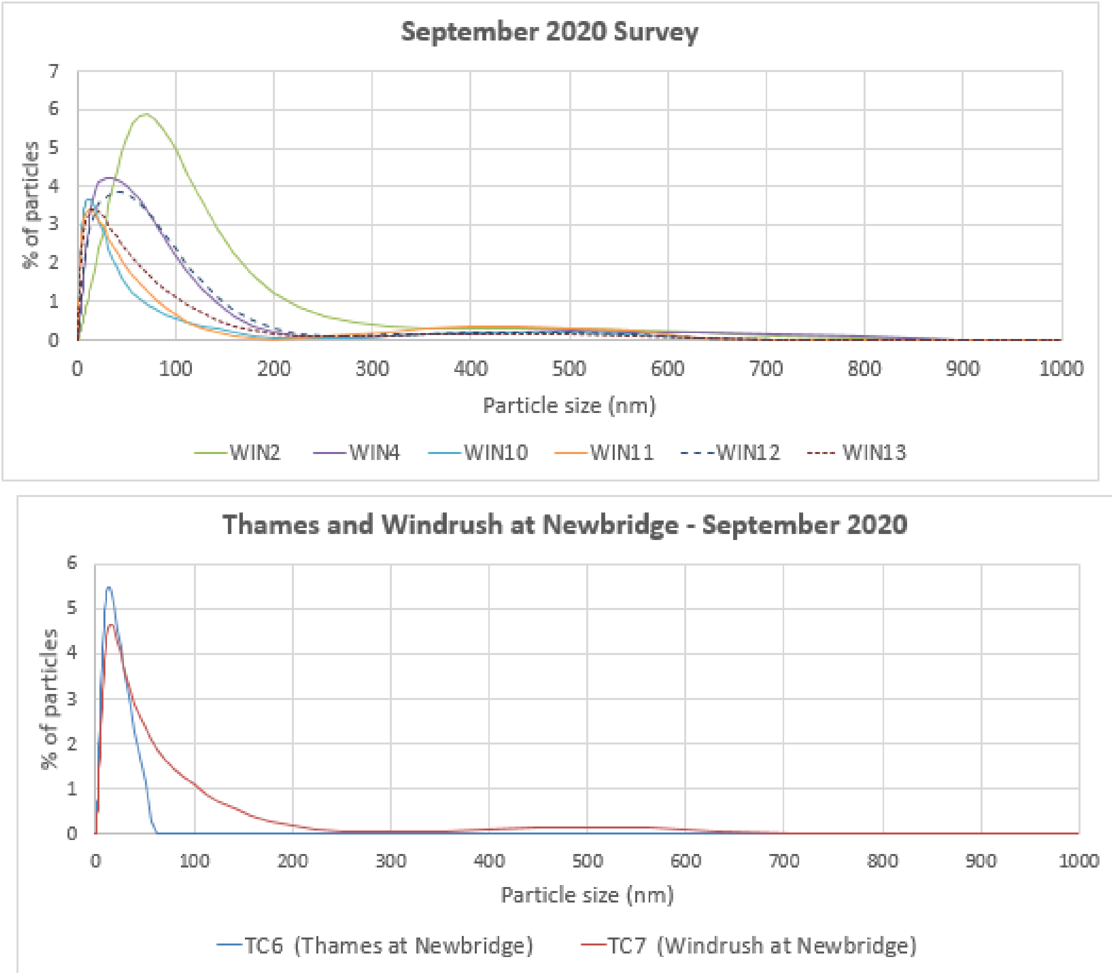

Figure 8. Particle size distributions at selected sites across the Windrush catchment. September 2020 survey.

November 2020 survey

Again there was a reduction in peak particle size downstream, ranging from 28 nm in the Dickler upstream of Bourton-on-the-Water (Win4) to 18 nm downstream (Win5). There was also a secondary peak in coarser material (ranging from 400 nm to up to 1200 nm, peaking at around 600 nm) for most sites, particularly those in the lower catchment that tend to be the more turbid sites (Windrush at Widford (Win11), downstream of Witney (Win13 and 14), and the Windrush at Newbridge (TC7). The highest secondary peak occurred in the Colwell Brook (Win12), which indicates that STW effluent can be a major source of this coarser material.

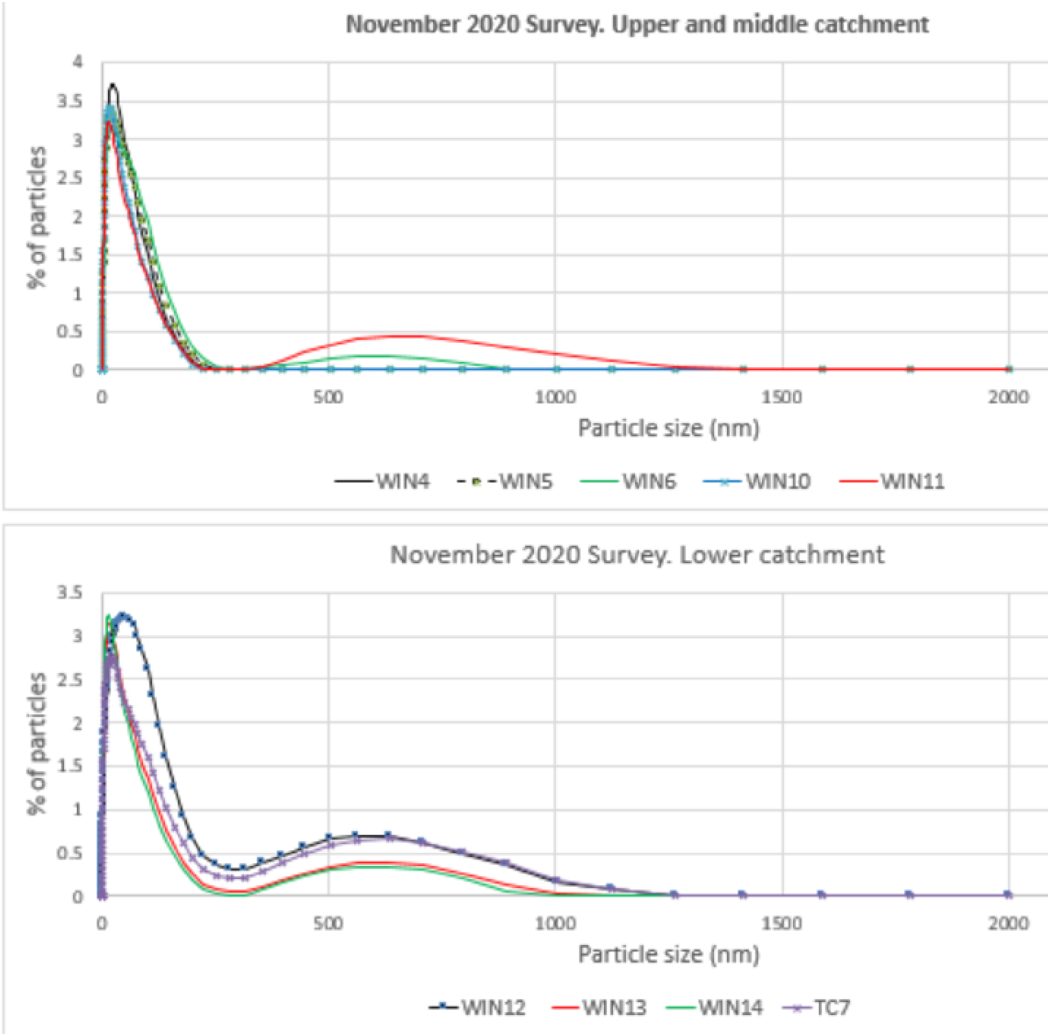

Figure 9. Particle size distributions at selected sites across the Windrush catchment. November 2020 survey.

January 2021 survey

This analysis is still ongoing, and will be reported in the final report

3.1.5 pH and alkalinity

The pH values were consistently high (>8) along the river during the low flow surveys of July and September 2020. The pH values were lower (<8) during the January 2021 flood survey, and reduced to 7.2 in the middle catchment, probably due to the input of low-alkalinity rainwater which would dilute the calcium carbonate-rich groundwater inputs. The lower pH in the Colwell Brook (ranging from 7.1 to 7.5) is likely to be due to chemical dosing as part of the sewage treatment process.

The highest pH value was observed in the Windrush at Newbridge, at the confluence with the Thames in September 2020. This coincided with the river having a very milky appearance and the highest turbidity. This suggests (along with the milky appearance) that it could be caused by mineral precipitation, potentially of calcite.

There were no drops in alkalinity along the Windrush, which may have also indicated calcium carbonate precipitation and subsequent deposition was taking place.

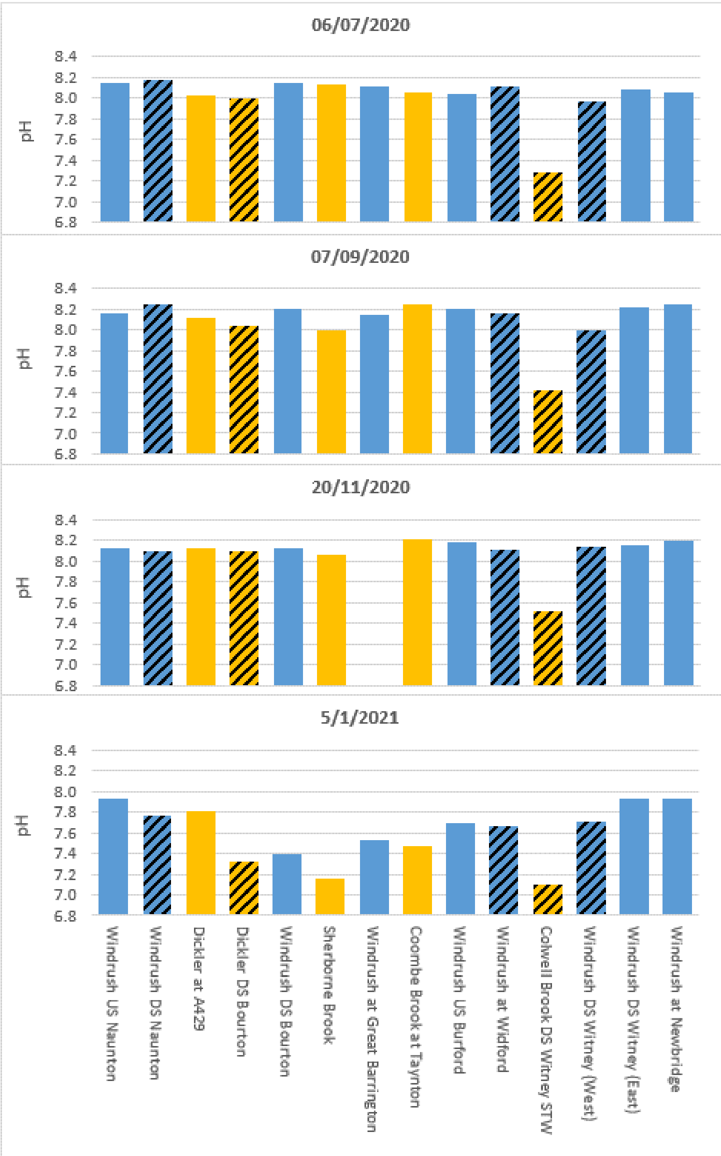

Figure 10. pH data from longitudinal surveys
(Blue = Windrush site. Orange = Tributary. Diagonal shading = immediately downstream of STW)

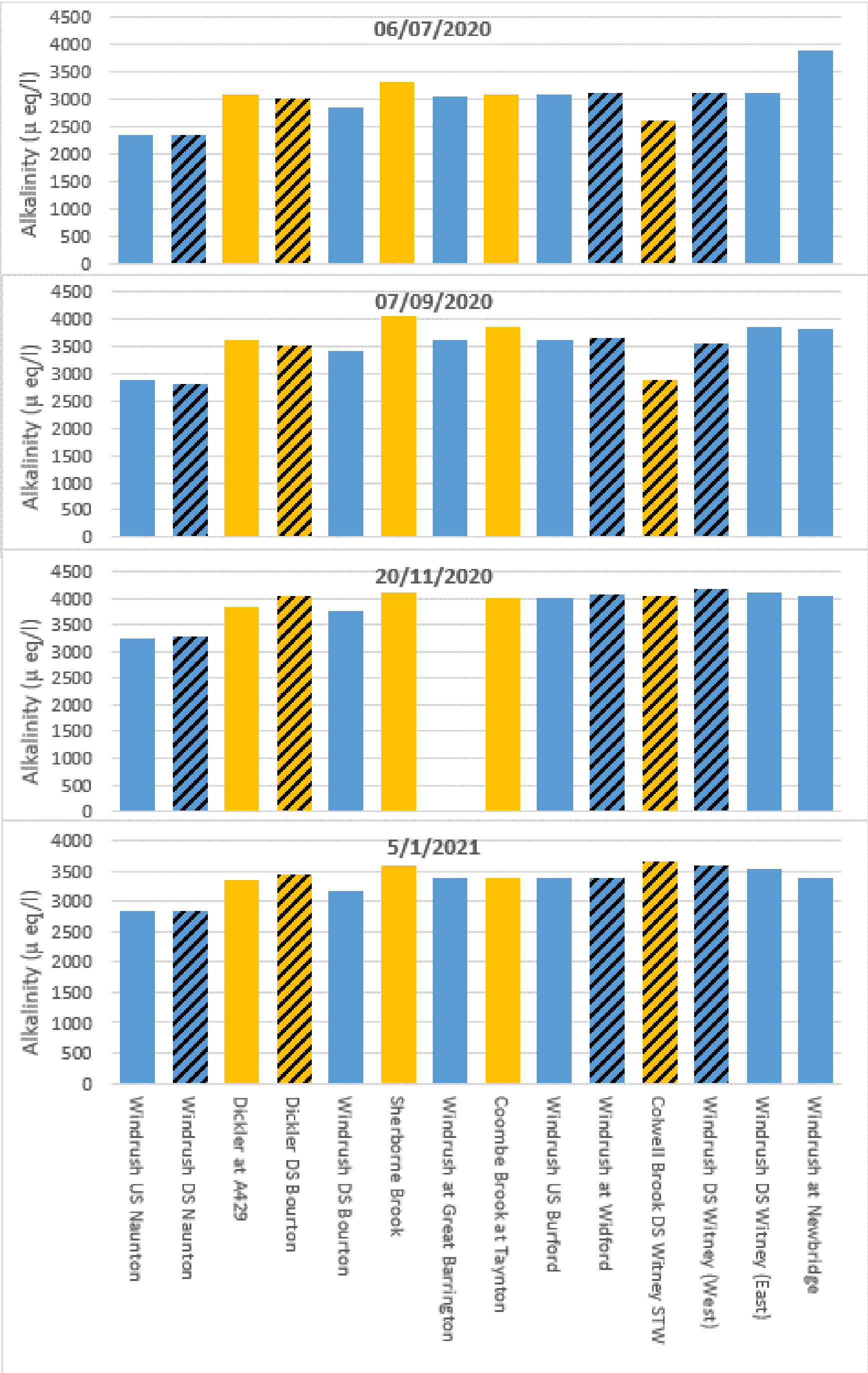

Figure 11. Alkalinity data from longitudinal surveys
(Blue = Windrush site. Orange = Tributary. Diagonal shading = immediately downstream of STW)

3.1.6 Conductivity

Conductivity, measured in microsiemens per centimetre (µS cm^{-1}), gives an indication of the quantity of dissolved substances, chemicals, and minerals that are present in water. There was a gradual and general increase in conductivity along the river in the downstream direction. The upper Windrush sites at Naunton had the lowest conductivities (432-502 µS cm^{-1}) in each of the survey rounds, with the highest Windrush conductivities observed at sites downstream of Witney. The sampling upstream and downstream of STWs showed there was no detectable increase in conductivity downstream of Naunton, Bourton-on-the-Water and Burford STWs. A larger increase was measured immediately downstream of Witney STW, particularly during the low flow surveys (July and September 2020), when conductivity in the Windrush increased by 110 µS cm^{-1}.

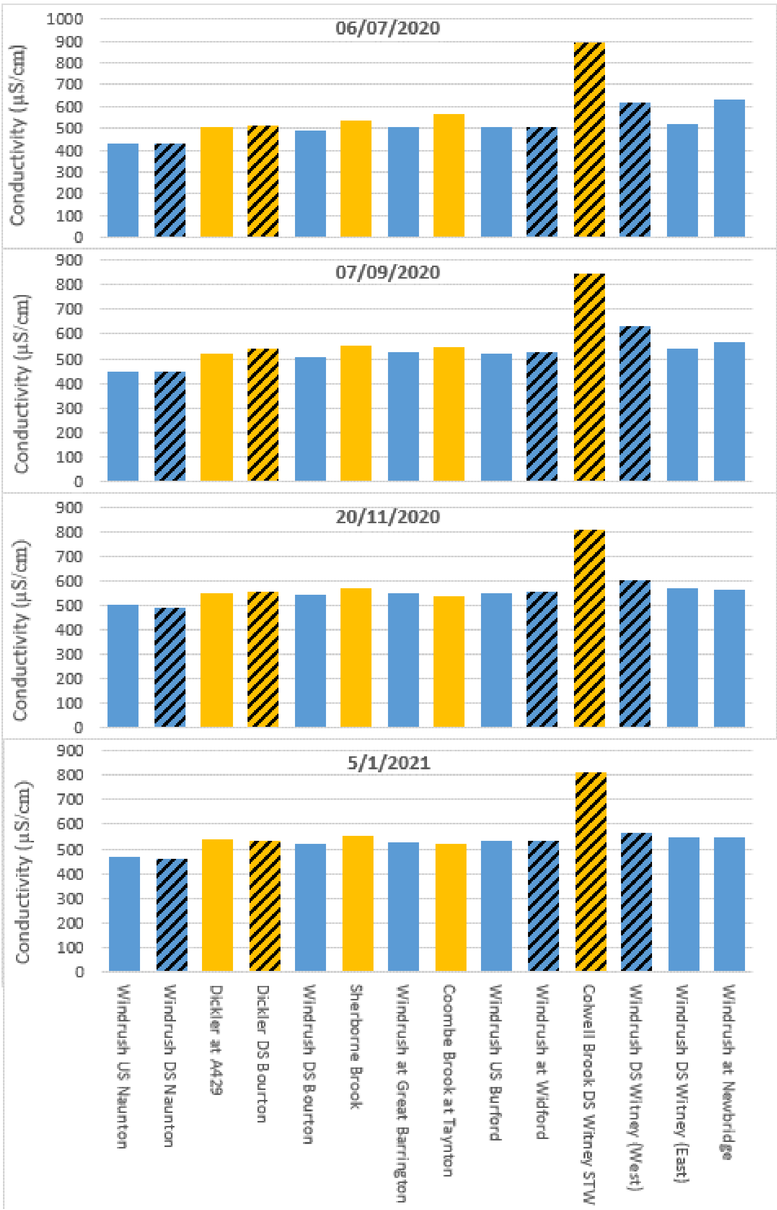

Figure 12. Conductivity data from longitudinal surveys
(Blue = Windrush site. Orange = Tributary. Diagonal shading = immediately downstream of STW)

Conductivities were consistently higher in the western branch of the Windrush in Witney (Win13), compared to the eastern branch (Win14), which also flows through Witney but does not receive effluent from Witney STW. The impact of Witney STW on river conductivity is confirmed by the very high conductivities in the effluent-impacted Colwell Brook (Win12), which consistently had conductivities of >800 $\mu S\ cm^{-1}$.

3.1.7 Phosphorus

Phosphorus concentrations were relatively low for much of the upper and mid-Windrush catchment (Figure 13), with soluble reactive phosphorus (SRP) concentrations of <60 $\mu g\ l^{-1}$ in the Windrush as far downstream as Witney for all four survey rounds (Figure 14). These levels have been found to limit algal growth in the River Thames and its tributaries (Bowes et al. 2012b, McCall et al. 2017), and have the potential to support good ecological status. The longitudinal pattern in total and soluble reactive P were very similar, with the majority of the phosphorus load being in soluble reactive form (equivalent to EA ortho-phosphorus data).

River SRP concentrations increased downstream of the STWs at Naunton, Bourton-on-the-Water and Witney in all four survey rounds. Very large increases in SRP concentration were seen downstream of the Bourton-on-the-Water and Witney STWs in particular, especially during the low flow surveys (July and September 2020) when the proportion of STW effluent in the river will be at its greatest due to lack of dilution (Figure 14). The biggest impact on Windrush TP and SRP concentrations was Witney STW, due to the high concentrations of phosphorus in its effluent (relative to river concentrations), as detected in the Colwell Brook (Win12), which had the highest TP and SRP concentration in all four surveys. The discharging CSO at Witney STW during the January 2021 flood survey had minimal effect on the phosphorus concentration of the Windrush (39 $\mu g\ l^{-1}$ in the Windrush downstream of Witney; Win13) due to the diluting effect of high river flows on the untreated effluent.

Burford STW had little impact on river P concentrations, with concentrations upstream of Burford (Win10) and downstream at Widford (Win11) being very similar across all four survey rounds.

Coombe Brook (Win9) had very high SRP concentrations of 288 and 198 $\mu g\ l^{-1}$ in the July and September 2020 low-flow surveys, but had no observable impact on the SRP concentrations of the Windrush downstream at Win10 (upstream of Burford), due to the tributary's small flow compared to the main river.

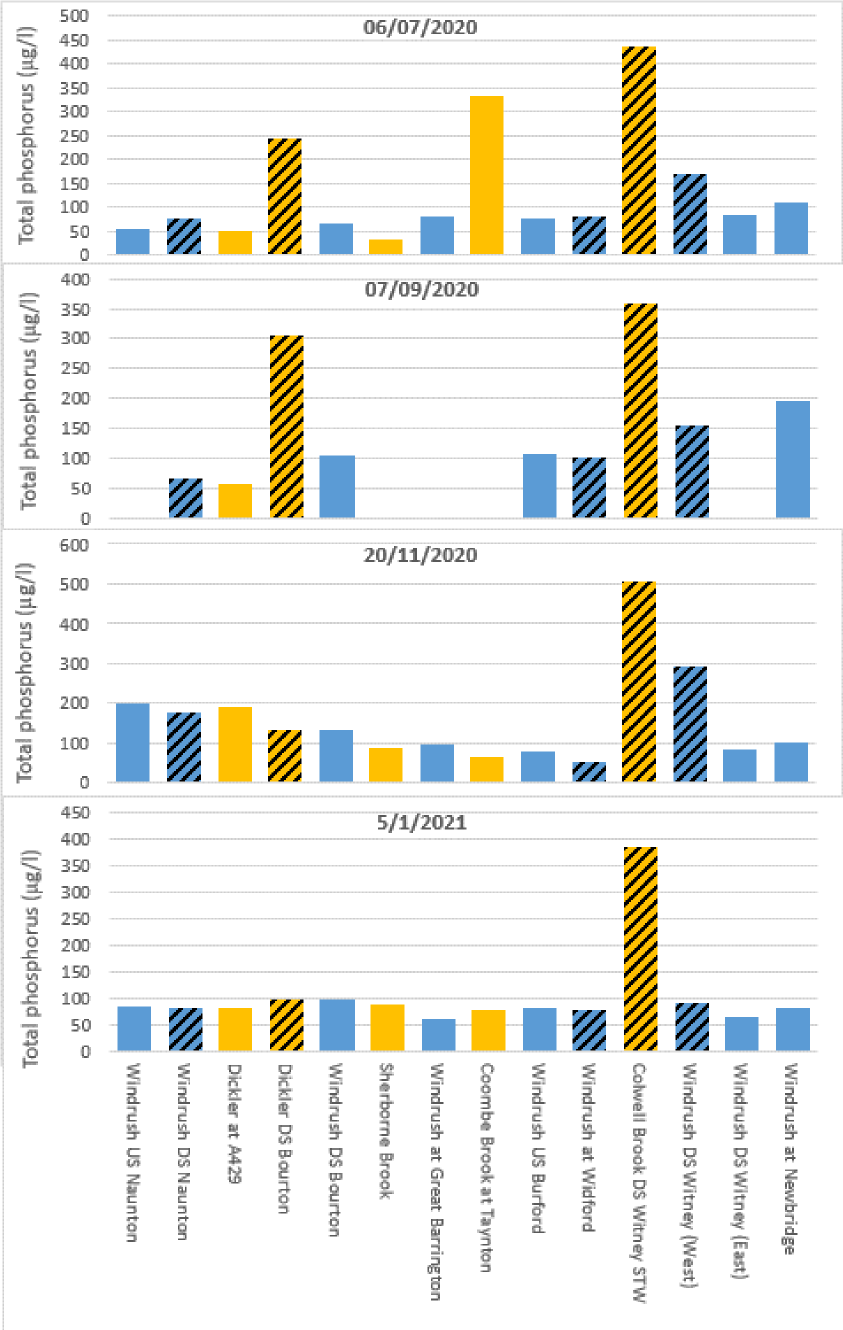

Figure 13. Total phosphorus concentrations from longitudinal surveys
(Blue = Windrush site. Orange = Tributary. Diagonal shading = immediately downstream of STW). TP data missing for some sites during September 2020 survey.

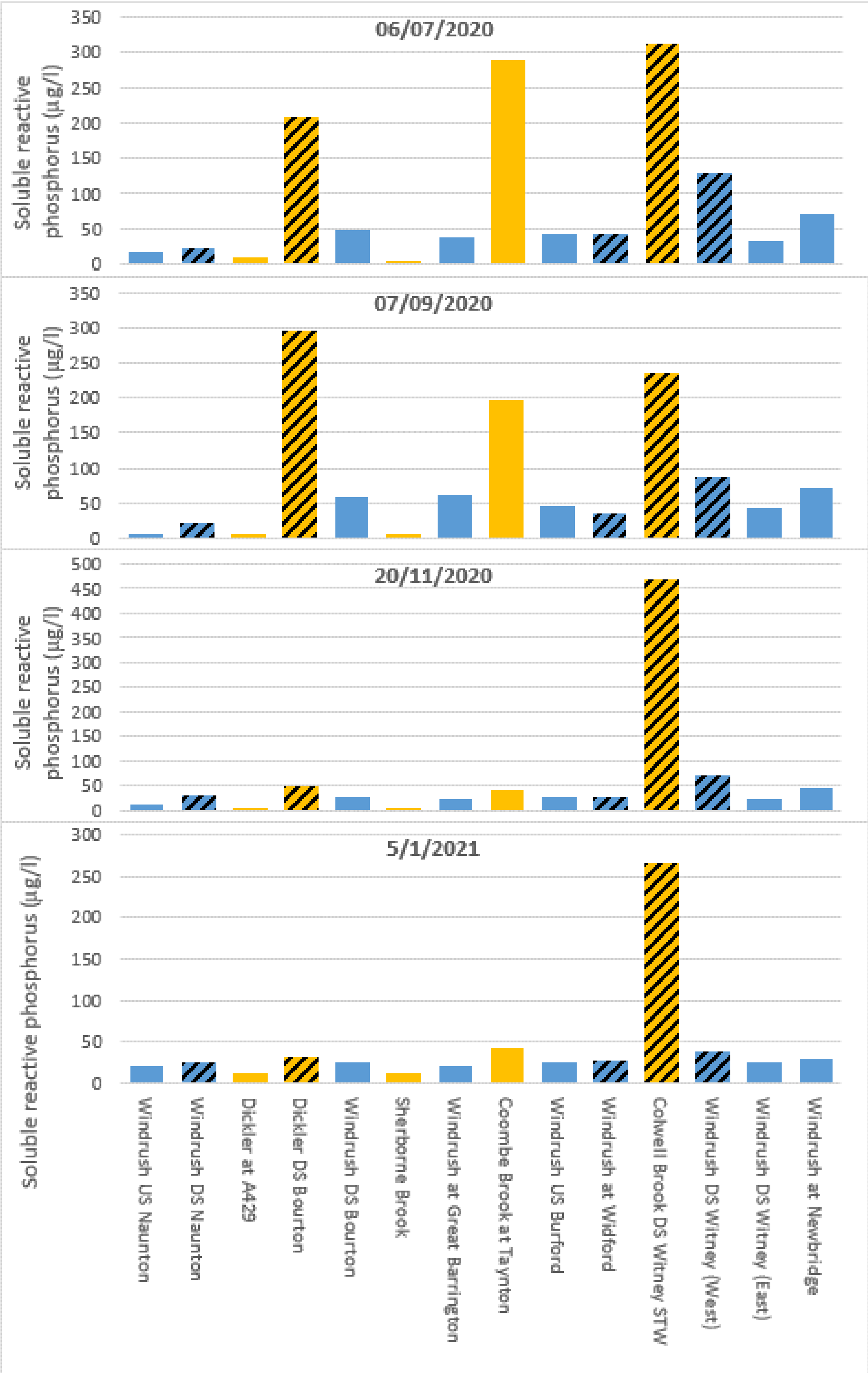

Figure 14. Soluble reactive phosphorus concentrations from longitudinal surveys
(Blue = Windrush site. Orange = Tributary. Diagonal shading = immediately downstream of STW)

3.1.8 Nitrogen

Nitrate concentrations were very consistent along the river continuum, and across the four surveys (varying between 27 and 38 mg NO_3 l^{-1}). This suggests that the primary nitrogen source was from rain-related diffuse inputs; most probably from groundwater. The exception to this was the Colwell Brook (Win12), which consistently had much higher nitrate concentrations of between 45 and 78 mg NO_3/l. The highest concentrations were observed at low flows, indicating a constant input from Witney STW. During the low-flow surveys in July and September 2020, this produced higher concentrations in the River Windrush downstream of Witney STW (Win13). During the higher flow surveys in November 2020 and January 2021, the nitrate concentrations in the two branches of the Windrush that pass through Witney (Win13 and 14) were virtually the same, indicating that the elevated nitrate concentrations from Witney STW were not impacting the downstream water quality of the Windrush during these high-flow periods..

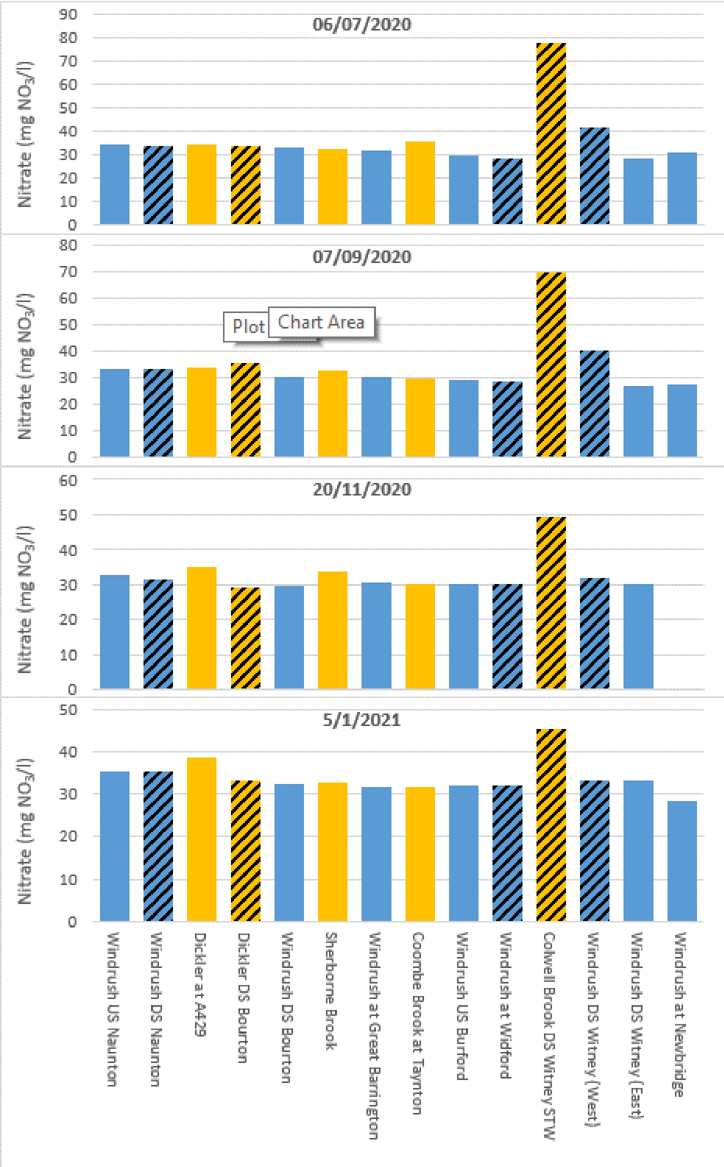

Figure 15. Nitrate concentrations from longitudinal surveys
(Blue = Windrush site. Orange = Tributary. Diagonal shading = immediately downstream of STW)

The pattern in ammonium concentration was more varied. The Colwell Brook (Win12) usually produced the highest concentrations, due to the dominance of effluent from Witney STW. The concentration was particularly high in January 2021, with a concentration of 2.78 mg NH_4 l^{-1}; probably related to the CSO discharges that were occurring at the time due to the high rainfall and flooding. There were also increases in river ammonium concentrations downstream of Burford in September and November 2020, and downstream of Bourton-on-the-Water STW in July 2020.

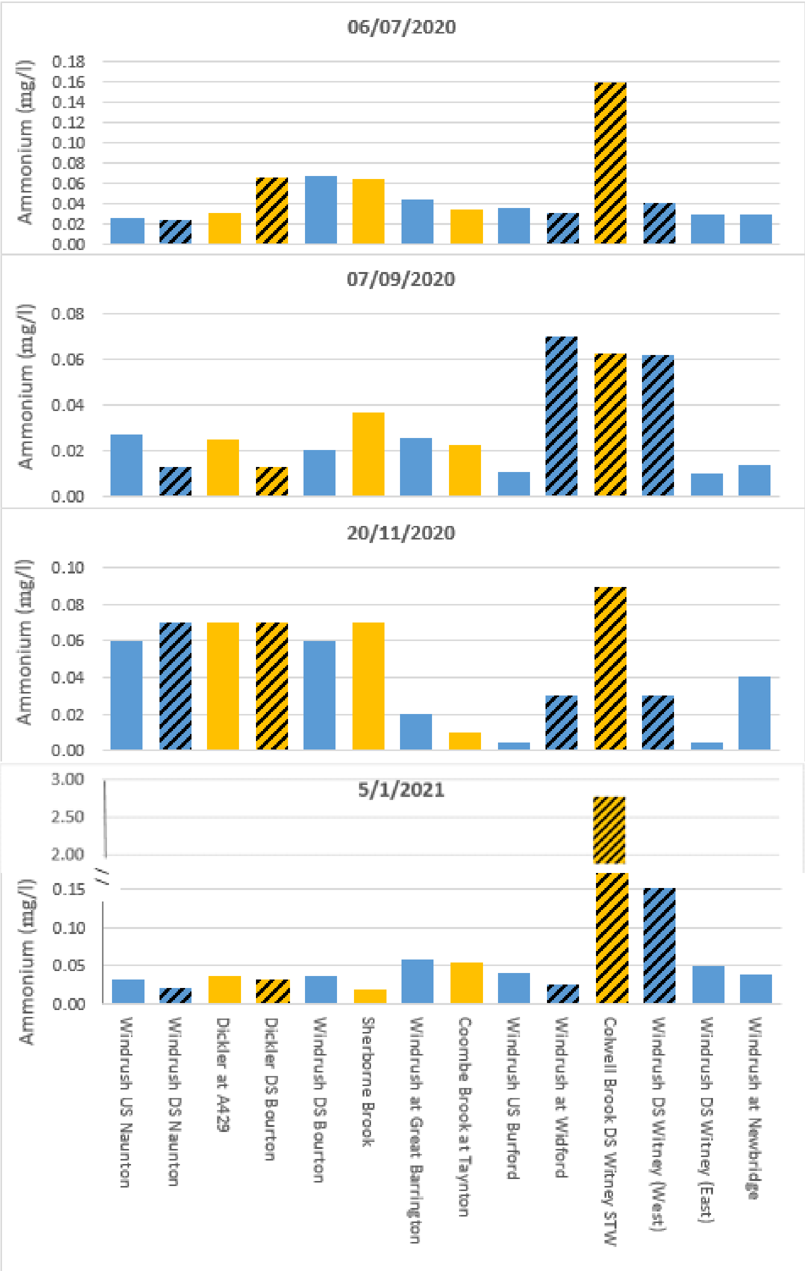

Figure 16. Ammonium concentrations from longitudinal surveys
(Blue = Windrush site. Orange = Tributary. Diagonal shading = immediately downstream of STW). Note break in y-axis in 5th January 2021 survey.

3.2 Microbiological surveys

3.2.1 Bacteria by flow cytometry

The highest bacterial concentrations usually occurred in the lower Windrush catchment, from Burford (Win10, Figure 1) to the confluence with the River Thames. The Colwell Brook (Win12) had consistently-high bacterial densities, particularly in the January 2021 survey when the CSO was active, showing that STWs can be a significant source of bacterial load to rivers. This resulted in significant development of bacterial mats (often described as sewage fungus) within the brook at that time.

Large increases in bacterial cell concentrations were observed in the R. Dickler, downstream of Bourton-on-the-Water STW (Win5), and the Windrush downstream of Witney STW (Win13).

Some of the highest bacterial densities were observed at Win1 (Windrush upstream of Naunton STW). This may possibly be due to close proximity to a bacterial source, such as a discharging septic tank or farmyard inputs, but demonstrates that agricultural activities and rural settlements can also be major sources of bacterial inputs to the river.

Figure 17. Bacterial cell counts per ml of river water, measured by flow cytometry
(Blue = Windrush site. Orange = Tributary. Diagonal shading = immediately downstream of STW).

3.2.2 Algal surveys

The phytoplankton cell densities increased along the upper Windrush to Win6, downstream of Bourton-on-the-Water (Figure 18). During the ecologically-active summer period of the July 2020 survey round, the algal cell densities continued to increase along the Windrush in the downstream direction. During the other three surveys, algal cell densities either stabilised (September and November 2020) or decreased (January 2021) downstream of Bourton-on-the-Water. The tributaries generally had low phytoplankton biomass, and the sewage effluent-dominated Colwell Brook was not a major source of algae to the Windrush.

The phytoplankton concentrations appeared to correlate with the pattern of visual turbidity/colour issues across the sites in the July and September 2020 surveys (Figure 18), with the highest algal cell counts at the visually-high turbidity sites: Dickler downstream of Bourton-on-the-Water (Win5), Windrush upstream of Burford (Win10), downstream of Burford at Widford (Win11) and the two sites downstream of Witney (Win13 and Win14). Therefore, algal biomass could potentially contribute to the colour and turbidity issues in the catchment. The algal community composition remained relatively consistent along the river, which would be expected for this relatively short river.

Large increases in algal cell densities between adjacent river sites are most likely due to either inputs from tributaries with high algal biomass, or related to areas of standing water/impoundments linked to the particular river reach that provide a long residence time for algal biomass to develop.

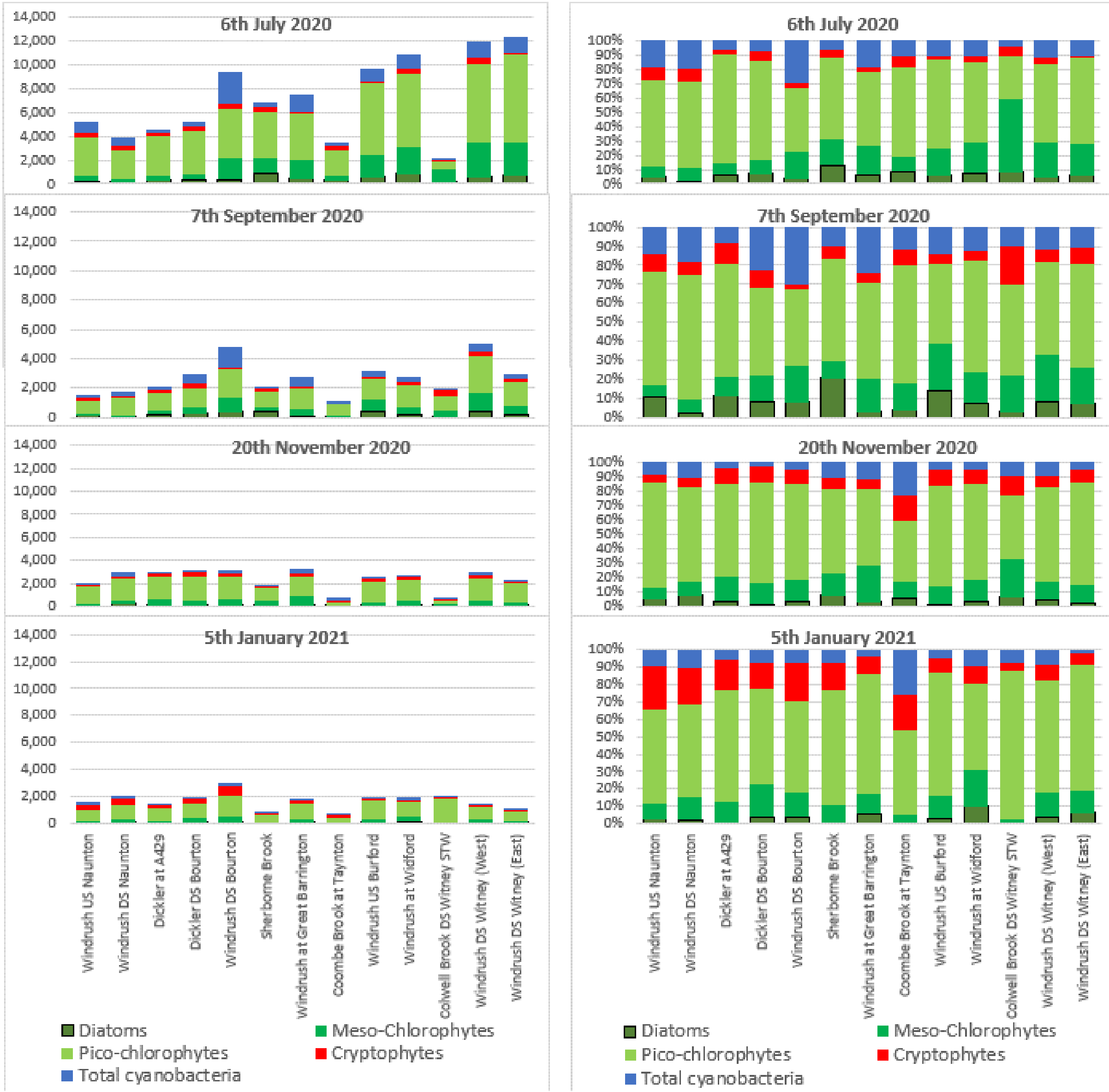

Figure 18. Phytoplankton cell counts per ml of river water, and percentage community composition, measured by flow cytometry

3.3 Comparison between the River Windrush and the Thames

The turbidity issues of the Windrush are most-clearly observed at the confluence with the River Thames at Newbridge. On some occasions during UKCEH's Thames Initiative routine monitoring, the Windrush has appeared highly turbid and milky in comparison to the Thames. In this study, samples from the Thames and Windrush at the confluence at Newbridge were taken and analysed for turbidity indicators and chemical and biological parameters that could potentially cause the variation in water clarity (Figure 19).

During the four survey rounds within this study, a major difference in water clarity between the two rivers was observed on 7th September 2020 (Figure 20). During this survey, the Windrush was extremely milky and turbid, whereas the Thames was clearer, with a typical green/brown algal colouration from the presence of diatoms and chlorophytes. The Windrush at Newbridge produced the highest turbidity value observed during the project of 34 NTU (Figure 4; Figure 5), and the suspended sediment concentration was also the highest observed at 41 mg/l; four times higher than in the Thames. There was also a major difference in the particle size distributions of the Windrush and Thames at this time, with the Thames being comprised of very fine material of less than 60 nm, whereas the Windrush sediment load had much coarser material of up to 600 nm. This high turbidity incident coincided with the highest observed pH value of 8.25 in the Windrush. The major difference in water quality between the two rivers at this time was that the Windrush had a higher pH and a relatively low soluble reactive phosphorus concentration of 71 $\mu g\ l^{-1}$ (cf. pH 8.05 and 198 $\mu g\ l^{-1}$ for the Thames). This may suggest that the milky-coloured turbidity in the lower catchment is potentially being caused by a within-river precipitation reaction. Previous studies of English Chalk streams have observed calcite precipitation occurring, which can produce a similar milkiness. It only occurs in high-alkalinity, high pH rivers with low soluble phosphorus concentrations, as phosphate ions inhibit the precipitation reaction. This is possibly why it is observed in the Windrush, and not in the Thames with its higher SRP concentration. Calcite precipitation is believed to be often related to river metabolism, with high rates of plant and algal photosynthesis reducing carbon dioxide concentrations in the water during the day, which produces the high pH values required for the chemical reaction to occur.

It would be more effective in future studies to target the Thames and Windrush sampling during these Windrush turbidity episodes, as this could provide vital information as to the cause of the milkiness of the Windrush. The use of high-frequency pH, temperature, dissolved oxygen, chlorophyll and turbidity monitoring in the lower Windrush would be valuable to understand the conditions associated with periods of high turbidity.

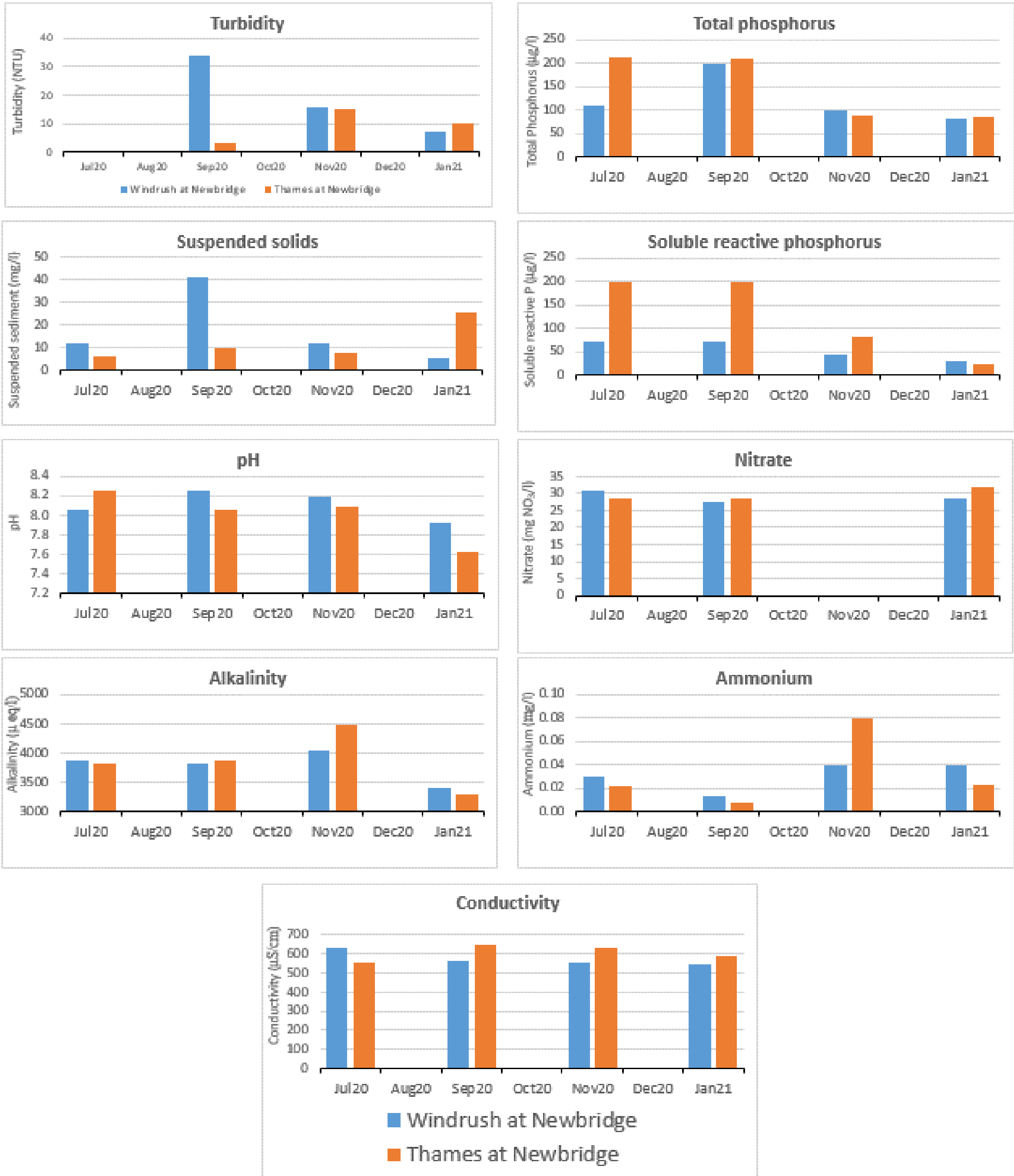

Figure 19. Comparison between the water quality of the River Windrush and the Thames at Newbridge

Figure 20. Photograph of the confluence of the Thames (left) and Windrush (right), showing difference in turbidity and colour in September 2020.

4 Conclusions

This initial limited study has not been able to definitively determine the cause of the turbidity and discolouration in the Windrush. It does, however, provide some indications as to what may be contributing to the problem.

The turbidity and suspended solids concentrations of the river were observed to increase downstream of the towns of Bourton-on-the-Water and Burford. This suggests that these turbidity issues could well be linked to the STW effluent discharges. However, the data suggests that other urban sources may also contribute for the following reasons –

- The east river channel that passes through Witney (Win14) and does not receive Witney STW effluent also sees increases in turbidity and suspended solids, and it often had a higher turbidity and suspended solids concentrations than the Witney STW-impacted west channel (Win13).
- The Colwell Brook (Win12) provides an insight into the water quality of sewage effluent discharges, and consistently had relatively low turbidity and suspended sediment concentrations in all surveys, including when the combined sewer overflow was operational in January 2021. However, the level of treatment at Witney STW is higher than the STWs serving the smaller towns, and therefore the characteristics of their effluent may well be different.

The particle size distribution (PSD) of the suspended solid loads could potentially contribute to the turbidity problems. The more turbid sites had double peaks in their PSD, having very fine primary peaks (less than 25 nm) and also a coarse secondary peak of >300 nm that was generally missing at non-turbid sites. The PSD of the sewage-impacted Colwell Brook also had this double-peak distribution, and therefore STWs could be one of the sources of this coarser material, resulting in light scattering that is creating the turbidity and colour issues. More detailed high-spatial resolution surveys through turbidity hotspots (including sampling of STW effluents and other potential inputs) may provide more insight into the changes in particle size and potential sources.

Large increases in soluble reactive phosphorus concentrations were observed downstream of the towns of Bourton-on-the-Water and Witney. In Witney, these concentrations were significantly higher in the channel receiving Witney STW effluent (Win13) than the channel that didn’t, which strongly suggests that the Witney STW was the primary source. The high nutrient concentrations in Colwell Brook provide further evidence of this. There was less change in nutrient concentrations as the Windrush passed through Burford, indicating that Burford STW was having little impact on river water quality in terms of nutrients during these surveys. As the Windrush downstream of Burford was one of the visually-turbidity “hotspots”, this suggests that the colour / clarity problems are not directly caused by nutrient pollution alone. It may be that STW phosphorus and nitrogen inputs indirectly play a part in chemical precipitation in the river, or increasing algal and bacterial cell densities, which could be causing some increase in turbidity.

The pH and alkalinities of all sites were relatively consistent across the catchment. There was no obvious input of very high alkalinity water from any of the sampled tributaries or at a specific point in the catchment that may be causing precipitation reactions to occur, which could produce the milky-coloured water that is periodically observed. However, the highest measured turbidity, suspended sediment and visually-observed milkiness occurred on the Windrush at its confluence with the Thames at Newbridge during the September 2020 survey. This coincided with the highest pH value observed in the study, which suggests that the milkiness was being caused by chemical precipitation, possibly of calcite (a calcium carbonate mineral) (House 2003). This observation also shows that the monitoring methods used in this study (suspended sediment and turbidity) were able to detect these periods of milky turbidity. Large-scale calcite precipitation in the lower Windrush could also be occurring at a smaller scale in the upper and middle catchment, which could also contribute to the hazy water clarity observed at some sites.

Some correlation was seen between algal cell densities and observed turbidity, with the sites with consistently poor clarity and colour issues (Dickler downstream of Bourton-on-the-Water, Windrush upstream and downstream of Burford, and the Windrush downstream of Witney) having highest algal concentrations. STW effluent discharges are unlikely to be major contributors to algal loading directly (as shown by the low algal concentrations in the sewage-dominated Colwell Brook), but the STW nutrient inputs to this low-phosphorus river are likely to increase algal growth rates and biomass, particularly of biofilms. These increased algal concentrations in the water could be responsible for causing the colouration, and the increased rates of photosynthesis (especially from algal biofilms on river surfaces) are likely to produce daily increases in pH and dissolved oxygen concentrations, which have been shown to contribute to calcite precipitation. Increased algal biomass can also be caused by hydrological river conditions such as impoundments, weir structures and connection to relatively-static water bodies such as lakes and canals (Bowes et al. 2012a), which provide the residence time for algal biomass to develop. The potential impact of such areas along the Windrush should be investigated further.

5 Recommendations for future research

The four survey rounds have given some insights, but have not been comprehensive enough to provide the key information and determine the causes of the colour and turbidity issues. Further catchment-scale surveys should cover the full year and flow conditions. Some surveys should specifically target periods where the turbidity and milkiness problems are at their greatest, possibly by collaboration with the Catchment Partnership or local people to alert fieldworkers when the problem is occurring.

Future surveys could be expanded to include other analyses related to water colouration and turbidity, such as -

- Total organic carbon / dissolved organic carbon (known to cause water colour issues, although this tends to be brown in colour)
- Fluorimetry, to quantify and characterise the dissolved organic matter, as this is known to cause issues with colour and turbidity.
- Turbidity measurements using more advanced and reliable turbidity instruments, especially continuous sonde data.
- X-ray diffraction to characterise mineralogy of sediments and potential precipitates in the water column. This could identify the mineralogy of clay particles and identify the chemical composition of precipitates.
- Integration of citizen science activities to provide greater spatial and temporal resolution.

This initial work has demonstrated that turbidity, nutrients, conductivity, bacterial and algal concentrations tend to increase as rivers flow through towns. Targeted, higher spatial-resolution, surveys along short stretches of the river could yield important information about how these key parameters change through the urban environment and identify the principal sources of turbidity, including STW effluents, road runoff, miscellaneous point inputs, misconnections, quarrying activities, river impoundments, etc.

Arguably the most effective means of investigating the turbidity issues would be to deploy high frequency (hourly) water quality monitoring (e.g. Sondes) at Windrush sites where the milkiness issue is most obvious. These sondes can measure some of the key parameters that could be associated with turbidity and precipitation episodes, in particular: turbidity; pH; temperature; dissolved oxygen; and chlorophyll. Any existing high-frequency data from previous studies could be examined.

Previous UKCEH studies have shown how precipitation reactions in high-alkalinity rivers can be caused by large daily pH and dissolved oxygen fluctuations due to high rates of photosynthesis and respiration (House and Denison, 1997). Deployment of water quality probes is the only way to capture these and relate them to turbidity. If Sonde turbidity meters were able to detect the clarity issues, they would pin-point the exact times and conditions when turbidity episodes occur.

The turbidity issue is most clearly seen at the confluence of the Windrush and Thames at Newbridge. UKCEH have gathered weekly water quality and algal monitoring data for these two sites over the last ten years, as part of their Thames

Initiative Platform (Bowes et al. 2018). Further analysis of these data, together with those from other nearby tributaries, collected as part of the same initiative (i.e. Leach, Coln, Cherwell, Ray and Evenlode), could provide key insights into the turbidity issues of the Windrush and help determine to what extent changes in the water quality over recent years have been causing the reported declines in the river's water clarity.

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7 Appendices

Appendix 1. Site photographs

July 2020 | Sept 2020 | Nov 2020 | Jan 2021

River Dickler downstream of Bourton-on-the-Water and STW

July 2020

Sept 2020

Nov 2020

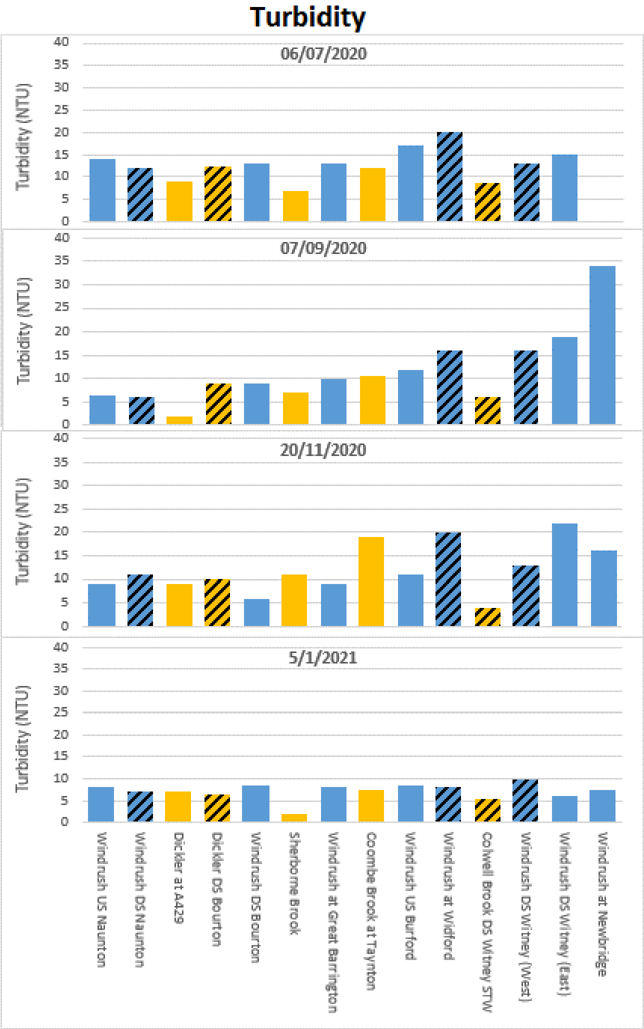
Jan 2021

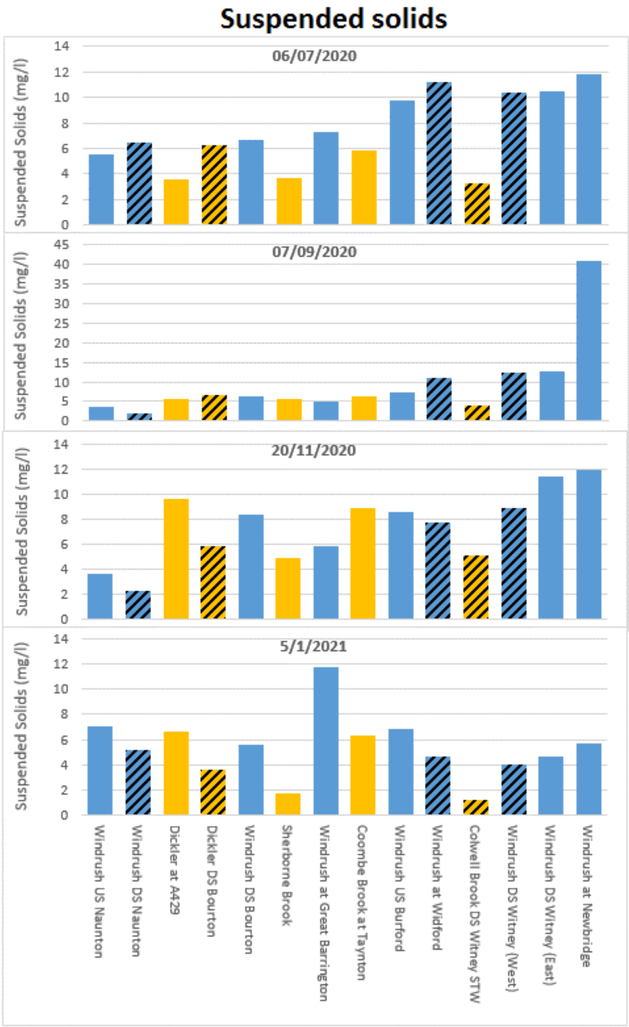
River Windrush downstream of Burford at Widford

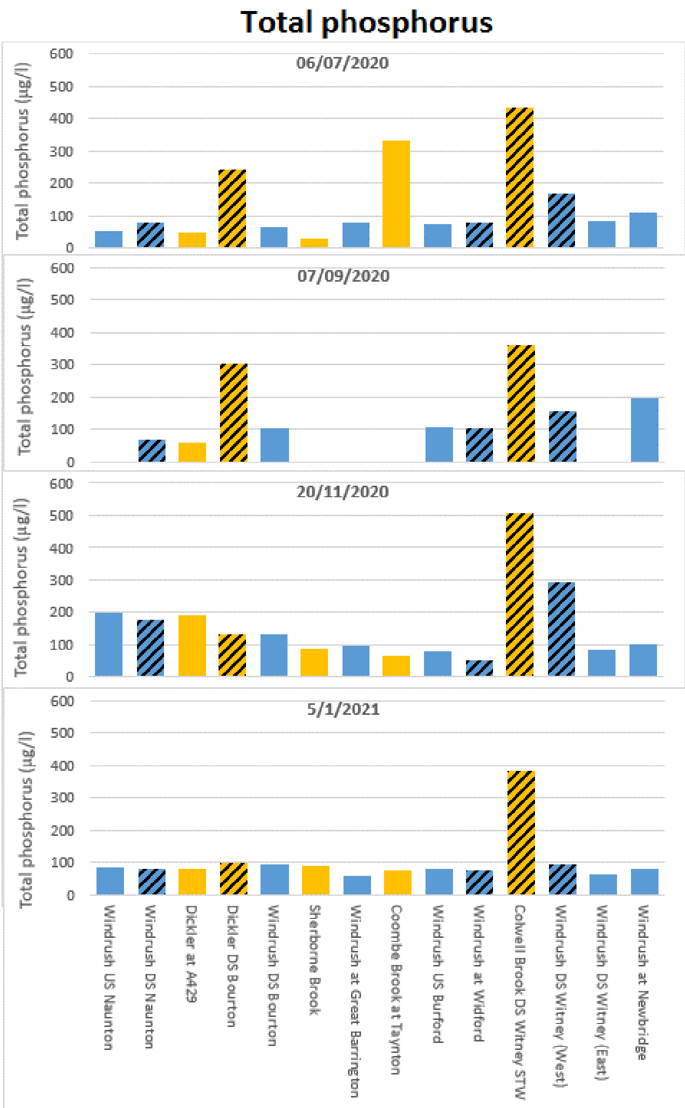
Sept 2020 **Nov 2020** **Jan 2021**

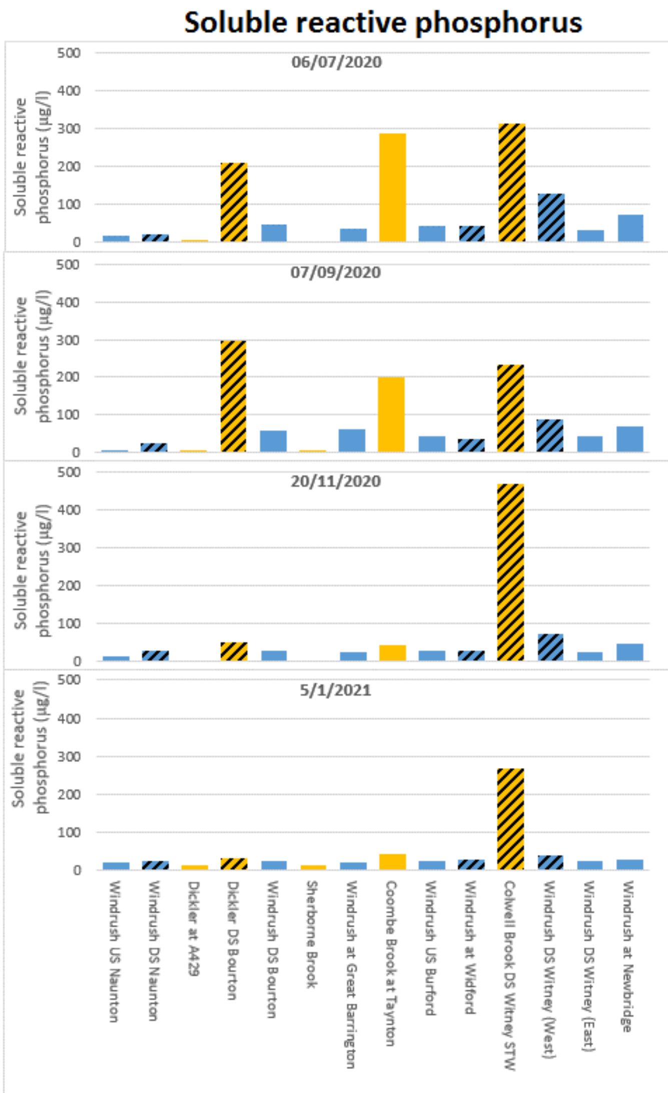
Confluence of River Windrush and River Thames at Newbridge

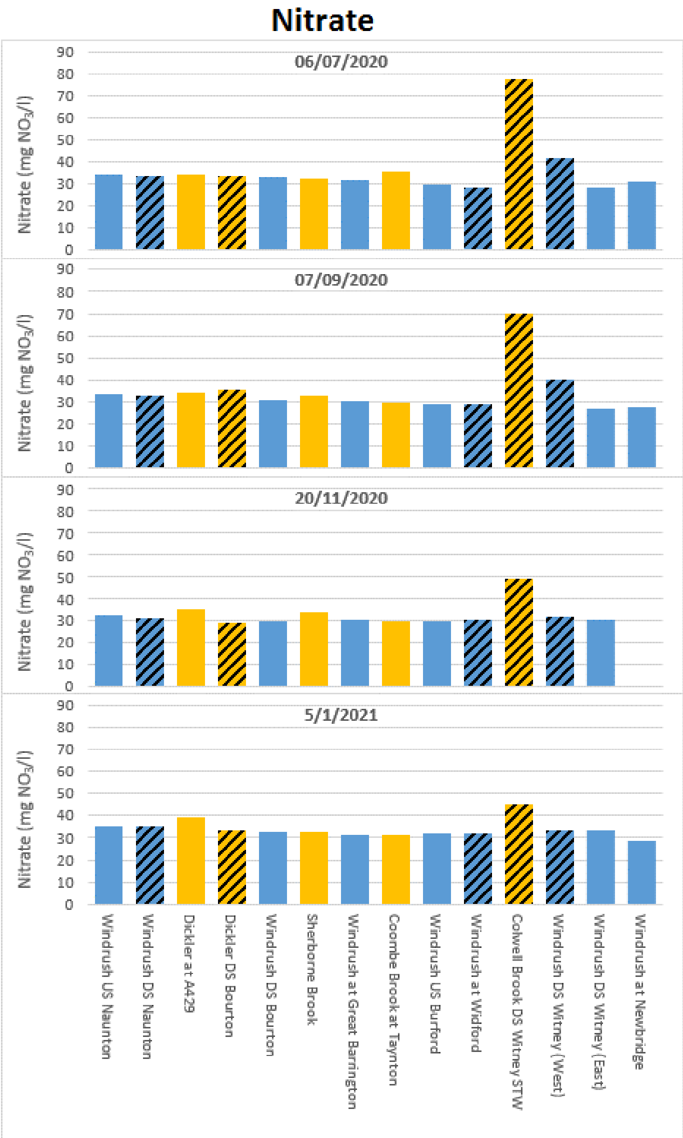
Appendix 2. Water quality survey data with common y-axes

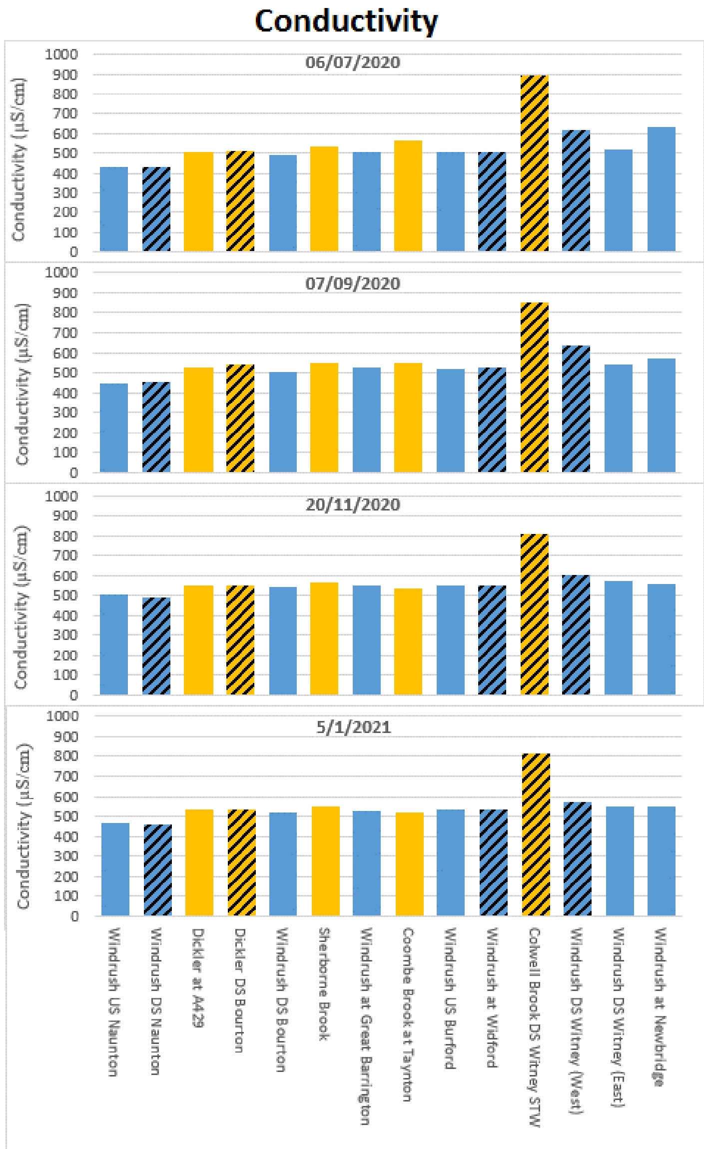





Total phosphorus
06/07/2020
07/09/2020
20/11/2020
5/1/2021
Total phosphorus (µg/l)
0
100
200
300
400
500
600
Windrush US Naunton
Windrush DS Naunton
Dickler at A429
Dickler DS Bourton
Windrush DS Bourton
Sherborne Brook
Windrush at Great Barrington
Coombe Brook at Taynton
Windrush US Burford
Windrush at Widford
Colwell Brook DS Witney STW
Windrush DS Witney (West)
Windrush DS Witney (East)
Windrush at Newbridge


Soluble reactive phosphorus
06/07/2020
07/09/2020
20/11/2020
5/1/2021
Soluble reactive phosphorus (µg/l)
0
100
200
300
400
500
Windrush US Naunton
Windrush DS Naunton
Dickler at A429
Dickler DS Bourton
Windrush DS Bourton
Sherborne Brook
Windrush at Great Barrington
Coombe Brook at Taynton
Windrush US Burford
Windrush at Widford
Colwell Brook DS Witney STW
Windrush DS Witney (West)
Windrush DS Witney (East)
Windrush at Newbridge


Nitrate
06/07/2020
07/09/2020
20/11/2020
5/1/2021
Nitrate (mg NO3/l)
Windrush US Naunton
Windrush DS Naunton
Dickler at A429
Dickler DS Bourton
Windrush DS Bourton
Sherborne Brook
Windrush at Great Barrington
Coombe Brook at Taynton
Windrush US Burford
Windrush at Widford
Colwell Brook DS Witney STW
Windrush DS Witney (West)
Windrush DS Witney (East)
Windrush at Newbridge


Conductivity
06/07/2020
07/09/2020
20/11/2020
5/1/2021
Conductivity (µS/cm)
Windrush US Naunton
Windrush DS Naunton
Dickler at A429
Dickler DS Bourton
Windrush DS Bourton
Sherborne Brook
Windrush at Great Barrington
Coombe Brook at Taynton
Windrush US Burford
Windrush at Widford
Colwell Brook DS Witney STW
Windrush DS Witney (West)
Windrush DS Witney (East)
Windrush at Newbridge

Bacteria
06/07/2020
07/09/2020
20/11/2020
5/1/2021
Bacteria (cells/ml)
7,000,000
6,000,000
5,000,000
4,000,000
3,000,000
2,000,000
1,000,000
0
Windrush US Naunton
Windrush DS Naunton
Dickler at A429
Dickler DS Bourton
Windrush DS Bourton
Sherborne Brook
Windrush at Great Barrington
Coombe Brook at Taynton
Windrush US Burford
Windrush at Widford
Colwell Brook DS Witney STW
Windrush DS Witney (West)
Windrush DS Witney (East)
Windrush at Newbridge

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