AtkinsRéalis

South Staffordshire Water

28th September 2023
5211472-ATK-RP-7.15.7-121

CLIMATE CHANGE IMPACTS ON WATER QUALITY

Notice

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Client	South Staffordshire Water
Project	Climate change impacts on water quality
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Contents

1. Introduction

AtkinsRéalis was commissioned by South Staffordshire Water to undertake an assessment of how climate change may impact on water quality. Two separate assessments were undertaken, the first considered the impact of climate change on surface water quality and the second the impact of climate change on groundwater quality. The assessments also considered the knock-on implications for South Staffordshire Water's and Cambridge Water's surface water sources and groundwater sources and future mitigation strategies to manage the impacts requirements.

The surface water quality and groundwater quality assessments followed a similar, high-level approach. The assessments will be used to inform the Long-Term Delivery Strategy (LTDS) component of South Staffordshire Water's and Cambridge Water's PR24 Business Plan.

This report provides a brief introduction to the two assessments and a summary of the deliverables. The final deliverables for each assessment are provided in Appendix A and Appendix B.

2. Surface water quality assessment

The surface water quality assessment focused on South Staffordshire Water's two large surface water abstractions; one at Hampton Loade on the River Severn (via Chelmarsh Reservoir that provides short term storage), and another from Blithfield Reservoir that receives pumped inputs from the River Blithe and natural inflow from a substantial catchment.

The surface water quality assessment included the following steps:

- Review outputs from climate change hydrological models to determine how the frequency of extreme events that can affect water quality is likely to change in the future.
- Review the historical relationship between river water quality and river flow for key chemicals of concern.
- Review historical water treatment risks to raw water quality to identify 'events' that can be considered as hazardous in terms of drinking water quality.
- Apply this information to assess the vulnerability of the water treatment works to water quality impacts related to climate change.
- Identify mitigation, including water treatment and storage options to reduce the risk of the water quality impacts on these sources.
- Identity the likely timeline over which mitigation options should be implemented.

3. Groundwater quality assessment

The groundwater quality assessment focused on Permo-Triassic Sandstone aquifer which South Staffordshire Water's abstracts groundwater from, and the Chalk aquifer which Cambridge Water abstracts groundwater from. The groundwater quality assessment included the following steps:

- Review of the relationship between climate change and groundwater quality identified in a scoping study undertaken by the British Geological Survey (BGS) in 2021.
- Undertaken, for each aquifer South Staffordshire Water and Cambridge Water abstract from, an assessment of the relationships between climate and groundwater quality to determine the relationships that are likely to be particularly relevant to each aquifer.
- Alongside the aquifer scale assessment, a high-level source screening exercise to identify sources that are likely to be more vulnerable to changes in groundwater quality.
- Review treatment risks and investment options.

4. Deliverables

The surface water quality assessment is documented in the following report, which is presented in Appendix A:

- Atkins (2023) Climate change impacts on raw water quality (Reference: 5211472-ATK-RP-7.15.4.2-122).

The deliverable from the groundwater quality assessment was a slide deck presentation, which is presented in Appendix B:

- Atkins (August 2023) Climate change and impacts on groundwater quality (Reference: 5211472-ATK-RP-7.15.6-116).

APPENDICES

Appendix A. Surface water quality assessment

Climate Change Impacts on Raw Water Quality

South Staffordshire Water

27 September 2023

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1. Introduction

South Staffordshire Water operates two large surface water abstractions; one at Hampton Loade on the River Severn (via Chelmarsh Reservoir that provides short term storage), and another from Blithfield Reservoir that receives pumped inputs from the River Blithe and natural inflow from a substantial catchment. Both sources are subject to poor water quality at times, and this can reduce the output from their respective water treatment works.

Climate change may affect water quality in these sources in a number of ways which, in turn, might affect the reliability of the yield from these sources:

1. *More frequent and more extreme high flows*: Water quality in rivers can deteriorate substantially during high flow events because of increased transportation of particulate materials from the catchment, remobilisation of contaminants from river sediments and an increase in storm wastewater discharges.
2. *More frequent droughts and low flow conditions:* Under low flow and drought conditions, there will tend to be less dilution of inputs of pollution to rivers from upstream wastewater treatment works and industrial discharges.
3. *Modified nitrate transport associated with dry periods:* Nitrate has a complex relationship with catchment hydrology, but the risk of elevated nitrate concentrations is increased by extreme river flow conditions.
4. *Increased algal growth in low flow periods:* In larger rivers, low flows can be associated with excessive algal populations and in some cases cyanobacteria (blue green algae)

The objective of this project is, firstly, to assess whether the reliability of these sources is likely to be affected by deterioration in water quality that results from climate change by interpretation of pre-existing data and climate model outputs. A second key objective is to identify mitigation options, if required, along with a timeline over which they need to be implemented.

This project provides a high-level assessment of these risks and mitigation options. Detailed modelling and engineering design do not form part of the scope. Other potential impacts of climate change, not related to catchment hydrology, such as impacts on land use and soil processes are not considered.

1.1. Project tasks

Specific model tasks are to:

1. Review outputs from climate change hydrological models to determine how the frequency of extreme events that can affect water quality is likely to change in the future.
2. Review the historical relationship between river water quality and river flow for key chemicals of concern.
3. Review historical water treatment risks to raw water quality to identify ‘events’ that can be considered as hazardous in terms of drinking water quality.
4. Apply this information to assess the vulnerability of the water treatment works to water quality impacts related to climate change.
5. Identify mitigation, including water treatment and storage options to reduce the risk of the water quality impacts on these sources.
6. Identity the likely timeline over which mitigation options should be implemented.

Project outputs related to these elements are presented in the following sections.

2. Climate change impacts of river flows

2.1. Flow gauge selection

This study focuses on two locations:

1. Hampton Loade on the River Severn - See map
2. The River Blithe near Blithfield Reservoir - See map

For these two locations, two flow gauges with historical flow measurement data from the National River Flow Archive[1] were identified, close to the locations of interest:

7. River Severn: ID 54001 - Severn at Bewdley: NRFA Station Data for 54001 - Severn at Bewdley (ceh.ac.uk)
8. River Blithe: ID 28002 - Blithe at Hamstall Ridware: NRFA Station Data for 28002 - Blithe at Hamstall Ridware (ceh.ac.uk)

Climate change projections for the flow gauges above can be derived from two datasets available in the UK. These provide climate change perturbed projections of flow gauge data:

1. **FutureFlows:** The FutureFlows dataset is a research project developed by the UK Centre for Ecology & Hydrology (CEH) in collaboration with other organizations. It focuses on assessing the potential impact of climate change on river flows in the UK based on UKCP09. The dataset provides hydrological model simulations of river flows at various locations across the country under different climate change scenarios. It includes data from over 280 flow gauges. FutureFlows has been widely used within the water industry and for various research purposes, making it a valuable tool for understanding and planning for future hydrological changes in the UK.
2. **eFLaG:** The eFLaG project is a successor to the Future Flows (FF) dataset, developed to enhance the resilience of the water sector to drought events in the UK. It delivers an 'enhanced Future Flows and Groundwater' (eFLaG) dataset of nationally consistent climatological and hydrological projections based on UKCP18. The eFLaG dataset includes data from 200 flow gauges. It aims to provide robust assessments of drought risk, supporting improved planning methods for drought resilience. It builds upon advancements in national-scale hydrological modelling and new climate products.

Given that these datasets only cover a limited number of flow gauges across the country, it is often necessary to use proxy or 'donor flow gauges' to broadcast results from locations with similar hydrology. A 'proxy' flow gauge refers to a substitute used to estimate river flows or water levels when direct measurements from flow gauges are not available or limited.

2.1.1. River Severn

For the River Severn the same flow gauge used to collect historical data (54001 - Severn at Bewdley) is present in both the FutureFlows and eFLaG datasets. This flow gauge was therefore selected from the eFLaG dataset.

2.1.2. River Blithe

The flow gauge used to collect historical data for the River Blithe is not available in either the eFLaG or FutureFlows datasets. For this reason, it was necessary to find a proxy flow gauge to estimate the effect of climate change indirectly. The quality of the donor flow gauge was assessed based on the similarity of hydrometric data from nearby gauges. In particular, the shape of the flow duration curve, the magnitude of the flow and the proximity between flow gauges were used to determine the best donor. Figure 2-1 shows the flow duration curve for the River Blithe.

[1] National River Flow Archive (ceh.ac.uk)

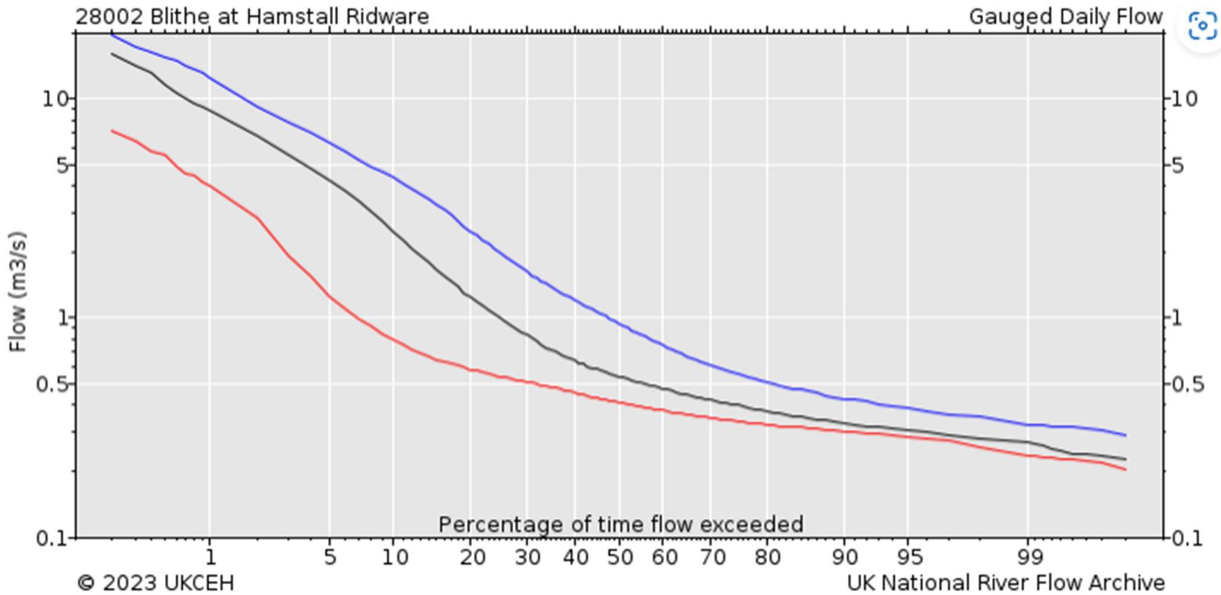

Figure 2-1 - Flow duration curve for the River Blithe flow gauge

The following flow gauges were considered, from both FutureFlows and eFLaG datasets (flow duration curves for the sites not chosen are shown in Appendix C):

- 28018 - Dove at Marston (NRFA Station Mean Flow Data for 28018 - Dove at Marston on Dove (ceh.ac.uk))

- 28055 - Ecclesbourne at Duffield (NRFA Station Mean Flow Data for 28055 - Ecclesbourne at Duffield (ceh.ac.uk))

- 28009 – Trent at Colwick (slightly better FDC, NRFA Station Mean Flow Data for 28009 - Trent at Colwick (ceh.ac.uk))

- 28046 - Dove at Izaak Walton (NRFA Station Mean Flow Data for 28046 - Dove at Izaak Walton (ceh.ac.uk))

From all the candidates assessed, the selected flow gauge was ‘28046 – Dove at Izaak Walton’ (the flow duration curve for this site is shown in Figure 2-2).

. This choice was based on the following reasons:

- **Data quality**: eFLaG is a revision on FutureFlows projections, based on UKCP18, a major upgrade compared to UKCP09. eFLaG data was therefore preferred to FutureFlows.
- **Flow magnitude**: The flow magnitude in this flow gauge is similar to that of the River Blithe.
- **Hydrometric data**: The cumulative frequency distribution (CFD) of the River Blithe is heavily influenced by the reservoir, and no good matches were found amongst the available flow gauges.
- **Proximity**: It is the closest flow gauge to the original from the eFLaG dataset (see Figure 2-3), and both flow gauges are in tributaries of the River Trent. This proximity should be enough to ensure the overall trend of climate change adjustments is still valid, as demonstrated by the recent assessments carried out by the Environment Agency (Environment Agency, 2022).

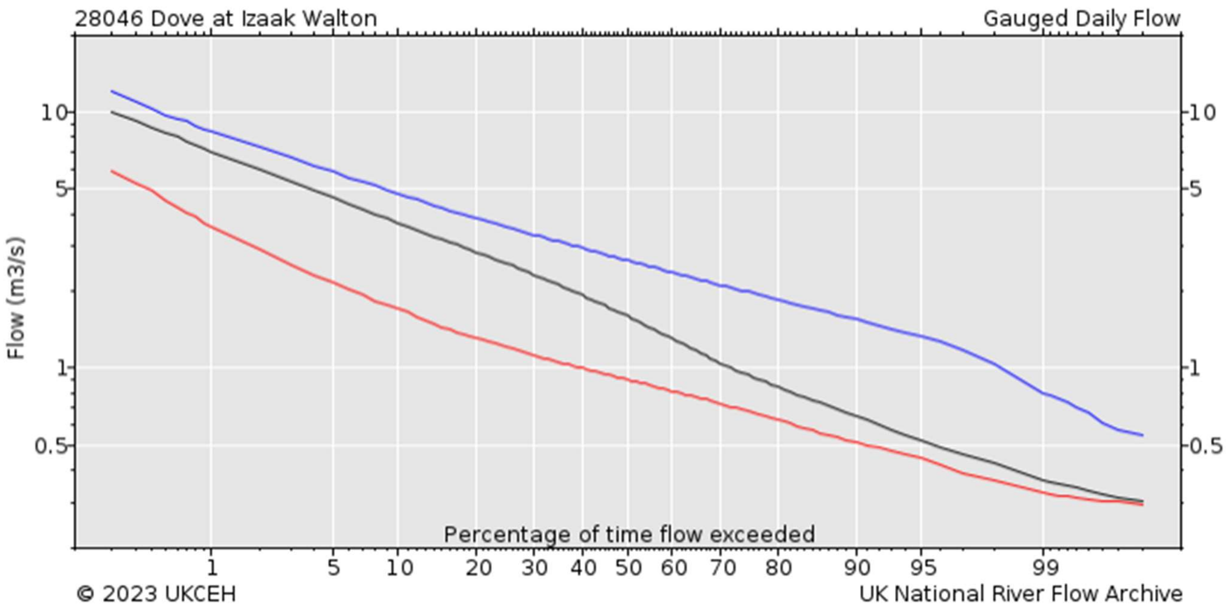

Figure 2-2 - Flow duration curve for the Izaak Walton flow gauge

The eFLaG dataset is based on RCP8.5, a representative pathway with comparatively high greenhouse gas emissions and no mitigation strategies, leading to a global average temperature rise of 4.3°C by 2100. Although this is the most up-to-date dataset, given the current scenario in climate actions a medium pathway with moderate levels of mitigation such as RCP6.0 could be considered more appropriate. However, this is only relevant for long term projections (i.e., 2060-2080). For the purposes in this study, in the medium term (e.g., 2030-2050), RCP8.5 and RCP6 largely overlap (Hannaford, et al., 2023.

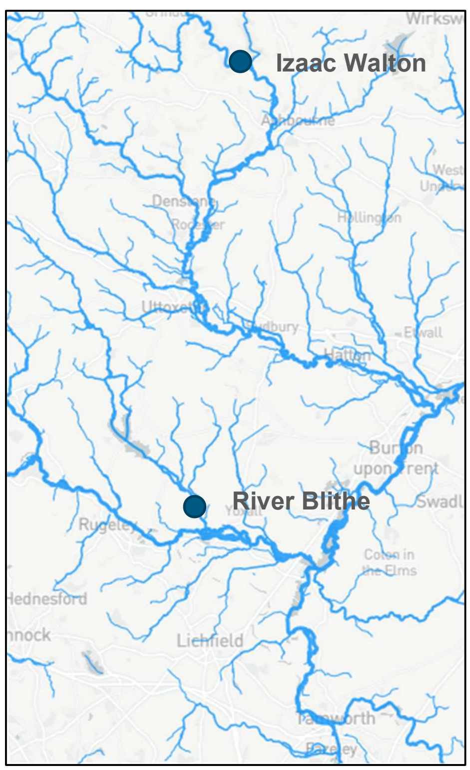

Figure 2-3 – Twin maps showing the locations of the River Blithe flow gauge (left) and the Izaak Walton flow gauge (right)

2.2. Data analysis

For each flow gauge, two datasets were selected: 1) flow measurements with historical data, and 2) projected flows with climate change perturbations from the eFLaG dataset. Historical measured data was used to evaluate the current relationship between flow and water quality (see Section 4), whereas eFLaG was used to assess the effect of climate change on the river's hydrology. Since historical data contains gaps in time, eFLaG data was used to extract both the current and future flow periods. eFLaG historical data has been fitted to flow measurements and therefore provides an accurate representation of historical flows while filling in the gaps with a peer-reviewed catchment model.

2.3. Projected flows

2.3.1. Heat maps

This section focuses on the River Severn, and analyses the flow gauge data, comparing historical flow measurements spanning ten-year time periods (each covering a range of hydrological conditions) a current period of 2010 to 2020, with eFLaG projections for the periods 2025 to 2035 and 2045 to 2055 (equivalent plots for the Izaac Walton gauge are shown in Appendix D). To ascertain the impacts of climate change on its hydrology, we have calculated key statistical moments for river hydrology using the flow time series data, plotted as heatmaps, enabling us to gain insights into the changing dynamics of the river's flow over time (see Figure 2-4 to Figure 2-9). Each cell shows the flow in m^3/s, across all ensemble members (Y axis) and time periods (X axis). The climate-induced variations have been examined through the 12 ensembles provided by the dataset, each possessing distinct calibration settings and thereby portraying a different potential future. By comparing these statistical moments across different periods and ensemble members, we aim to discern trends that emerge because of climate-induced alterations. Each one of the statistics is discussed below.

Figure 2-4 shows the variation in mean flow. Changes in climate are expected to increase the extreme weather and river flow conditions, which includes both droughts and extreme weather. For this reason, the mean is not the best value to assess the impact of climate change as these effects often counteract each other. In the figure we see that The future trend is uncertain, with some ensembles showing an increase in mean flow, and others showing a decrease.

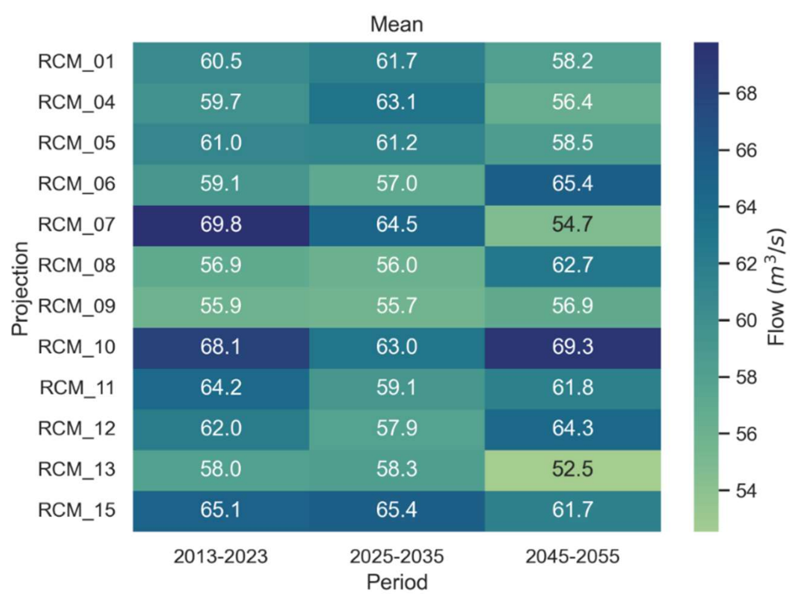

Figure 2-4 – Heatmap showing the mean flow for different periods from 2013 to 2055 for each ensemble member in the eFLaG dataset

The median (Figure 2-5) shows a clearer picture of the state of flows in future trends. In general, most ensemble members expect the median flow to be lower in the future. The implication is that this trend poses considerable challenges for water availability and resource management. As rivers experience diminished flow during normal periods, water scarcity could become a pressing concern for various sectors, including agriculture, industry, and domestic use.

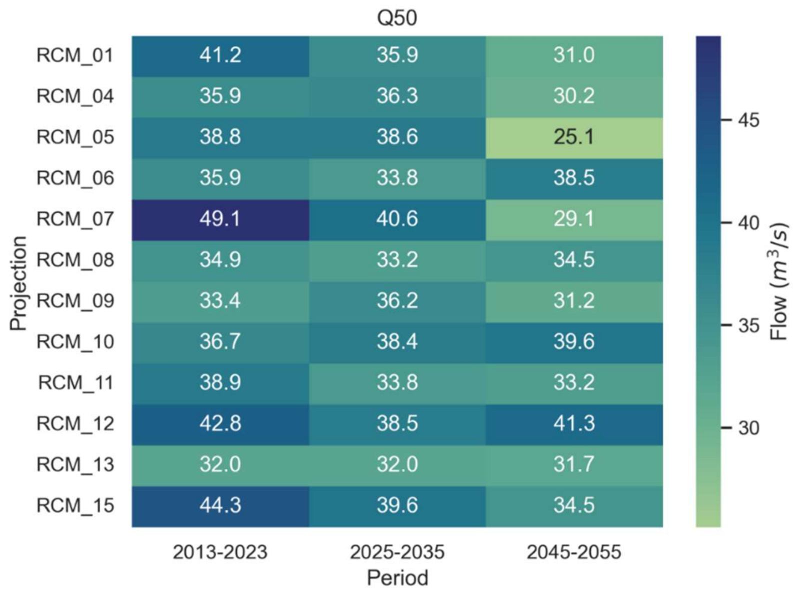

Figure 2-5 – Heatmap showing the median flow for different periods from 2013 to 2055 for each ensemble member in the eFLaG dataset

Another useful metric is the 95th and 5th percentile (Figure 2-6 and Figure 2-7 respectively), which show how the extreme river flows are going to be transformed by climate change. The 5th percentile (or Q95) in particular shows likelihood a very dry future events (i.e., the flow that is surpassed 95% of the time), with all values being smaller across all scenarios in 2045-2055.

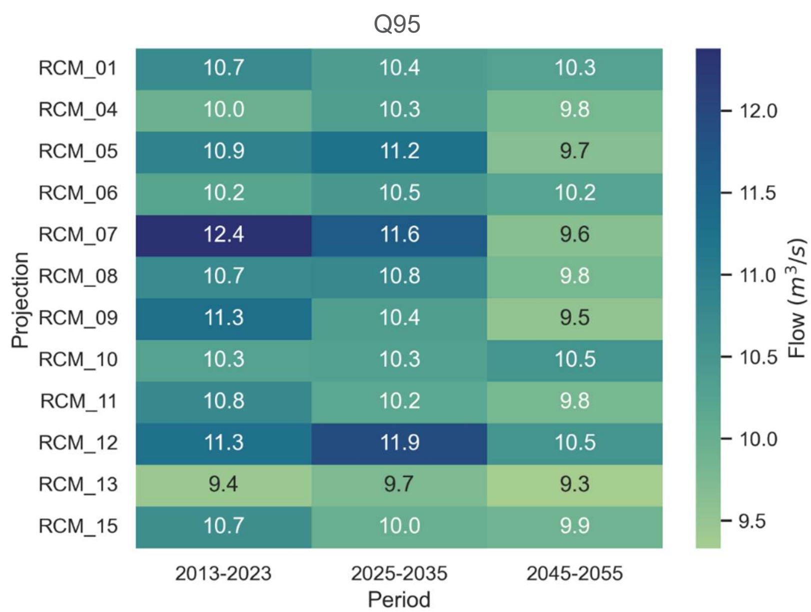

Figure 2-6 – Heatmap showing the 5th percentile flow (Q95) for different periods from 2013 to 2055 for each ensemble member in the eFLaG dataset

The 95th percentile (or Q5) shows an increase in extreme events for many of the ensemble members, especially for RCM_10. This could lead to severe flooding and erosion. The accelerated flow may also increase the transport of sediment, nutrients, and pollutants into water bodies, negatively impacting water quality.

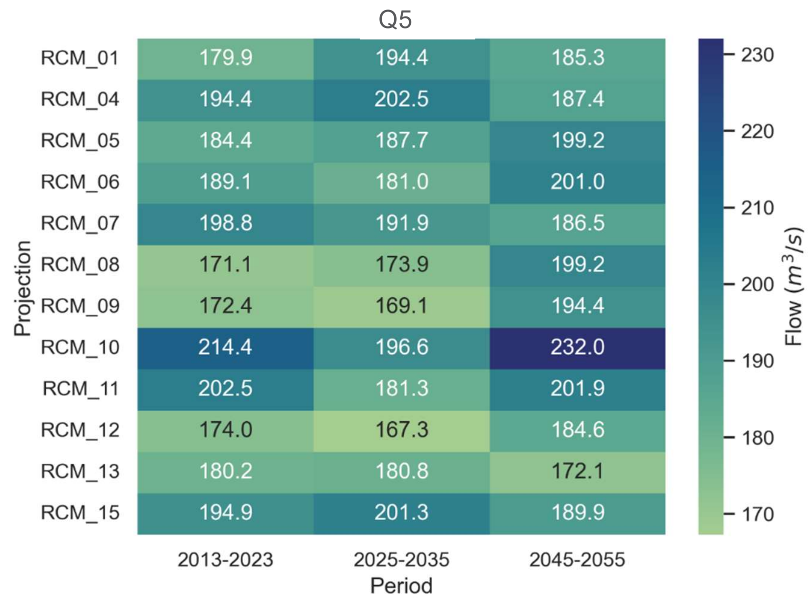

Figure 2-7 – Heatmap showing the 95th percentile flow for different periods from 2013 to 2055 for each ensemble member in the eFLaG dataset

The same trends are observed in the 1th (Q99) and 99th (Q1) percentiles (Figure 2-8 and Figure 2-9 respectively). The decrease in median and low-flow conditions threatens water availability, while the increase in extreme events poses risks to water quality and ecosystem stability.

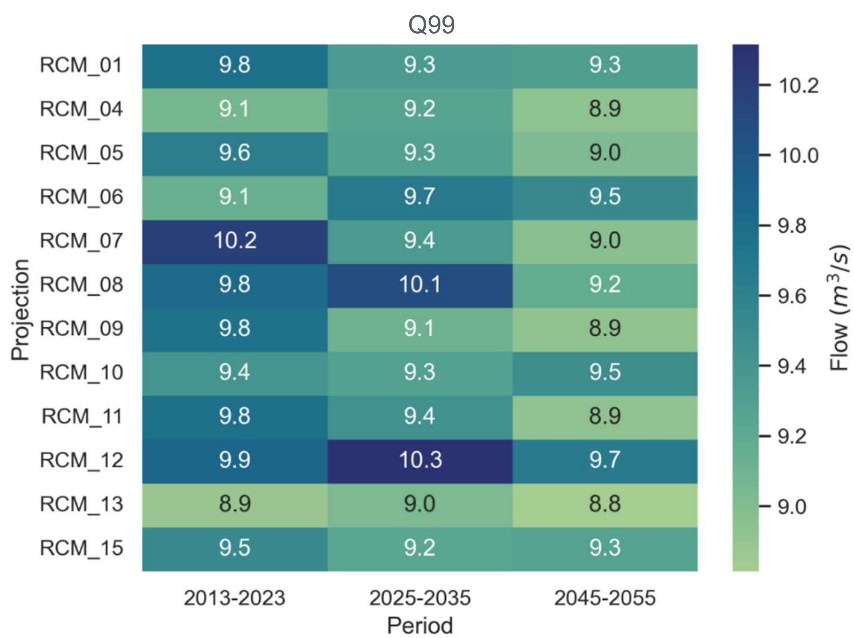

Figure 2-8 – Heatmap showing the 1th percentile flow for different periods from 2013 to 2055 for each ensemble member in the eFLaG dataset

Figure 2-9 – Heatmap showing the 99th percentile flow for different periods from 2013 to 2055 for each ensemble member in the eFLaG dataset

2.3.2. Time series for extreme percentiles

Figures 2-13 and 2-14 show the projected long-term change in annual flow statistics for high and low flows in the River Severn and the Isaac Walton gauge (proxy for River Blithe). The grey lines show the individual ensemble members and the bold black line the statistics for all of the members combined. There is a clear long term downward trend in the 1st and 5th percentile flows (Q99 and Q95) at both locations, but this is most evident for the Isaac Walton gauge. In contrast, there is a smaller upward trend in the high flow percentiles at both sites. Variability between the ensemble members tends to increase toward the later part of the time series which is not the case for low flows.

Overall, therefore, the change in low flows is greater than high flows so this is more likely to stress the existing water supply systems, by increasing the likelihood of poor water quality that is associated with low flows. In addition, the number of days when abstraction can take place or the amount of water that can be abstracted above the Hands-Off Flows is likely to reduce which may impact on the flexibility of managing abstraction at other times in order to protect the yield of the system. Section 4 looks more closely at the potential implication of these changes on water quality and water availability and the reliability of these sources.

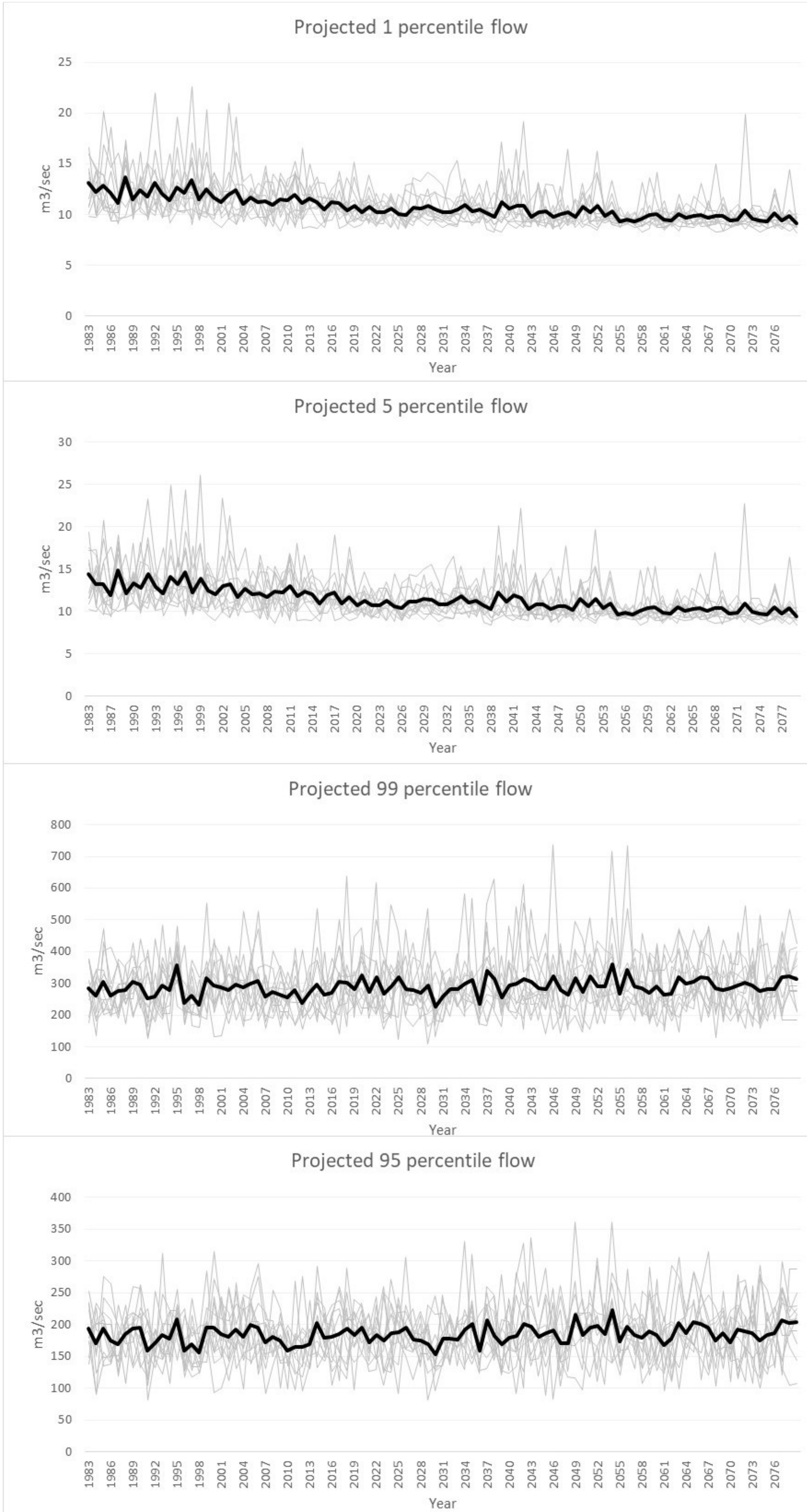

Figure 2-10 – Long term projection of annual flow statistics – Severn

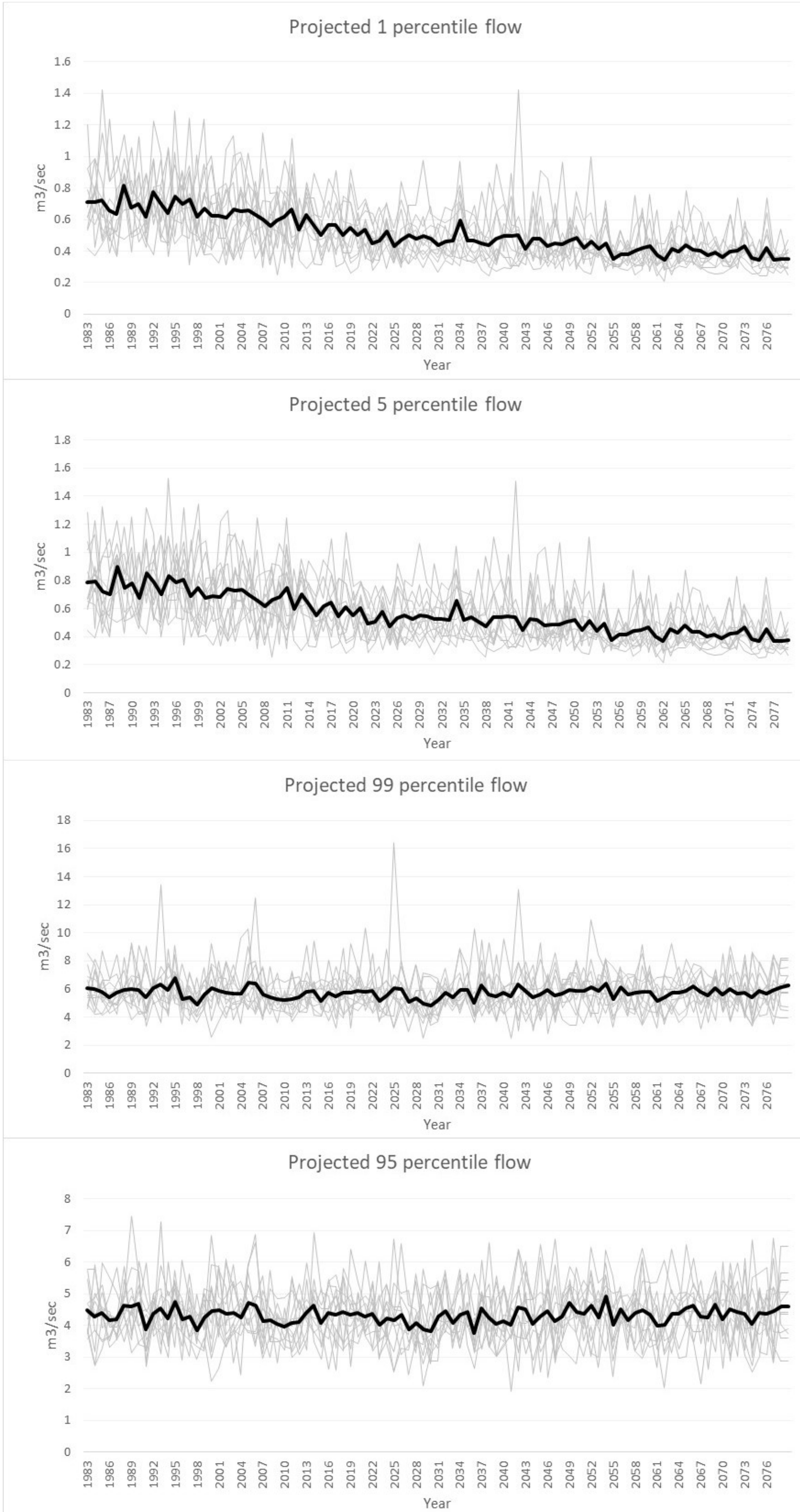

Figure 2-11 – Long term projection of annual flow statistics – Izaac Walton (proxy for Blithe)

3. Relationship between river flow and water quality

3.1. Data analysis

Water quality data was provided by South Staffordshire Water and obtained from the Environment Agency's WIMS water quality archive[2] (year 2000 to present). WIMS data was downloaded in June 2023 for the sites summarised in Table 3-1. Table 3-2 summaries the continuous and spot sampling locations provided by South Staffordshire Water. Where multiple sampling sites occurred at the same location, sites were combined for analysis. Sampling locations are displayed in Figure 3-1 (Hampton Loade) and Figure 3-2 (River Blithe/Blithfield reservoir).

Determinands of interest included suspended solids, colour, turbidity, pH, temperature, conductivity, metals, nutrients, faecal indicator organisms, chlorophyll-a, dissolved organic carbon (DOC) and pesticides which were selected as those most likely to impact on drinking water risk based on previous projects on these sites and elsewhere. Summary of the determinands available for each site is provided in Figure 3-4 and

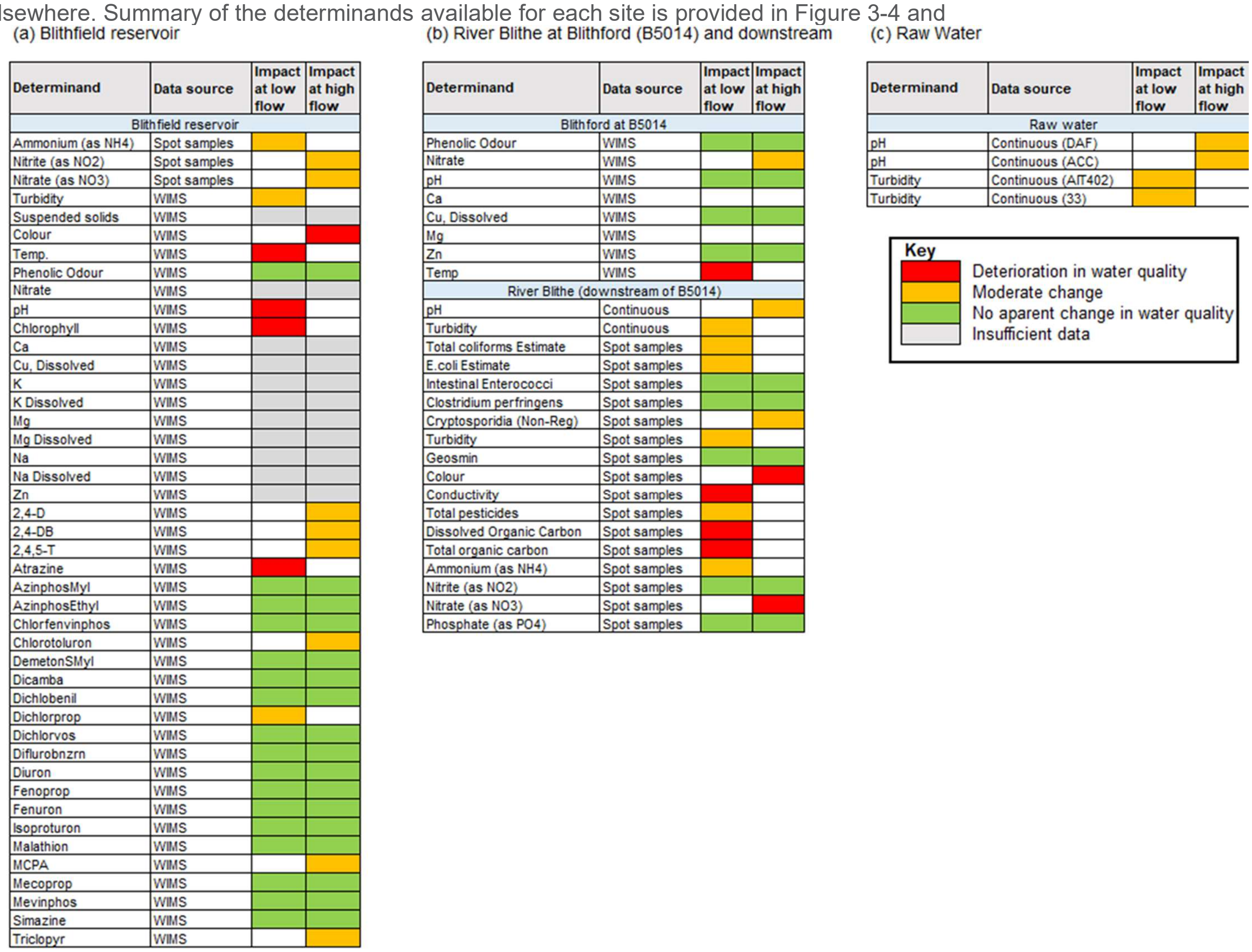

Figure 3-5.

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[2] Open WIMS data

Data was processed prior to analysis; for spot samples, concentrations were halved if below the limit of detection. For the continuous monitoring, the frequency of the data was converted from every 5 minutes to every 15 minutes. Each measurement was then matched with the corresponding mean flow rate for that day, as obtained from the National Flow Archive[3] (flow gauge locations described in Section 2.1) and plotted against a flow duration curve.

Table 3-1 - Site locations for WIMS data

Site name	Sampling point ID	Easting, northing
River Severn at Hampton Loade Bridge	MD-00041180	374600, 287050
Blithfield reservoir causeway	MD-67419610	405820, 323850
River Blithe - Blithford at B5014	MD-67418570	408300, 321700

Table 3-2 - Site locations for spot sampling data continuous monitoring data provided by South Staffordshire Water.

Site name	Combined sites	Easting, northing	Spot samples	Continuous monitoring
River Severn	n/a	374585, 287153	✓	pH, turbidity, colour
Chelmarsh Reservoir	n/a	373616, 287427	✓	
Hampton Loade Raw Water	n/a	374630, 287025	✓	pH, turbidity, colour
River Blithe	33 Main and 36 Main	411474, 317649	✓	pH, turbidity
Blithfield Reservoir	Blithfield Reservoir Sampling Point 1 - 6 Blithfield Reservoir, 36 Ext Reservoir Blithfield Reservoir, Surface Blithfield Reservoir, Depth	407070, 322811	✓	
DAF RAW	n/a			pH
ACC RAW	n/a			pH
AIT402	n/a			Turbidity
33 Raw Water	n/a			Turbidity

[3] National River Flow Archive (ceh.ac.uk)

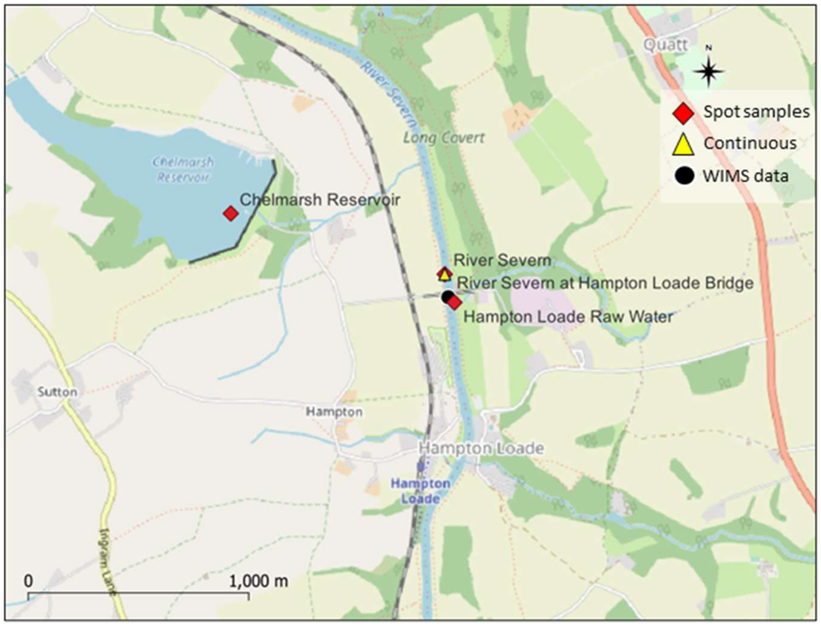


Figure 3-1 - Water quality sampling locations for Chelmarsh Reservoir, the River Severn and Hampton Loade Raw Water (flow data location is ~13.5 km downstream of Hampton Loade Raw Water).

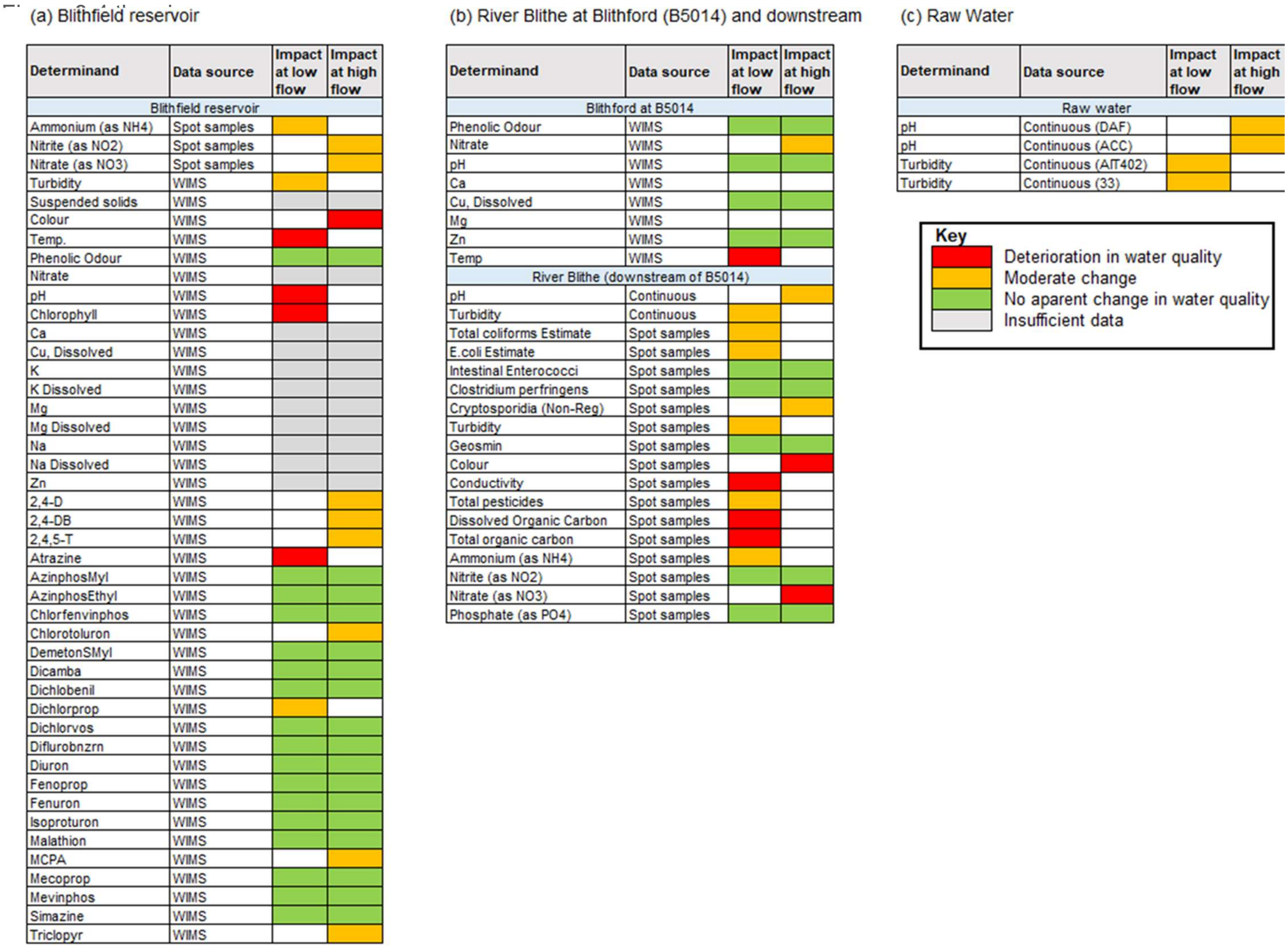
Figure 3-2 - Water quality sampling locations for the Blithfield Reservoir and the River Blithe.

3.2. Results

To understand the impact of future flows on water quality, we undertook an analysis to understand how flow relates to the concentration of pollutants/determinands at each location (i.e., whether it promotes an increase or decrease in water quality). Increases in the concentration of determinands have been interpreted as representing a deterioration in water quality. Assessment of the strength of the relationship between water quality and flow was based on visual judgement, considering both the slope and degree of scatter.

This section provides a brief overview of all the determinands that display a relationship with flow (figures comparing determinand concentration with flow are presented in 7.Appendix A (Hampton Loades sites) and 7.Appendix B (Blithfield reservoir/River Blithe sites)).

More significant changes in water chemistry associated with changes in flow were observed at the Hampton Loade sites compared to the Blithfield Reservoir/River Blithe (demonstrated by more 'red category' impacts in



(a) Blithfield reservoir

Determinand	Data source	Impact at low flow	Impact at high flow
Blithfield reservoir			
Ammonium (as NH4)	Spot samples	Amber	
Nitrite (as NO2)	Spot samples		Amber
Nitrate (as NO3)	Spot samples		Amber
Turbidity	WIMS	Amber	
Suspended solids	WIMS	Grey	Grey
Colour	WIMS		Red
Temp.	WIMS	Red	
Phenolic Odour	WIMS	Green	Green
Nitrate	WIMS	Grey	Grey
pH	WIMS	Red	
Chlorophyll	WIMS	Red	
Ca	WIMS	Grey	Grey
Cu, Dissolved	WIMS	Grey	Grey
K	WIMS	Grey	Grey
K Dissolved	WIMS	Grey	Grey
Mg	WIMS	Grey	Grey
Mg Dissolved	WIMS	Grey	Grey
Na	WIMS	Grey	Grey
Na Dissolved	WIMS	Grey	Grey
Zn	WIMS	Grey	Grey
2,4-D	WIMS		Amber
2,4-DB	WIMS		Amber
2,4,5-T	WIMS		Amber
Atrazine	WIMS	Red	
AzinphosMyl	WIMS	Green	Green
AzinphosEthyl	WIMS	Green	Green
Chlorfenvinphos	WIMS	Green	Green
Chlorotoluron	WIMS		Amber
DemetonSMyl	WIMS	Green	Green
Dicamba	WIMS	Green	Green
Dichlobenil	WIMS	Green	Green
Dichlorprop	WIMS	Amber	
Dichlorvos	WIMS	Green	Green
Diflurobnzrn	WIMS	Green	Green
Diuron	WIMS	Green	Green
Fenoprop	WIMS	Green	Green
Fenuron	WIMS	Green	Green
Isoproturon	WIMS	Green	Green
Malathion	WIMS	Green	Green
MCPA	WIMS		Amber
Mecoprop	WIMS	Green	Green
Mevinphos	WIMS	Green	Green
Simazine	WIMS	Green	Green
Triclopyr	WIMS		Amber

(b) River Blithe at Blithford (B5014) and downstream

Determinand	Data source	Impact at low flow	Impact at high flow
Blithford at B5014			
Phenolic Odour	WIMS	Green	Green
Nitrate	WIMS		Amber
pH	WIMS	Green	Green
Ca	WIMS		
Cu, Dissolved	WIMS	Green	Green
Mg	WIMS		
Zn	WIMS	Green	Green
Temp	WIMS	Red	
River Blithe (downstream of B5014)			
pH	Continuous		Amber
Turbidity	Continuous	Amber	
Total coliforms Estimate	Spot samples	Amber	
E.coli Estimate	Spot samples	Amber	
Intestinal Enterococci	Spot samples	Green	Green
Clostridium perfringens	Spot samples	Green	Green
Cryptosporidia (Non-Reg)	Spot samples		Amber
Turbidity	Spot samples	Amber	
Geosmin	Spot samples	Green	Green
Colour	Spot samples		Red
Conductivity	Spot samples	Red	
Total pesticides	Spot samples	Amber	
Dissolved Organic Carbon	Spot samples	Red	
Total organic carbon	Spot samples	Red	
Ammonium (as NH4)	Spot samples	Amber	
Nitrite (as NO2)	Spot samples	Green	Green
Nitrate (as NO3)	Spot samples		Red
Phosphate (as PO4)	Spot samples	Green	Green

(c) Raw Water

Determinand	Data source	Impact at low flow	Impact at high flow
Raw water			
pH	Continuous (DAF)		Amber
pH	Continuous (ACC)		Amber
Turbidity	Continuous (AIT402)	Amber	
Turbidity	Continuous (33)	Amber	

Key
Red: Deterioration in water quality
Amber: Moderate change
Green: No aparent change in water quality
Grey: Insufficient data

Figure 3-5).

3.2.1. Hampton Loade sites

Some of the most distinct relationships between water quality and flow were observed in the continuous data sets (turbidity, colour and pH) (Figure 3-3), as well as some determinands from the spot samples/WIMS data such as conductivity.

3.2.1.1. River Severn at Hampton Loade

For the River Severn at Hampton Loade, high flow rates were associated with high turbidity and colour, as well as increases in total coliforms, *E.coli* (estimate), *Cryptosporidia*, ammonium and nitrite, and to a lesser extent intestinal Enterococci and *Clostridium perfringens* (Figure 3-4a). From the WIMS data, high flow rates were associated with an increase in suspended solids, Cd, Cr, Fe (dissolved), Pb, Zn, and some pesticides (although to a lesser extent) (Figure 3-4b).

In contrast, low flow was associated with an increase in pH, geosmin (also indicative of blue-green algae), DOC, TOC, nitrate and phosphorous, and to a lesser extent conductivity and total pesticides (Figure 3-4a). From the WIMS data, low flow was associated with and increase in Ca, Mg and temperature and to a lesser extent chlorophyll, 2,4-D and some other pesticides (atrazine, dichlobenil, diuron and MCPA) (Figure 3-4b).

3.2.1.2. Hampton Loade Raw Water

At the Hampton Loade Raw Water, high flow was associated with increases in turbidity, colour (Figure 3-3), total coliforms, *E.coli* (estimate), intestinal Enterococci, *Clostridium perfringens*, *Cryptosporidia*, ammonium and to a lesser extent nitrite and geosmin (Figure 3-4c). In contrast, low flow was associated with an increase in conductivity, DOC, TOC and to a lesser extent phosphate, pH, total pesticides and nitrate (Figure 3-4c).

3.2.1.3. Chelmarsh Reservoir

At Chelmarsh Reservoir, high flows were associated with an increase in turbidity, whereas low flows were associated with an increase in phosphate and nitrate (Figure 3-4d). In general, storage of water in Chelmarsh Reservoir would be expected to 'dampen' the relationship between river flow and water quality because of mixing and attenuation. Higher flows will, however, affect both direct run off from the local catchment as well as the water quality at the intake which will then influence water quality in the reservoir.

3.2.2. Blithfield Reservoir and the River Blithe sites.

3.2.2.1. River Blithe

High flows in the river were associated with increased colour and nitrate, and to a lesser extent pH and *Cryptosporidia*. Low flows were associated with increased temperature, conductivity, DOC, TOC, and ammonium and to a lesser extent turbidity, total coliforms, ammonium, *E.coli*, and total pesticides.

3.2.2.2. Blithfield Reservoir

Within the reservoir, high flows were associated with an increase in colour and to a lesser extent nitrite and nitrate. Low flow rates were associated with high temperatures, pH and chlorophyll, and to a lesser extent ammonium and turbidity.

Insufficient data was available through WIMS to determine relationships between metals and flow. Most pesticide concentrations from the WIMS data showed no apparent change in water quality with flow, or slight/moderate changes with flow (e.g., 2,4-D, 2,4-DB, 2,4,5-T, chlorfenvinphos, MCPA, and triclopyr concentrations increased slightly with high flows and dichlorprop increased slightly with low flows). Atrazine was the only pesticide increasing in the reservoir in relation to flow, with the highest concentrations associated with low flows.

Because of the length of storage and mixing in Blithfield Reservoir, the relationship between water quality and river flow would be expected to be less than for the river sites.

3.2.2.3. Raw Water

Continuous monitoring of the raw water suggests there is a slight increase in turbidity at low flow, whereas pH remains near-constant with flow.

3.2.3. Summary

3.2.3.1. Hampton Loade sites

- Water quality at all three Hampton Loade sites is impacted by changing flow.
- Increased river flows may result in a deterioration in water quality in the River Severn at Hampton Loade due to increased turbidity, colour, total coliforms, E.coli, *Cryptosporidia*, turbidity, ammonium, nitrite, suspended solids, chromium, dissolve Fe, Pb, and Zn.
- Decreased flows in the river may result in a deterioration in water quality in the River Severn at Hampton Loade due to increased pH, geosmin, conductivity, DOC, TOC, nitrate and phosphate, temperature, Ca and Mg.
- Increased river flow may result in a deterioration in water quality to the Hampton Loade Raw Water due to increased turbidity, colour, total coliforms, E.coli, Intestinal Enterococci, *Clostridium perfringens, Cryptosporidia*, turbidity and ammonium.
- Decreased river flow may result in a deterioration in water quality to the Hampton Loade Raw Water due to increased conductivity, DOC and TOC.
- Deterioration of water quality at Chelmarsh Reservoir may occur due to increased turbidity associated with high flows and increased nitrate and phosphate associated during periods of low flow.

3.2.3.2. Blithfield Reservoir/River Blithe sites

- Water quality is less impacted by flow in Blithfield Reservoir and the River Blither compared to the Hampton Loade sites.
- Deterioration of water quality at Blithfield Reservoir may occur due to increased colour during high flows, and increased temperature, pH, chlorophyll, and atrazine during low flows.
- Increased river flow may result in a deterioration in water quality to the River Blithe due increases in colour and nitrate.
- Decreased river flow may result in a deterioration in water quality to the River Blithe due increases in temperature, conductivity, DOC and TOC.
- The Raw Water from Blithfield Reservoir for Seedy Mill was not significantly impacted by changing flow. However, reduction in water quality may occur due to increase pH during high flows and increased turbidity during low flows.
- However, the result for the raw water is somewhat unexpected, as pH and turbidity display the opposite relationship with flow compared to other sites.

3.2.3.3. Common patterns

- Broadly the relationships between water quality and river flow are similar for all river sites with the relationships weaker for the reservoir sites, particularly Blithffield where storage is much longer than at Chelmarsh.
- Colour, turbidity, metals and pathogens increase at high flows in the river sites.
- Organic carbon, chlorophyll-a and nitrate tend to increase at low flows.

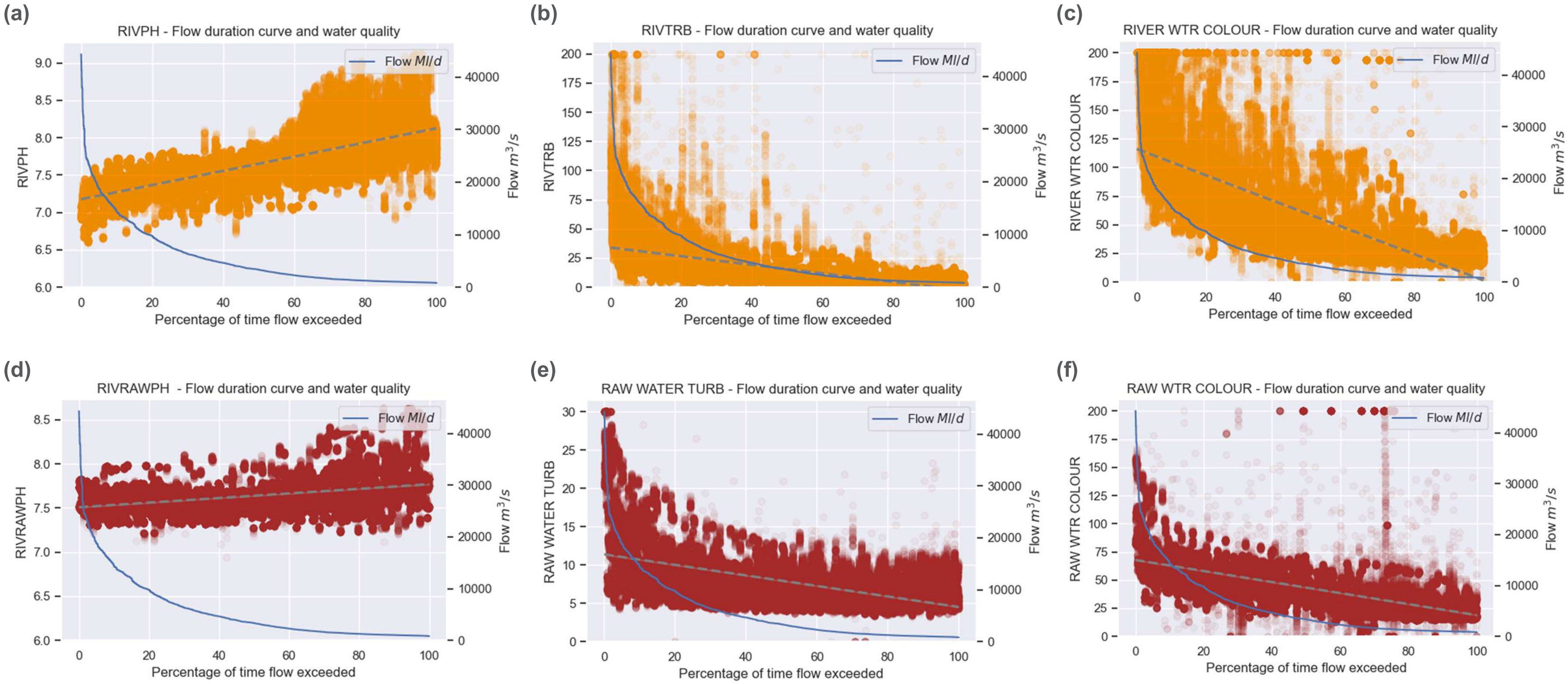


Figure 3-3 - Hampton Loade continuous water quality monitoring data against flow for the River Severn (upper row, orange points) showing (a) pH, (b) turbidity, and (c) colour. The lower row (brown points) displays water quality against flow for Hampton Loade Raw Water for (d) pH, (e) turbidity and (f) colour.

(a) River Severn at Hampton Loade Bridge

Determinand	Data source	Impact at low flow	Impact at high flow
pH	Continuous		
Turbidity	Continuous		
Colour	Continuous		
Total coliforms	Spot sample		
E.coli Estimate	Spot sample		
Intestinal Enterococci	Spot sample		
Clostridium perfringens	Spot sample		
Cryptosporidia (Non-Reg)	Spot sample		
Turbidity	Spot sample		
Geosmin	Spot sample		
Colour	Spot sample		
Conductivity	Spot sample		
Total pesticides	Spot sample		
Dissolved Organic Carbon	Spot sample		
Total organic carbon	Spot sample		
Ammonium (as NH4)	Spot sample		
Nitrite (as NO2)	Spot sample		
Nitrate (as NO3)	Spot sample		
Phosphate (as PO4)	Spot sample		

(b) River Severn at Hampton Loade Bridge (continued)

Determinand	Data source	Impact at low flow	Impact at high flow
Suspended solids	WIMS		
Nitrate	WIMS		
pH	WIMS		
Temp	WIMS		
Chlorophyll	WIMS		
Cd	WIMS		
Cd Dissolved	WIMS		
Ca	WIMS		
Cr	WIMS		
Cr Dissolved	WIMS		
Cu	WIMS		
Cu Dissolved	WIMS		
Fe Dissolved	WIMS		
K	WIMS		
Pb	WIMS		
Pb Dissolved	WIMS		
Mg	WIMS		
Ni	WIMS		
Ni Dissolved	WIMS		
Zn	WIMS		
Zn Dissolved	WIMS		
2,4-D	WIMS		
2,4-DB	WIMS		
2,4,5-T	WIMS		
Atrazine	WIMS		
AzinphosMyl	WIMS		
Chlorotoluron	WIMS		
Diazinon	WIMS		
Dicamba	WIMS		
Dichlobenil	WIMS		
Dichlorprop	WIMS		
Diflurobenzuron	WIMS		
Diuron	WIMS		
Fenoprop	WIMS		
Fenuron	WIMS		
Ioxynil	WIMS		
Isoproturon	WIMS		
MCPA	WIMS		
Mecoprop	WIMS		
Simazine	WIMS		
Triclopyr	WIMS		

(c) Hampton Loade Raw Water

Full name	Data source	Impact at low flow	Impact at high flow
pH	Continuous		
Turbidity	Continuous		
Colour	Continuous		
Total coliforms Estimate	Spot sample		
E.coli Estimate	Spot sample		
Intestinal Enterococci	Spot sample		
Ent Estimated	Spot sample		
Clostridium perfringens	Spot sample		
Cryptosporidia (Non-Reg)	Spot sample		
Turbidity	Spot sample		
Geosmin	Spot sample		
Colour	Spot sample		
Conductivity	Spot sample		
Total pesticides	Spot sample		
Dissolved Organic Carbon	Spot sample		
Total organic carbon	Spot sample		
Ammonium (as NH4)	Spot sample		
Nitrite (as NO2)	Spot sample		
Nitrate (as NO3)	Spot sample		
Phosphate (as PO4)	Spot sample		

(d) Chelmarsh reservoir

Determinand	Data source	Impact at low flow	Impact at high flow
Turbidity	Spot sample		
Ammonium (as NH4)	Spot sample		
Nitrite (as NO2)	Spot sample		
Nitrate (as NO3)	Spot sample		
Phosphate (as PO4)	Spot sample		

Key

- Deterioration in water quality
- Moderate change
- No aparent change in water quality
- Insufficient data

Figure 3-4 - Summary of the impact of high and low flow on water quality parameters at (a) River Severn at Hampton Loade (continuous data and spot samples), (b) River Severn at Hampton Loade (WIMS data), (c) Hampton Loade Raw water (spot samples and continuous data) and (d) Chelmarsh Reservoir (spot samples).

(a) Blithfield reservoir

Determinand	Data source	Impact at low flow	Impact at high flow
Blithfield reservoir			
Ammonium (as NH4)	Spot samples		
Nitrite (as NO2)	Spot samples		
Nitrate (as NO3)	Spot samples		
Turbidity	WIMS		
Suspended solids	WIMS		
Colour	WIMS		
Temp.	WIMS		
Phenolic Odour	WIMS		
Nitrate	WIMS		
pH	WIMS		
Chlorophyll	WIMS		
Ca	WIMS		
Cu, Dissolved	WIMS		
K	WIMS		
K Dissolved	WIMS		
Mg	WIMS		
Mg Dissolved	WIMS		
Na	WIMS		
Na Dissolved	WIMS		
Zn	WIMS		
2,4-D	WIMS		
2,4-DB	WIMS		
2,4,5-T	WIMS		
Atrazine	WIMS		
AzinphosMyl	WIMS		
AzinphosEthyl	WIMS		
Chlorfenvinphos	WIMS		
Chlorotoluron	WIMS		
DemetonSMyl	WIMS		
Dicamba	WIMS		
Dichlobenil	WIMS		
Dichlorprop	WIMS		
Dichlorvos	WIMS		
Diflurobnzrn	WIMS		
Diuron	WIMS		
Fenoprop	WIMS		
Fenuron	WIMS		
Isoproturon	WIMS		
Malathion	WIMS		
MCPA	WIMS		
Mecoprop	WIMS		
Mevinphos	WIMS		
Simazine	WIMS		
Triclopyr	WIMS		

(b) River Blithe at Blithford (B5014) and downstream

Determinand	Data source	Impact at low flow	Impact at high flow
Blithford at B5014			
Phenolic Odour	WIMS		
Nitrate	WIMS		
pH	WIMS		
Ca	WIMS		
Cu, Dissolved	WIMS		
Mg	WIMS		
Zn	WIMS		
Temp	WIMS		
River Blithe (downstream of B5014)			
pH	Continuous		
Turbidity	Continuous		
Total coliforms Estimate	Spot samples		
E.coli Estimate	Spot samples		
Intestinal Enterococci	Spot samples		
Clostridium perfringens	Spot samples		
Cryptosporidia (Non-Reg)	Spot samples		
Turbidity	Spot samples		
Geosmin	Spot samples		
Colour	Spot samples		
Conductivity	Spot samples		
Total pesticides	Spot samples		
Dissolved Organic Carbon	Spot samples		
Total organic carbon	Spot samples		
Ammonium (as NH4)	Spot samples		
Nitrite (as NO2)	Spot samples		
Nitrate (as NO3)	Spot samples		
Phosphate (as PO4)	Spot samples		

(c) Raw Water

Determinand	Data source	Impact at low flow	Impact at high flow
Raw water			
pH	Continuous (DAF)		
pH	Continuous (ACC)		
Turbidity	Continuous (AIT402)		
Turbidity	Continuous (33)		

Key

- Deterioration in water quality
- Moderate change
- No aparent change in water quality
- Insufficient data

Figure 3-5 - Summary of the impact of high and low flow on water quality parameters at (a) Blithfield Reservoir (WIMS data and spot samples), (b) The River Blithe at B5014 (WIMS data) and further downstream (continuous data and spot samples), and (c) Raw Water (continuous data)

4. Impacts on the drinking water supply system.

Changes in river flow might impact on water quality at the South Staffordshire Water's intakes in a number of ways that may, in turn, affect the drinking water supply system.

1. If river flow falls below critical flows (e.g., the hands-off-flow) in the river at an intake more often than occurs now, this may increase the requirement to abstract on more of the remaining days when water quality is poor, reducing the flexibility by which water quality can be managed through abstraction controls.
2. Operational rules have been developed to manage drinking water quality risk at the intakes with thresholds for water quality at which abstraction is reduced or ceased. The frequency at which these thresholds are exceeded will increase if water quality worsens. These thresholds are primarily related to reducing or ceasing abstraction during high flow events when water quality tends to be poor.
3. If water quality deteriorates, either at high or low flow events and the frequency of such events changes, this will change the water quality of water entering the treatment works if abstraction is not reduced or ceased.
4. If the water quality of water draining or pumped into either at Blithfield or Chelmarsh Reservoir deteriorates, this may result in further deterioration of water quality due to within reservoir processes. A potentially significant process is likely to be the input of nutrients that may lead to increased algal growth which, in turn, may have a further impact on water quality through increasing the particulate and organic load and by the release of taste and odour chemicals such a geosmin.

These processes are considered in turn in the following sections.

4.1. Abstraction as intakes and river flow

4.1.1. Hampton Loade (River Severn)

South Staffordshire Water provided information that when flows in the River Severn are below 1100 Ml/day, abstraction is restricted to be below 280 Ml/day (between November and March, the maximum abstraction rate is 400 Ml/day and between April and October it is 320 Ml/day).

Figure 4-1 shows the number of days per year that the flow in the River Severn is below 1100 Ml/day (presented as a five-year rolling mean). Reference lines are shown, marking a 25% and 50% increase compared to the current rate. This shows a clear upward trend in the number of days in which river flow constrains abstraction with a 25% increase reached by the 2040s and a 50% increase reached by the late 2050s. Abstraction is currently constrained for about 2 months a year which will increase to about 3 months by the end of the analysis period. The result would be that abstraction would need to be increased during the rest of the year to make up the shortfall.

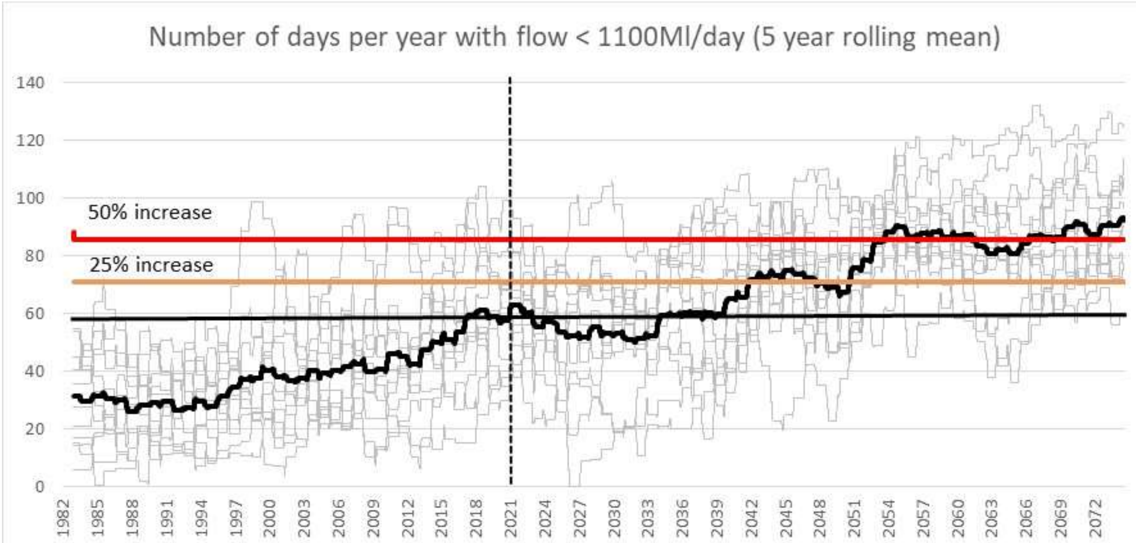


Figure 4-1 - Number of days per year that river flows in the River Severn are below the threshold of 1100 Ml//day presented as a five-year rolling mean. Grey lines show each ensemble member and the back line show the average for all members.

4.1.2. River Blithe

Similar analysis was carried out for the River Blithe but because, in this case, a proxy location was used for the eFLaG outputs, the number of days were calculated when river flows fall below the 5th percentile (Q95) and the 20th percentile (Q80). There is a very clear increase in the number of days with extremely low flows (< Q95). The number of days below the Q20 also shows a marked increase (Figure 4-2).

4.2. Operational abstraction rules

Operational rules were provided by South Staffordshire Water that control whether abstraction from the River Severn at Hampton Loade is constrained. Upper and lower thresholds were provided related to the number of pumps operated at the intake. The lower thresholds are Turbidity 70 NTU, Colour 70 units and Ammonia 0.05mg/l N. The upper thresholds at which greater pumping restrictions are applied are Turbidity 120 NTU, Colour 120 hazen units and Ammonia 0.1mg/l N.

A spreadsheet tool was developed to estimate future water quality in relation to future eFLaG flows based on the historical correlation between chemical concentration and river flow. Using the historical correlation, and water quality data, new concentrations were created stochastically correlated to future river flows (sampling from the original water quality data set). The tool was tested by taking a sub-sample of the historical flow data, generating new chemical time series from this data and comparing this to the observed water quality from the sampled data, which showed an almost perfect match. A comparison between the historical and generated time series for turbidity is shown in Figure 4-3 and 4.4.

Projected water quality time series were created in this way for turbidity and colour using historical continuous monitoring data and, for ammonia using historical spot data. Figure 4-5 shows the projected exceedance of the turbidity and colour thresholds derived from the eFLaG data (ammonia shows no clear relationship with flow so was not analysed further). The projections show little change in threshold exceedance over time which is to be expected because the high percentile flows are only projected to show a small increase.

No operational rules were provided by South Staffordshire Water on operational rules for the River Blithe/Blithfield Reservoir system so the analysis could not be repeated in this case.

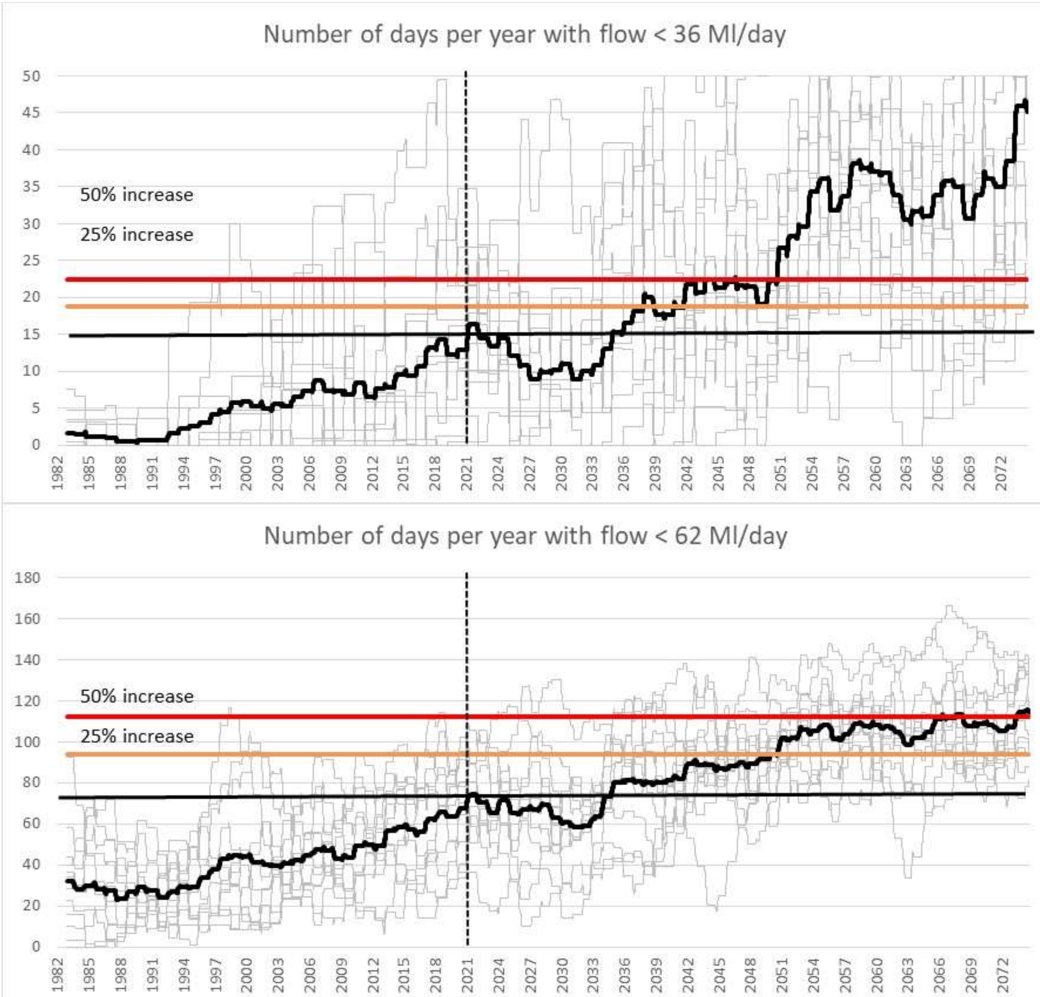


Figure 4-2 - Number of days per year that river flows are below the threshold of 36 and 62 Ml/day presented as a five-year rolling mean. Grey lines show each ensemble member and the back line show the average for all members.

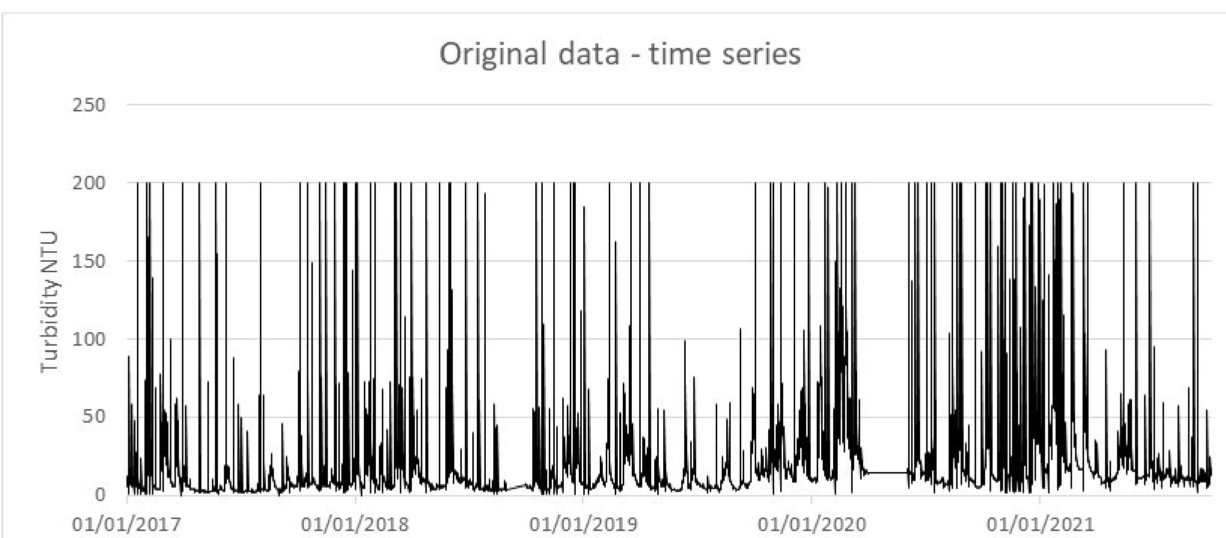


Figure 4-3 – Original historical turbidity time series (continuous monitoring data for the intake at Hampton Loade)

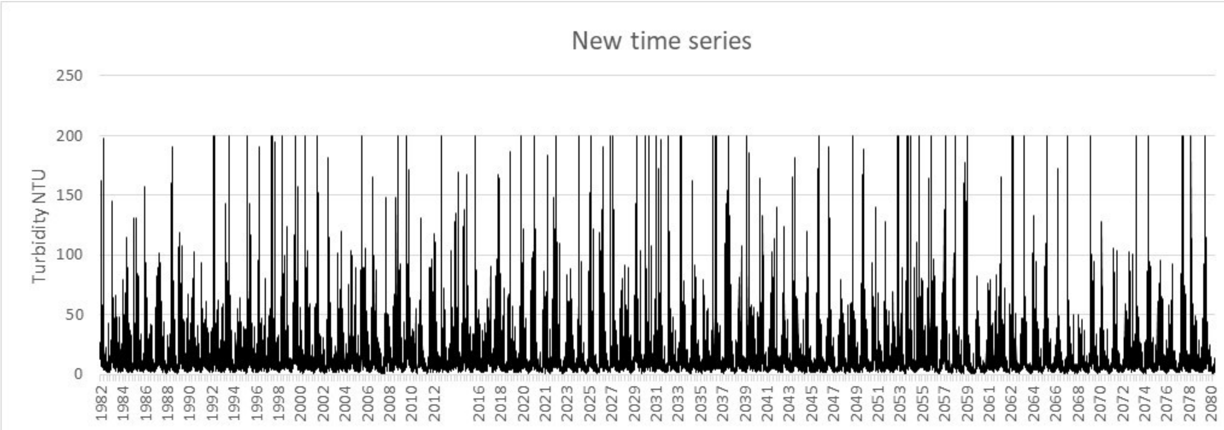


Figure 4-4 – Generated turbidity time series derived from e-Flag flows.

Turbidity

Colour

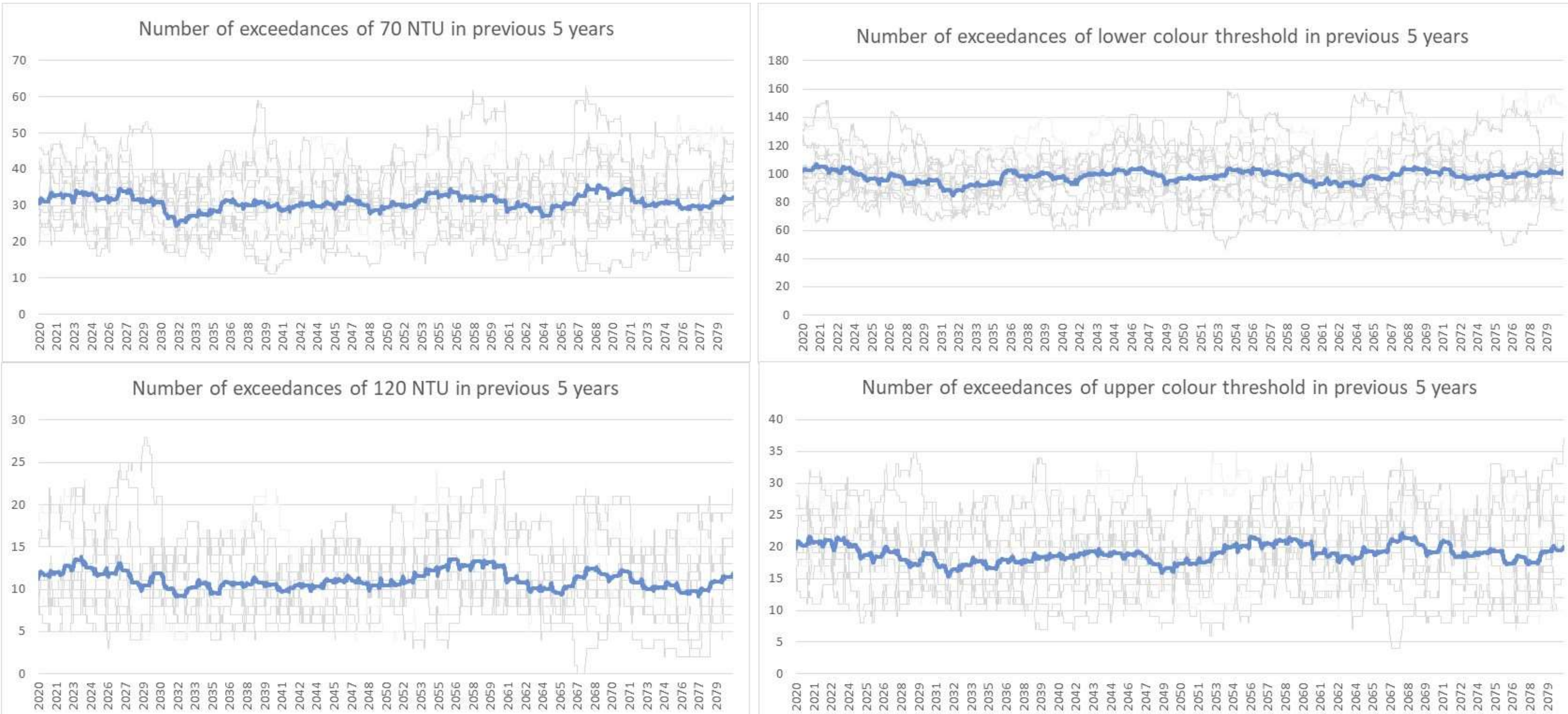


Figure 4-5 – Projected threshold exceedance of turbidity and colour thresholds in the River Severn derived from eFLaG flows (fainter lines show individual climate change members).

4.3. Deterioration of water quality at low flows

As outlined in Section 4.2, climate change impacts on river hydrology are projected to have a more substantial impact on low flows than high flows. The analysis presented in Section 3 indicates that deterioration in water quality at low river flows may occur for phosphorus, chlorophyll-a, magnesium, pH, nitrate and geosmin. The most significant of these in terms of drinking water risk are chlorophyll-a and geosmin (associated with algal growth in the river).

Figure 4-6 shows the projected long-term trend in the frequency of high chlorophyll-a concentration events in the River Severn in relation to nominal threshold of 30µg/l and 50µg/l (the latter represents significant algal population that might cause treatment problems) and nominal thresholds of geosmin of 7ug/l and 10ug/l. Less historical data are available for geosmin than chlorophyll-a, which may, in part, explain less of an upward trend for this determinand. The changes in the frequency of high concentrations of both these determinands is, however, modest and unlikely to impact greatly on drinking water quality risk, although they may increase treatment costs because of increased inputs of organic matter to the works.

Chlorophyll-a shows some relationship with river flow in Blithfield Reservoir (see Section 3), but this is insufficient to result in more than a slight projected increase in concentration in the reservoir. In this case, a causative relationship between the concentration and river flow is less likely because of the long-term storage of water in the reservoir.

4.4. Deterioration of water quality at reservoir intakes

An indirect impact of climate change on drinking water risk might occur because of greater nutrient inputs into the reservoirs, reflecting increased concentrations at the intakes. Increased nutrient concentration might then result in greater algal growth and therefore increased concentrations of determinands associated with algae such as taste and odour, trihalomethanes and algal toxins. Figure 4-8 shows the projected change in the frequency of high phosphorus and nitrate concentrations in the River Severn which shows a marked increase in both nutrients from 2040 onwards. The only clear relationship for the River Blithe, identified by data analysis (Section 3) was for nitrate but the projected water quality shows little change (Figure 4-9, while no relationship was identified for phosphorus; Section 3). The difference may be partly due to wastewater treatment works contributing less phosphorus in the smaller Blithe catchment than the Severn. The nature of the catchments are also different in terms of land use and urban development.

On the basis of this analysis, there is a clear risk of increase nutrient inputs to Chelmarsh Reservoir but there is no indication of this occurring at Blithfield Reservoir. The risk at Chelmarsh Reservoir is, however, likely to be reduced by water company investment in phosphorus removal at wastewater treatment works in the upstream River Severn and, to a lesser extent, improved agricultural practices in relation to nitrate. In considering the risk of excessive algal populations, phosphorus is of more concern because this is normally the limiting nutrient for algal growth in reservoirs.

Geosmin

Chlorophyll-a

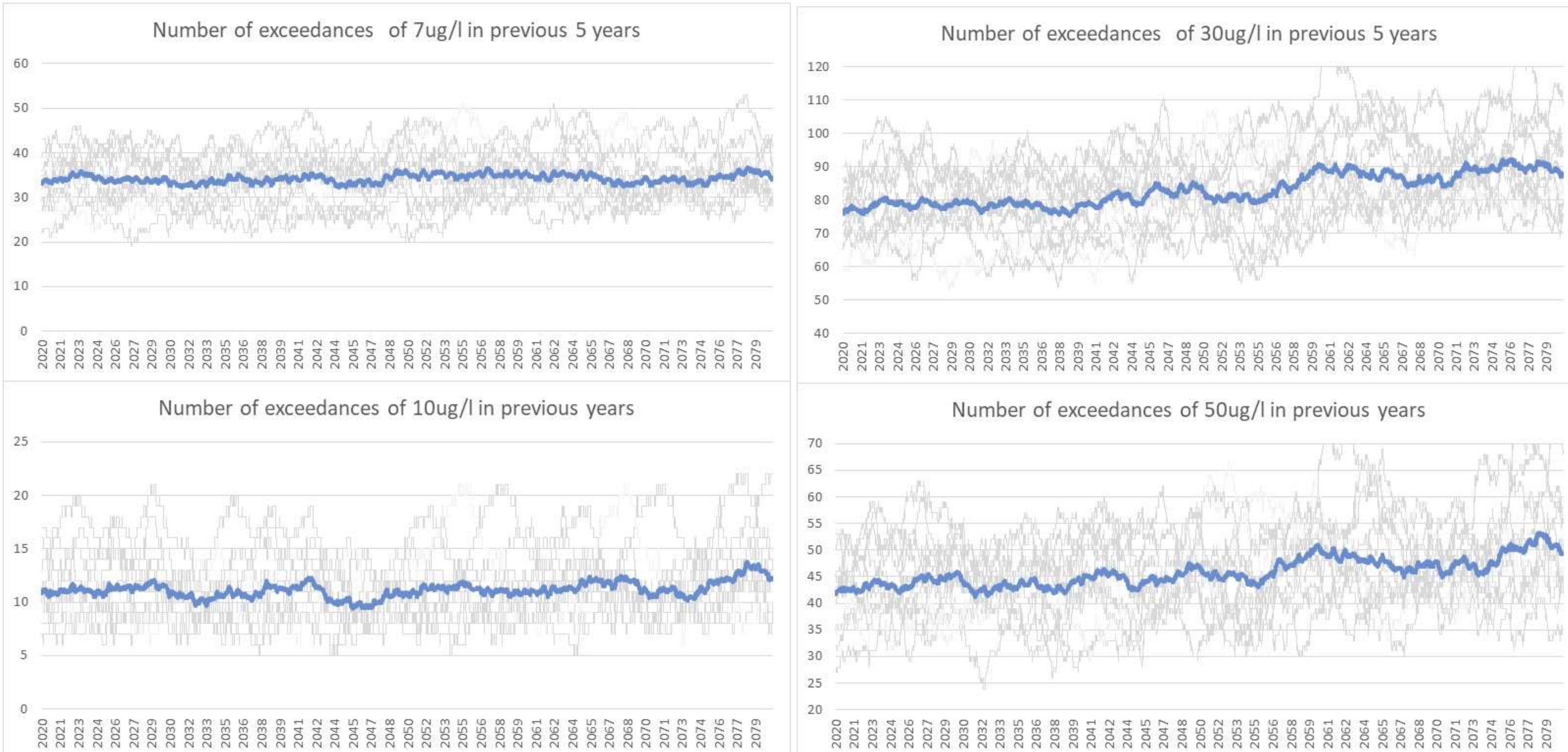


Figure 4-6 – Projected threshold exceedance for chlorophyll-a and geosmin in the River Severn derived from eFLaG flows (fainter lines show individual climate change members).

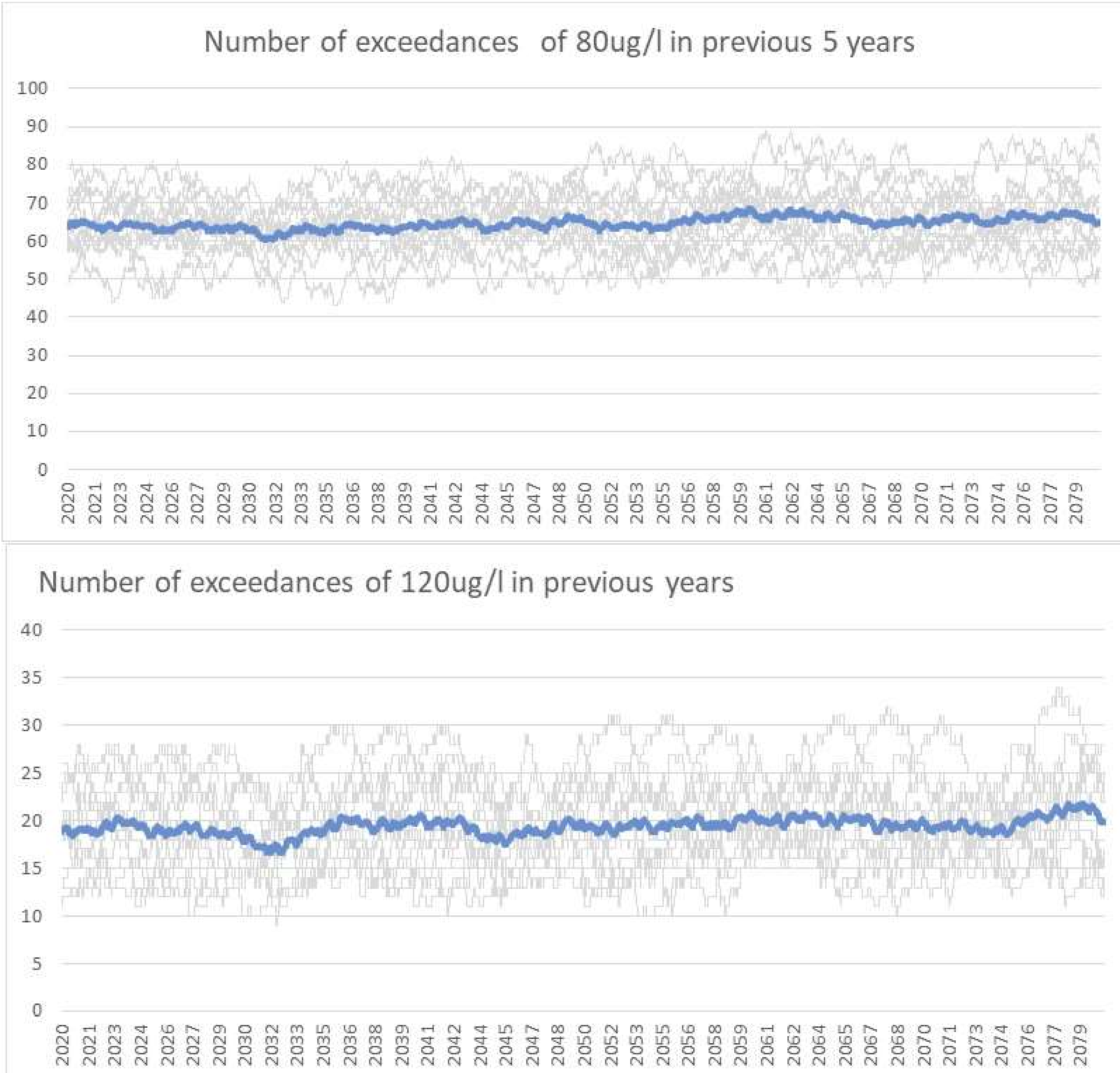


Figure 4-7 – Projected threshold exceedance for chlorophyll-a in Blithfield Reservoir derived from eFLaG flows (fainter lines show individual climate change members).

Ortho-phosphate **Nitrate**

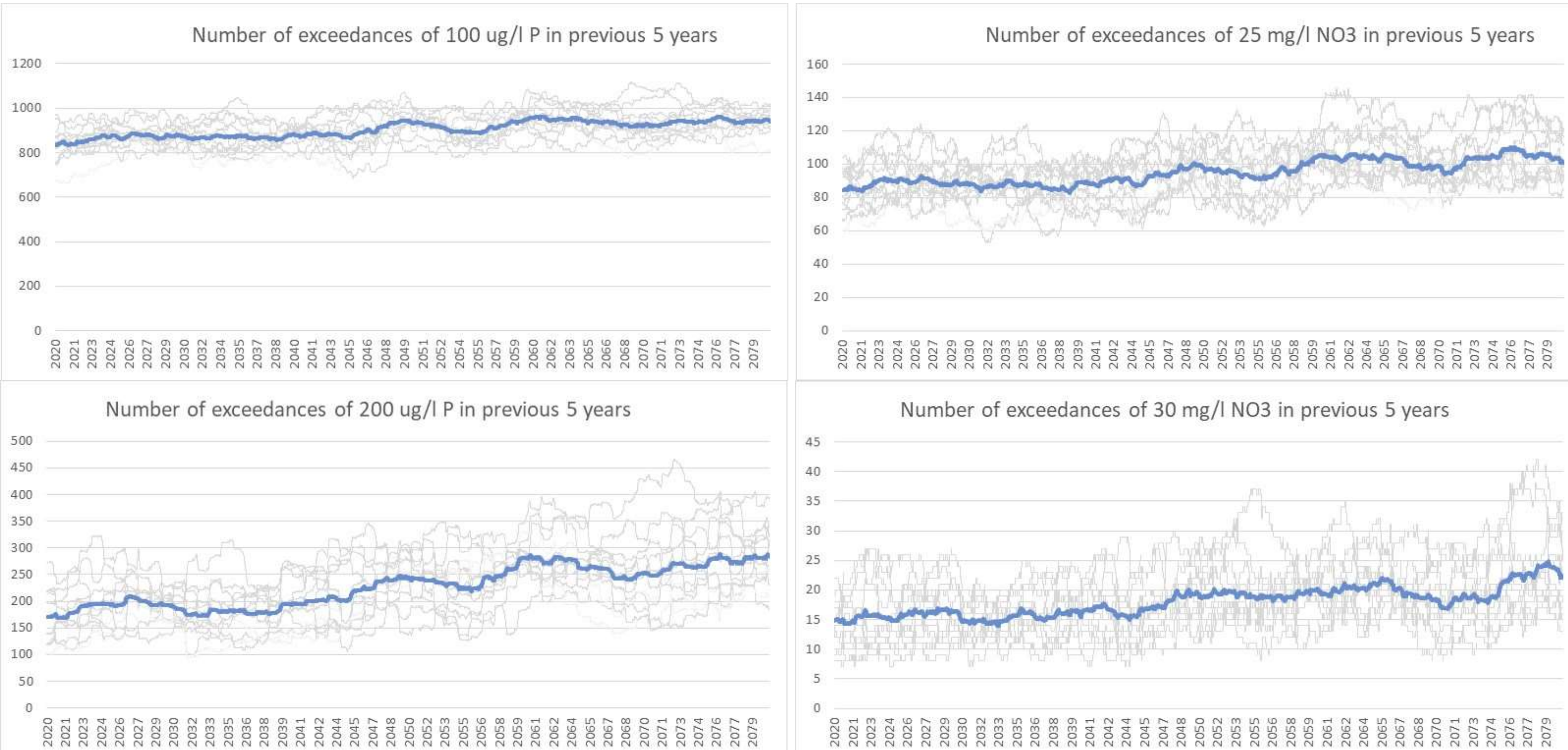


Figure 4-8 – Projected threshold exceedance for ortho-phosphate and nitrate in the River Severn derived from eFLaG flows (fainter lines show individual climate change members).

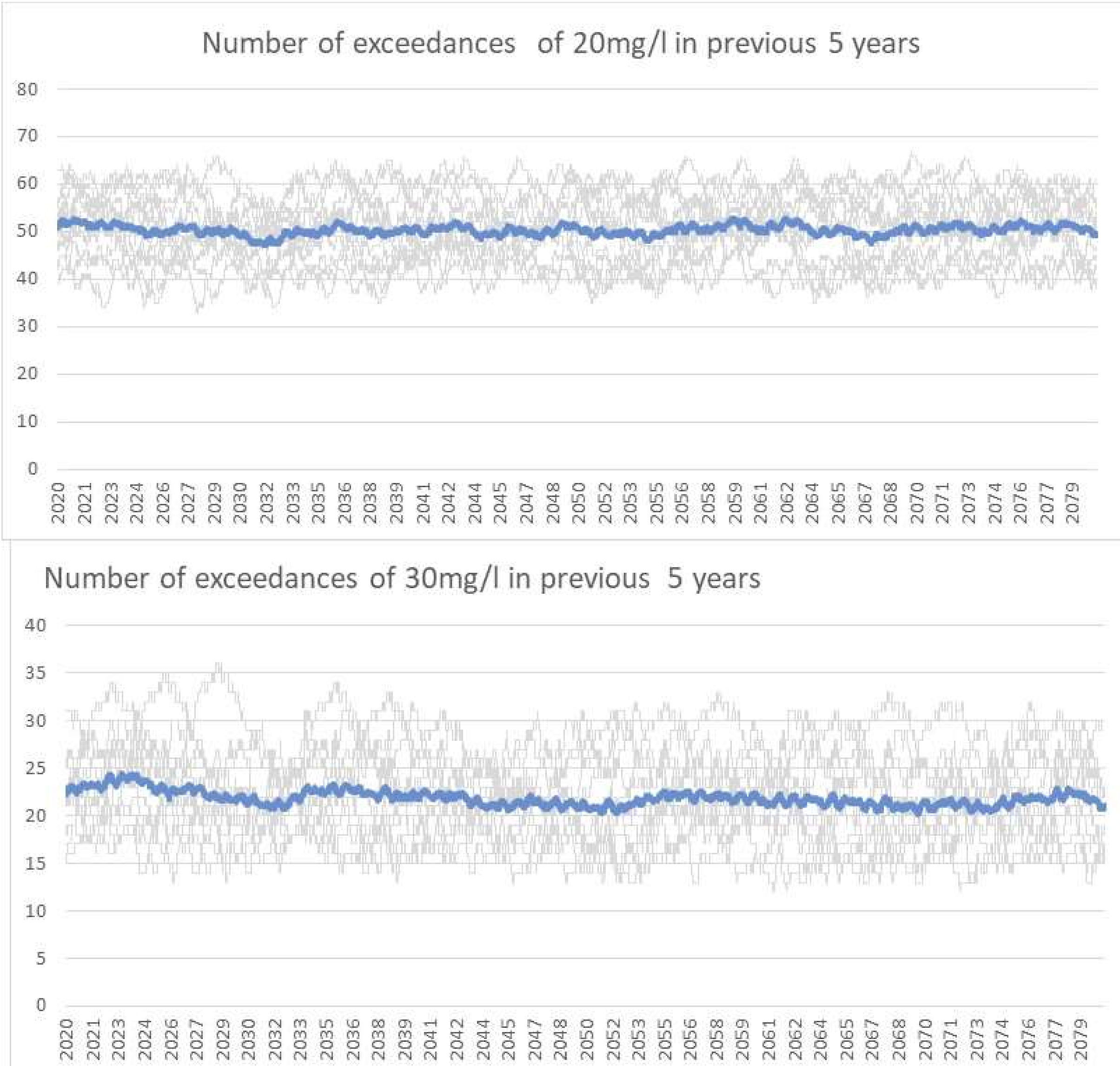


Figure 4-9 – Projected threshold exceedance for nitrate in the River Blithe derived from eFLaG flows (fainter lines show individual climate change members).

4.5. Assumptions and uncertainties

The analysis presented in the report is based on historical analysis of the relationship between water quality and river flow, alongside climate change projections for river flow. It assumes that these relationships will continue to the same in the future which may not be the case. Other changes are likely to occur in the future such a population growth and other impacts climate change on water quality that are not related to river flow such as increased temperature and changes in land use (e.g., cropping). Changes in management of water company assets, including wastewater treatment (e.g., P removal), agricultural management and regional water transfers will also affect water quality and, for some chemical determinands, may be of greater importance than changes in river flow. Quantifying these diverse impacts is difficult and would require a wider ranging and more complex study. River flow will, however, continue to modify drinking water quality risk alongside these other changes and, over the short to medium term, it is likely to be a primary influence on water quality.

Of particular relevance to the findings of this study is the planned regional transfer of water from the River Severn to the River Thames. If the scheme is taken forward, it will modify river flows at Hampton Loade, and offset the projected climate change related increased frequency of low river flow events. Further work would be necessary to fully assess the impact of this transfer once the plans have been more developed than is currently the case.

Confidence in the projected outputs for future water quality is also dependent on the amount of water quality data available for each determinand. Chemicals covered by the continuous monitoring data, therefore, have a higher degree of confidence than chemicals covered by sport sampling data which in most cases have fairly small data sets. Confidence in the water quality events associated with high flows for which the continuous monitoring is available, is, therefore, greater e than for those associated with low flow events.

In addition, there is uncertainty associated the with climate change projections. Outputs for the eFLaG ensemble members vary considerably with greater impacts on water quality for some members than others.

In addition, there is lower confidence in the outputs for Blithfield Reservoir than for the River Severn and Chelmarsh Reservoir because the longer residence time of storage in this reservoir will reduce the relationship of water quality in the raw water with river flow. Other climate change impacts on reservoir water quality such as increased water temperature are also likely to be of greater importance for this source.

5. Implications for drinking water quality risk and investment

The likely changes in river water quality due to climate change are discussed in the preceding sections of this report. Atkins were asked by South Staffordshire water to make some judgements and estimates regarding the likely interventions required to manage these changes, together with best estimates on timescales for these investments.

Water from the River Severn is abstracted and stored in Chelmarsh reservoir prior to treatment at the circa 200ML/d Hampton Loade WTW.

Water from the River Blithe is abstracted and stored in Blithfield reservoir, prior to treatment at the circa 100ML/d Seedy Mill WTW

5.1. Drinking water quality risks

As set out in section 4, climate change is likely to result in reduced river flow rates in dry conditions and (to a lesser extent) higher flows during wet periods. The data suggests that the river water quality during the high and low flow events may deteriorate for a range of parameters including:

- Turbidity
- Organics – DOC, colour, pesticides
- Metals – iron and manganese
- Nutrients – Nitrate, ammonia, phosphate

If the quality of the river water abstracted deteriorates in this way, this is deterioration may have a knock-on effects in the raw water reservoirs. The water quality hazards and risks expected to be of concern from the raw water reservoirs include:

- Algae blooms
- Algal by-products – taste & odour (geosmin / MIB), microcystin
- Increased suspended solids.
- Increased organics – DOC, colour, pesticides
- Disinfection by-product formation potential
- Nitrate
- Lower UV Transmittance

5.2. Investment options

The strategy for managing the impacts of climate change and risk to water quality broadly fall into two categories. Either:

- Abstract water of lower quality and enhance treatment processes to provide adequate control measures for the foreseeable water quality risks, or
- Refrain from abstracting lower quality water (high/low flow events) resulting in a more days per year when abstraction is inhibited. This would require additional raw water storage to maintain a resilience water supply.

Opportunities for managing water quality deterioration through catchment/nature-based solutions could be investigated further but have not been quantified or evaluated in this high-level review.

5.2.1. Potential effects and responses

The potential effects of climate change on river flows and water quality, together with responses and interventions are summarised in Figure 5-1 below:

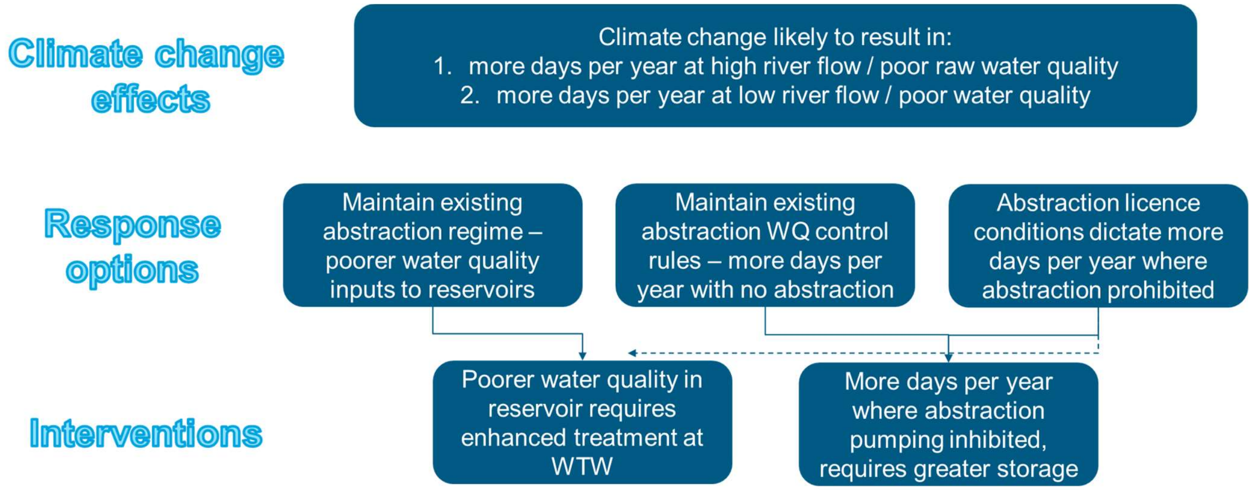


Figure 5-1 – Summary of impacts and interventions

5.2.2. Treatment enhancements

Section 5.1 identifies the increased water quality risks that can reasonably be expected from the raw water reservoirs. The increasing organics load to the WTWs may result in disinfection by-product production and other drinking water quality hazards such as taste and odour.

Two potential treatment enhancements are described below, it should be noted that either one of these enhancements might prove necessary, but are unlikely to both be required.

5.2.2.1. DOC removal at front end of WTWs

Other WTWs in the UK have added enhances organics removal processes at the beginning of the treatment process where the conventional coagulation/clarification proves inadequate to manage these high organic load risks.

For this high-level review, it has been assumed that installation of suspended ion exchange as a new 'front end' process for elevated organics including disinfection bi-product precursors.

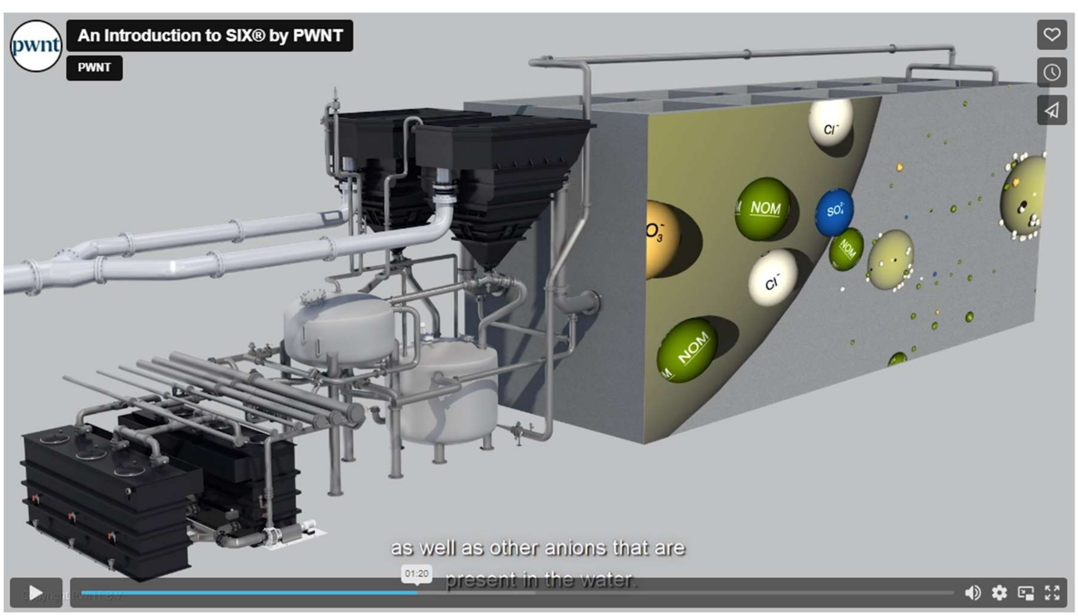


Figure 5-2 – Diagram of suspended ion exchange courtesy of PWNT website

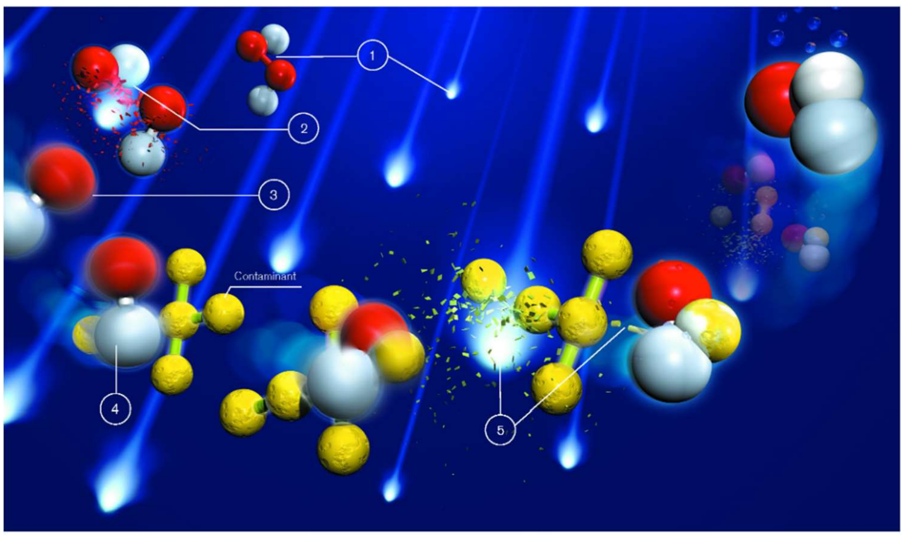
The investment cost estimates for this treatment enhancement at Hampton Loade and Seedy Mill WTWs has been based on Mayflower WTW (South West Water) using the PWNT SIX® process pro rata for flow from public domain data.

5.2.2.2. Advanced oxidation at the end of the WTWs

If the raw water quality deterioration in the reservoirs results in elevated trace organics, such as:

- taste & odour forming compounds e.g., geosmin and MIB.
- algal toxins e.g., microcystin
- pesticides
- emerging contaminants

In addition, installing advanced oxidation after the existing filtration would provide enhanced control measures for these risks. Advanced oxidation is illustrated in Figure 5-3.



1. UV-oxidation requires two components: UV light and an oxidant such as hydrogen peroxide.
2. When UV light is introduced to the water, the dissolved hydrogen peroxide molecules absorb UV light.
3. Highly energetic and reactive hydroxyl radicals are then formed.
4. Hydroxyl radicals react indiscriminately with environmental contaminants in the water.
5. Working simultaneously with direct UV-photolysis (the photochemical process that inactivates microorganisms and breaks down contaminants using UV alone), these highly reactive radicals break down contaminants.

Most contaminants are treated with a combination of UV-photolysis and UV-oxidation. Some, like NDMA, require only UV-photolysis.

Figure 5-3 –Advanced oxidation illustration courtesy of Trojan UV website

The investment cost estimates for this treatment enhancement at Hampton Loade and Seedy Mill WTWs has been based on Advanced oxidation UVAOP as installed at Hall WTW (Anglian Water) using the Trojan UV and hydrogen peroxide dosing pro rata for flow from public domain data.

5.2.3. Increased storage

As shown in Figure 5-1, if the river abstraction regime is modified to prevent pumping lower quality water into the reservoirs, there will be more days per year when abstraction is inhibited. This requires additional raw water storage to maintain the water supply. Increased storage volume determined by the frequency/duration abstraction will be constrained in future (either because of reduced river flows or deteriorating water quality)

- Hampton Loade WTW (Chelmarsh reservoir)
  - Extra 1400ML (7 days at full flow) by raising dam 3m.
- Seedy Mill WTW (Blithfield reservoir)
  - Extra 1400ML (14 days at full flow) by raising dam.

Increasing storage in the raw water reservoirs was the subject of option evaluation during WRMP24 so the indicative costs have been used from that exercise.

5.3. Future investment profile

Section 4 identifies the likely timescales for the change in river flows/water quality. For the purpose of planning, the tipping point is defined as a substantive change of more than 25% from the current baseline and a second greater of a 50% change. Changes of these degree are considered to take the environmental constraints on the source beyond the current situation (see Figure 4-2).

The interventions, described above, increased storage or enhanced treatment, are summarised below with an indication of investment cost.

Increasing storage within Chelmarsh and Blithered reservoirs has been previously investigated by Atkins under WRMP24 and the high-level costs come from that exercise.

Enhancing treatment at Hampton Loade and Seedy Mill WTWs involves treatment processes that are uncommon in the UK water industry so there is limited comparable cost data.

Table 5-1 - Summary of key outputs from mitigation timeline and interventions

Metric	River Severn	River Blithe	Comment
25% increase in days with low flows	2040	2035	
50% increase in days with low flows	2050	2040	
>100% increase in days with low flows	N/A	2060	River Blithe shows significant low flows looking further ahead
Increase storage in raw water reservoir	Chelmarsh circa £18M	Blithfield circa £20M	Low-cost confidence
Enhance treatment – add suspended ion exchange at front end	Hampton Loade WTW £30M to £50M	Seedy Mill WTW £15M to £40M	Low-cost confidence TR61 higher, public domain pro rata lower
Enhance treatment – add UVAOP upstream of existing GAC	Hampton Loade WTW £15M to £50M	Seedy Mill WTW £10M to £25M	Low-cost confidence TR61 lower, public domain pro rata higher

6. Conclusions

The analysis presented in this report provides a high-level evaluation of potential risk to drinking water quality at Hampton Loade and Seedy Mill water treatment works, related to climate change impacts on river flow. Other impacts of climate change such as changes in water temperature or changes in land use are not considered.

Key findings are:

1. Changes in the frequency of low events are greater and of more significance than changes in the frequency of high flow events.
2. More frequent low flow events will increase the numbers of days on which abstraction from the river is constrained. This may increase the need to abstract water more often on other days when water quality is poor, reducing the degree to which water quality passing into the treatment works can be managed at the intake.
3. Some increase in algal populations are projected in the River Severn due to an increase in low flow events but these changes are modest and unlikely to result in a substantial increase in the risk to drinking water.
4. A moderate increase in inputs to phosphorus and nitrate into Chelmarsh Reservoir is predicted which could increase eutrophication of the reservoir and associated water quality problems (i.e., algal blooms, taste and odour, algal toxins and organic load to the works.
5. These changes are likely to occur in the medium term from 2040 onward and increase in magnitude beyond this date.
6. Mitigation options are presented in the form of adding new process to the treatment stream, or by increasing storage. Because the most significant impacts are related to increased frequency of low flow events, storage is likely to be the preferred option.
7. Consideration should also be given to catchment solutions including nature-based solutions beyond this project.
8. Before these changes in water quality at the intakes come into effect, water company investment in nutrient removal and implementation of the Severn to Thames regional water transfer scheme may modify these risks. These influences would need to be considered before water company investment takes place to mitigate the projected increased risk to drinking water quality.
9. This project is high level in nature and only presents general information on options and costs.
10. Key uncertainties are presented in the report which will need to be reviewed before water company investment takes place.

7. References

Environment Agency, 2022. *SIMCAT stress-testing water quality permits with climate change,* London: Environment Agency.

Hannaford, J. et al., 2023. The enhanced future Flows and Groundwater dataset: development and evaluation of nationally consistent hydrological projections based on UKCP18. *Earth System Science Data,* 15(6), p. 2391–2415.

Appendix A. River Severn/ Hampton Load water quality against flow

A.1. River Severn at Hampton Loade

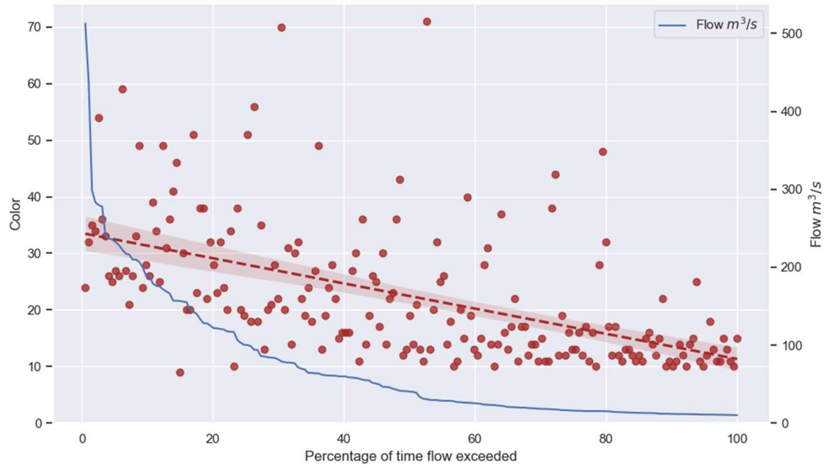


Figure 7-1 - Colour (mg/l Pt/Co) (orange) (River Severn at Hampton Loade, spot sample data) against a flow duration curve (blue) (River Severn).

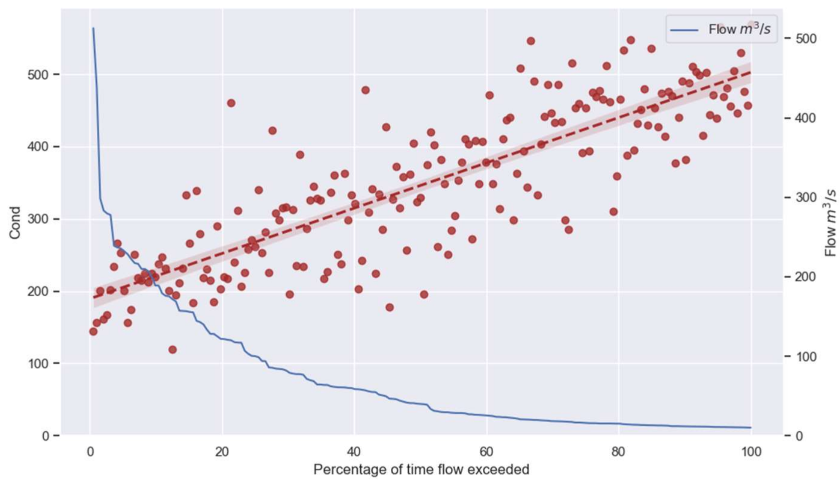


Figure 7-2 – Conductivity (uS/cm) (orange) (River Severn at Hampton Loade, spot sample data) against a flow duration curve (blue) (River Severn).

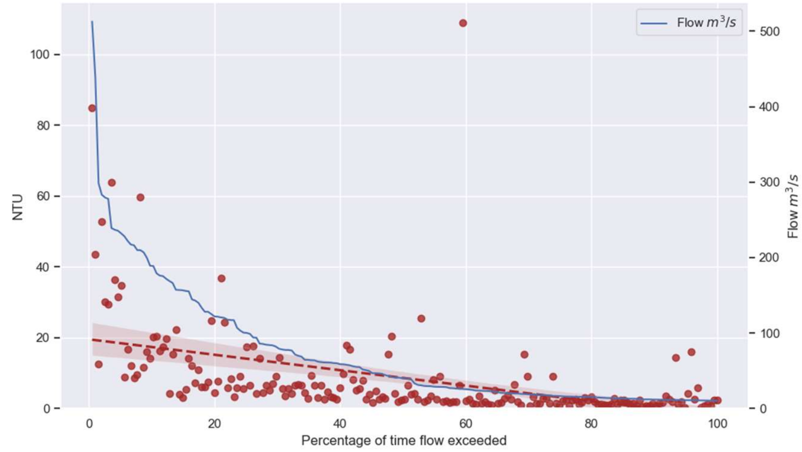


Figure 7-3 - Turbidity (FTU) (orange) (River Severn at Hampton Loade, spot sample data) against a flow duration curve (blue) (River Severn).

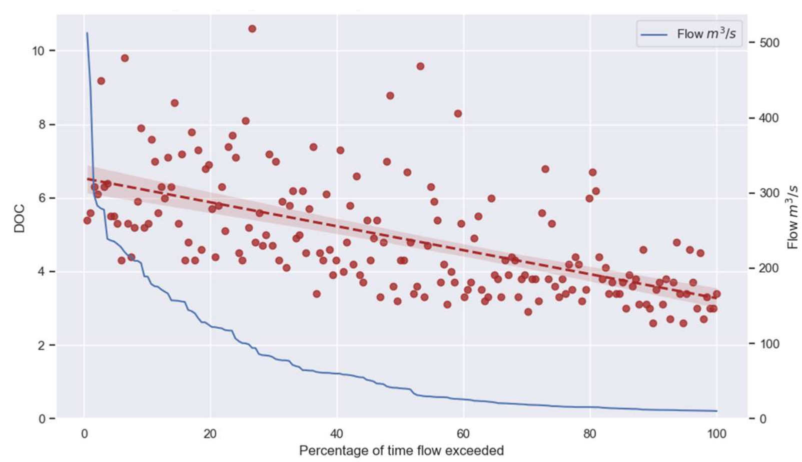


Figure 7-4 - Dissolved organic carbon concentrations (DOC) (mg/l) (orange) (River Severn at Hampton Loade, spot sample data) against a flow duration curve (blue) (River Severn).

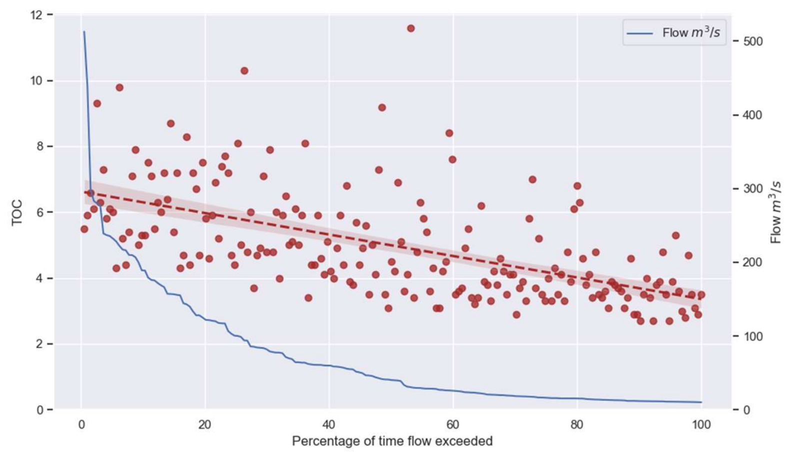


Figure 7-5 - Total organic carbon (TOC) (mg/l) (orange) (River Severn at Hampton Loade, spot sample data) against a flow duration curve (blue) (River Severn).

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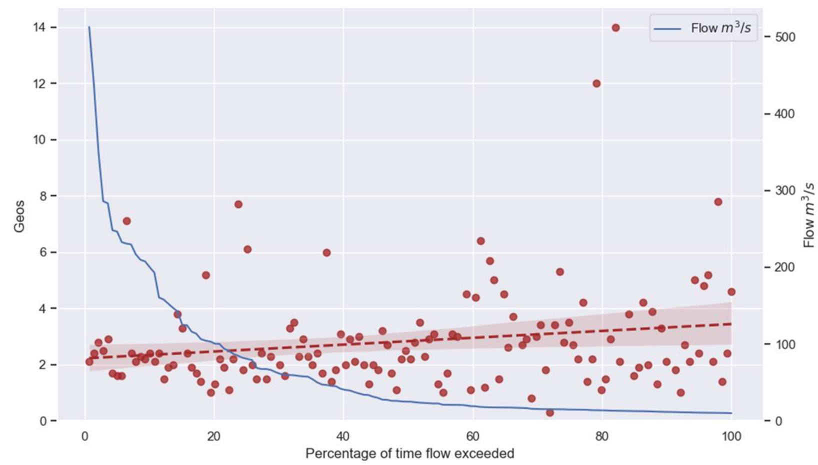

Figure 7-6 - Geosmin (ng/l) concentrations (orange) (River Severn at Hampton Loade, spot sample data) against a flow duration curve (blue) (River Severn).

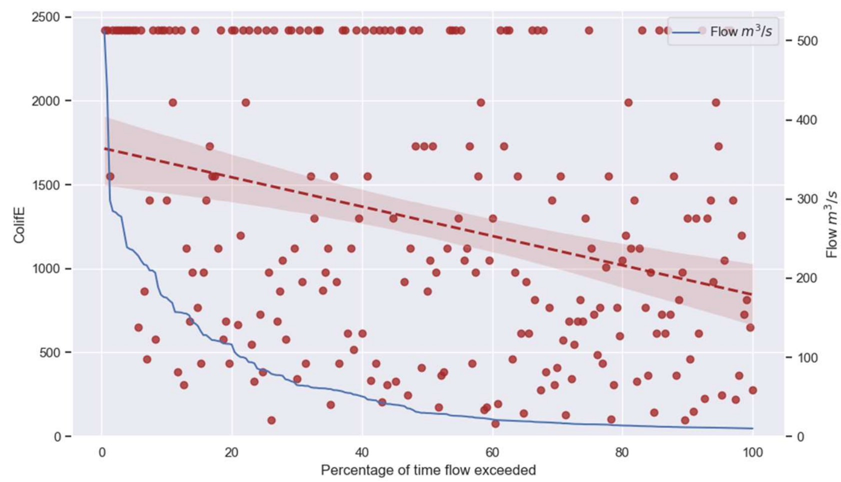

Figure 7-7 - Total coliform concentrations (MPN) (orange) (River Severn at Hampton Loade, spot sample data) against a flow duration curve (blue) (River Severn).

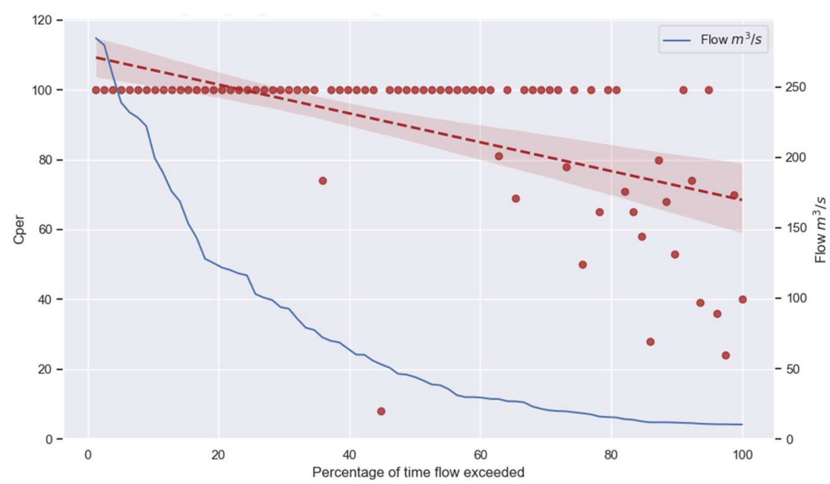

Figure 7-8 - Clostridium perfringens concentrations (No./100 ml) (orange) (River Severn at Hampton Loade, spot sample data) against a flow duration curve (blue) (River Severn).

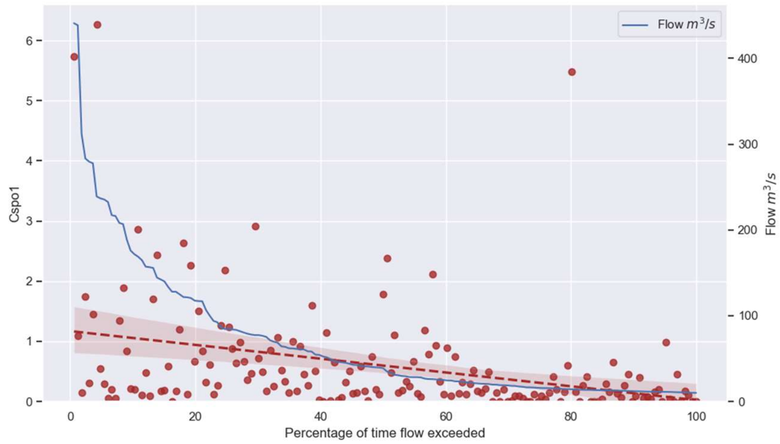

Figure 7-9 - Cryptosporidia (Non-Reg) concentrations (No./10l) (orange) (River Severn at Hampton Loade, spot sample data) against a flow duration curve (blue) (River Severn).

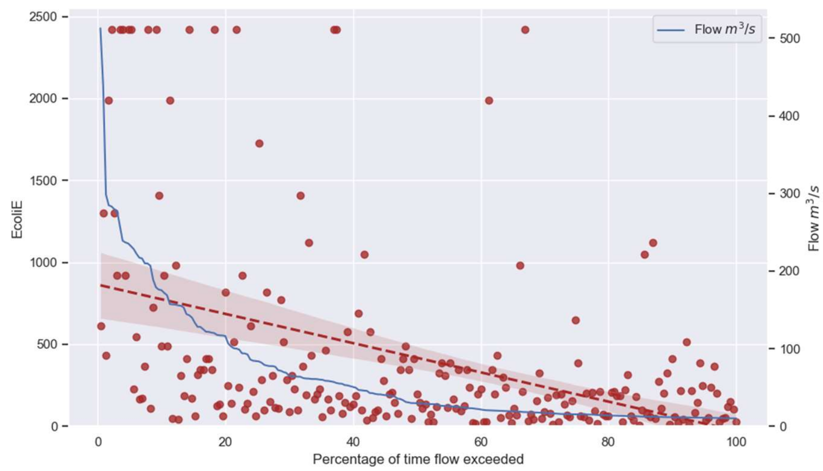

Figure 7-10 - E.coli Estimate (MPN) (orange) (River Severn at Hampton Loade, spot sample data) against a flow duration curve (blue) (River Severn).

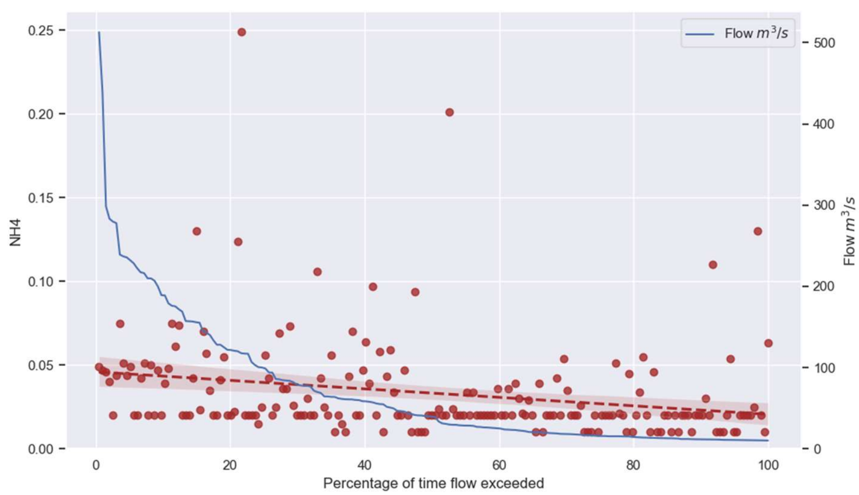

Figure 7-11 - Ammonium concentrations (as NH_4) (mg/l) (orange) (River Severn at Hampton Loade, spot sample data) against a flow duration curve (blue) (River Severn).

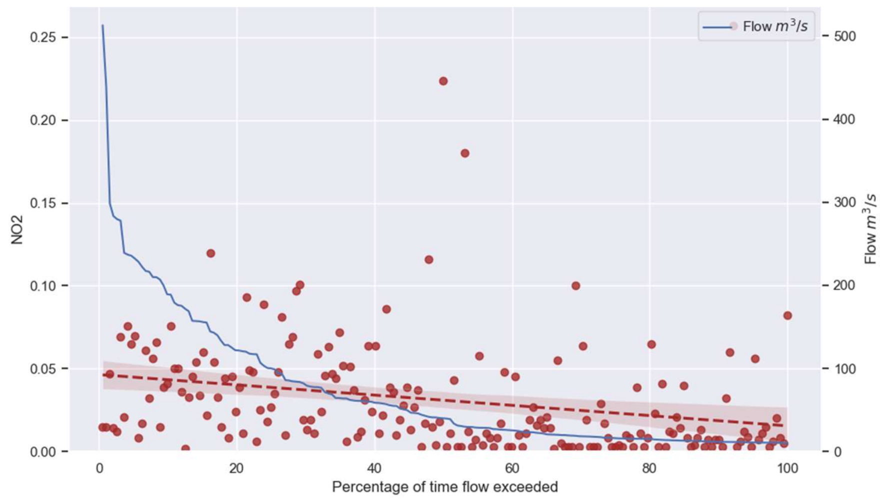

Figure 7-12 - Nitrite concentrations (as NO_2) (mg/l) (orange) (River Severn at Hampton Loade, spot sample data against a flow duration curve (blue) (River Severn).

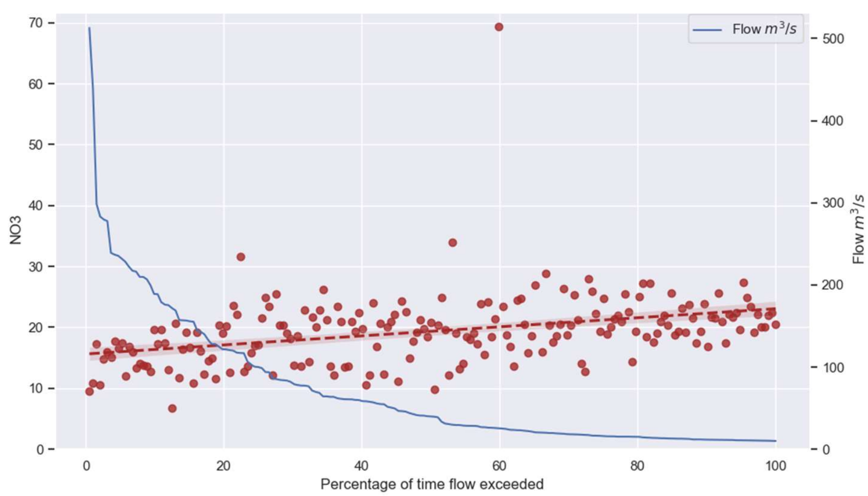

Figure 7-13 - Nitrate concentrations (as NO_3) (mg/l) (orange) (River Severn at Hampton Loade, spot sample data) against a flow duration curve (blue) (River Severn).

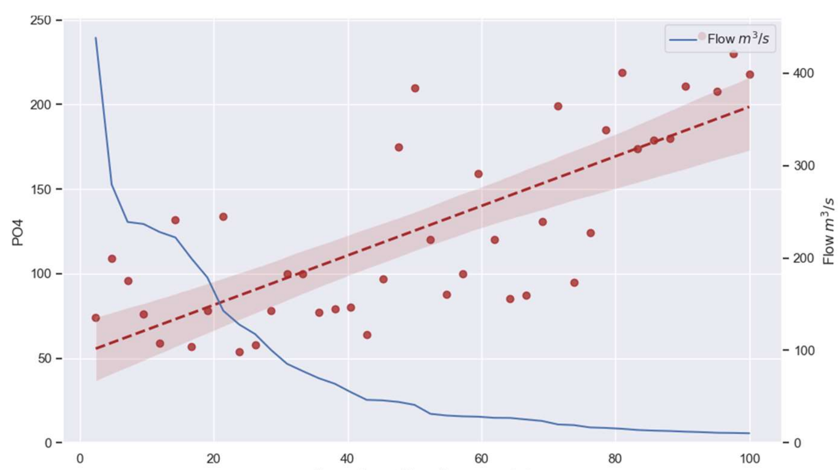

Figure 7-14 - Phosphate concentrations (as PO_4) (mg/l) (orange) (River Severn at Hampton Loade, spot sample data) against a flow duration curve (blue) (River Severn).

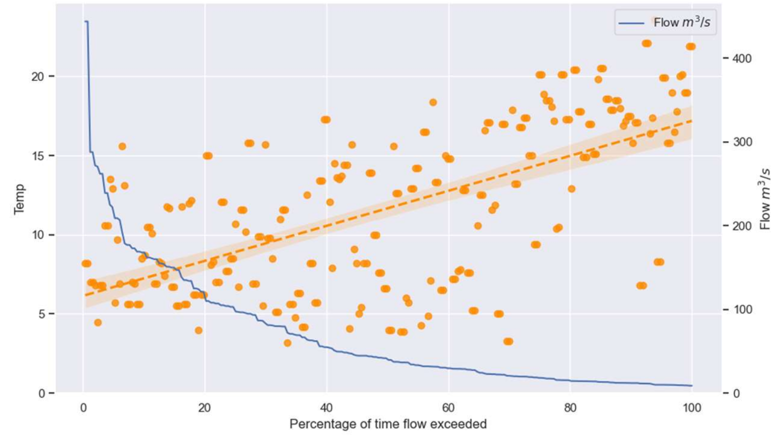

Figure 7-15 - Temperature (°C) (orange) (River Severn at Hampton Loade, WIMS data) against a flow duration curve (blue) (River Severn).

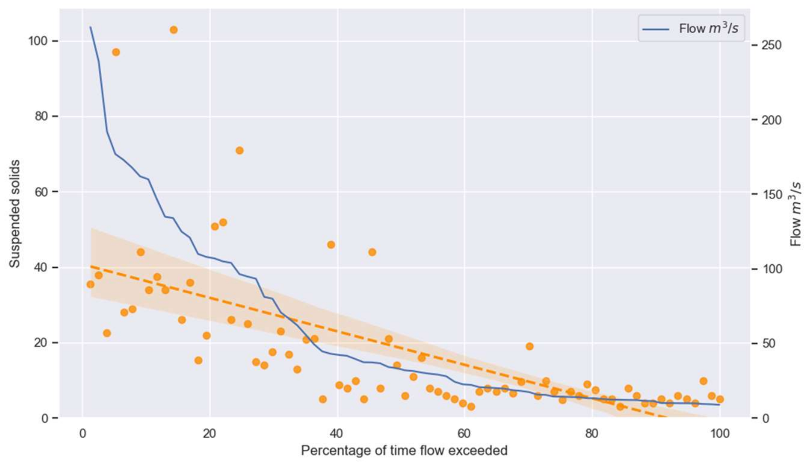

Figure 7-16 - Suspended solids (at 105°C) (orange) (River Severn at Hampton Loade, WIMS data) against a flow duration curve (blue) (River Severn).

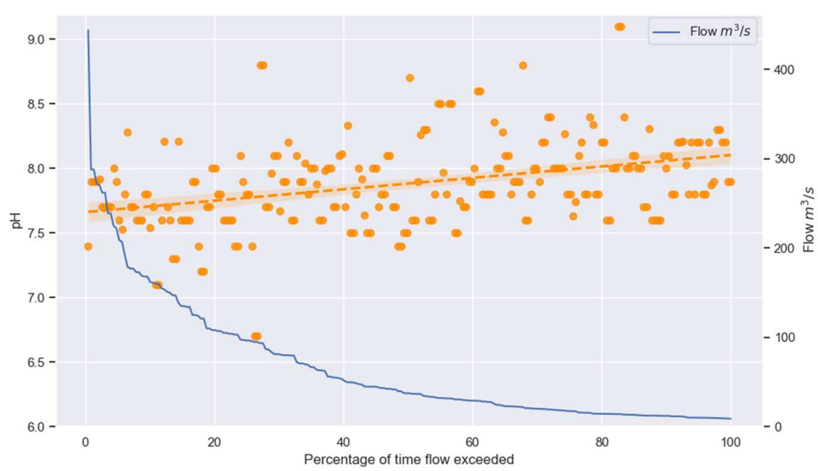

Figure 7-17 - pH (orange) (River Severn at Hampton Loade, WIMS data) against a flow duration curve (blue) (River Severn).

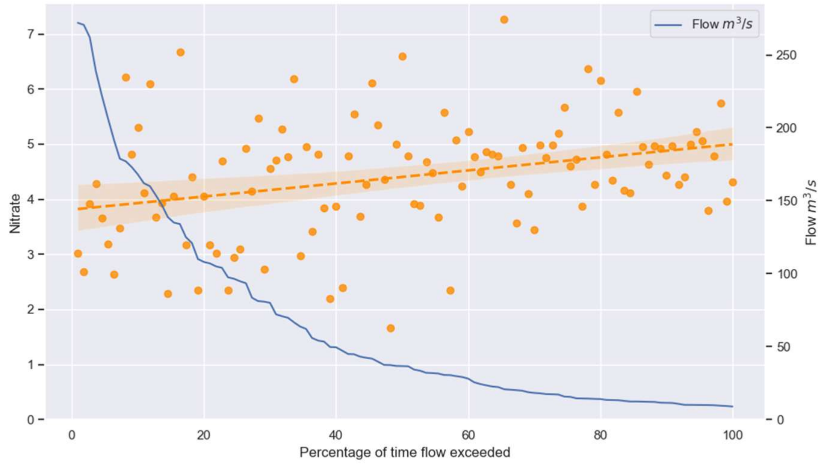

Figure 7-18 - Nitrate concentrations (as N) (mg/l) (orange) (River Severn at Hampton Loade, WIMS data) against a flow duration curve (blue) (River Severn).

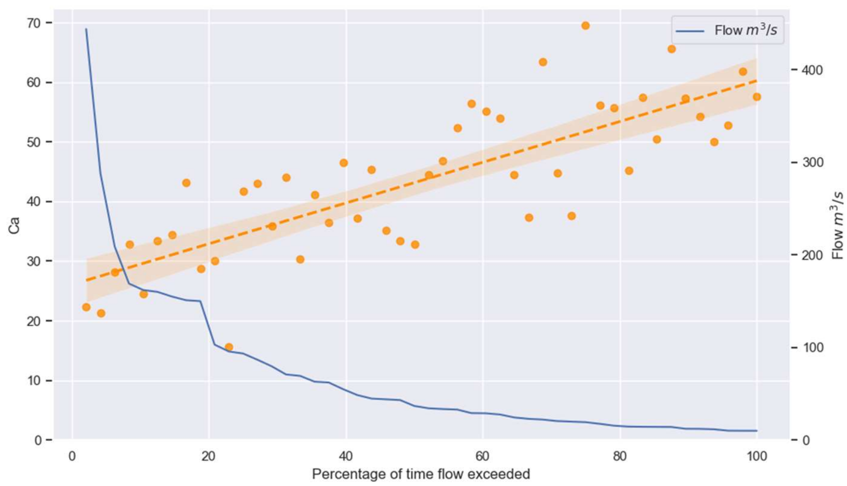

Figure 7-19 - Calcium concentrations (Ca) (mg/l) (orange) (River Severn at Hampton Loade, WIMS data) against a flow duration curve (blue) (River Severn).

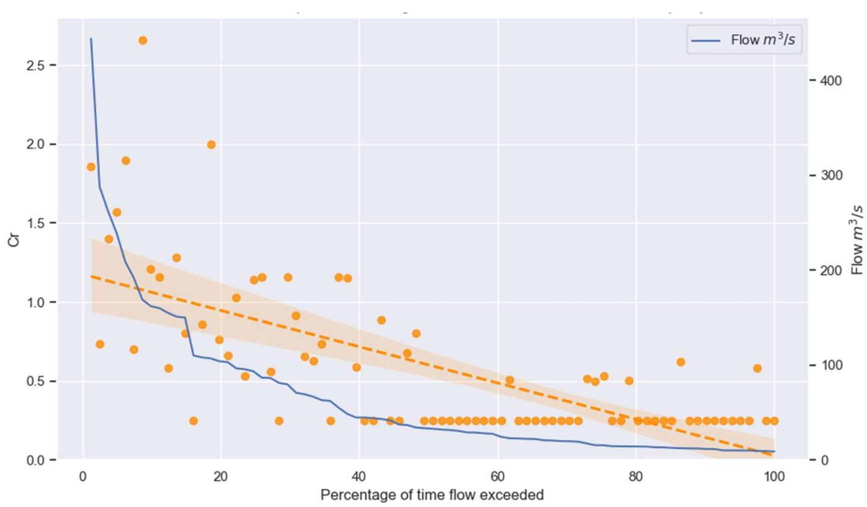

Figure 7-20 - Chromium concentrations (Cr) (mg/l) (orange) (River Severn at Hampton Loade, WIMS data) against a flow duration curve (blue) (River Severn).

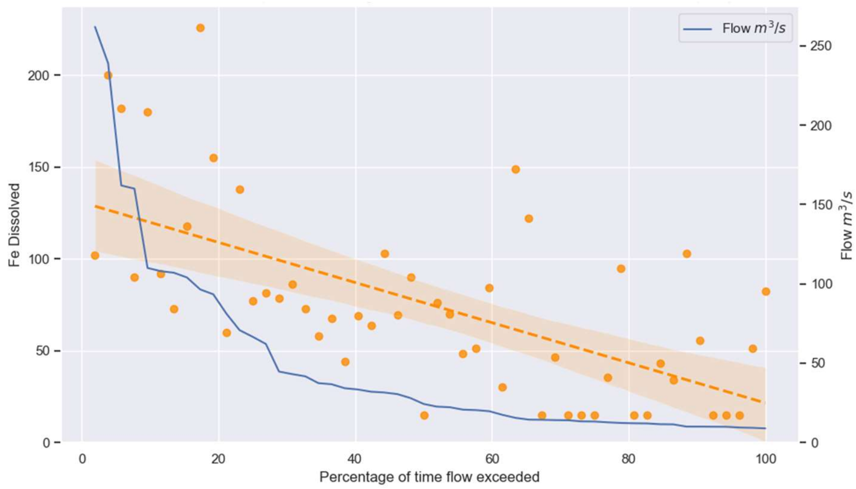

Figure 7-21 - Dissolved iron concentrations (Fe dissolved/filtered) (µg/l) (orange) (River Severn at Hampton Loade, WIMS data) against a flow duration curve (blue) (River Severn).

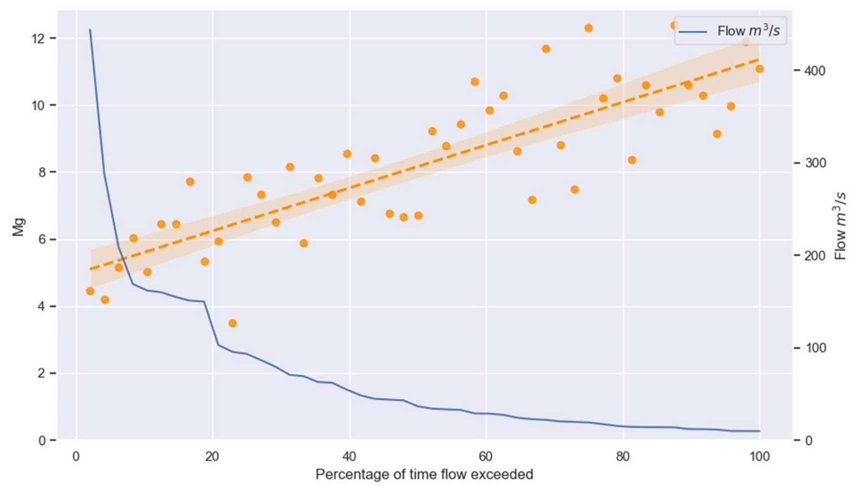

Figure 7-22 - Magnesium concentrations (Mg) (mg/l) (orange) (River Severn at Hampton Loade, WIMS data) against a flow duration curve (blue) (River Severn).

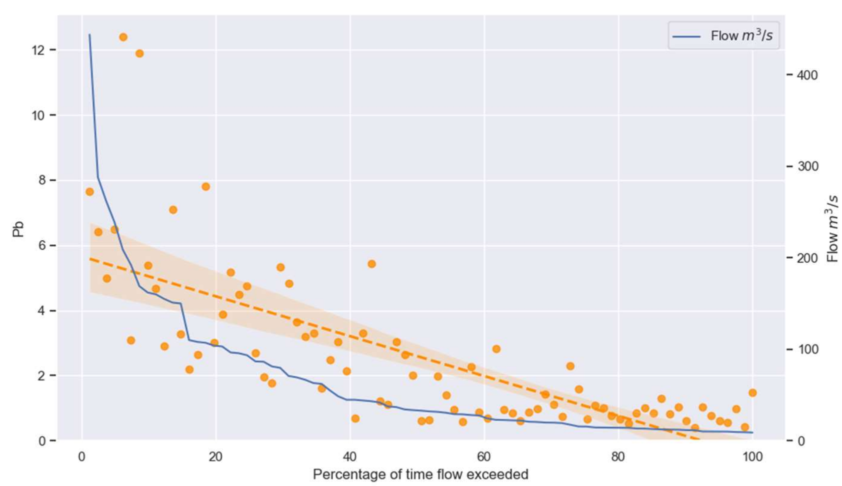

Figure 7-23 - Lead concentrations (Pb) (µg/l) (orange) (River Severn at Hampton Loade, WIMS data) against a flow duration curve (blue) (River Severn).

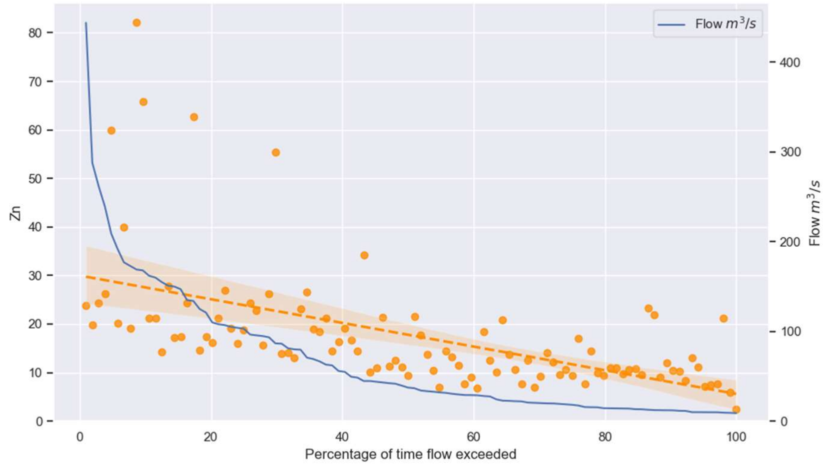

Figure 7-24 – Zinc concentrations (Zn) (µg/l) (orange) (River Severn at Hampton Loade, WIMS data) against a flow duration curve (blue) (River Severn).

A.2. Hampton Loade Raw Water

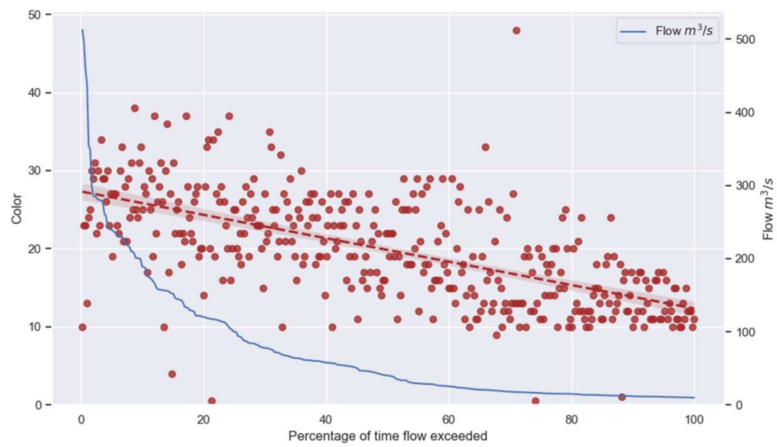

Figure 7-25 - Colour (mg/l Pt/Co) (brown) (Hampton Loade Raw Water, spot sample data) against a flow duration curve (blue) (River Severn).

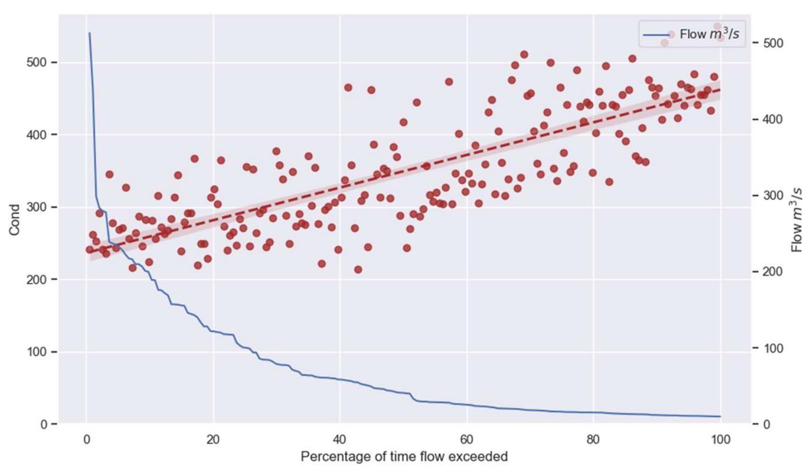

Figure 7-26 - Conductivity (µS/cm) (brown) (Hampton Loade Raw Water, spot sample data) against a flow duration curve (blue) (River Severn).

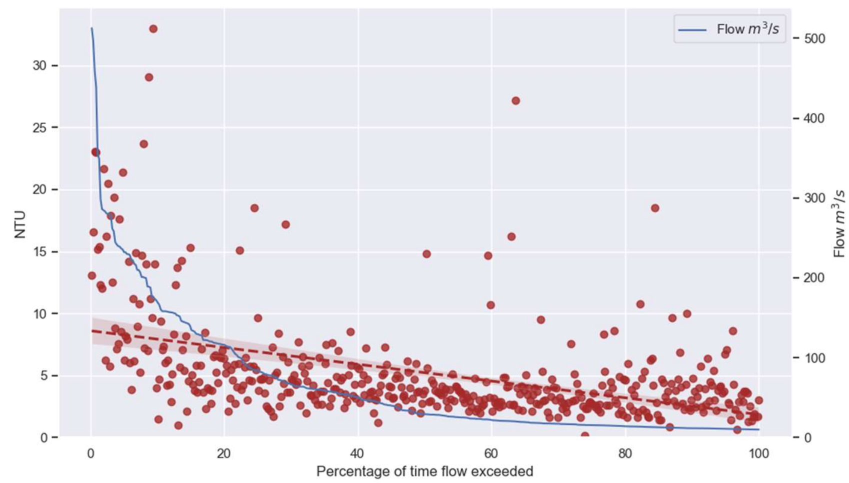

Figure 7-27 - Turbidity (FTU) (brown) (Hampton Loade Raw Water, spot sample data) against a flow duration curve (blue) (River Severn).

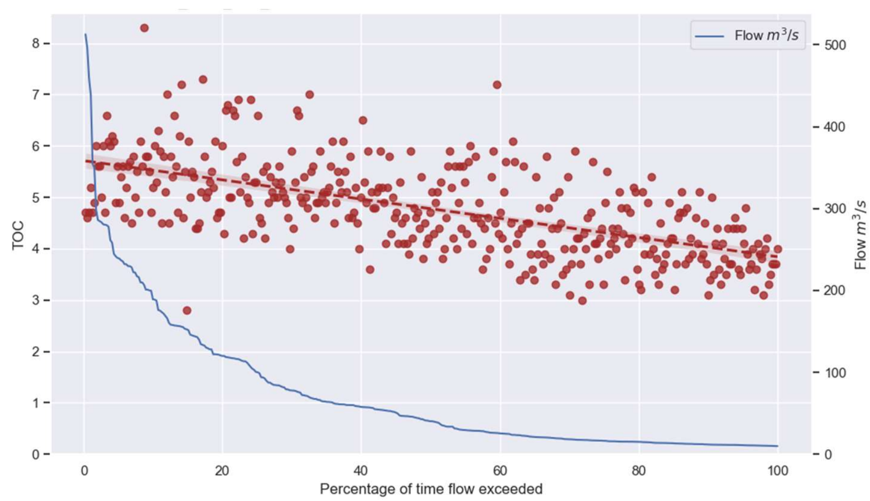

Figure 7-28 - Total organic carbon concentrations (TOC) (mg/l) (brown) (Hampton Loade Raw Water, spot sample data) against a flow duration curve (blue) (River Severn).

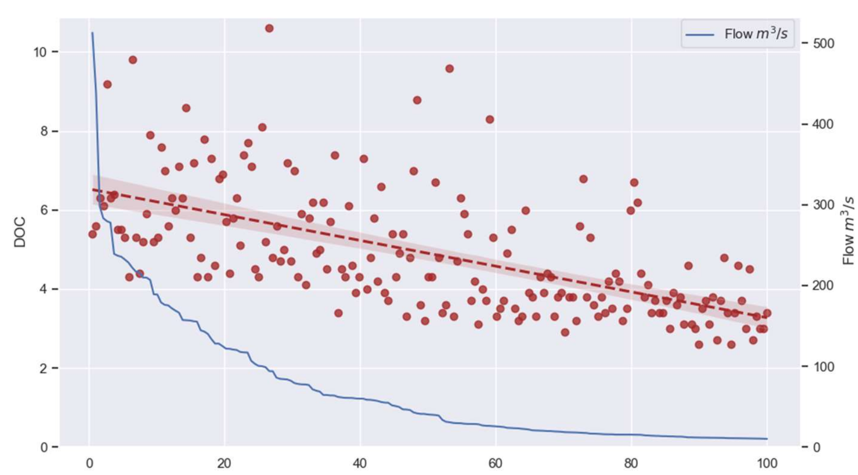

Figure 7-29 - Dissolved organic carbon (DOC) (mg/l) (brown) (Hampton Loade Raw Water, spot sample data) against a flow duration curve (blue) (River Severn).

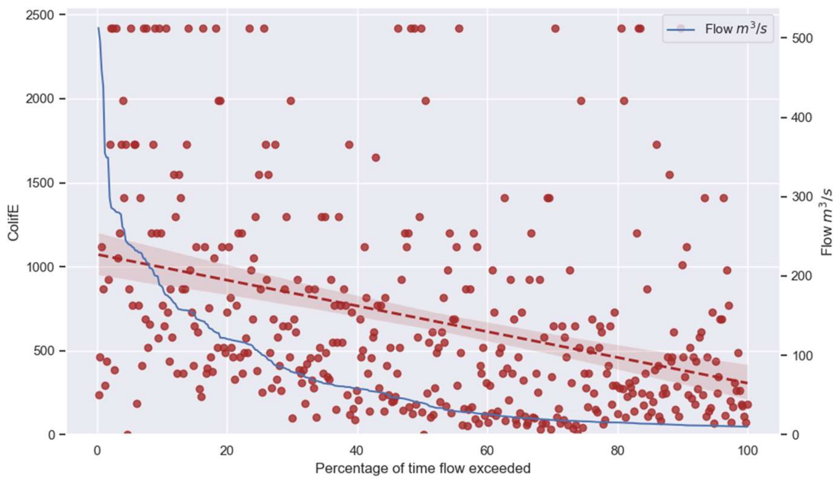

Figure 7-30 - Total coliforms Estimate (MPN) (brown) (Hampton Loade Raw Water, spot sample data) against a flow duration curve (blue) (River Severn).

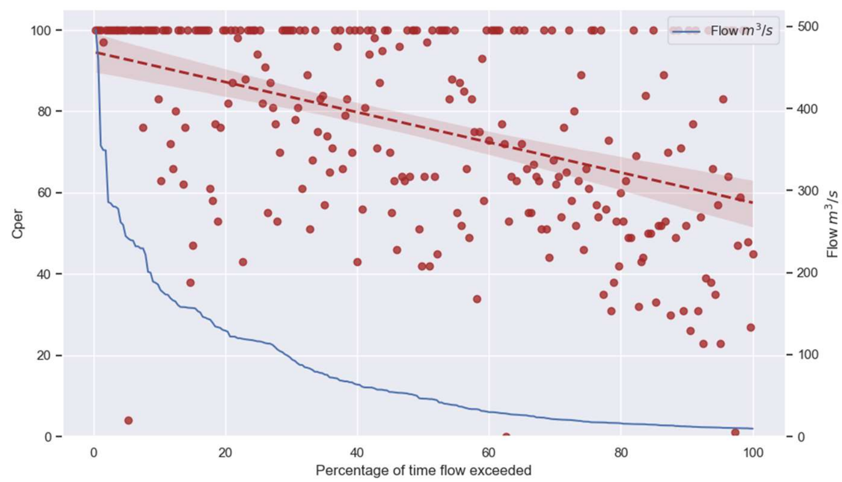

Figure 7-31 - Clostridium perfringens (No./100ml) (brown) (Hampton Loade Raw Water, spot sample data) against a flow duration curve (blue) (River Severn).

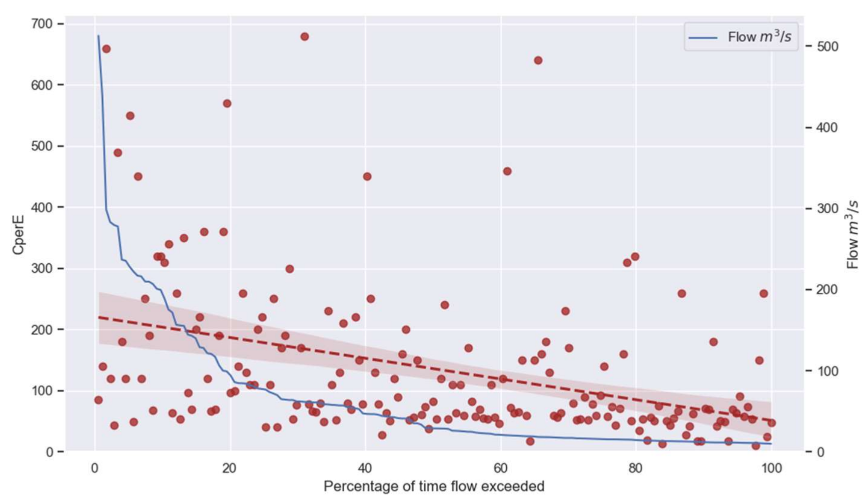

Figure 7-32 - Clostridium perfringens estimate (No./100l) (brown) (Hampton Loade Raw Water, spot sample data) against a flow duration curve (blue) (River Severn).

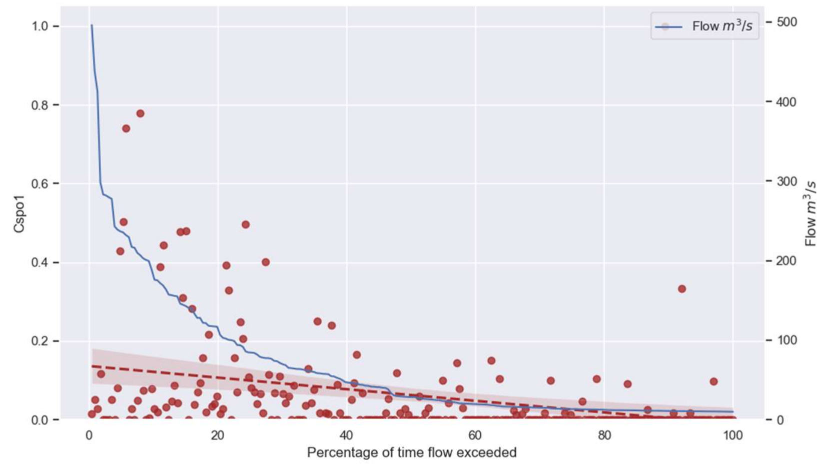

Figure 7-33 - Cryptosporidia (Non-Reg) (No./10l) (brown) (Hampton Loade Raw Water, spot sample data) against a flow duration curve (blue) (River Severn).

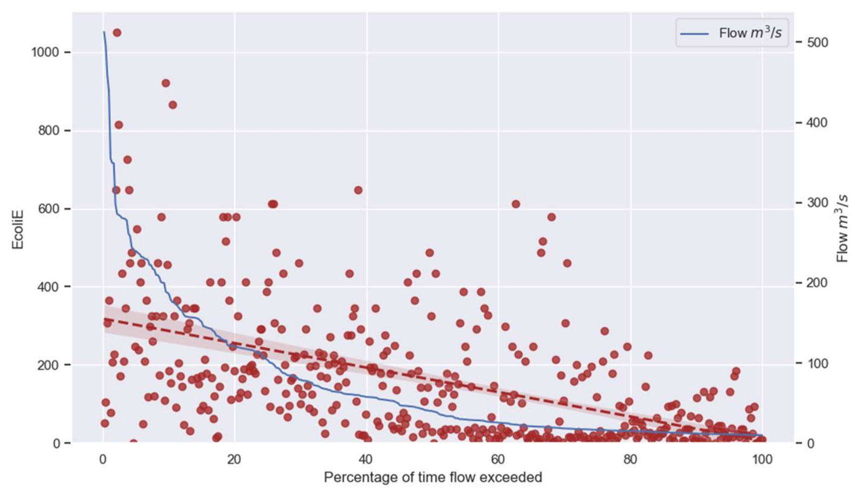

Figure 7-34 - E.coli Estimate (MPN) (brown) (Hampton Loade Raw Water, spot sample data) against a flow duration curve (blue) (River Severn).

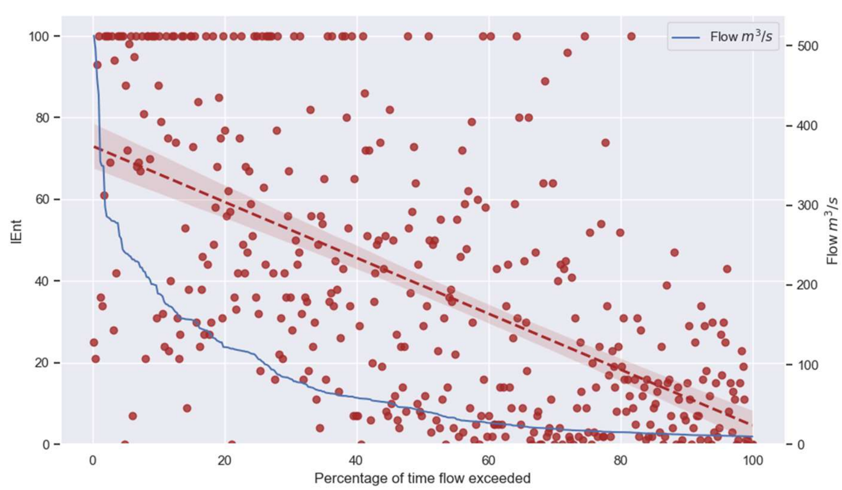

Figure 7-35 - Intestinal Enterococci estimate (cfu/100ml) (brown) (Hampton Loade Raw Water, spot sample data) against a flow duration curve (blue) (River Severn).

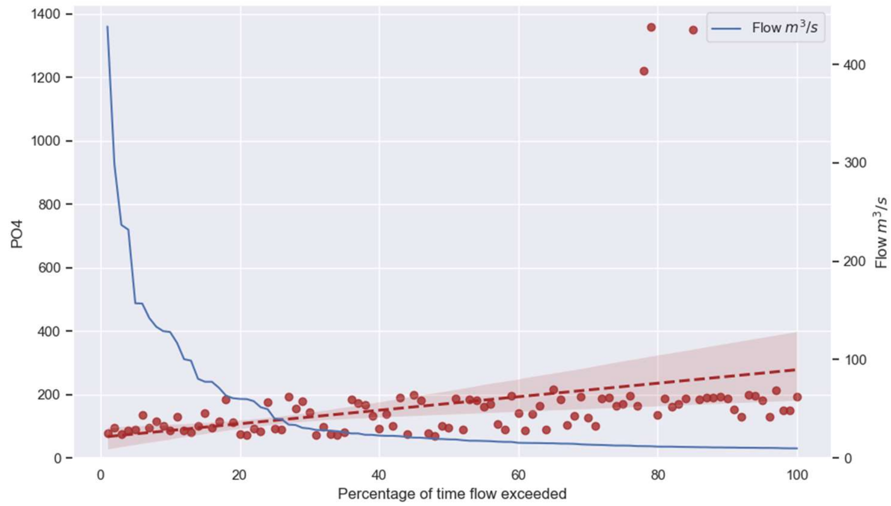

Figure 7-36 - Phosphate (as PO_4) (µg/l) (brown) against a flow duration curve (blue) for Hampton Loade Raw Water (spot sample data).

A.3. Chelmarsh Reservoir

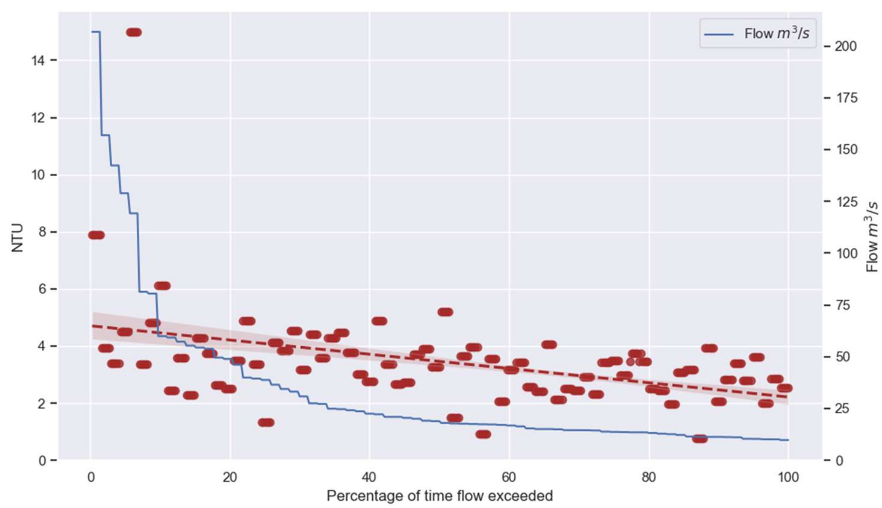

Figure 7-37 – Turbidity (FTU) (brown) (Chelmarsh Reservoir, spot sample data) against a flow duration curve (blue) (River Severn).

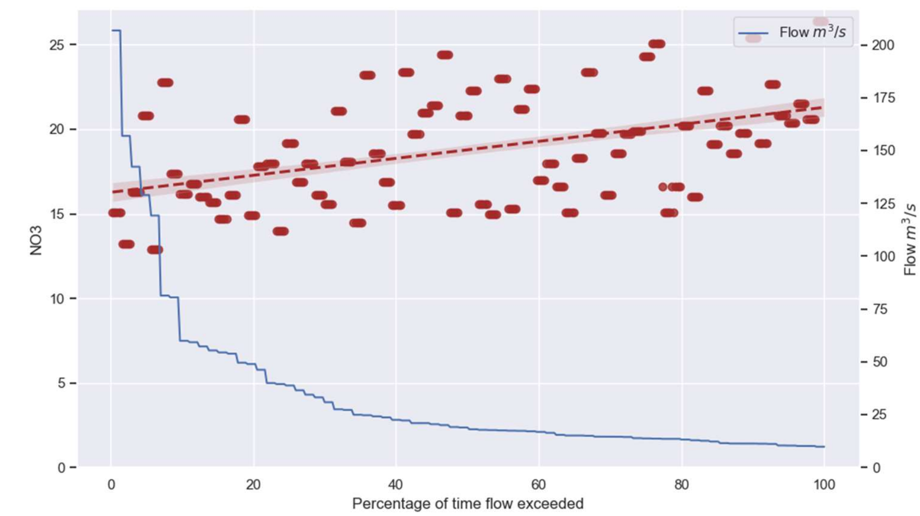

Figure 7-38 - Nitrate concentrations (as NO_3) (mg/l) (brown) (Chelmarsh Reservoir, spot sample data) against a flow duration curve (blue) (River Severn).

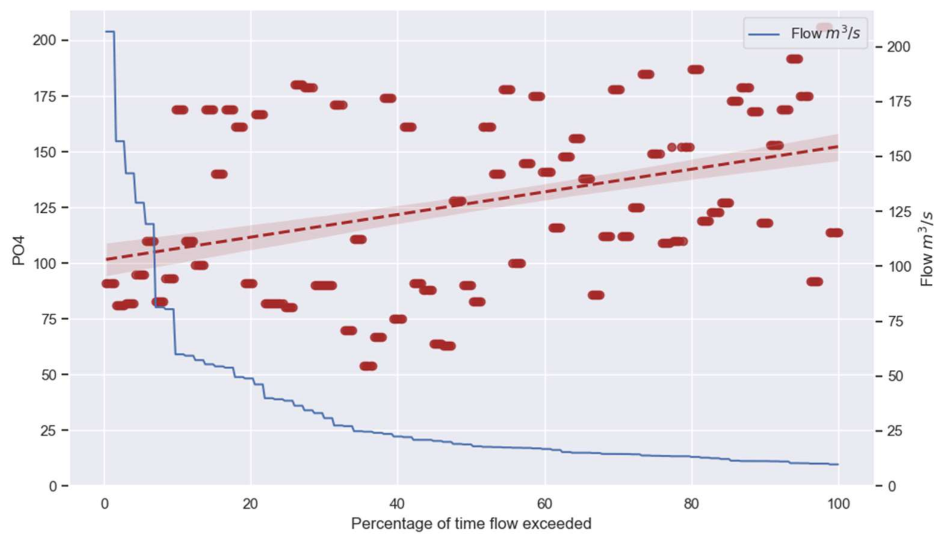

Figure 7-39 – Phosphate concentrations (as PO_4) (mg/l) (brown) (Chelmarsh Reservoir, spot sample data) against a flow duration curve (blue) (River Severn).

Appendix B. River Blithe/ Blithfield Reservoir water quality against flow

B.1. Blithfield Reservoir

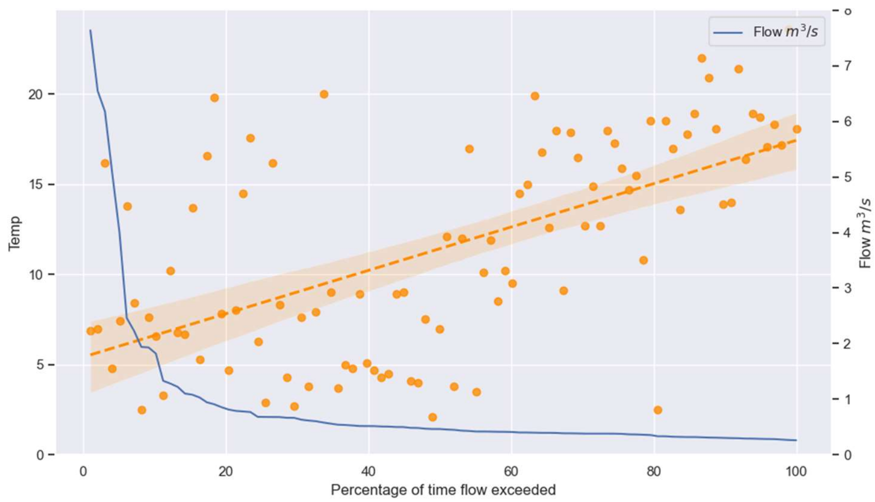

Figure 7-40 – Temperature (°C) (orange) (Blithfield Reservoir, WIMS data) against a flow duration curve (blue) (River Blithe).

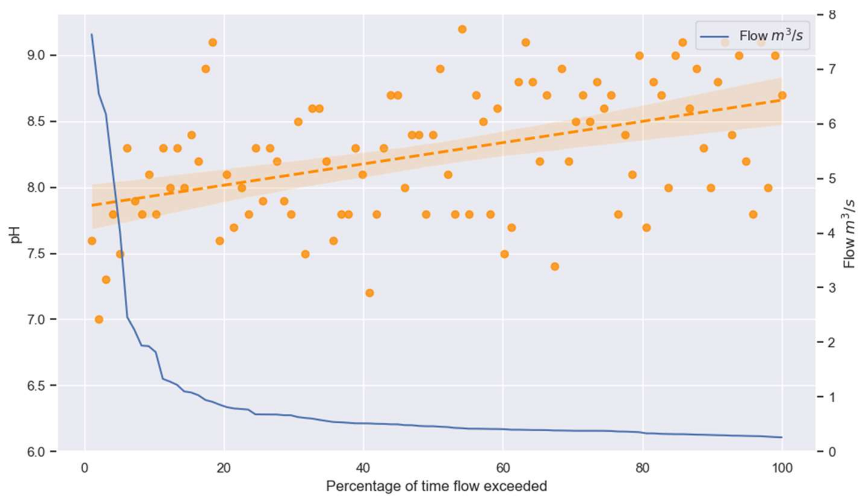

Figure 7-41 – pH (orange) (Blithfield Reservoir, WIMS data) against a flow duration curve (blue) (River Blithe).

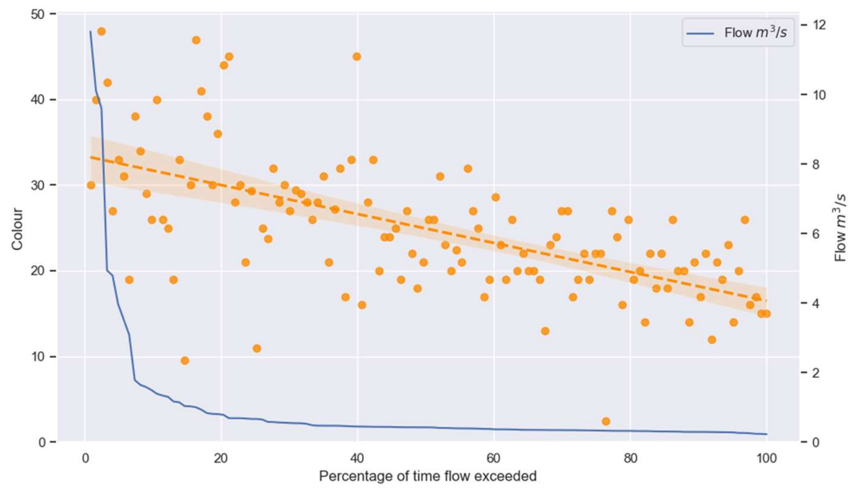

Figure 7-42 - Colour (Hazen) (orange) (Blithfield Reservoir, WIMS data) against a flow duration curve (blue) (River Blithe).

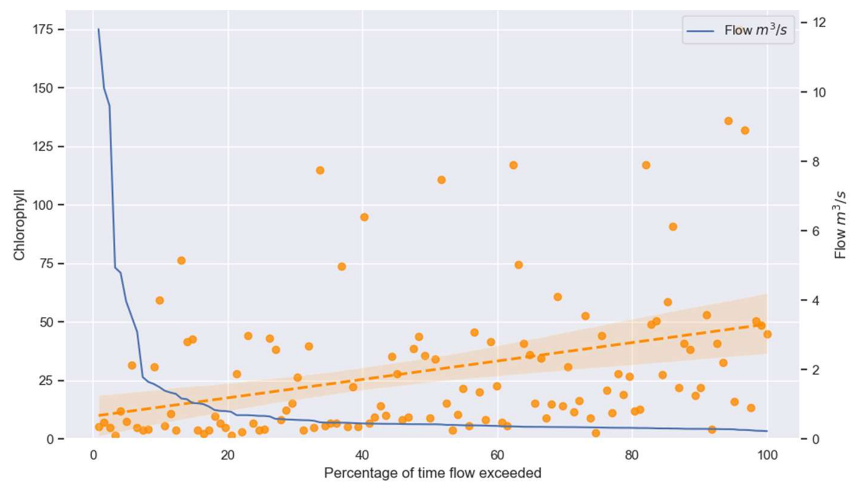

Figure 7-43 – Chlorophyll concentrations (µg/l) (Blithfield Reservoir, WIMS data) against a flow duration curve (blue) (River Blithe).

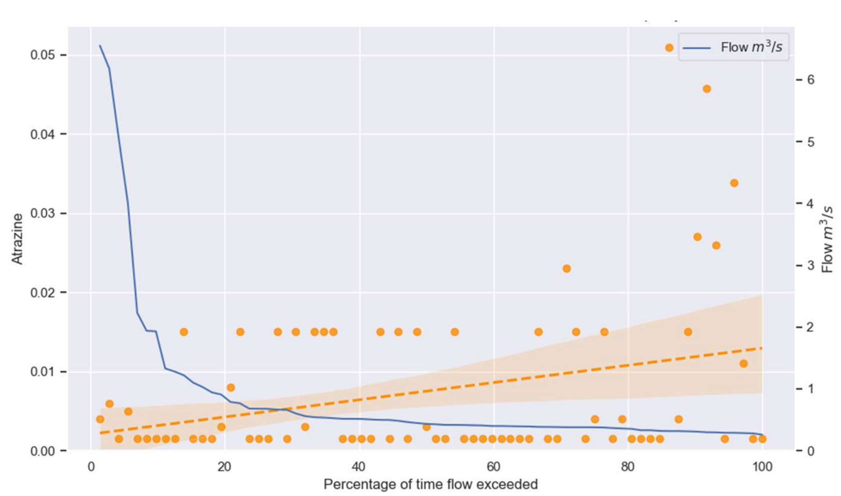

Figure 7-44 – Atrazine concentrations (µg/l) (Blithfield Reservoir, WIMS data) against a flow duration curve (blue) (River Blithe).

B.2. River Blithe

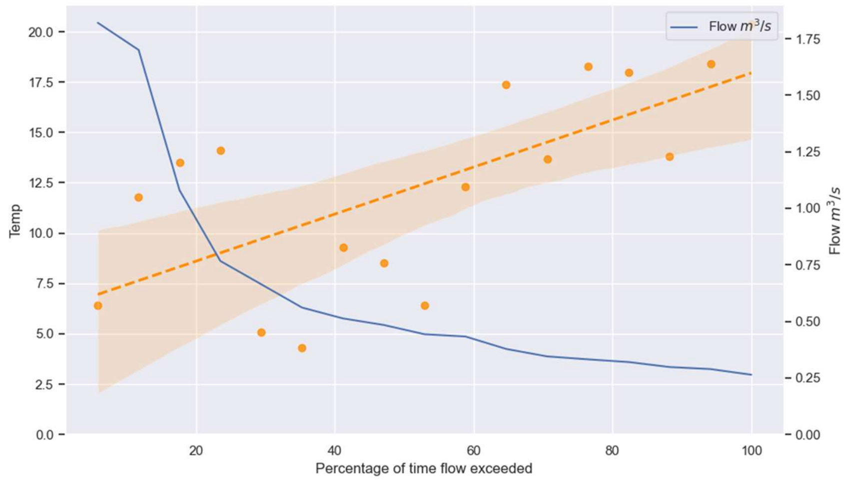

Figure 7-45 – Temperature (°C) (orange) (Balford at B5014, WIMS data) against a flow duration curve (blue) (River Blithe).

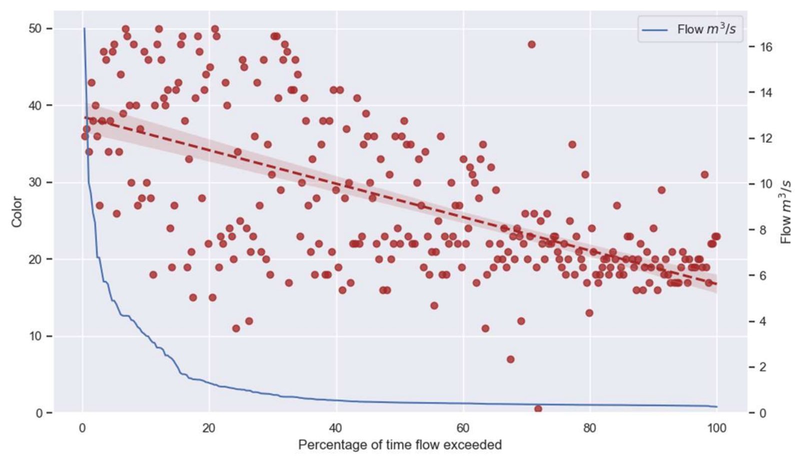

Figure 7-46 - Colour (mg/l Pt/Co) (brown) (River Blithe, spot sample data) against a flow duration curve (blue) (River Blithe).

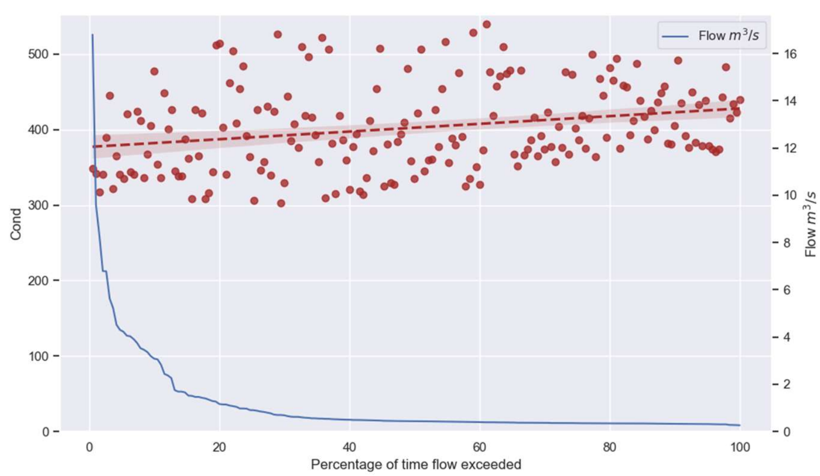

Figure 7-47 – Conductivity (µs/cm) (brown) (River Blithe, spot sample data) against a flow duration curve (blue) (River Blithe).

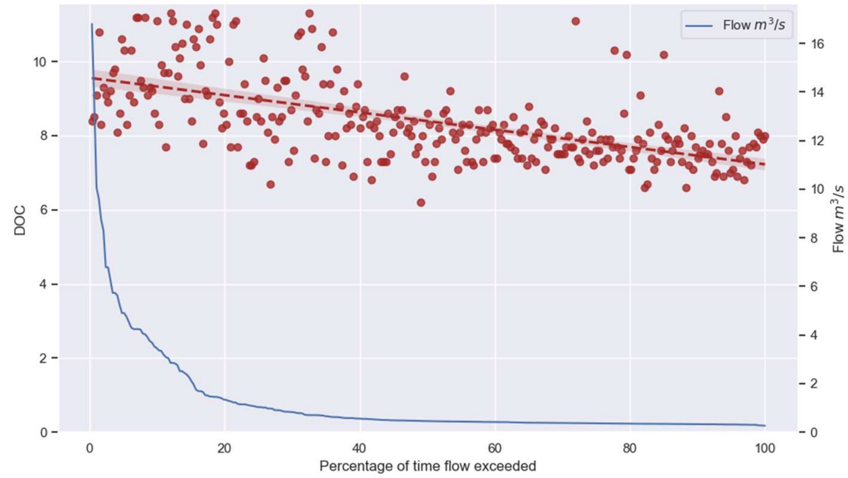

Figure 7-48 - Dissolved organic carbon (DOC) (mg/l) (brown) (River Blithe, spot sample data) against a flow duration curve (blue) (River Blithe).

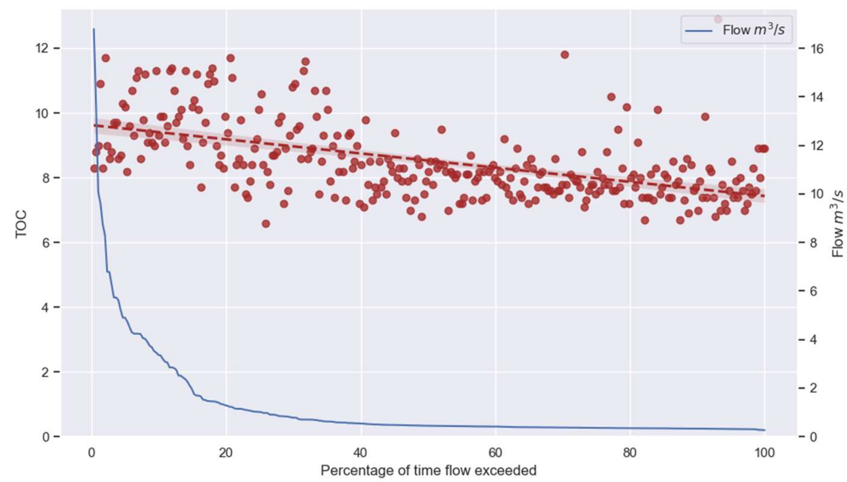

Figure 7-49 - Total organic carbon (TOC) (mg/l) (brown) (River Blithe, spot sample data) against a flow duration curve (blue) (River Blithe).

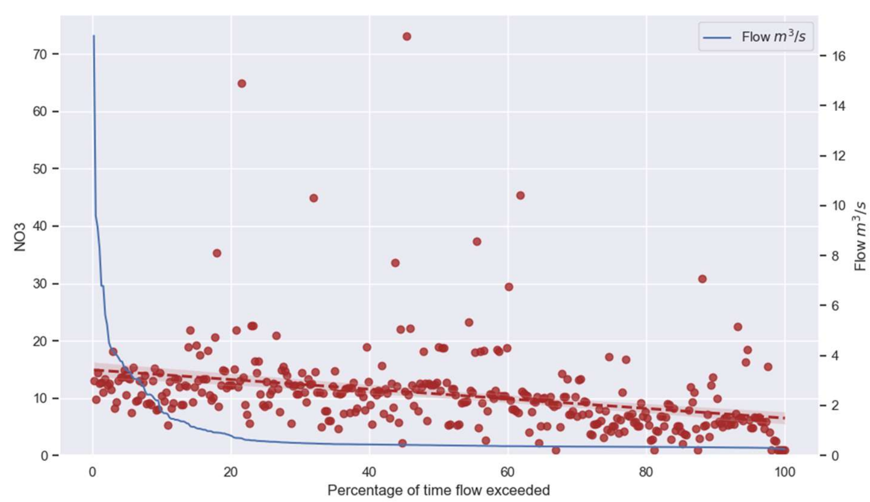

Figure 7-50 – Nitrate (as NO_3) (mg/l) (brown) (River Blithe, spot sample data) against a flow duration curve (blue) (River Blithe).

Appendix C. Flow duration curves for potential ‘proxy’ flow gauges

1. *28018 - Dove at Marston* (NRFA Station Mean Flow Data for 28018 - Dove at Marston on Dove (ceh.ac.uk))

This flow gauge from the FutureFlows dataset is the closest in distance to the original, but the flow duration curve does not show the same characteristics, and the magnitude of the flow is ~10 times higher. **Error! Reference source not found.** shows the flow duration curve for this flow gauge.

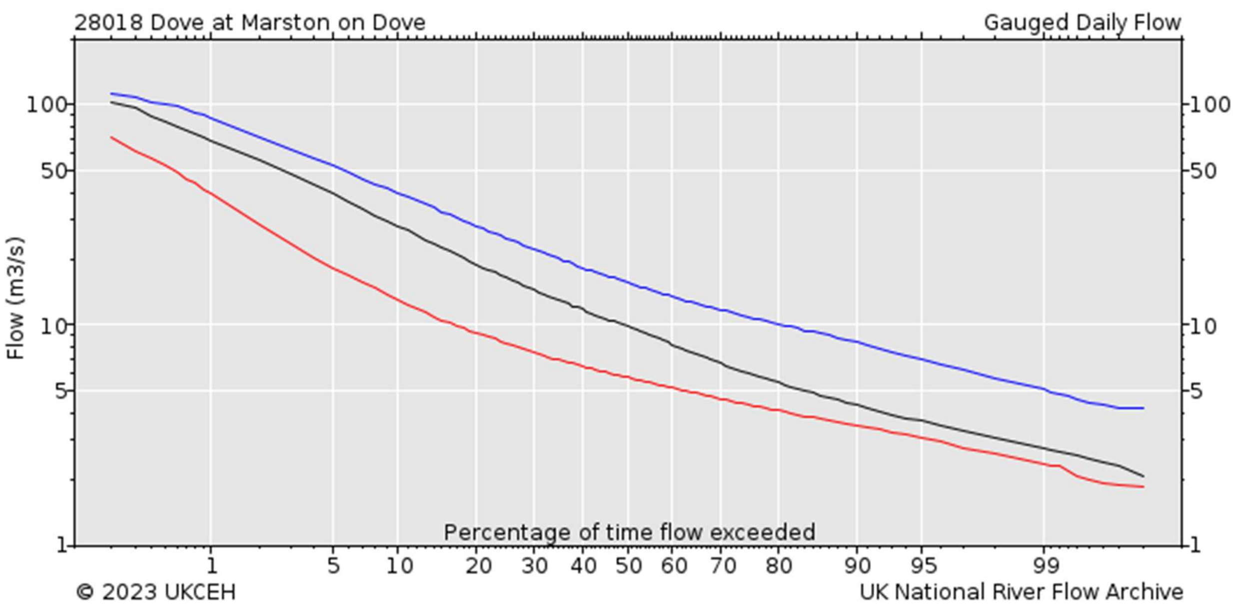

Figure 7-51 - Flow duration curve for the Dove at Marston flow gauge

2. 28055 - Ecclesbourne at Duffield (NRFA Station Mean Flow Data for 28055 - Ecclesbourne at Duffield (ceh.ac.uk))

This flow gauge from the FutureFlows dataset shows a similar flow magnitude to that of the River Blithe, but it is further away from the original source, which may compromise the effect of climate change perturbations. The flow duration curve (**Error! Reference source not found.**) is still different from River Blithe.

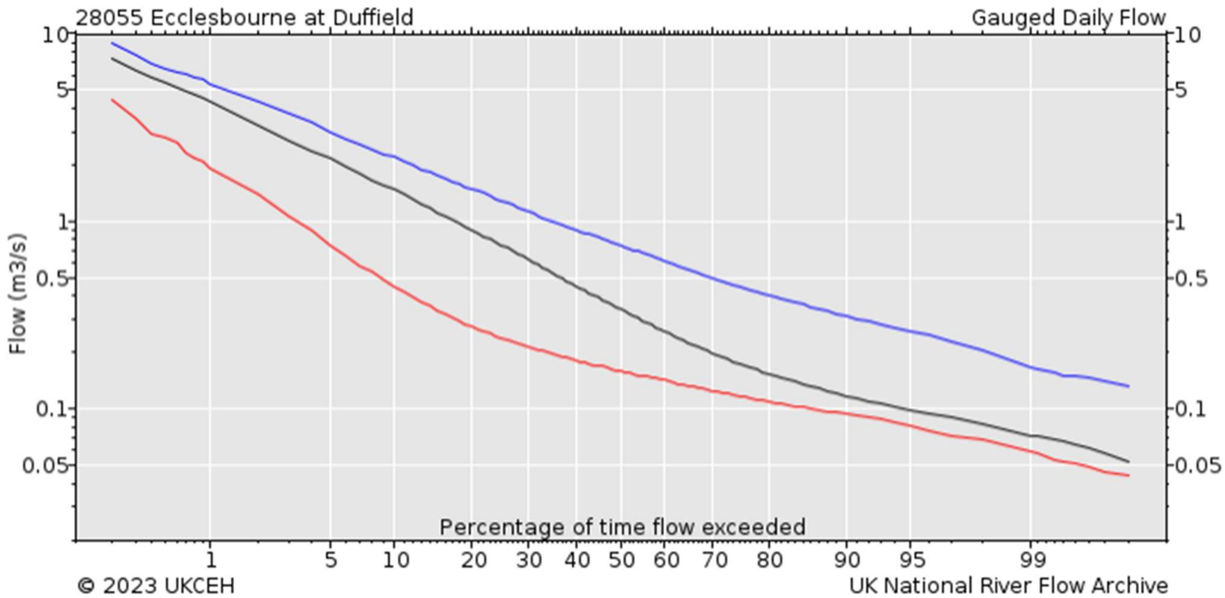

Figure 7-52 - Flow duration curve for the Ecclesbourne at Duffield flow gauge

3. 28009 – Trent at Colwick (slightly better FDC, [NRFA Station Mean Flow Data for 28009 - Trent at Colwick (ceh.ac.uk)](#))

This flow gauge from the eFLaG dataset is not too far away from the original and shows a flow duration curve (**Error! Reference source not found.**) slightly better than other flow gauges. However, the flow magnitude is ~100 times higher than River Blithe.

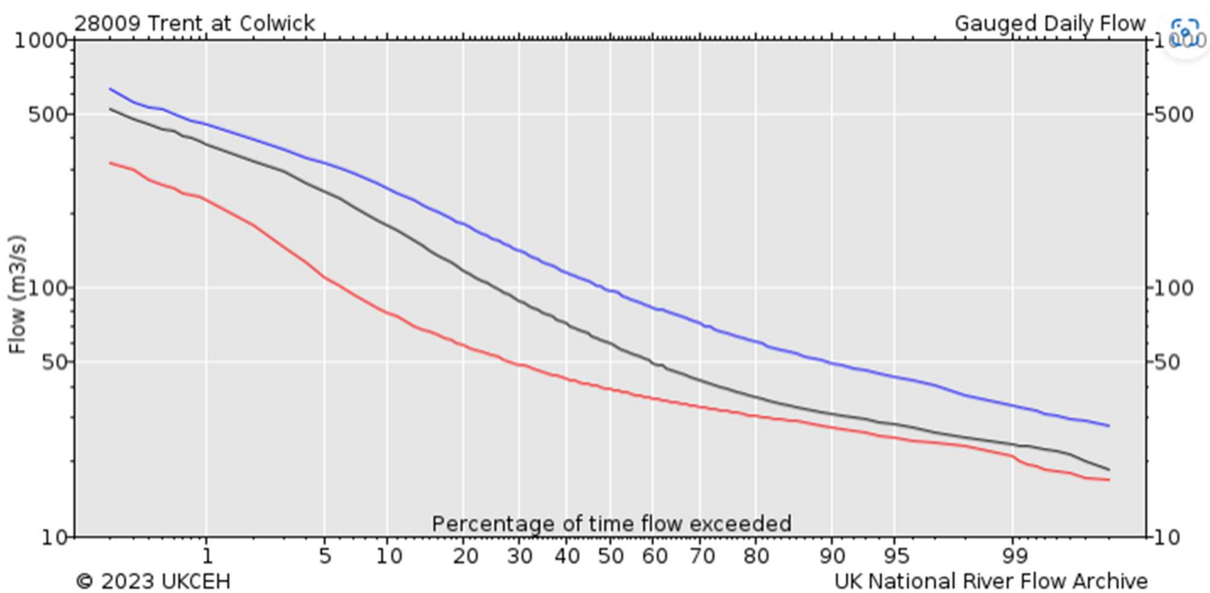

Figure 7-53 - Flow duration curve for the Colwick flow gauge

4. 28046 - Dove at Izaak Walton ([NRFA Station Mean Flow Data for 28046 - Dove at Izaak Walton (ceh.ac.uk)](#))

This flow gauge is the closest in distance from the eFLaG dataset; it is similar in flow magnitude but shows a different flow duration curve than the observed for River Blithe. The flow duration curve is shown in Figure 2-2.

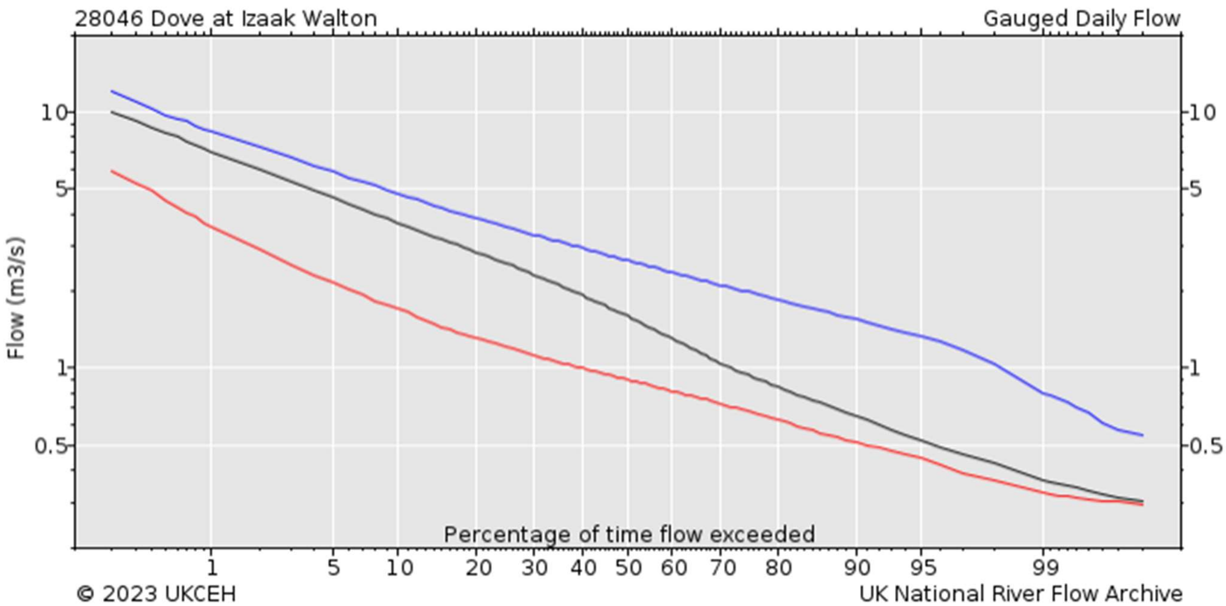

Figure 7-54 - Flow duration curve for the Izaak Walton flow gauge

Appendix D. Climate Change data

D.1. Heat maps with projected flows for the River Blithe

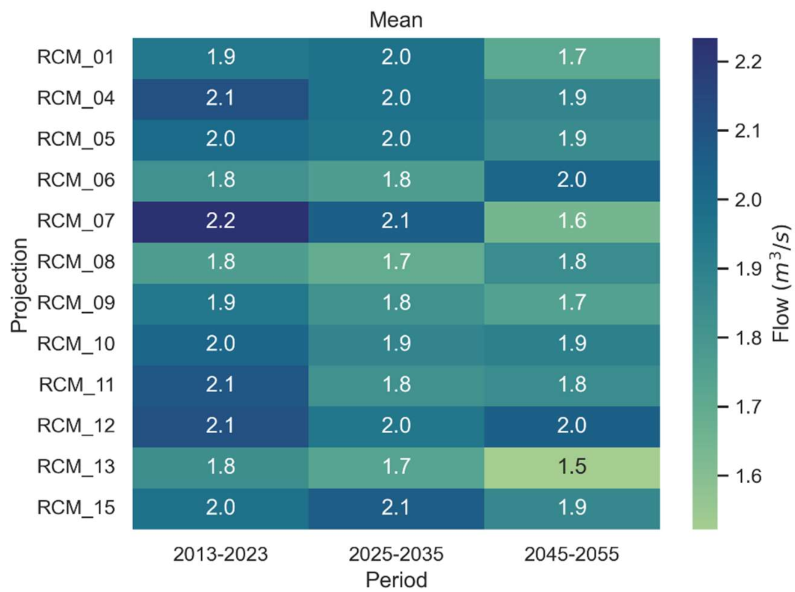

Figure 7-55 – Heatmap showing the mean flow for different periods from 2013 to 2055 for each ensemble member in the eFLaG dataset

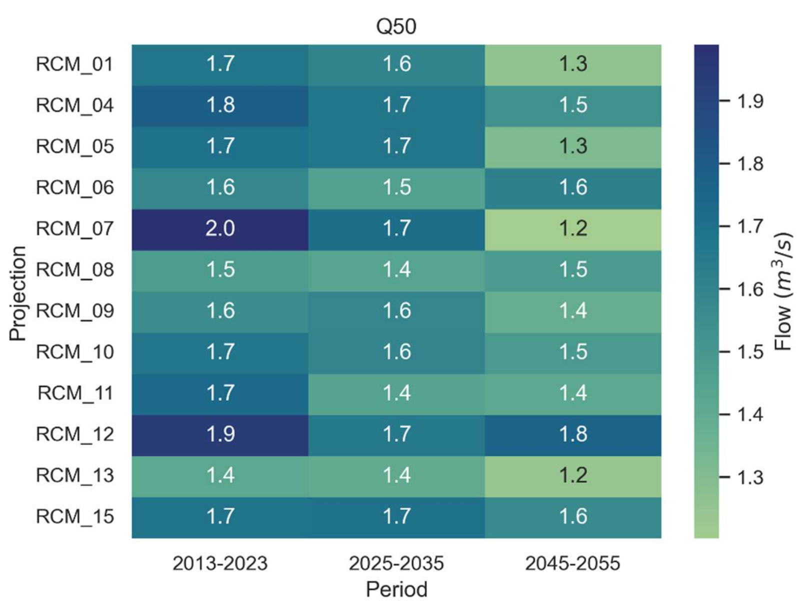

Figure 7-56 – Heatmap showing the median flow for different periods from 2013 to 2055 for each ensemble member in the eFLaG dataset

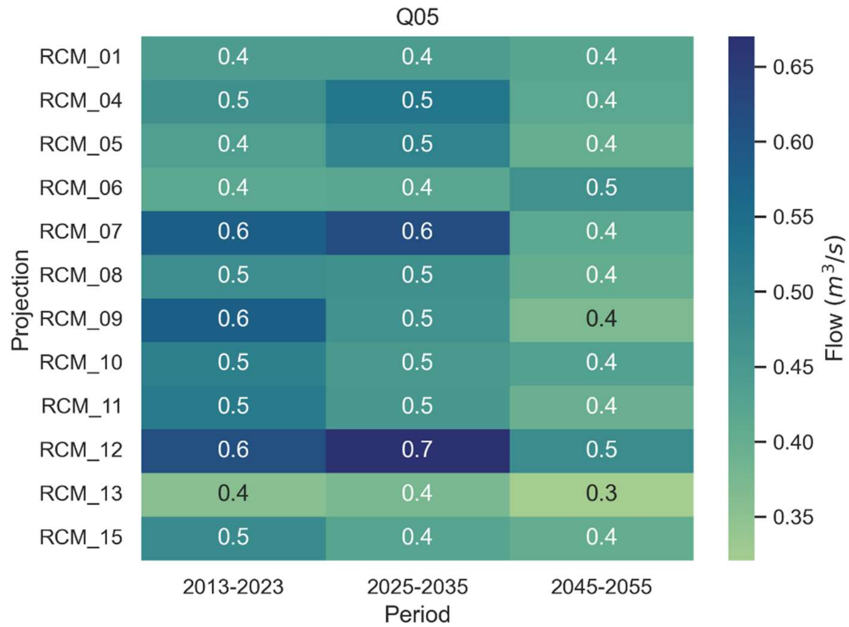

Figure 7-57 – Heatmap showing the 5th percentile flow for different periods from 2013 to 2055 for each ensemble member in the eFLaG dataset

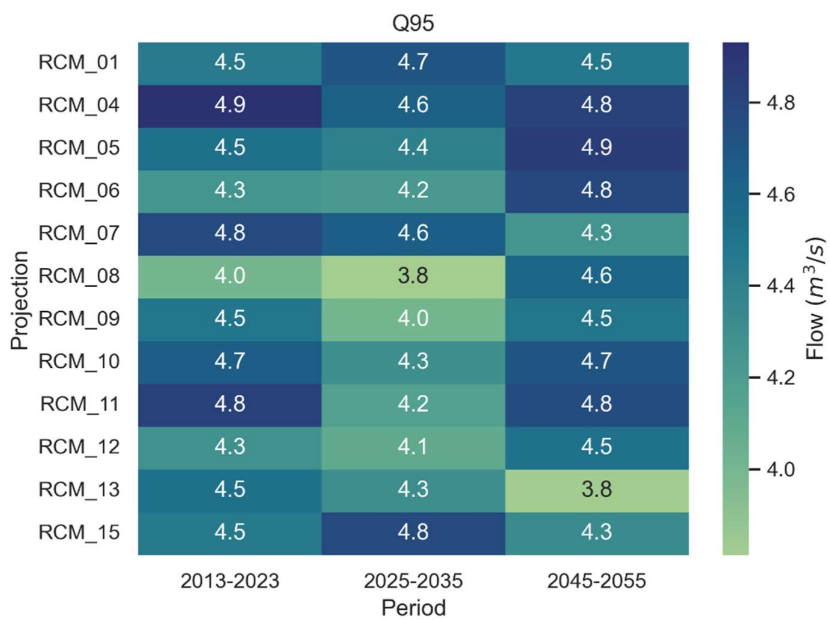

Figure 7-58 – Heatmap showing the 95th percentile flow for different periods from 2013 to 2055 for each ensemble member in the eFLaG dataset

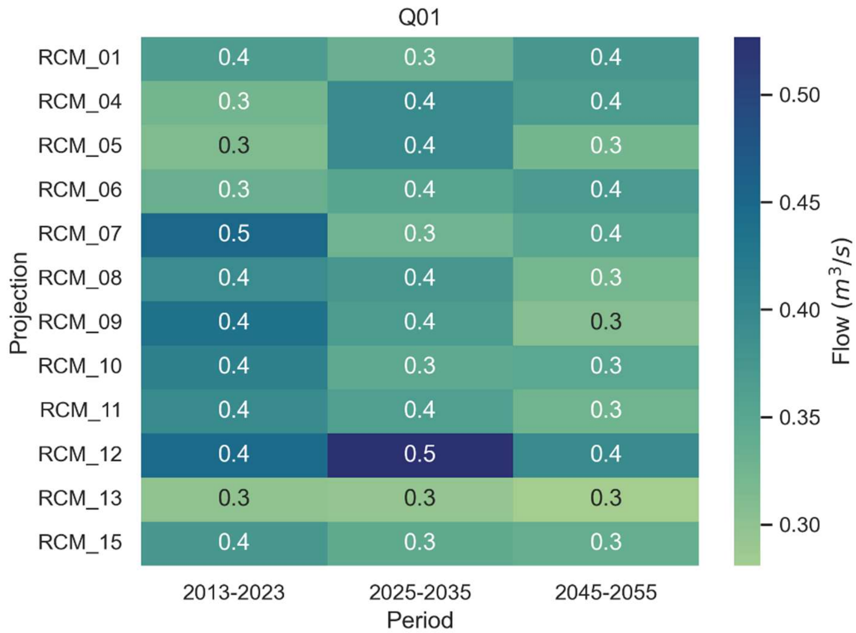

Figure 7-59 – Heatmap showing the 1th percentile flow for different periods from 2013 to 2055 for each ensemble member in the eFLaG dataset

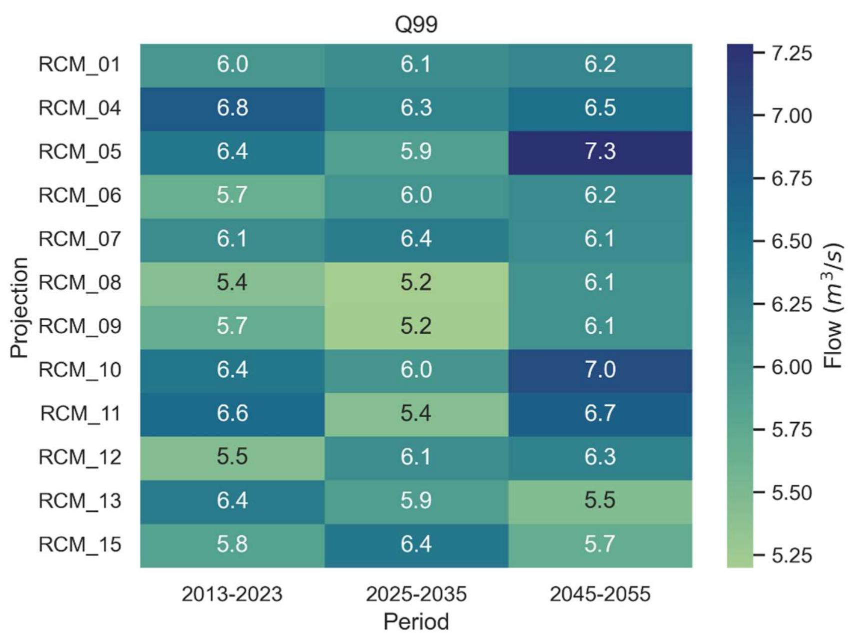

Figure 7-60 – Heatmap showing the 99th percentile flow for different periods from 2013 to 2055 for each ensemble member in the eFLaG dataset

SNC-Lavalin
Peter Daldorph

Appendix B. Groundwater quality assessment

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Member of the SNC-Lavalin Group

Climate change and impacts on groundwater quality

August 2023

5211472-ATK-RP-7.15.6-116

Introduction

Atkins has been asked to undertake an assessment of how climate change may impact on groundwater quality and the knock-on implications for South Staffs Water’s (SST) and Cambridge Water’s (CAM) groundwater sources and future treatment requirements.

A parallel assessment has already been completed by Atkins looking at potential climate change impacts on raw water quality from surface water abstractions and associated treatment risks.

These assessments are to inform the Long-Term Delivery Strategy component of SST & CAM's PR24 Business Plan.

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Assessment approach

Step 1 – Potential impacts of climate change on groundwater quality

Step 2 – Aquifer assessment

Step 3 – Source data

Step 4 – Treatment costs and investment budgets

This has been a rapid assessment based on readily available data.

Deliverables of the assessment are:

› this slide deck
› spreadsheet showing source data and derivation of the proposed investment budgets: CAM_SST GW CC WQ risk - Source data and budget estimate_v1.0

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Step 1

Potential impacts of climate change on groundwater quality

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Climate change and groundwater quality

“Impacts of Climate and Land Use Change on Groundwater Quality in England: A Scoping Study”
(Ascott et al., 2022)

- Environment Agency (EA) commissioned the British Geological Survey (BGS) to undertake a scoping study to improve our understanding of the impacts of climate change on groundwater quality in England
- This study has been used to determine what the key risks to groundwater quality associated with climate change may be
- The study includes:
  - Literature review
    - *Impacts of climate change on physical meteorological and hydrogeological variables that may affect groundwater quality in England*
    - *Impacts of climate change on groundwater quality*
  - Case studies
    - *5 case studies - Brighton, Chichester, Birmingham, Eden and Dove. Each case study covers a range of different hydrogeological, geographical and land use settings.*

Climate change and groundwater quality

Main findings from the BGS scoping study – literature review (Ascott et al., 2022)

Impact of climate change on physical hydro-meteorological variables within the context of groundwater recharge and levels

- UKCP18 projections – Increasing temperatures hence warmer (and wetter) winter & hotter (and drier) summers. Greater magnitude of extreme winter rainfall events
- Predicted increase in winter recharge and decrease in summer recharge with a mixed pattern in autumn and spring
- Increased probability of groundwater drought & high groundwater level events (possible groundwater-induced flooding)

Summary of potential changes to groundwater recharge and levels due to climate change in England from literature review (Ascott et al., 2022)

Variable	Long term average	Seasonality	Extremes
Groundwater recharge	Uncertain	Increased recharge in winter, decreased recharge in summer, shorter recharge window	Not reported
Groundwater levels		Increased levels in winter, decreased levels in summer	Increases in winter high levels, decreases in summer low levels, increased frequency of extreme high and low groundwater level events

Impact of climate change on groundwater quality

Selected processes discussed in the literature review

- Higher temperatures and increased rates of recharge may enhance biogeochemical reactions and transport of point and diffuse source contaminants
- Wetter years can cause groundwater chemistry to vary especially for major elements ratios due to modified gw-sw interaction times
- Changes in temperature, precipitation and atmospheric carbon dioxide will influence the agricultural nitrate source term due to changes in soil processes and agricultural activity.
- Increase in dissolved organic matter due to enhanced degradation of soil organic matter from increasing temperatures.
- Higher temperatures will likely increase LNAPL biodegradation, mobility and spreading. Hence, favoring the release of more LNAPL compounds to groundwater
- Shallow groundwater temperature may increase from increasing temperature, hence changing the groundwater quality: decrease in pH and oxygen saturation from increased microbial activity and enhanced organic matter mineralization

Main conclusions

- Predicted worsening of groundwater quality from climate change over next 50-80 years
- Considerable uncertainty

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Climate change and groundwater quality

Main findings from the BGS scoping study (Ascott et al., 2022)

Findings of literature review (cont.)

"Some parameters have a high level of confidence in a relationship with climate variables (e.g. shallow groundwater temperature and air temperature, sea level rise and salinity in coastal aquifers). However, for many components of climate change and water quality parameters, our understanding of relationships is near non-existent and speculative."

Case studies – for Chalk and Permo-Triassic Sandstone discussed in next step

General conclusions from case studies:

- Increase in temperature could increase degradation rates of contaminants but could be marginal
- Direction of changes in long term recharge is uncertain
- High confidence in increased rainfall/recharge seasonality and greater magnitude of extreme winter rainfall and recharge events, which may result in pollutant spikes. May be offset by dilution.

Other conclusions/outcomes

- Effects on nitrate concentration uncertain. Is a clear focus of interest
- Recommendations made for monitoring and further research

Prioritisation of potential risks to groundwater quality associated with climate change:

High priority

Land use change (induced by climate change or otherwise). May change contaminant sources and pathways. Highly uncertain and has potentially high impact.

Changes in rainfall/recharge seasonality and extremes. High confidence. Impacts through changes to leaching, spikes and dilution.

Increases in sea level affecting coastal aquifers. Local scale.

Increases in temperature

Changes in long term average rainfall and recharge

Small effects

Low priority

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Step 2

Aquifer assessment

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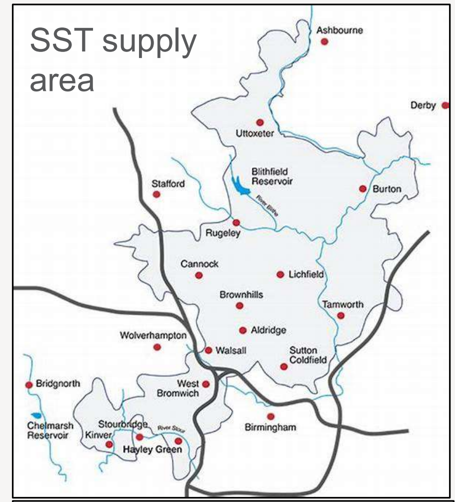
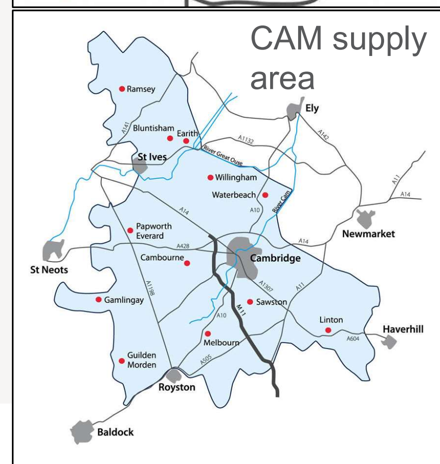
South Staffs Water and Cambridge Water – overview

Water company	Number of sources (No. of boreholes)	Aquifer
South Staffs Water (SST)	20 (49)	Permo-Triassic Sandstone
Cambridge Water (CAM)	24 (40)	Chalk





CAM Lower Greensand sources understood to be no longer in service.

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Chalk – aquifer information

Aquifer designation[1]

- White Chalk Subgroup: Highly productive principal aquifer
- Grey Chalk Subgroup: Highly productive principal aquifer

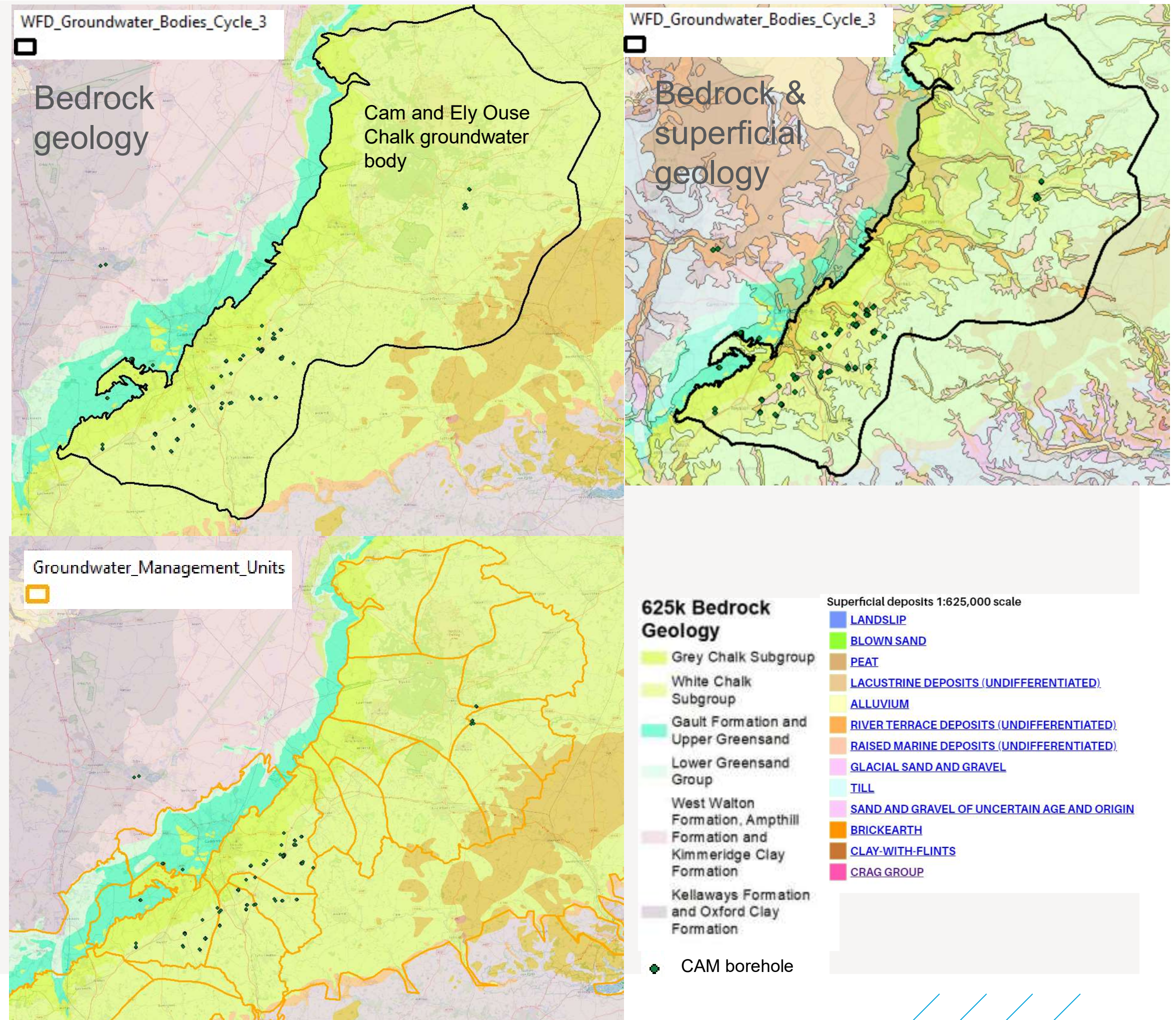
Superficial geology: Chalk overlain by sparse alluvium, river terrace and alluvial fan sands and gravels and in the east of the supply area by chalky till

Water Framework Directive[2]: Cam and Ely Ouse Chalk groundwater body

Groundwater management units[3]:

- Cambridge and Lodes Chalk
- Granta Chalk
- Upper Cam Chalk
- Rhee Chalk
- Thet Chalk
- Upper little Ouse Chalk

[1] MagicMap
[2] Catchment explorer
[3] Open Gov data



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Chalk – groundwater quality information

WFD[1]: Cam and Ely Ouse Chalk groundwater body

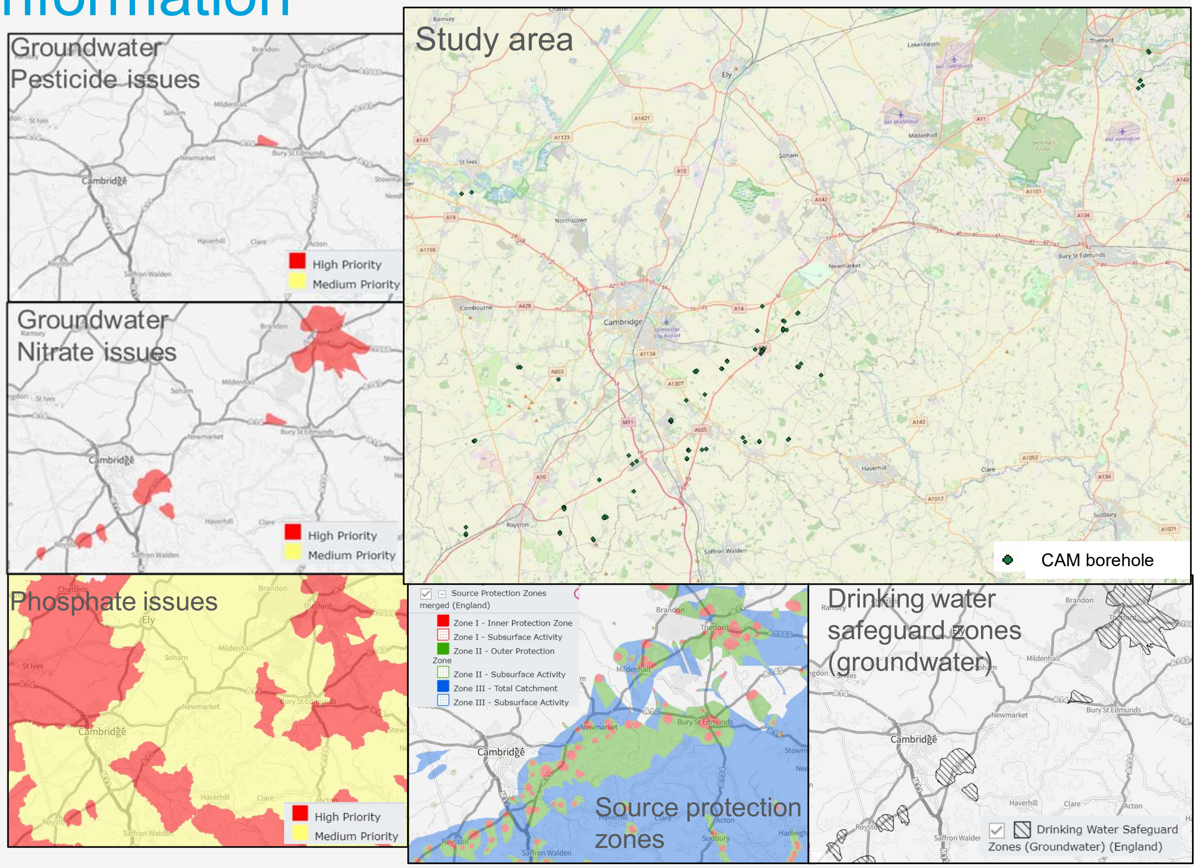
- Poor overall status
- Reasons for not achieving good status (RNAGS): Poor nutrient management, groundwater abstraction, transport drainage & sewage discharge

Groundwater vulnerability[2]: High to medium risk (inc. soluble rock risk)

Nitrate vulnerable zones (NVZ)[2]: Whole study area in NVZ

Phosphate, Nitrate and Pesticide issues[2]: Present in study area

Source Protection Zones[2]: Indicate spread of gw use and the source catchments



[1] Catchment explorer
[2] MagicMap

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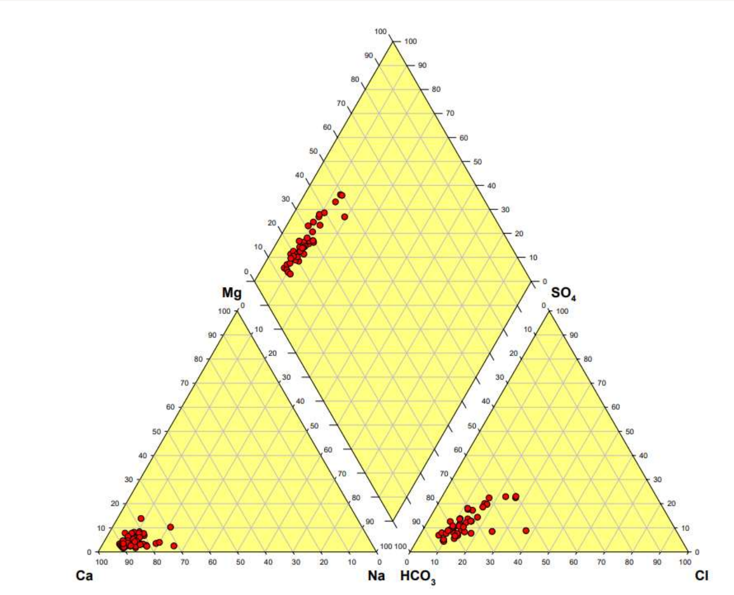
Chalk – groundwater quality information

"Baseline Report Series: 13. The Great Ouse Chalk aquifer, East Anglia" (Ander et al., 2004) – Key findings:

- Baseline groundwater chemistry is controlled by natural reactions within the aquifer minerals
- Chemical composition is derived from water rock interactions – natural acidity of rainfall reacting with calcite matrix creating rapid congruent dissolution of the carbonate fraction.
- Dissolution of the aquifer's calcite matric controls the major ion chemistry (predominantly Ca and HCO_3) and some trace elements.
- Till deposits provide contribution of trace metals to the Chalk such as Ni and Co.
- The median value of pH (7.14) is consistent with the well buffered groundwater controlled by carbonate equilibrium.
- **Nitrate (high concentrations of NO_3) deviates the greatest from expected baseline – due to diffuse agricultural sources**.



Piper plot of major ions in groundwaters of the Great Ouse Chalk aquifer

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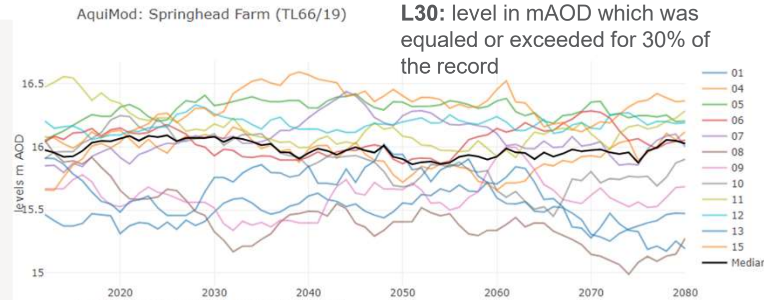
Chalk – climate change predictions

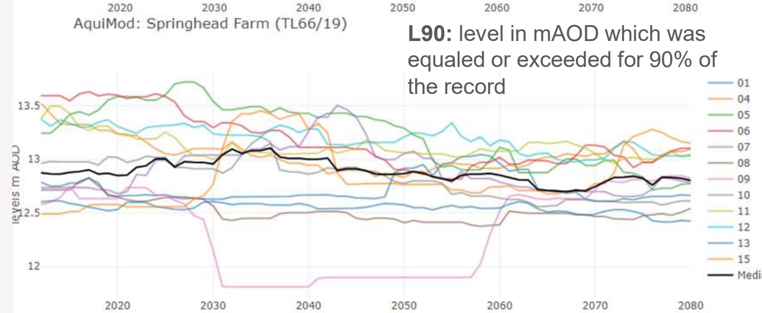
Enhanced Future Flows and Groundwater (eFLaG)[1]

- Recharge: Cam and Ely Ouse Chalk Groundwater body (BL/NF)
- Changes are small: in each season -0.05 mm/d to +0.05 mm/d
  - % change July: - 8.4 %
  - % change February: 6.2 %
- Groundwater levels (BL/NF) (median of runs)
  - Springhead Farm
    - *% change L90: 0 %*
    - *% change L30: -2.2 %*
  - Dullingham
    - *% change L90: -2.2 %*
    - *% change L30: -1.6 %*

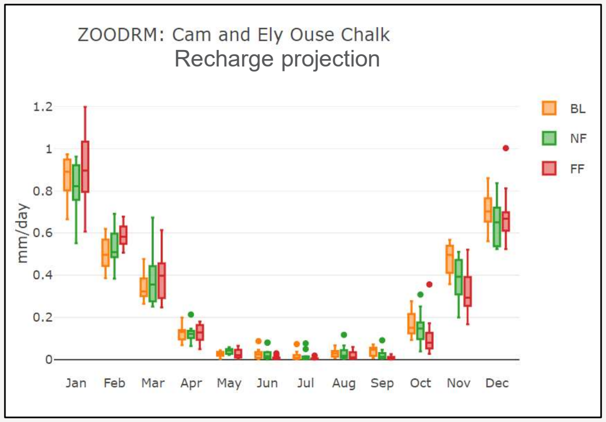
Does not suggest higher winter GWLs in this area. But the readily accessible processed data do not include the highest levels (e.g. L5)



L30: level in mAOD which was equaled or exceeded for 30% of the record



L90: level in mAOD which was equaled or exceeded for 90% of the record



Baseline (BL): 1989–2018 and Near Future (NF): 2020–2049
Baseline (BL): 1989–2018 and Far Future (FF): 2050–2079

AquiMod model boreholes used for eFLaG

[1] eFLaG eFLaG is a set of nationally consistent climatological and hydrological projections based on UKCP18 that can be used by the water industry for water resources and drought planning amongst many other uses. Climate projections have been put through hydrological and groundwater models to provide projections of river flows, groundwater levels and groundwater recharge. CEH, BGS, HR Wallingford

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Chalk – climate change impacts on groundwater water quality

Baseline data

- 24 CAM Chalk sources
- Unconfined Chalk aquifer
- Chalk scarcely overlain by alluvium and river terrace deposits. Till present in the east.
- $Ca\text{-}HCO_3$ groundwater type
- Chalk groundwater – neutral pH
- Current phosphate, nitrate and pesticide groundwater WQ issues
- Poor WQ status for the 'Cam and Ely Ouse Chalk' groundwater body

Climate change projections

Ascott et al. (2022) projections:

- Increasing temperatures
- Increase in winter rainfall & recharge and decrease in summer rainfall
- More extreme winter rainfall and recharge
- Stable LTA GWLs but greater seasonality, in some cases including extremes (e.g. higher max GWL)

eFLaG projections in study area:

- Small decrease in future GWLs
- Little change in recharge. Small increase in winter/spring months, small decrease in summer months
- Does not show extremes

BGS paper – Chalk case studies

- Increased temperature – increase reaction rates for degradation but marginal
- Increase in extreme winter recharge – winter spikes in nitrate and pesticides from flushing but may be offset by dilution
- Drier summer – possible increases in summer concentrations from reduced dilution
- Wetter winters and drier summers – decrease thickness of unsaturated zone in spring potentially decreasing the timelag for pollutants to reach water table
- Higher groundwater level maxima – may increase groundwater flooding and mobilisation of agricultural pollutants
- Rise in sea level – increase in seawater intrusion (case studies were in coastal Chalk but not relevant for CAM)
- Potential changes of land use may have more influence on agricultural pollution than other changes in climate.

LTA = long term average
GWL = groundwater level

Chalk - climate change impacts on groundwater water quality

Climate change projection	Potential impact and risk for CAM Chalk BHs
Increased temperature	Increased reaction rates for degradation of contaminants but likely to be a small effect.
Increase in extreme winter rainfall	Increased spikes of pollutants from flushing. May be offset by dilution. Surface flooding may mobilize contaminants and increase vulnerability at headworks. Could result in increases in nitrates, pesticides, turbidity and local point source pollutants.
Higher groundwater level maxima from increased winter recharge	Mobilization of agricultural pollutants (nitrate and pesticides) stored in the soils, infill materials and unsaturated zone. However, eFLaG data do not indicate higher winter GWL in this area (but do not show the extreme highs/lows).
Drier summers	Increases in summer concentrations of contaminants from reduced dilution but baseline summer recharge is low so unlikely to be a large effect.
Wetter winters and drier summers	Increase in size of seasonal fluctuations in water levels. Decrease in thickness of unsaturated zone in spring, potentially decreasing the timelag for nitrate to reach the water table. However, eFLaG data do not indicate higher winter GWL in this area (but do not show the extreme highs/lows).
Land use change (climate induced)	Change in contaminant sources and recharge pathways. Potential to lead to significant change but highly uncertain.

Based on current available information this is the most tangible risk to consider

Note: The Chalk aquifer has a strong pH-buffering capacity and hence strong resilience to any increased dissolved CO_2 concentrations (Ascott et al., 2022)

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Permo-Triassic Sandstone – aquifer information

Aquifer designation[1]

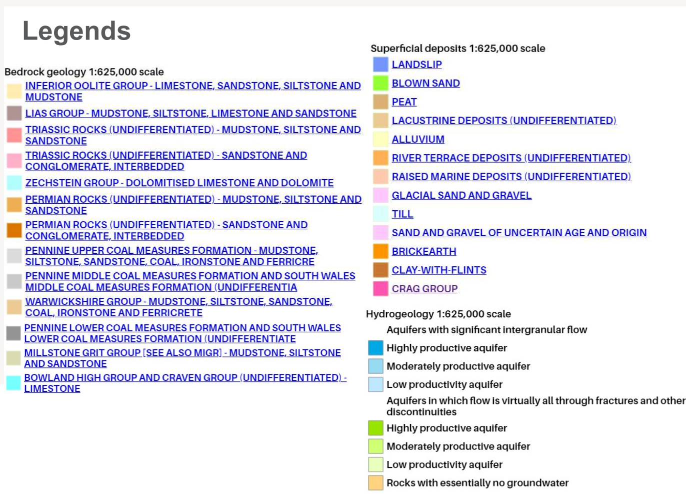
- Permo–Triassic Sandstone: Principal, Secondary A and Secondary B aquifer

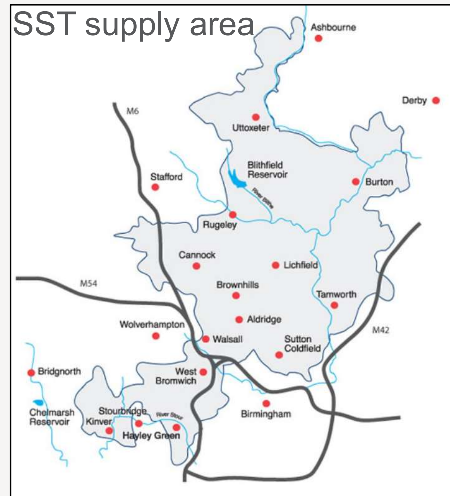
WFD Groundwater bodies[2]:

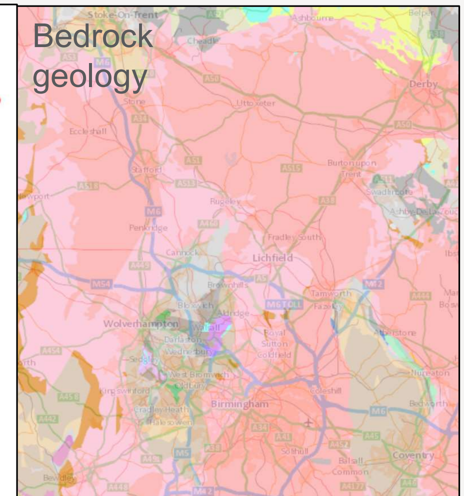
- Multiple: Tame Anker Mease - Permo-Triassic Sandstone Birmingham Lichfield, Staffordshire Trent Valley - Permo-Triassic Sandstone Staffordshire etc.

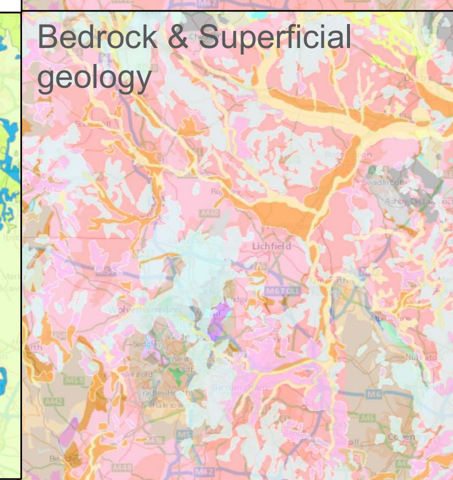
Groundwater management units (GWMU)[3]:

- Multiple









1 MagicMap
2 Catchment explorer
3 Open Gov data

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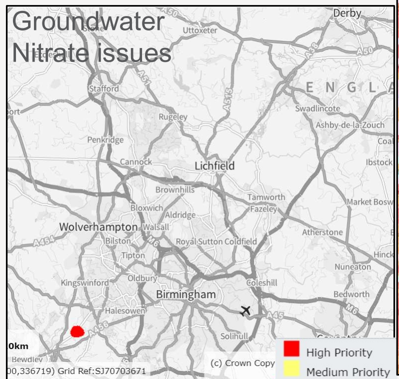
Permo-Triassic Sandstone – groundwater quality information

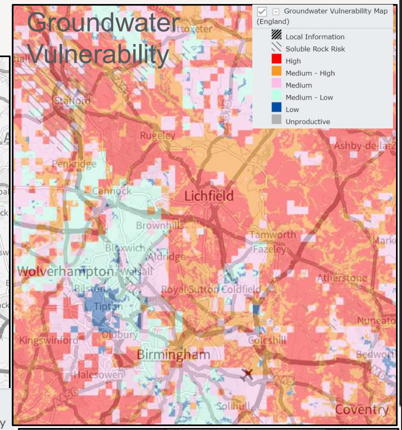
Groundwater vulnerability[2]: High to low risk (inc. soluble rock risk)

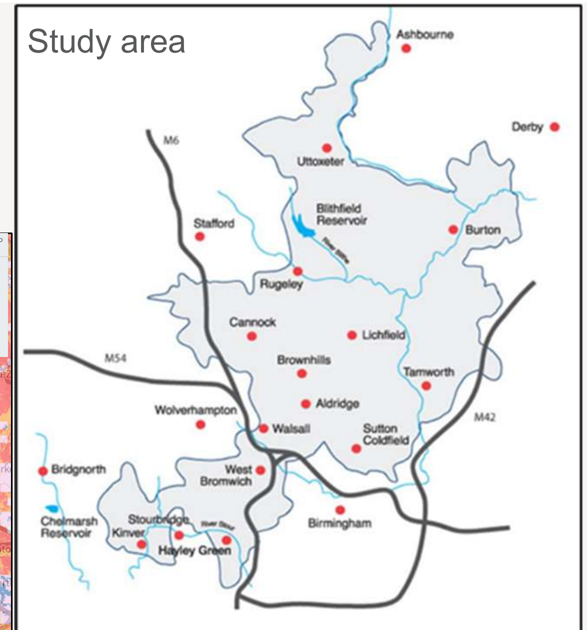
Nitrate vulnerable zones (NVZ)[2]: Nearly whole supply area in NVZ

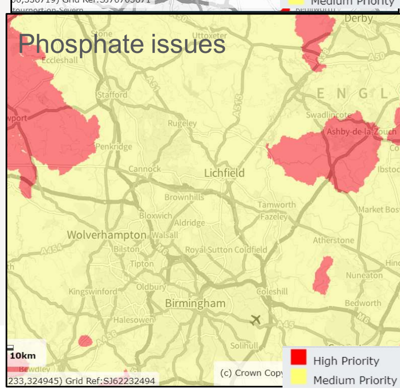
Phosphate and Nitrate issues[2]: Present in supply area

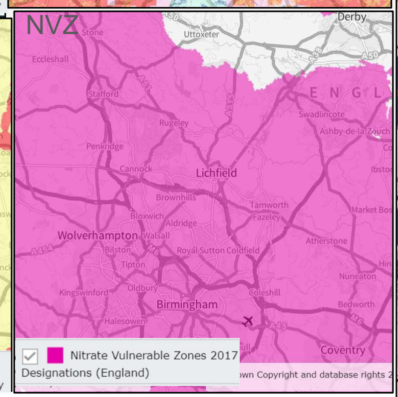
Source Protection Zones[2]: Indicate spread of gw use and the source catchments

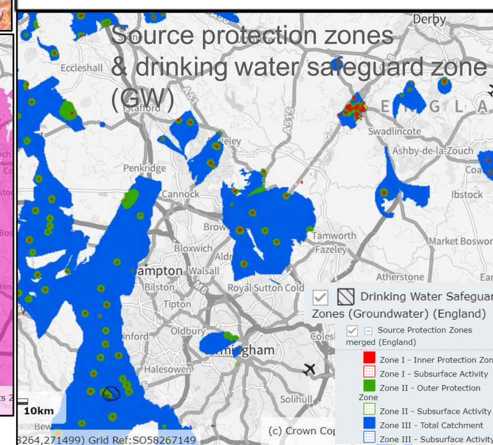












[1] Catchment explorer
[2] MagicMap

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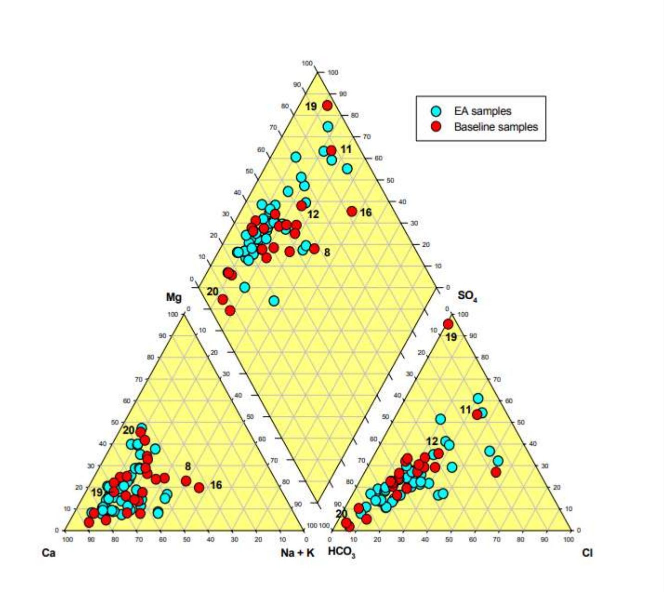
Permo-Triassic Sandstone – groundwater quality information

“Baseline Report Series: 3. The Permo-Triassic Sandstones of South Staffordshire and North Worcestershire“ (R Tyler-Whittle et al., 2002) – Key findings:

- Land use is dominated by **agriculture,** but **industries** are present around some of the larger towns.
- Difference in hydrochemistry between and within formations of the Permo-Triassic sandstone.
- Dominant control on groundwater chemistry is dissolution of carbonate (calcite, dolomite) and sulphate (gypsum) cements. The hydrochemistry is modified by residence time and redox status of the aquifer.
- Oxidizing conditions present in the unconfined area of the aquifer whereas reducing conditions are present beneath the Mercia Mudstone.
- The main groundwater types include Ca-HCO_3 and Ca-Mg-HCO_3 type waters
- **High concentrations of nitrate – due to diffuse agricultural sources**.
- **High concentration of barium and arsenic in some areas – due to natural processes.**



Piper plot of major ions in groundwaters of the Permo-Triassic

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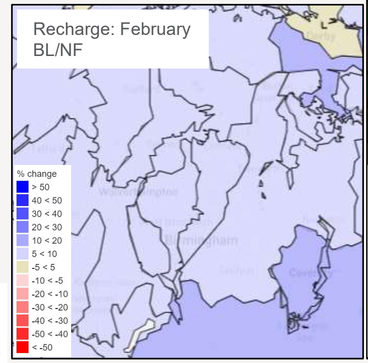
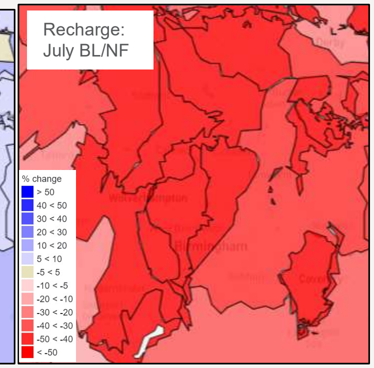
Permo-Triassic Sandstone – climate change predictions

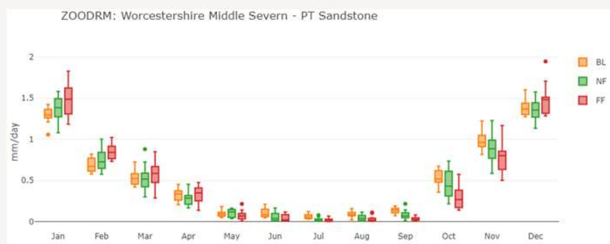
Enhanced Future Flows and Groundwater (eFLaG)[1]

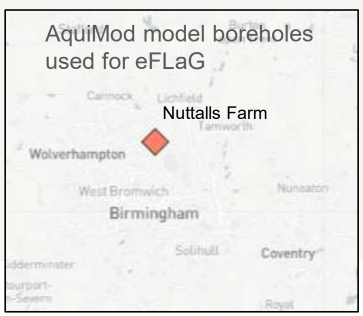
- Recharge: BL/NF
- Changes are small: eg in each season -0.05 mm/d to +0.05 mm/d apart from autumn (-0.1 mm/d) for Worcestershire Middle Severn PT Sst and Tame Anker Mease PT Sst Birmingham Lichfield GWBs
  - % change July: less recharge < 50 %
  - % change February: more recharge >5 %
- Groundwater levels (BL/NF)
  - Nuttalls Farm
    - *% change L90: -3.2 %*
    - *% change L30: -7.5 %*

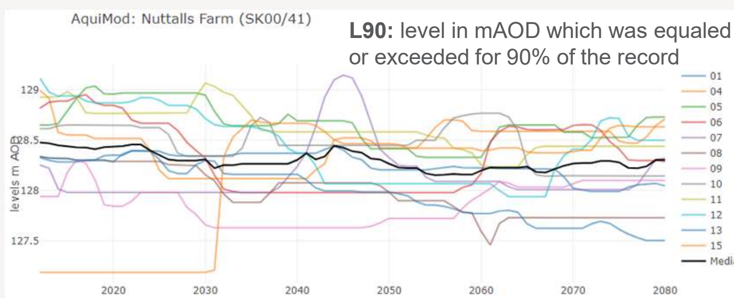


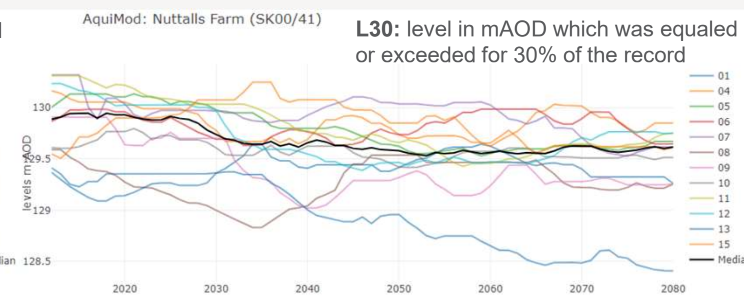


Baseline (BL): 1989–2018 and Near Future (NF): 2020–2049
Baseline (BL): 1989–2018 and Far Future (FF): 2050–2079









[1] eFLaG

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Permo –Triassic Sandstone – climate change impacts on groundwater water quality

Baseline data

20 SST sources

Permo-Triassic Sandstone aquifer

Aquifer partially overlain by superficial deposits including till

Ca-HCO_3 and Ca-Mg-HCO_3 groundwater type

Current phosphate and nitrate groundwater WQ issues. Some high concentrations of barium and arsenic from natural processes. Possible industrial contaminants present.

WQ status of groundwater bodies are variable across the supply area

Climate change projections

Ascott et al. (2022) projections:

Increasing temperatures

Increase in winter rainfall & recharge and decrease in summer rainfall

More extreme winter rainfall and recharge

Decrease in GWLs. Increased seasonality in some locations

eFLaG projections in study area:

Decrease in future GWLs, particularly winter levels

Increase in winter recharge and decrease in summer recharge

BGS paper – Permo-Triassic Sandstone case studies

Increased temperature – increase reaction rates for degradation but marginal

Increase in extreme winter recharge – winter spikes in nitrate, pesticides, metals and solvents from mobilisation and leaching but may be offset by dilution.

Drier summer – possible increases in summer concentrations from reduced dilution

Decrease in GWLs due to CC however around Birmingham there will be an overall rise in water levels due to recovery from long-term abstraction (increasing potential for water pollution due to less attenuation or opportunity for adsorption). Likely more significant than CC impacts on GWL.

Transient events may be less significant due to high storage of the aquifer.

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Permo-Triassic Sandstone - climate change impacts on groundwater water quality

Climate change projection	Potential impact and risk for SST P-T sandstone BHs
Increased temperature	Increased reaction rates for degradation of contaminants (nitrate, pesticides & industrial contaminants) but likely to be a small effect.
Increase in extreme winter rainfall	Increased spikes of pollutants from flushing, leaching and mobilization. May be offset by dilution. Surface flooding may mobilize contaminants and increase vulnerability at headworks. Could result in increases in nitrates, pesticides, turbidity and local point source pollutants (e.g. industrial contaminants such as metals, sulphate, chloride and organic compounds).
Drier summers	Increases in summer concentrations of contaminants from reduced dilution but baseline summer recharge is low so unlikely to be a large effect.
Land use change (climate induced)	Change in contaminant sources and recharge pathways. Potential to lead to significant change but highly uncertain.

Based on current available information this is the most tangible risk to consider

Around Birmingham, groundwater level recovery from historical over-abstraction, may have a greater impact on groundwater quality than changes in climate (Ascott et al., 2022)

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Step 3

Source data

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Groundwater sources – source data overview

Source data used in this step:

- Source list, locations, volume – DWI submission spreadsheets: CAM-RWDetailJAN23.xlsx & SST-RWDetailJAN2023 - version 2.xlsx
  - *For CAM sources the volume is given per source but for STT given per BH and for final water – assumptions made to derive source volume*
  - *Total for all groundwater sources: CAM 97 Ml/d, SST 177.56 Ml/d*
- MASTER DATABASE.xlsx for CAM sources. Includes depth to water table, casing length, geology including superficial deposits
- Summary tables of water quality issues at each source and how/whether treated – from: Copy of SST and CAM Treatment summary.xlsx

Assessment is presented in:

CAM_SST GW CC WQ risk - Source data and budget estimate_v1.0

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Source vulnerability rating

Data on borehole setting has been used to consider the source vulnerability to groundwater contamination

Only for CAM sources

Borehole setting risk category assigned as follows:

› If confined aquifer or there is more than 20 m thickness of low permeability drift deposits → Green

or

› If rest water level is more than 30 m below ground (i.e. unsaturated zone is thick) → Green

› Categories assigned based on RWL and casing length:

› Assigned for each BH

› Judgement used to combine RWL and casing categories

for each BH to give an overall RAG for each source

CAM:	
Borehole setting risk category	No. of sources
Red	8
Amber	10
Green	6

Category	Red	Amber	Green
Confined/unconfined	unconfined	unconfined	confined
RWL (mbd) = unsaturated zone thickness	<10	10 to 30	>30
Plain casing (length in m)	<15	15 to 30	>30

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Current and historical WQ issues

- Current water quality issues can also indicate source vulnerability and presence of pathways from the surface to the aquifer

- There are some examples of 'Green' sources (from borehole setting vulnerability) with current bacti and turbidity issues.
- Similarly, Great Wilbraham classed as 'Red' but has no current issues
- Indicates limitations of a simplified screening process

Issue	Total no. of sources with issue	No. of SST	No. of CAM
Bacti	33	14	19
NO3	18	10	8
Turbidity	17	7	10
Chlorthal	4	4	0
Fe/Mn/As/Sb	3	3	0
Crypto	3	2	1
Atrazine	3	2	1
Solvents	2	1	1
NH4	1	1	0
Pesticides	1	0	1
Hardness	1	1	0
pH	1	1	0
PFAS	1	0	1
SO4	1	1	0
Bentazone	1	0	1
Gross Alpha	1	1	0

Step 4

Treatment costs and investment budgets

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Risk of climate change driven WQ issues

For both major aquifers used by the company:

- The effect of climate change on future water quality is highly uncertain
- Potential processes could have positive or negative effects (or cancel each other)
- There is a risk of worse WQ, particularly associated with more frequent and/or more intense winter storms and possibly higher winter/spring water table

Consideration of source data indicates:

- Variation in vulnerability due to setting
- Current WQ issues indicating pathways for contamination

Therefore to manage the risk of future poorer WQ it is suggested that a risk budget is assigned for future investment to improve groundwater resilience

Water quality trends should continue to be monitored and reviewed

The likely future WQ at a particular source cannot be quantified

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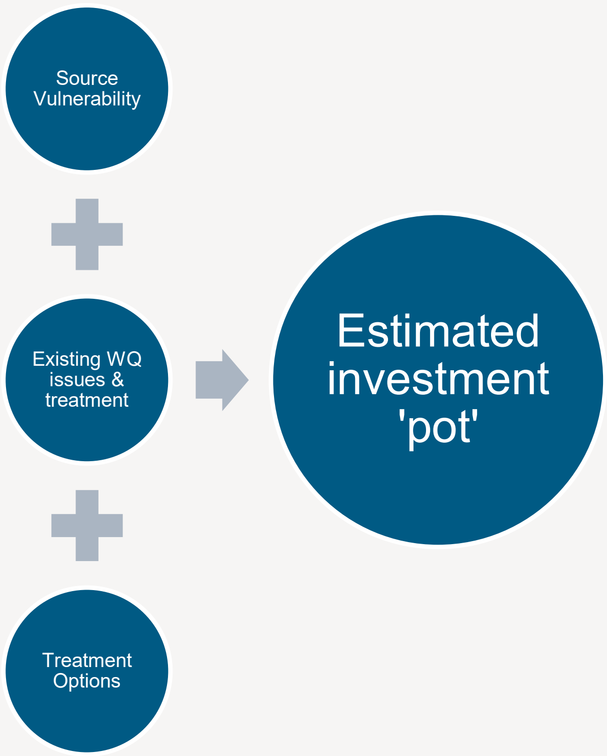
Estimating investment budget



A risk budget (or GW quality resilience fund) is proposed, derived from consideration of:

- Source vulnerability based on setting – RAG (CAM only)
- Assume existing issues may need treatment in future (or more treatment where there currently is some)
- For some sites new WQ issues will emerge requiring treatment
- Source volume used to give scale of treatment that may be required
- Typical costs of treatment types

Gives a transparent approach to derive an overall proposed budget per company

In practice other types of intervention may be more appropriate than treatment e.g. borehole protection, blending

Does not take into account existing planned investment in treatment at particular sites.

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Estimating investment budget

CAM:

No allowance at Green sources

At Amber and Red:

- If there is a current WQ issue but it is not treated*, assume investment equivalent to treating 50% of the source volume
- If there is a current WQ issue and there is treatment, assume investment equivalent to treating 25% of the source volume
- If a WQ issue is not currently noted at a source, assume investment equivalent to treating 10% of the source volume (for bacti, turbidity, nitrate and pesticide – contaminants which may be widespread in the aquifers)

SST:

For all sources, apply the three steps listed for Amber and Red above

Reduce the total budget by 50% to acknowledge that some sources will be low risk/Green

* Temporary treatment plants and blending are grouped with no treatment

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Treatment costs

Estimated typical costs for each treatment type:

Treatment	Purpose example	CAPEX unit cost £ per Ml/d	OPEX unit cost £ per Ml/d per year	Opex cost as % of capex
Rapid gravity filter (RGF)	Fe/Mn	£271,000	£2,700	1%
UV disinfection	Bacti, crypto	£76,000	£3,800	5%
Ion exchange (IEX)	Nitrate	£1,022,000	£40,900	4%
Granular activated carbon (GAC)	Pesticides	£178,000	£17,800	10%
Cartridge filter*	Turbidity	£79,000	£1,600	2%

Costs are based on Atkins experience and application of a range of available industry cost bases

Based on costs for small works, approx. 5 Ml/d (SST/CAM groundwater sources average 6 Ml/d)

Opex costs have been derived based on a % of capex - this has used some previous expense knowledge and engineering judgement; however, evidence base to confirm figures is very limited so these figures should be used with caution.

Client should sense check the costs presented here against their own cost database and opex understanding

*There is significant uncertainty in cartridge filter costs and limited cost curves available

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Conclusions

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Conclusion

Reasoned indicative estimates of investment required to maintain source resilience in response to groundwater quality changes resulting from climate change for each water company

› Cambridge Water: £23million capex with associated opex of £1million per year
› South Staffs Water: £34million capex with associated opex of £1.5million per year

The phasing of investment should be considered: the estimates do not represent a single AMP spend but will likely be incurred across multiple AMPs

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Uncertainties and recommendations

- The effect of climate change on future groundwater quality is highly uncertain
- The likely future WQ at a particular source cannot be quantified
- Adequacy of current (and planned) treatment and management strategies under future groundwater quality is unknown
- Unit treatment costs are uncertain and will depend on scale of works

Recommendations:

Allow an investment budget for managing potential changes in groundwater quality

Continue to monitor and review water quality trends and anticipated treatment needs

In current calculations check:

- Treatment unit costs against company database
- Source volumes used for SST sources

For a future iteration, the estimate of investment budget could be refined by e.g.

- More detailed source vulnerability analysis, aligned with existing risk assessments where these exist eg from water safety plans
- More detailed understanding of current and planned treatment capacity and how source volumes should relate to treatment design volume e.g. consideration of average vs peak

However, there will remain a fundamental uncertainty in forecasting future groundwater quality changes due to climate change

Consider findings of new research in this area and future guidance

Monitoring recommendations

Continue to monitor the parameter suite currently used and review trends periodically, in particular:

- Bacti
- Turbidity
- Nitrate

Routine reviews across all sources e.g. every 2 years, or when prompted by a WQ change or concern

This is likely already being done. The climate change risk doesn't need to change this process or trigger more frequent reviews but the issue should be considered when interpreting the trends e.g.

- Does the trend appear to be changing over time?
- Do water quality changes (e.g. spikes in contaminants) appear to coincide with storm events?
- If so are the water quality changes transient or ongoing?
- Reviewing across groups of sources or company-wide, are incidents of contamination occurring more frequently or are there any general declines in WQ? Can these be linked to known catchment changes or trends in rainfall / other parameters?

Investment in new treatment or other mitigation measures would be triggered in same way / at the same levels as for ongoing water quality management. The investment budget proposed is to recognise that this need could start to occur more frequently due to climate change.

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