Grand Union Canal Transfer

Appendix 22-PD-5: River Tame Dissolved Oxygen Modelling Report

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1. Introduction

1.1 Background

1.1.1 Affinity Water, along with Severn Trent Water (STW) and Anglian Water are developing Strategic Resource Options (SRO) through the Regulators Alliance for Progressing Infrastructure Development (RAPID) process.

1.1.2 Assessment of environmental data during the RAPID process has identified that operation of some SROs has the potential to impact on flows in the River Tame, both as individual schemes and in combination. The SROs of relevance are Minworth, Grand Union Canal (GUC), and the Severn to Thames Transfer (STT). The Minworth SRO comprises the diversion of recycled water from Minworth Wastewater Recycling Centre (WwRC) which is currently discharged into the River Tame. This diverted recycled water will be subject to further treatment before being transferred and used as a supply source to the GUC SRO or the STT SRO (via the River Avon). For simplification within this report, reference is made to Minworth SRO as the main SRO assessed and implies its use as support to either the GUC SRO and/or the STT SRO.

1.1.3 Operation of the Minworth SRO would result in a flow reduction in the River Tame and the RAPID process therefore included a detailed hydrological and hydraulic modelling study (Ref. 1) to quantify the scale of flow and river hydraulic changes the SRO could have. The outputs were used to support assessment of potential abstraction licence impacts (for abstractors in the catchment), a hydro-ecological assessment and a review of potential mitigation measures required. The work identified that further detail on the potential for acute impacts on dissolved oxygen (DO) concentrations in the River Tame as a result of the operating of the SRO would be important to understand the potential effect of the scheme (in combination with climate change) on fish populations. This would supplement catchment scale water quality modelling of dissolved nutrients using the Environment Agency's SIMCATn (Simulation Catchments) model of the Tame and Trent system (reported elsewhere).

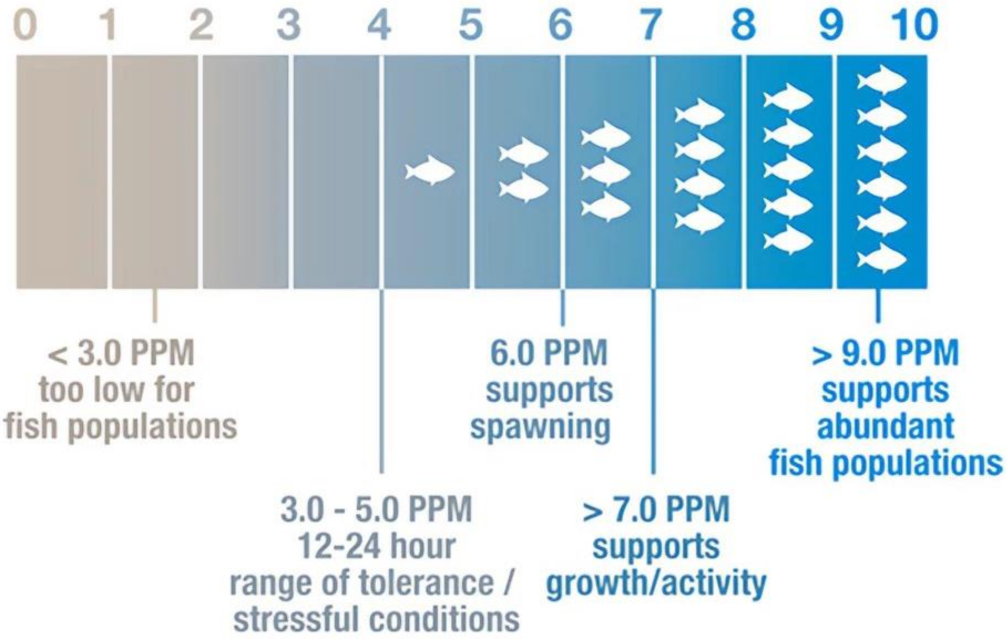

Plate 1 : Range of tolerance for dissolved oxygen (Parts Per Million) in fish (Ref. 4)

1.1.4 **Plate 1** shows the general range of tolerance for dissolved oxygen in fish. If the DO concentration in the water body falls below 4-5 PPM (mg/l), aquatic organisms particularly fish will experience reduced functionality and become inhibited in completing essential life tasks such as feeding, growth and reproduction (Ref. 2). Even the most tolerant fish would perish if DO levels falls below 3 mg/l (Ref. 2). The 3-5 mg/l range aligns with the Environment Agency's review of Urban Pollution Management (UPM) standards which determined that a minimum DO concentration of 4.0 mg/l "*should ensure protection of salmonid…fisheries from short-term mortality and macroinvertebrate drift, irrespective of the duration of exposure*."(Ref. 3)

1.1.5 Minworth SRO has potential to impact on DO in the River Tame if reduction in river flow makes the water in the River Tame more vulnerable to heating in summer. The likelihood of water heating may increase in future due to climate change which may both raise air temperature and reduce summer river flows. A scope of DO modelling was therefore developed and agreed with the Environment Agency and a 2D biogeochemical model capable of simulating DO exchange between the River Tame and the atmosphere, sediment and ecological systems has been developed in TUFLOW FV for a specific Pilot Reach. Continuous monitoring of water temperature and DO concentrations in the Pilot Reach have also been carried out, as agreed with the Environment Agency, to allow for calibration of the model and verification of the model results. This report sets out the monitoring data collected, the model calibration process and the outcomes of the water quality modelling in terms of acute impacts on DO due to flow reductions during operation of the SRO.

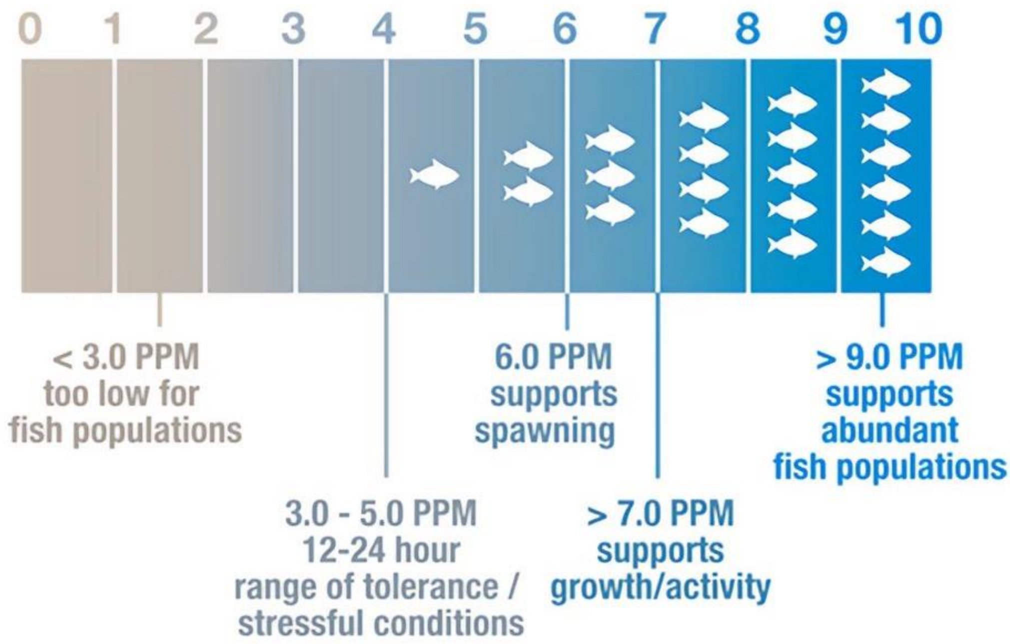

Plate 1 : Range of tolerance for dissolved oxygen (Parts Per Million) in fish (Ref. 4)

1.2 Objectives

1.2.1 The overall objective of this work is to determine whether the Minworth SRO will impact DO concentrations and, by extension, fish populations in the River Tame. A 2D modelling approach has been taken to allow for simulation of varying impact in deeper waters compared with shallow or stagnant river sections. The shallow water sections may be more vulnerable to warming and may extend spatially in response to reduced river flows.

1.2.2 Projects which include 2D modelling of DO concentrations in rivers have not been carried out commonly in the UK (to the best of AECOM's knowledge) and require significant input data, computational time and calibration effort. There is currently no formal guidance or specification to follow. For this reason, it was agreed with the Environment Agency that the 2D modelling approach would first be applied within a specific reach of the River Tame as a Pilot study. The model could then be extended to incorporate additional reaches, but only if the Pilot project shows significant impact as a result of the SRO.

1.2.3 A Pilot TUFLOW FV 2D model has been constructed of the River Tame from immediately downstream of the River Bourne inflow to Lea Marston Lakes covering a length of 3.3 km (shown in **Plate 2**). This reach (referred to as the "Pilot Model Reach" hereafter) has been selected based on the hydraulic modelling carried out as part of the RAPID which identified a risk of reduced wetted perimeter in the River Tame between Minworth WwRC discharge points and the Lea Marston Lakes. The selection of this reach also avoids complex interactions with other watercourses and inflows which would need to be considered in the reach immediately upstream. Observed DO and water temperature data at the upstream and downstream extent of the Pilot Model Reach has been collected (section 2.4) and used to calibrate the model.

1.3 SRO Scenarios

1.3.1 The Minworth SRO is planned to divert up to 230 Ml/d of treated wastewater currently discharged to the River Tame for further advanced treatment before supply to two supply options:

a. GUC SRO (up to 115 Ml/d); and,
b. STT SRO (up to 115 Ml/d).

1.3.2 In order to account for the maximum loss of discharge from the Pilot Model Reach due to the Minworth SRO the water quality model has been run with scenarios in which the inflow has been reduced by:

a. 115 Ml/d - to represent the scenario of supply to the GUC SRO **or** the STT SRO at their maximum volume individually; and,
b. 230 Ml/d - to represent the scenario of supply to both GUC **and** STT SROs at their maximum volume together.

1.4 Requirement for Dissolved Oxygen Modelling

1.4.1 The DO concentrations in river water are dependent on a number of biotic and abiotic factors, which are summarised below. These processes are represented in the TUFLOW FV model:

a. Water temperature, with increased water temperature resulting in reductions in DO and (generally) more rapid biological and chemical reaction processes;
b. Photosynthetic and respiratory activity by phytoplankton, as oxygen is one of the products of photosynthesis and is consumed in respiration;
c. Chemical processes which remove oxygen (Chemical Oxygen Demand, COD, including processes such as oxidation of ammonia to nitrate);
d. Biological oxygen demand (BOD, related to the breakdown of organic matter by bacteria);
e. Sediment oxygen demand, driven by chemical processes occurring within sediment such as oxidation of iron and phosphorous; and
f. Turbulence within the water column which leads to the entrainment of air from the atmosphere. This can occur as a result of hydraulic jumps in the channel (e.g. at the location of weirs and waterfalls), or due to wind-driven waves and ripples. There are no hydraulic jumps within the Pilot Model Reach and therefore wind-driven processes will be the only control on turbulent aeration.

1.4.2 Water temperature is determined by weather conditions such as wind speed, air temperature and solar gain and in turn controls the rate of chemical and sediment oxygen demand. Reduction in river flow velocity and depth arising from the SRO could potentially result in a significant increase in water temperature along the River Tame due to reductions in the thermal mass of water available for heating and/or the development of shallow water sections which will be more prone to warming.

1.4.3 An additional factor which does not need to be represented is altitude - the density of atmospheric O_2 available for dissolution at higher altitude is lower than at sea level, however there is no significant variation in altitude through the Pilot Model Reach.

1.5 Modelling Approach

1.5.1 Several methods of DO modelling exist and were reviewed to determine the most appropriate. Three standard approaches were discounted for the following reasons:

a. Urban Pollution Manual (UPM) methods for modelling DO focus on short term inputs from combined sewer overflows resulting in extreme but very short-lived reductions in DO. This approach does not account for the heating of shallow water during hot weather, daily variations in insolation or biological oxygen production, all of which are important for the risk assessment needed for the SRO impact;

b. SIMCAT includes options for simulating DO but only considers degradation and direct inputs. It is a statistical dilution/degradation water quality model and does not take account of air temperature or river morphology, both of which are important for the assessment needed; and

c. MIKE11 can simulate DO concentrations along a river reach and does include methods to take account of air temperature and biological processes which remove DO from rivers. However, it provides a single, averaged DO concentration for an entire river cross section and does not assess variations in quality across the channel or in shallow sections. A two-dimensional (2D) modelling approach is required to show DO variations across the channel cross section and to identify if low DO concentrations occur in shallow water.

1.5.2 Two software packages have been identified as options for creating a 2D water quality model: MIKE21 (with Ecolab) and TUFLOW FV. TUFLOW FV has been selected for the following reasons:

a. A TUFLOW Classic model of the Lea Marston Lake system has been developed (and reported elsewhere) to assess impacts of SRO operation on fish passage. Use of TUFLOW FV would facilitate conversion of the existing TUFLOW Classic model to a TUFLOW FV model if it was found necessary to extend the DO model through Lea Marson Lakes;

b. Use of TUFLOW FV is consistent with the modelling carried out to date and avoids the use of a third river modelling package and potential future difficulties reconciling the results of different hydraulic modelling approaches; and

c. The TUFLOW FV model hydraulics and water quality calculations are more transparent than those in the MIKE21 and Ecolab models, allowing error checking and fixes to be identified faster.

1.5.3 The DO modelling is supported by a bespoke bathymetric survey of the Pilot Model Reach and the installation of continuous temperature and DO monitoring sondes at the Reach's upstream and downstream limits. The model has been calibrated based on the observed sonde data.

1.6 Overview of Study Area

Land Use

1.6.1 The catchment area of Pilot model Reach is approximately 799 km^2 and is extensively urbanised, being dominated by the West Midlands conurbation.

1.6.2 The two discharge points from the Minworth WwRC are approximately 1.5 km and 4.6 km upstream of the upstream limit for the Pilot Model Reach, and the two discharge points for the Coleshill Sewage Treatment Works are 1.8 km and 2.2 km upstream. The Rivers Bourne and Blythe enter the River Tame immediately upstream of the Pilot Model Reach and an additional three minor tributaries enter the Pilot Model Reach approximately 45%, 78%, and 79% along the length of the reach. The locations of the minor tributaries are shown in **Plate 2**.

1.6.3 The Pilot Model Reach ends immediately upstream of the weirs and flow bifurcation at the inlet of Lea Marston Lakes.

1.6.4 Defra's Magic Map Application (Ref. 5) shows one Site of Special Scientific Interest (SSSI) within the Pilot Model Reach- Whitacre Heath SSSI. The citation for this SSSI (Ref. 6) stipulates that the site has been designated for its wetland breeding birds. The site comprises disused gravel workings and wet meadows, with the latter flooding regularly. Minor tributaries 2 and 3 connect the River Tame to the wetlands at Whitacre Heath SSSI on the left and right banks of the River Tame. The minor tributary 1 connects the River Tame to the wetlands at Ladywalk Nature Reserve on the left bank of the Tame.

Geology and Soils

1.6.5 The British Geological Survey 'Geology Viewer' (Ref. 7) shows that the bedrock geology across the entirety of the Pilot Model Reach is Sidmouth Mudstone Formation. The bedrock geology in the middle reaches of the catchment is primarily Wildmoor Sandstone Member, the Alveley Member, and the Helsby Sandstone Formation, whereas in the upper reaches of the catchment the primary constituents of the bedrock geology are the Etruria Formation and the Pennine Middle Coal Measures Formation.

1.6.6 The superficial deposits are primarily composed of alluvium, with river terrace deposits also present most notably in proximity to the inlet for Lea

Marston Lakes. There are also large sections of the floodplain on the right bank where the bedrock is not overlain by superficial geological deposits. Further upstream in the catchment, where the River Tame runs through the north of Birmingham, there are extensive glaciofluvial deposits.

1.6.7 Within the Pilot Model Reach, the floodplain areas immediately adjoining the River Tame are classified as having ‘loamy and clayey floodplain soils with naturally high groundwater’, whilst the higher ground bordering these floodplain areas is classified as having ‘loamy soils with naturally high groundwater’ (Ref. 8). In the middle and upper reaches of the catchment, the soils are generally classified as being either ‘slowly permeable seasonally wet slightly acid but base-rich loamy and clayey soils’, or ‘slightly acid loamy and clayey soils with impeded drainage’.

1.6.8 In both cases, the impeded drainage of these soils is likely to contribute high rates of overland flow, as well as the transfer of fine sediment and pollutants into the river network, with subsequent impacts on sediment oxygen demand. Given the bedrock and superficial geology of the catchment described above, the sediment load of the River Tame will consist mainly of suspended clay particles and sandstone gravels.

Topography

1.6.9 The LiDAR (Ref. 9) data for the catchment shows that its elevations range from a maximum of 181 m above ordnance datum (AOD) close to the source of the River Tame’s southern arm in Oldbury, to a minimum of 51 m AOD near to the confluence of the River Tame with the River Trent. Within the Pilot Model Reach, the River Tame is bounded by low-lying floodplain areas with elevations ranging from 68 m AOD to 71 m AOD.

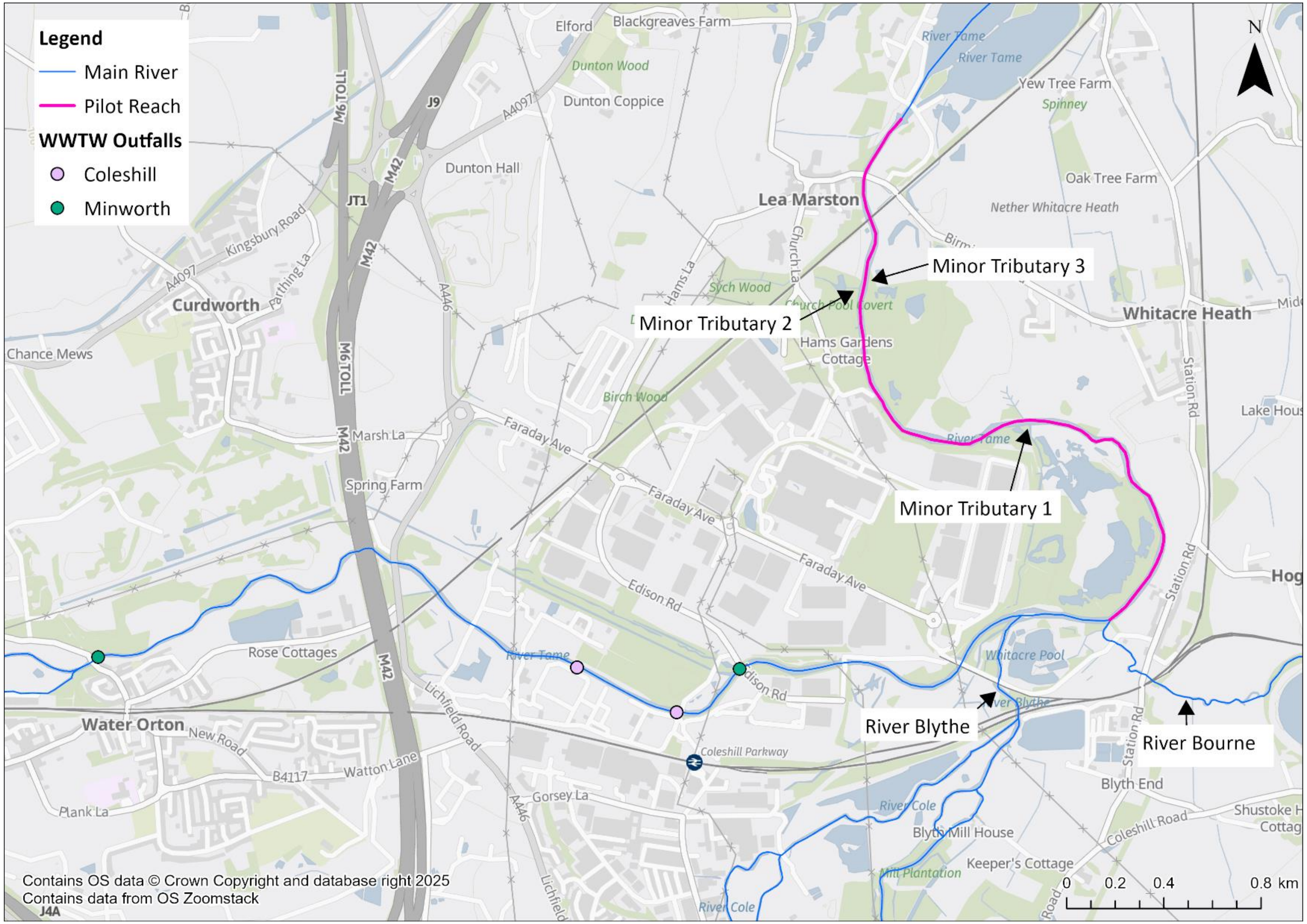

Plate 2 Map of Study Area

2. Collated Data

2.1 Overview

2.1.1 This section presents the data collected, documents how the data were reviewed and discusses any limitations or uncertainties in the data which may influence the DO modelling methodology or results. These datasets mostly relate to the external boundary conditions which need to be specified for the TUFLOW FV model.

2.2 Channel Bathymetry

Available Data and Review

2.2.1 A high-resolution digital terrain model (DTM) model of channel bathymetry is essential for water quality modelling so that the impact of small-scale undulations in the riverbed on flow velocity, flow depth and oxygen exchange at the air-water interface can be accurately resolved. A new bathymetric survey was therefore specified and procured for this for this project to record bed elevations below the water level, and a topographic survey was carried out to record elevations of the river edges and banks. A maximum 1 m interval between the surveyed points was requested from the surveyor and Survey Solutions Ltd carried out the survey in March and April 2024.

2.2.2 The bathymetry of the river channel in the 3.3 km reach was surveyed at a spatial resolution of 0.5 m along the transect routes of the survey vessel. However, the transect routes have not been undertaken at regularly spaced spatial intervals, and overlap in many locations, resulting in areas of the channel where the spatial resolution is much lower than 0.5 m. The spacing between points is generally 1.5-2.5 m but in places where access is difficult, they are greater than 5 m apart. An example is shown in **Plate 2**.

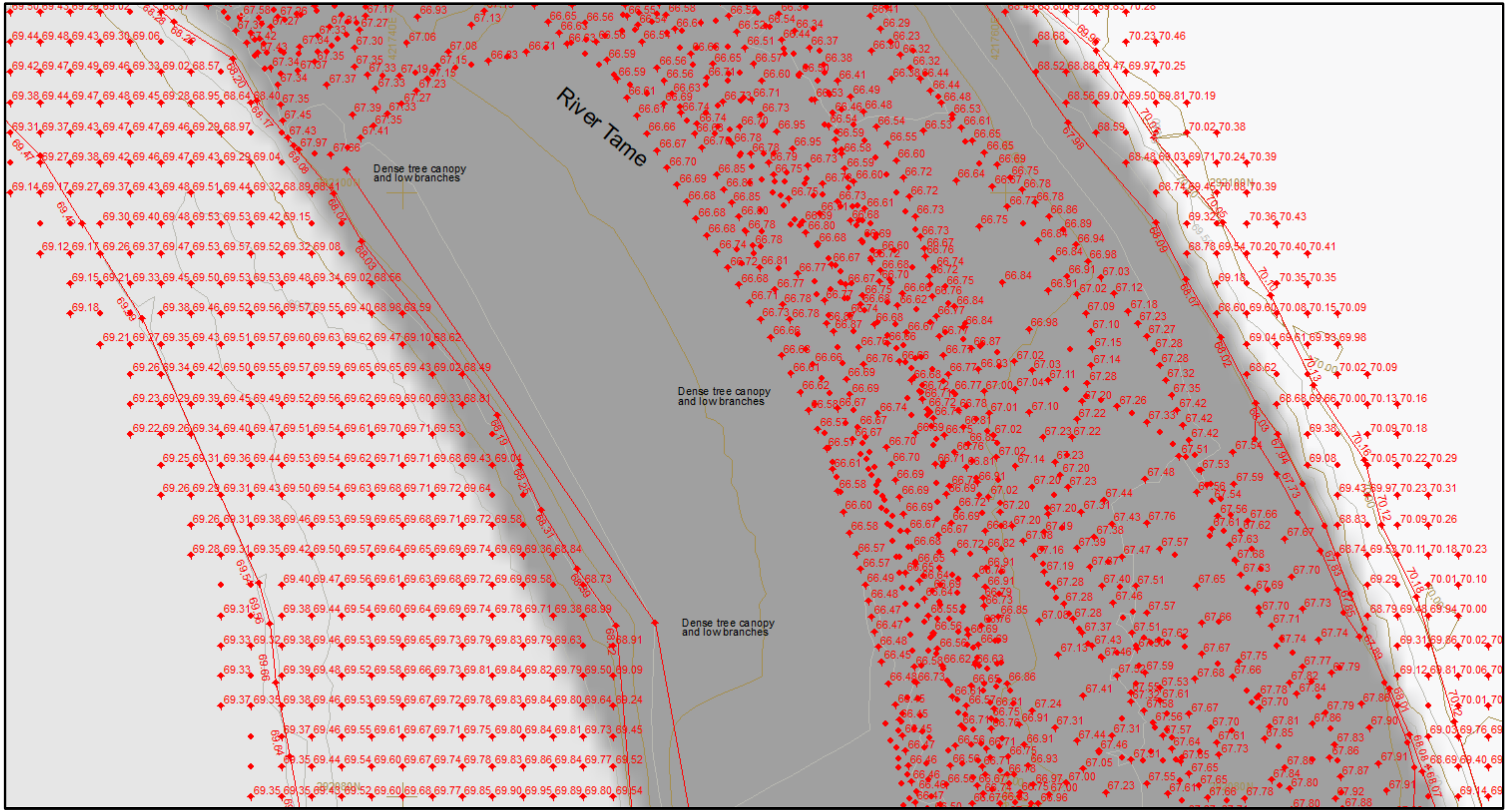

Plate 3 : Example of surveyed elevations from Survey Solutions in March-April 2024

2.2.3 The survey deliverables included:

a. three continuous ASCI files at a 0.1 m, 0.5 m and 1 m resolution which have been generated using n4ce software;
b. a 3D drawing of all the survey data; and
c. a series of photographs and videos from the drone and boat (selected photographs shown in **Plate 2** and **Plate 5**).

2.2.4 The surveyor explained the larger gaps in the bathymetric survey are either due to:

a. Overhanging vegetation, roots, trapped fallen branches, obstructions (shopping trolleys) in the river, and shallow water (anything less than 0.5 m) which prevents the boat from accessing these areas; or
b. Areas of dense vegetation, or below structures where there is poor GPS reception. Where these areas of poor GPS reception were accessible, a total station was used to fill the gaps.

2.2.5 Depth measurements taken without GPS coverage have been flagged with the code LS. There are 271 points (out of a total of 190,965 points) that have been assigned the LS code. Where the flow of the river is calm, and the boat could be beached, areas such as this have been measured by wading using a total station. However, in some areas there is no easy access, generally due to obstructing vegetation, or fast flowing water, and no place to exit and re-enter a boat safely.

2.2.6 The topographic data of the riverbanks was surveyed by a LiDAR mounted on a drone, with a stated tolerance horizontally of 100 mm and vertically of 50 mm. The surveyed points from the drone are consistently a regular 1 m spacing.

Plate 4: Selected photographs from Survey Solutions bathymetric survey

Plate 5: Selected photographs from Survey Solutions LiDAR drone survey

Use in DO Modelling

2.2.7 Whilst there are limitations with the surveyed data, it is considered that it is suitable to create the model geometry of the Pilot Model Reach to a high level of accuracy. The main concern is the areas where there are larger gaps and the interpolation process to create the ASCII grid may not represent the precise characteristics of the riverbed.

2.2.8 Due to the limitations noted above, the QGIS profile tool was used to create elevation profiles perpendicular to the flow of the channel from the ASCII grid where there were large gaps in surveyed points. The plotted profiles were compared with profiles taken immediately upstream and downstream of the gaps in order to appraise whether the interpolation method used by Survey Solutions had resulted in excessive smoothing of the bed profile or exaggeration of the slope length. On the basis of this analysis, it was concluded that further improvements were either considered unnecessary as the profiles were deemed acceptable, or impossible due to the absence of suitable elevation points close to or within the areas of interest.

2.2.9 A single modification was made to the ASCII grid at Ordnance Survey National Grid Reference (OS NGR) SP 20628 92512, where a gap in the surveyed bank levels prevented the accurate specification of the thalweg in the Aquaveo Surface Water Modelling System (SMS) 13.3 used to construct the 2D mesh used within TUFLOW FV. The software initially incorrectly designated this location as the outlet of the model reach, as opposed to the actual downstream limit of the model reach at the inlet of Lea Marston Lakes. In order to remedy this, a Triangulated Irregular Network (TIN) elevation surface was generated from the surrounding surveyed elevation points and then converted to a raster file. This raster file was then merged with the ASCII grid provided by Survey Solutions.

2.3 Atmospheric Data

Available Data and Review

2.3.1 The TUFLOW FV GetAtmos tool allows users to download freely available, global gridded atmospheric data from the European Centre for Medium Range Weather Forecasts (ECMWF) ERA5 reanalysis which spans the period from January 1940 to the present (Ref. 10). ERA5 provides hourly estimates for a range of atmospheric, land and oceanic climate variables on a regular latitude-longitude grid of 0.25 degrees. The ERA5 reanalysis employs the principle of data assimilation to combine historical observations with model data.

2.3.2 Atmospheric data has been downloaded from the ERA5 reanalysis for the period January 2023 to May 2024 using a bounding box with co-ordinates ranging from 0 degrees longitude to -2 degrees longitude, and y coordinates ranging from 52 degrees latitude to 54 degrees latitude. The following atmospheric variables relevant to this project are:

a. Mean sea level pressure (millibars);
b. Wind speed and direction (metres/second);
c. Shortwave and longwave radiation (W/m^2);
d. Air temperature (supplied in degrees K, converted to °C); and
e. Relative humidity (%).

2.3.3 Observed Met Office data is also available for the Coleshill weather station (approximately 4.7 km southwest of the Pilot Model Reach), as summarised in **Table 1**. The Met Office data is observed data recorded with equipment that adheres to strict criteria and international standards set by meteorological organisations worldwide.

Table 1: Available Weather Data

Station Name (Station Number)	Source	Location (Latitude, Longitude)	Data Available	Years of Data
Coleshill	Met Office	52.47975, -1.68925	Hourly Air Temperature (^0C), Hourly Mean Wind Speed (knots), Hourly Rainfall (mm), Hourly Shortwave Radiation (Supplied in kJ/m^2 , converted to W/m^2),	Oct 1997-Jan 2024

2.3.4 Meteorological data has been purchased for this project from the Met Office for Coleshill weather station. The changes and trends noted for the four selected variables (hourly air temperature, hourly mean wind speed, hourly rainfall, and hourly total radiation) across the monitoring period (1997-2024) are described in the following sections. For visualisation purposes the data for these four selected variables has been converted to monthly averages for each year in the time series, where appropriate.

Air temperature

2.3.5 A time series of monthly mean air temperature (^0C) at Coleshill Weather Station from 2006 to 2024 is shown in **Plate 6**. The observed monthly mean air temperature values generally fall within the range of 17^0C to 4^0C, with notable minima and maxima outside this range in summer 2006, summer 2018, winter 2009-2010, and winter 2010-2011. The monthly average air temperature data in **Plate 7** shows average winter temperatures of approximately 5^0C and summer air temperatures exceeding 16^0C. Hourly air temperatures recorded at Coleshill Weather for a particularly warm summer day (26/07/2018) and cold winter day (01/02/2019) are shown in **Plate 8** and **Plate 9**. The summer daily timeseries show temperatures falling below 15°C at night before exceeding 30°C during the day, while winter night-time temperatures fell to -0.4°C and daytime temperatures did not reach 2.5°C.

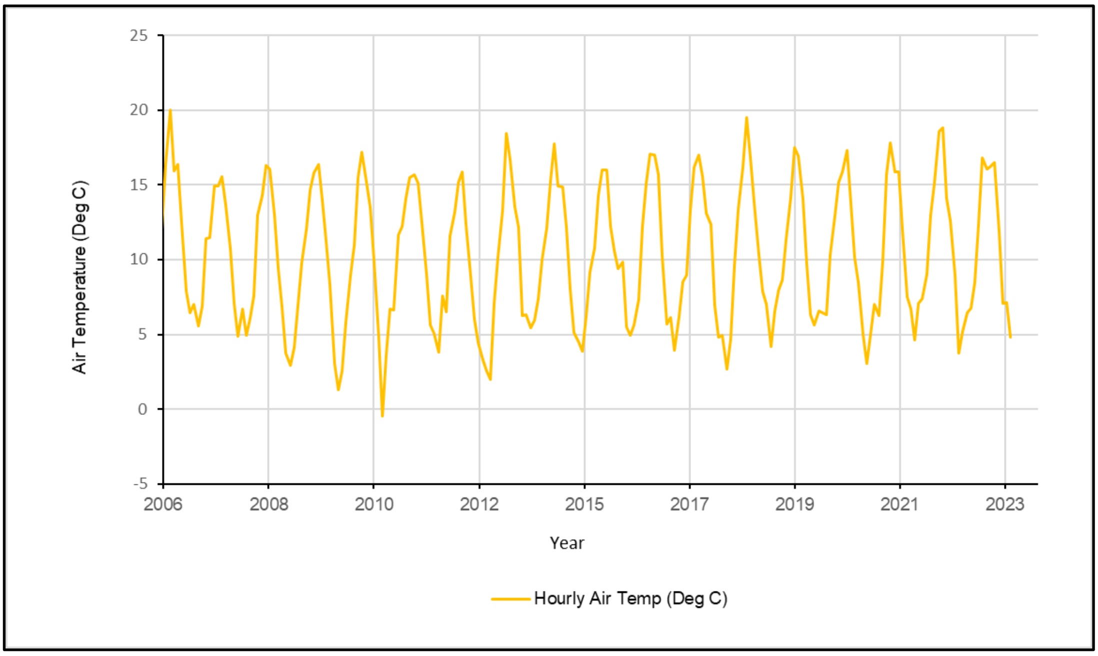

Plate 6: Time series of hourly air temperature (^{0}C) averaged at monthly intervals at Coleshill Weather Station 1997-2024

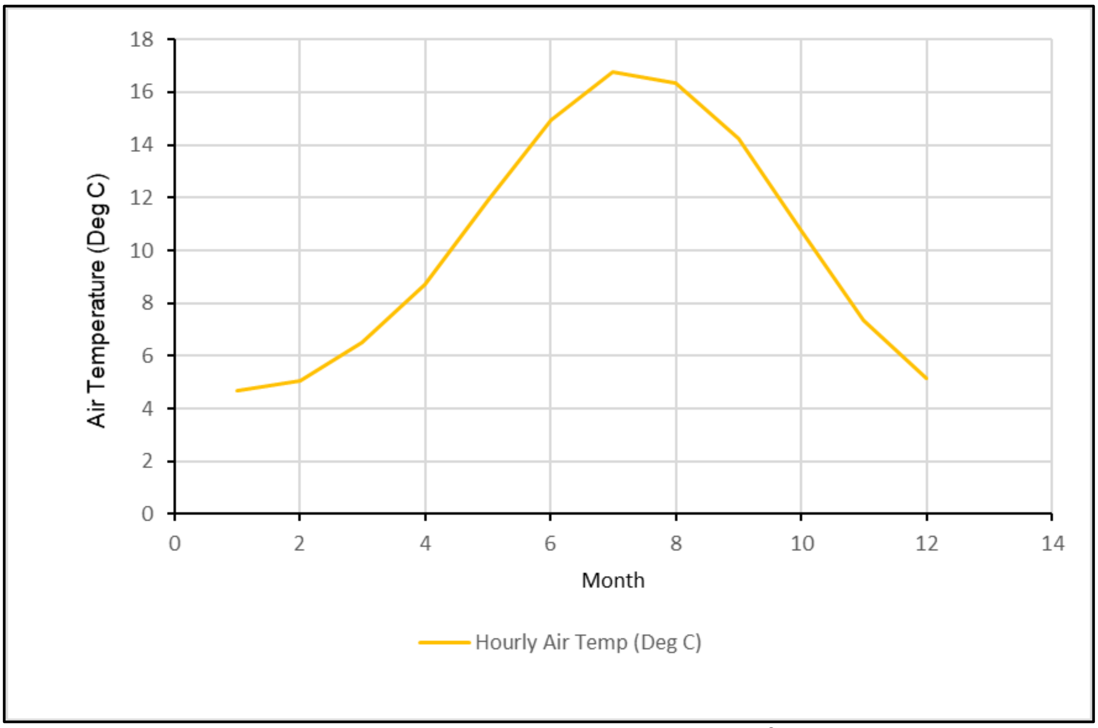

Plate 7: Monthly averaged hourly air temperature (^{0}C) at Coleshill Weather Station over the period 1997-2024

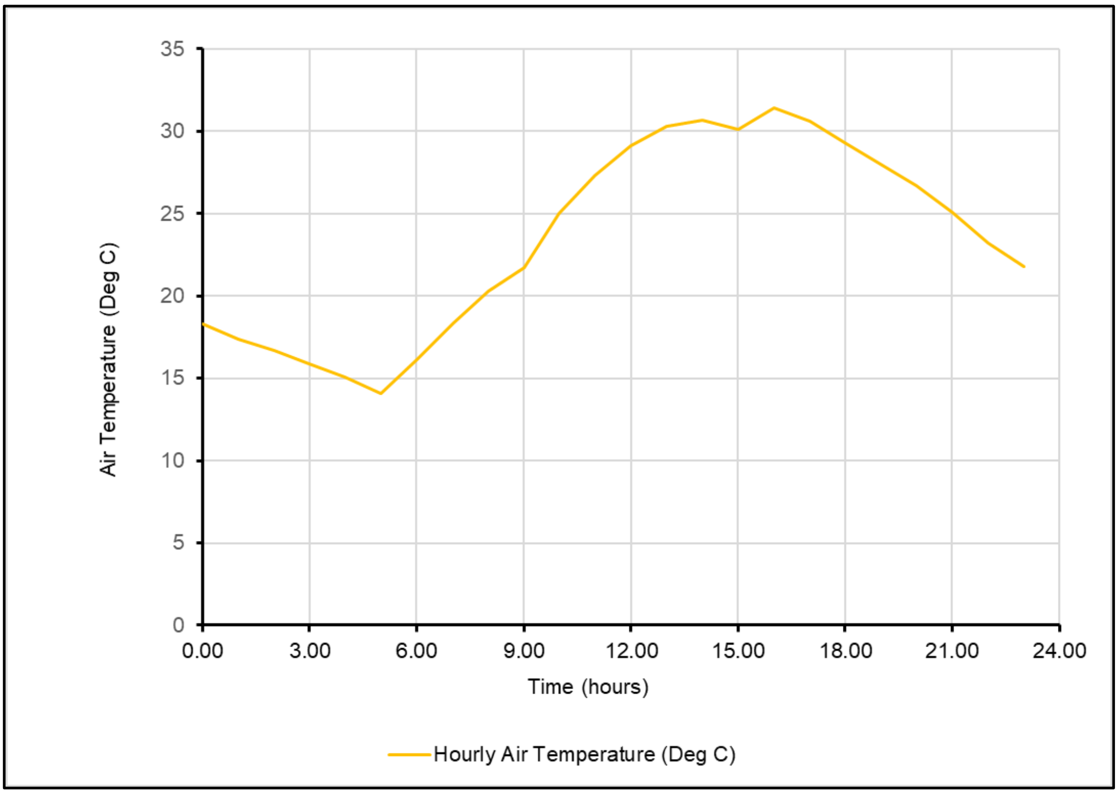

Plate 8: Profile of hourly air temperatures (^{0}C) recorded at Coleshill on 26/07/2018

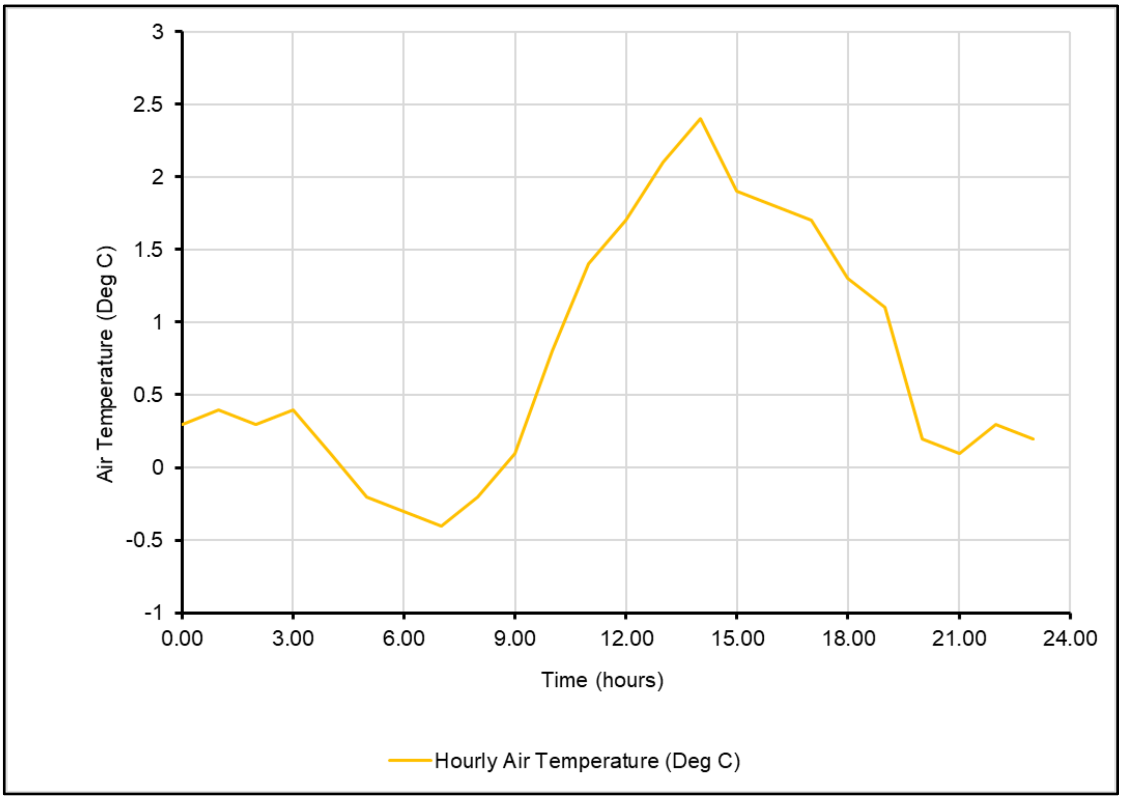

Plate 9: Profile of hourly air temperature (^{0}C) recorded at Coleshill on 01/02/2019

Wind speed

2.3.6 A time series of monthly mean wind speed at Coleshill Weather station from 1997 to 2024 is shown in **Plate 10**. Wind speed values generally fall within the range of 5 knots to 10 knots. There are small gaps in the record at the start of the recording period (Oct 1997-Dec 1997 and Apr 1998) and the record shows a gradual reduction in the monthly averaged wind speed.

2.3.7 The average hourly wind speed in each month over the period of the Coleshill Weather Station record is shown in **Plate 11**. Lowest wind speeds of 5.8 knots are seen in the summer months and higher wind speeds are observed in the winter and early spring and approach 8 knots.

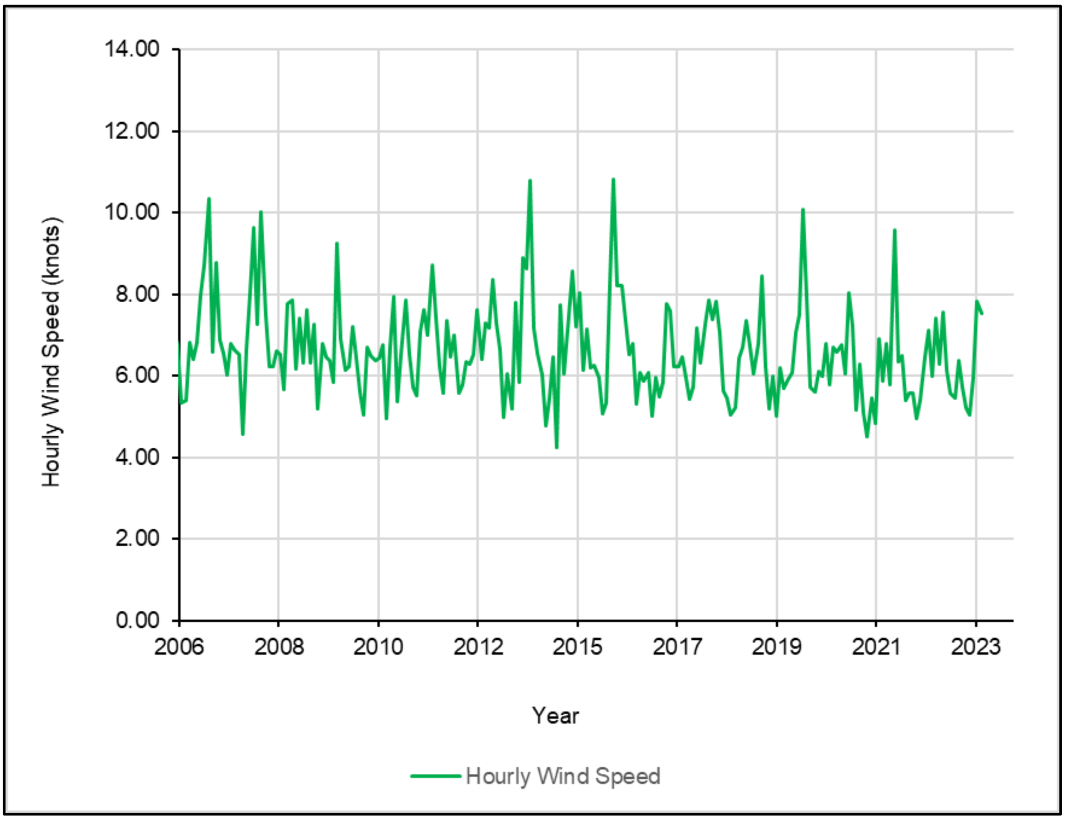

Plate 10: Time series of hourly wind speed (knots) averaged at monthly intervals at Coleshill Weather Station 1997-2024

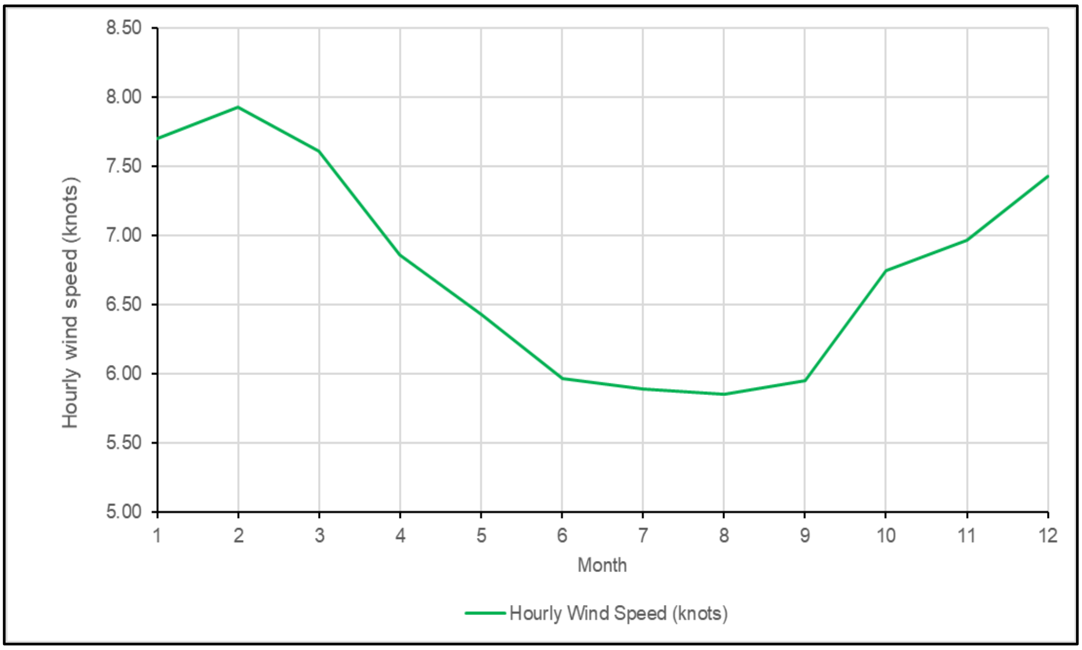

Plate 11: Monthly averaged hourly wind speed (knots) at Coleshill Weather Station over the period 1997-2024

Rainfall

2.3.8 Monthly rainfall totals are shown as a timeseries in **Plate 12** and generally fall within the range of 0-150 mm. The average monthly rainfall totals are shown in **Plate 13** and the highest rainfall totals are observed between October and December, with values of up to 80 mm. Slightly lower average monthly rainfall totals of approximately 45-55 mm are observed from January to April, and slightly higher average rainfall totals in the range 60-65 mm are seen in the summer.

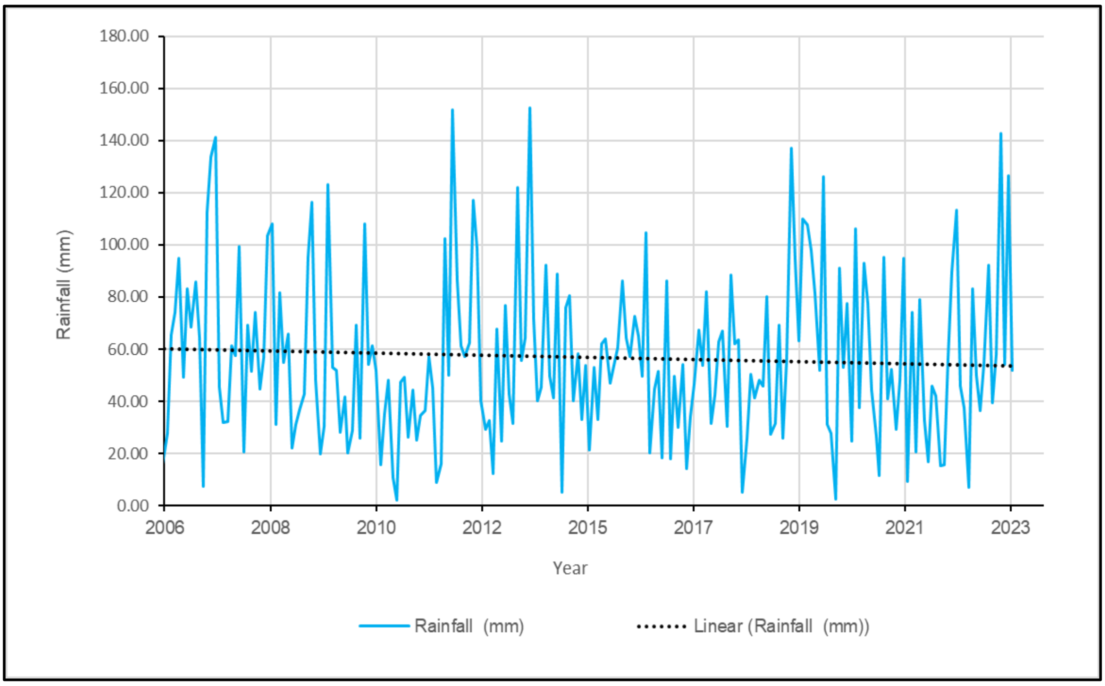

Plate 12: Monthly rainfall (mm) recorded at Coleshill Weather Station 1997-2024

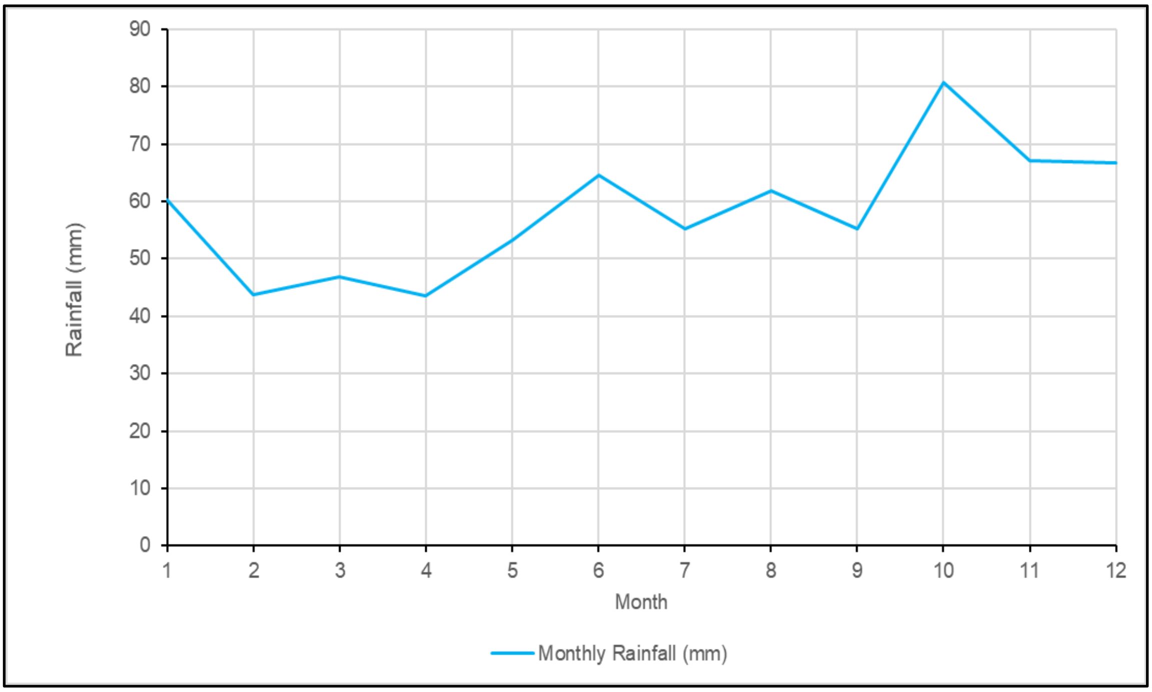

Plate 13: Average monthly rainfall (mm) at Coleshill Weather Station over the period 1997-2024

Shortwave Radiation

2.3.9 Data for shortwave radiation begin in June 2006 at Coleshill Weather Station. **Plate 14** shows the monthly mean shortwave radiation values as a timeseries – the monthly mean shortwave radiation values generally fall from 900 kJ/m^2 in summer to 100 kJ/m^2 in winter, with no visible change over the recording period 2006-2024.

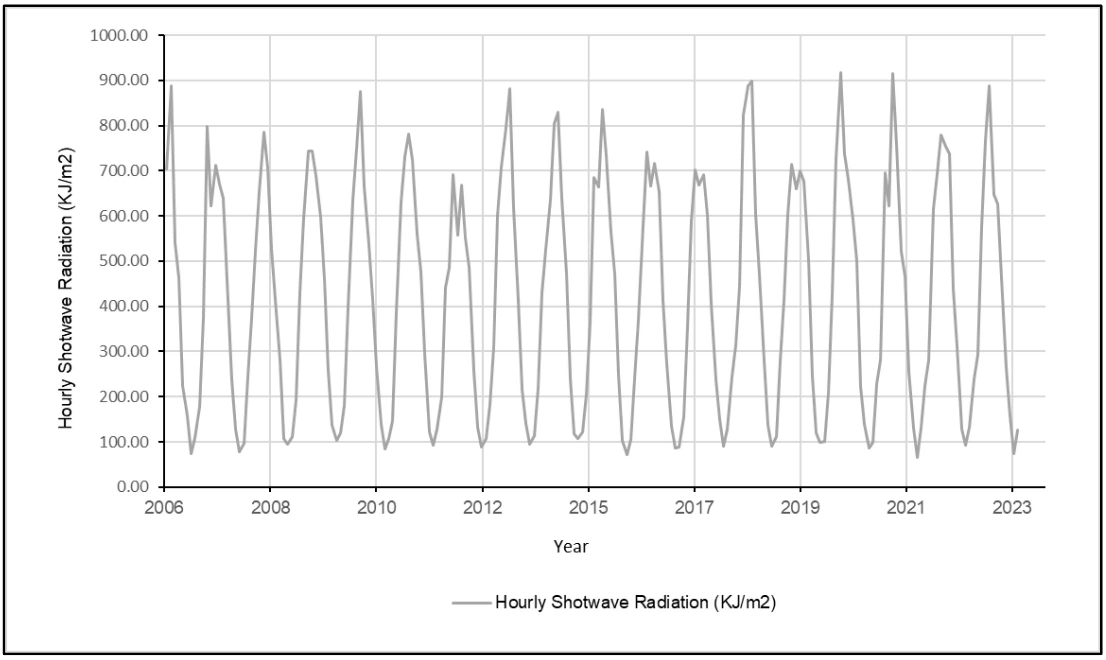

Plate 14: Time series of hourly incoming shortwave radiation (kJ/m^2) averaged at monthly intervals at Coleshill Weather Station 2006-2024

2.3.10 Hourly incoming shortwave radiation (kJ/m^2) recorded at Coleshill Weather for a representative cold winter day (01/02/2019) and a representative warm summer day (26/07/2018) are shown in **Plate 15**. The hourly shortwave radiation reached 2500KJ/m^2 in summer and only 600 KJ/m^2 in winter.

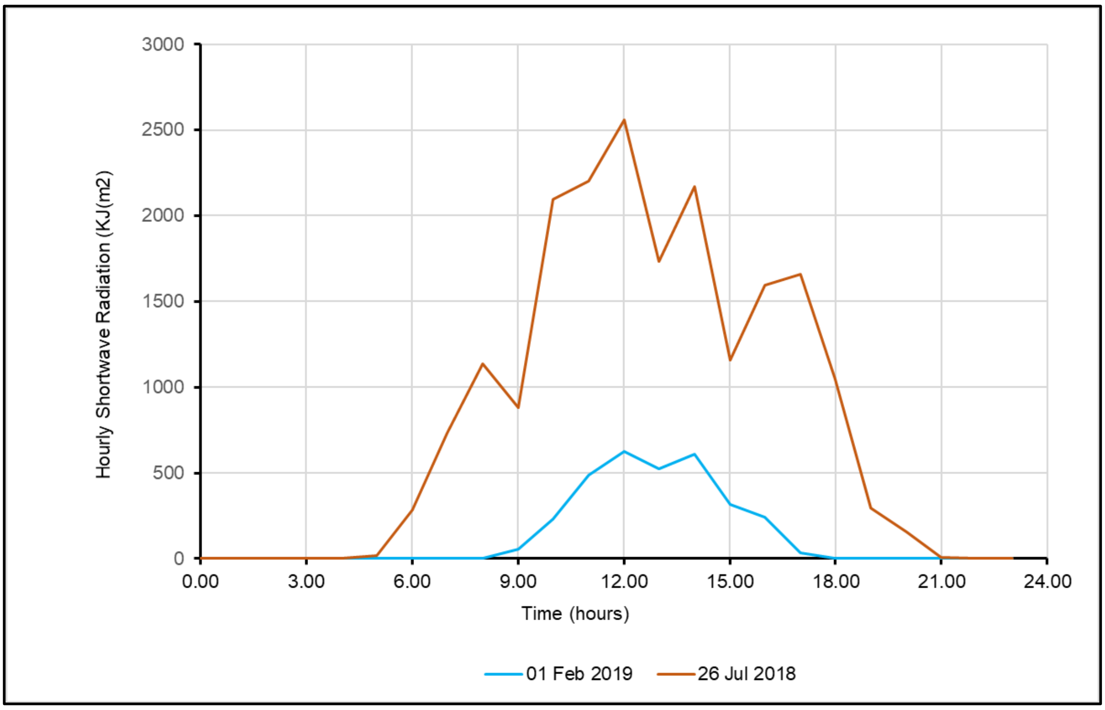

Plate 15: Profile of hourly incoming shortwave radiation (kJ/m^2) recorded at Coleshill on 01/02/2019 and 26/07/2018

Use in DO Modelling

2.3.11 Within TUFLOW FV, fluxes of oxygen between the atmosphere and the surface layer of the water are determined by wind speed and ambient water temperature. TUFLOW FV has been developed to apply atmospheric data across the whole model domain using the NetCDF files downloaded from the ERA5 Reanalysis Data described in the above section. To validate the ERA5 Reanalysis Data, the modelled air temperatures, shortwave radiation, and wind speed have been compared to the observed data at the Met Office Coleshill weather station in the sections below.

Air Temperature

2.3.12 **Plate 16** provides a comparison of the daily averaged temperatures (^{0}C) recorded over the period 01/01/2023 to 31/01/2024 at the Met Office Coleshill weather station and ERA5 Reanalysis Data. The graph shows that there is strong agreement between the two datasets, both in terms of the timing of temperature fluctuations and the magnitude of recorded air temperatures.

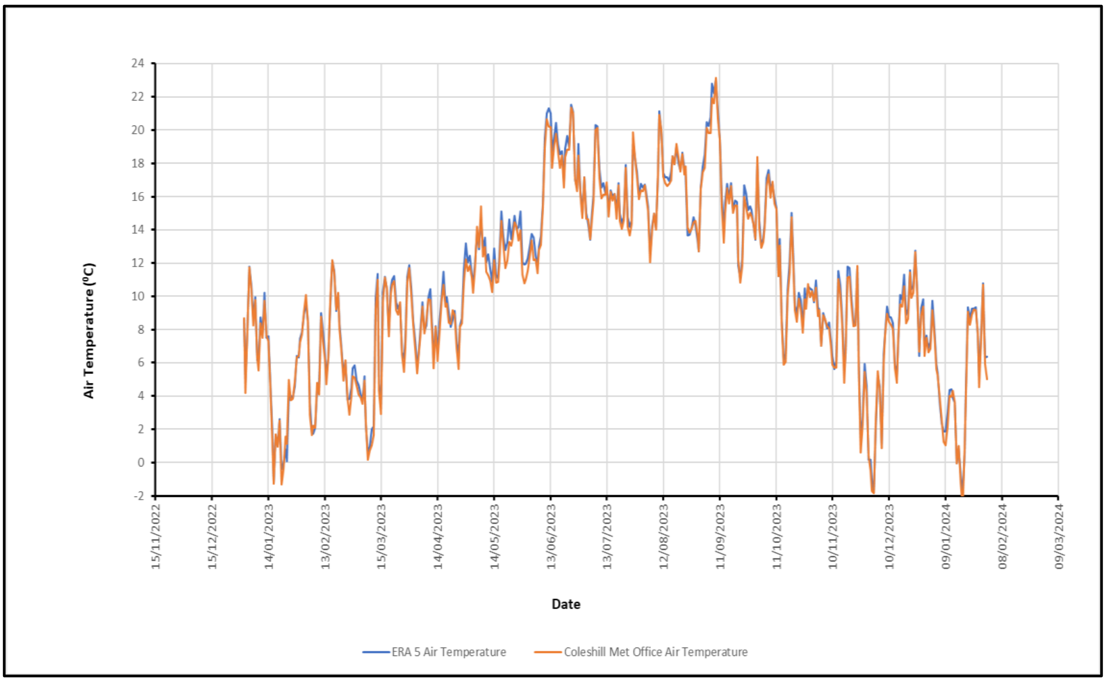

Plate 16: Comparison of daily averaged temperature (^{0}C) recorded at Coleshill and ERA5 Reanalysis data over the period 01/01/2023 to 31/01/2024

2.3.13 **Plate 17** and **Plate 18** provide a comparison of air temperatures recorded at Coleshill Weather Station and those in the ERA 5 Reanalysis data for two cold days in winter (15/01/2024 and 16/01/2024), and two hot days in summer (08/09/2023 and 09/09/2023). As shown in **Plate 17** and **Plate 18**, the ERA5 data provides a good representation of the observed data.

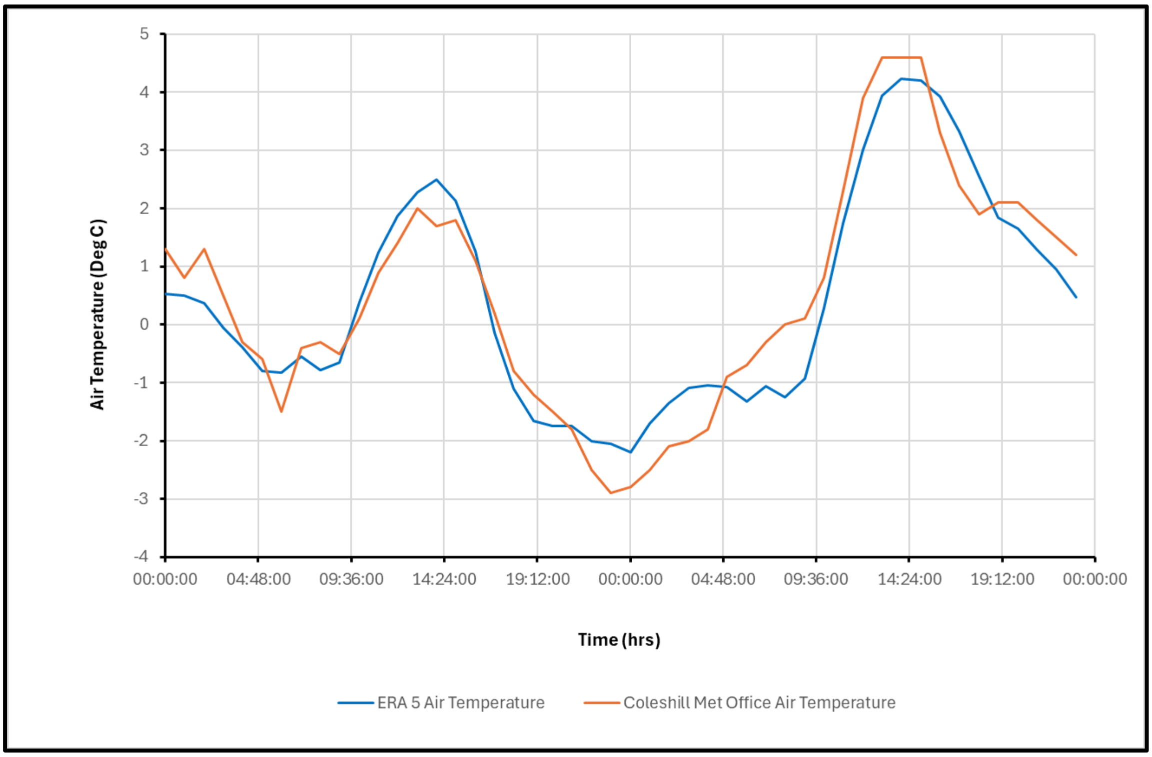

Plate 17: Comparison of the hourly air temperature (^{0}C) recorded at Coleshill and ERA5 Reanalysis data on 15/01/2024 and 16/01/2024

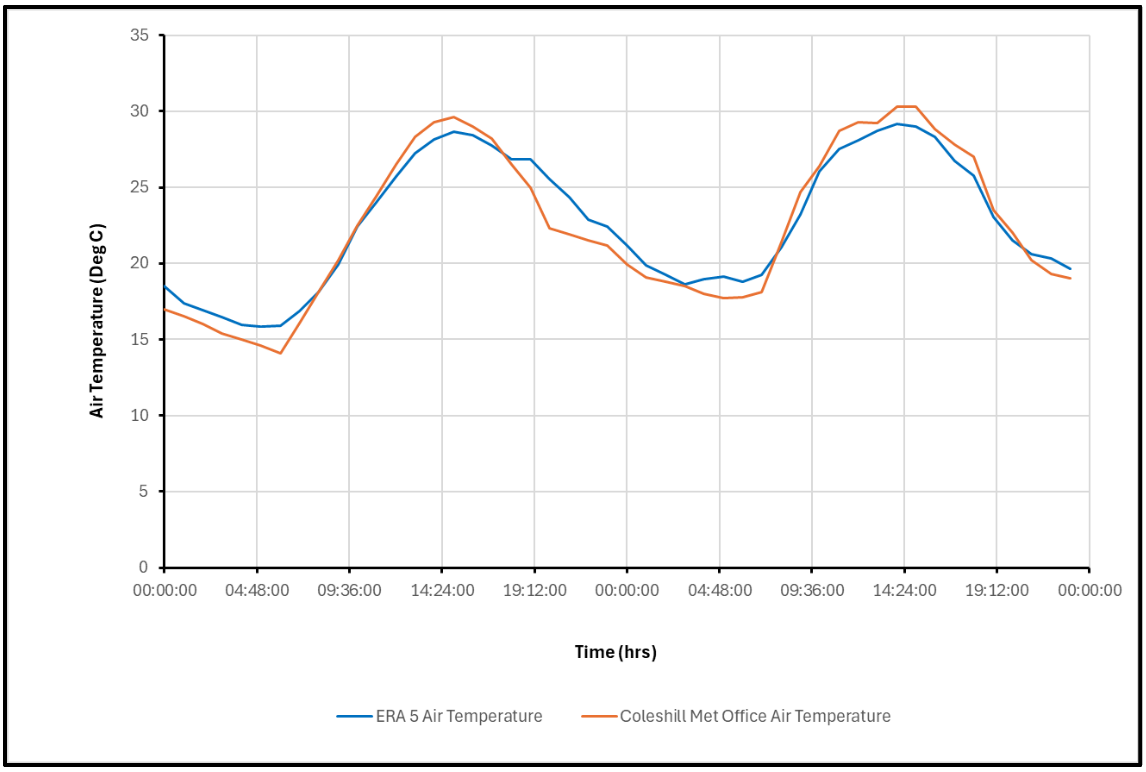

Plate 18: Comparison of the hourly air temperature (^{0}C) recorded at Coleshill and ERA5 Reanalysis data on 08/09/2023 and 09/09/2023

Wind Speed

2.3.14 Over the period 01/01/2023 to 31/01/2024 the ranges of wind speed values (m/s) recorded in the summer and winter at the Met Office Coleshill are

8.74 m/s and 13.36 m/s, whereas the ranges in the ERA5 data for the summer and winter are 9.16 m/s and 13.06 m/s, respectively. There is good general agreement in the range of wind speed values between the two datasets for both the summer and winter conditions, although there is a tendency for the ERA5 data to overestimate summer wind speeds. Wind speed is a highly variable parameter in terms of both speed and direction and the ERA5 data can differ from the Coleshill data significantly over short timescales.

Shortwave Radiation

2.3.15 **Plate 19** provides a comparison of the shortwave radiation fluxes (W/m^2) recorded over the period 01/01/2023 to 31/01/2024 at the Met Office Coleshill weather station and simulated within the ERA5 Reanalysis Data. The graph shows that there is strong agreement between the two datasets, both in terms of the timing of fluctuations in shortwave radiation fluxes and the magnitude of recorded shortwave radiation fluxes.

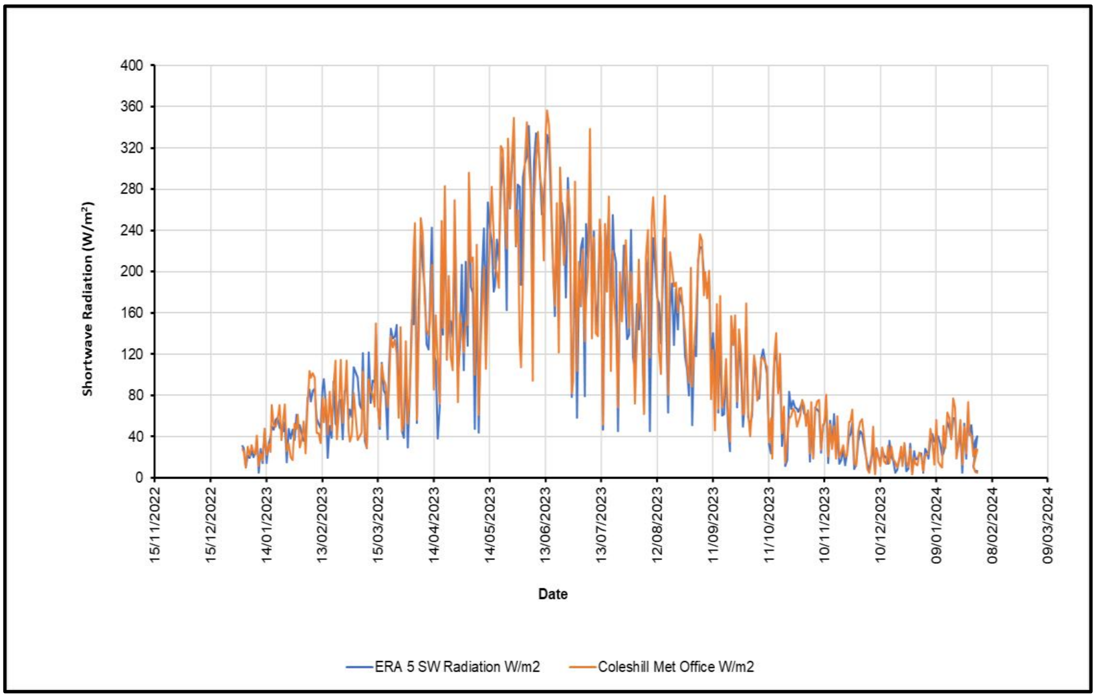

Plate 19 : Comparison of daily averaged shortwave radiation (W/m^2) recorded at Coleshill and ERA5 Reanalysis data over the period 01/01/2023 to 31/01/2024

Summary

2.3.16 Comparison between the observed Met Office data at Coleshill and the ERA5 data show that the air temperature, wind speed and shortwave radiation at the Pilot Model Reach are well-represented by the ERA5 data. The greatest differences between the two datasets occur in the wind speed values; wind speed is a highly variable parameter and a sensitivity analysis will be carried out to ensure that assumptions in simulating wind speed do not impact on the conclusions of the DO modelling. Wind speed will be adjusted ±25% in this sensitivity analysis based on the normal range of difference between simulated and observed data.

2.4 Water Quality Data

Available Data and Review

Environment Agency Water Quality Monitoring Data

2.4.1 The available Environment Agency water quality monitoring data available to inform the DO model is summarised in **Table 2**. The locations of the available Environment Agency water quality monitoring stations are shown in **Plate 20.**

Table 2: Available Water Quality Monitoring Data

Station Name (Station Number)	Source	Location (Latitude, Longitude)	Data Available	Years of Data
R. Bourne - Confluence With R. Tame (MD-61471060) 'River Bourne'	Environment Agency	52.519836, -1.6813037	Oxygen (% Saturation), Ammoniacal Nitrogen as N, Orthophosphate (reactive as P), Temperature of Water	2000-2024
Western Aggregates Ltd Dewatering & Sd (MD-61642220) 'River Blythe'	Environment Agency	52.515312, -1.6909442	Oxygen (% Saturation), Ammoniacal Nitrogen as N, Orthophosphate (reactive as P), Temperature of Water	2000-2024
RIVER COLE - COLESHILL (MD-61671530) 'River Cole'	Environment Agency	52.503148, -1.7081184	Oxygen (% Saturation), Ammoniacal Nitrogen as N, Orthophosphate (reactive as P), Temperature of Water	2000-2024
R Tame - D/S Minworth Stw Bacteria Beds (MD-59009850) 'DS Minworth'	Environment Agency	52.520099, -1.6993110	Oxygen (% Saturation), Ammoniacal Nitrogen as N, Orthophosphate (reactive as P), Temperature of Water	2000-2024
R Tame - Lea Marston (Inlet To Lake 1) (MD-59008980) 'Lea Marston'	Environment Agency	52.538344, -1.6978301	Oxygen (% Saturation), Ammoniacal Nitrogen as N, Orthophosphate (reactive as P), Temperature of Water	2000-2024

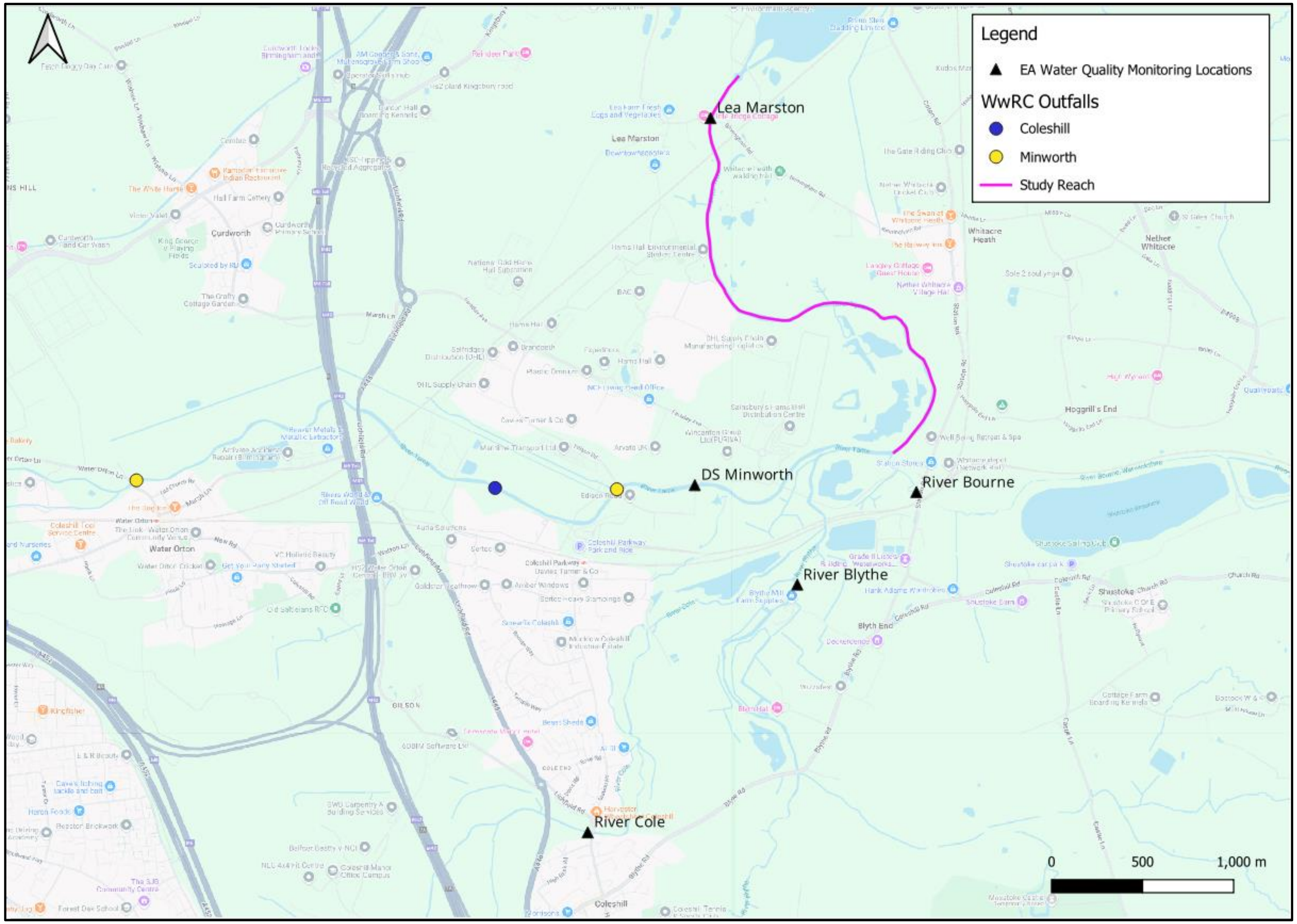

Plate 20: Map of Environment Agency water quality monitoring stations

2.4.2 Water quality data has been downloaded from the Environment Agency Water Quality Archive (Ref. 11) at the sampling points listed in **Table 2**. The Environment Agency water quality sample data collected between 2000 and 2024 at the River Cole, River Blythe, River Bourne, and DS Minworth sampling points provide snapshot values for oxygen, ammoniacal nitrogen, oxygen, and water temperature for water feeding into the Pilot Model Reach. This data provides an indication of seasonal and spatial variability, as well as indicative ranges in values for each of the four variables.

2.4.3 The changes and trends noted for the four selected variables (water temperature, dissolved oxygen, orthophosphate, and ammoniacal nitrogen) across the monitoring period (2000 to 2024) are described in the following sections.

Water Temperature

2.4.4 The recorded water temperatures at the sampling points on the River Tame tributaries are shown in **Plate 21** and water temperature on the River Tame itself are shown in **Plate 22**. There are no visible trends beyond the expected annual fluctuations in water temperature at the five selected sampling points. Water temperatures vary seasonally between 0.2^0C and 23.1^0C. The sampling point DS Minworth is upstream of the Pilot Model Reach whilst the sampling point at Lea Marston is close to the downstream limit of the Pilot Model Reach and **Plate 22** shows that there are no significant differences in water temperature between these two points.

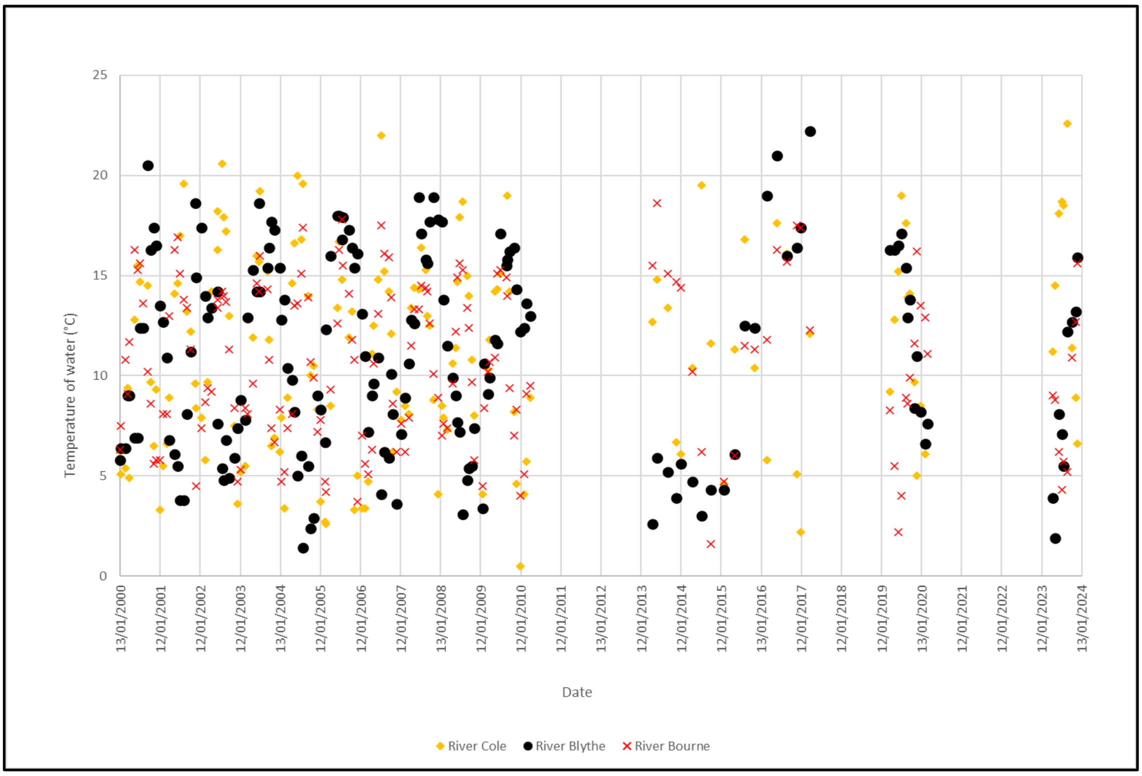

Plate 21 : Water temperature (°C) across the monitoring period 2000-2024 at the River Cole, River Blythe, and the River Bourne sampling points

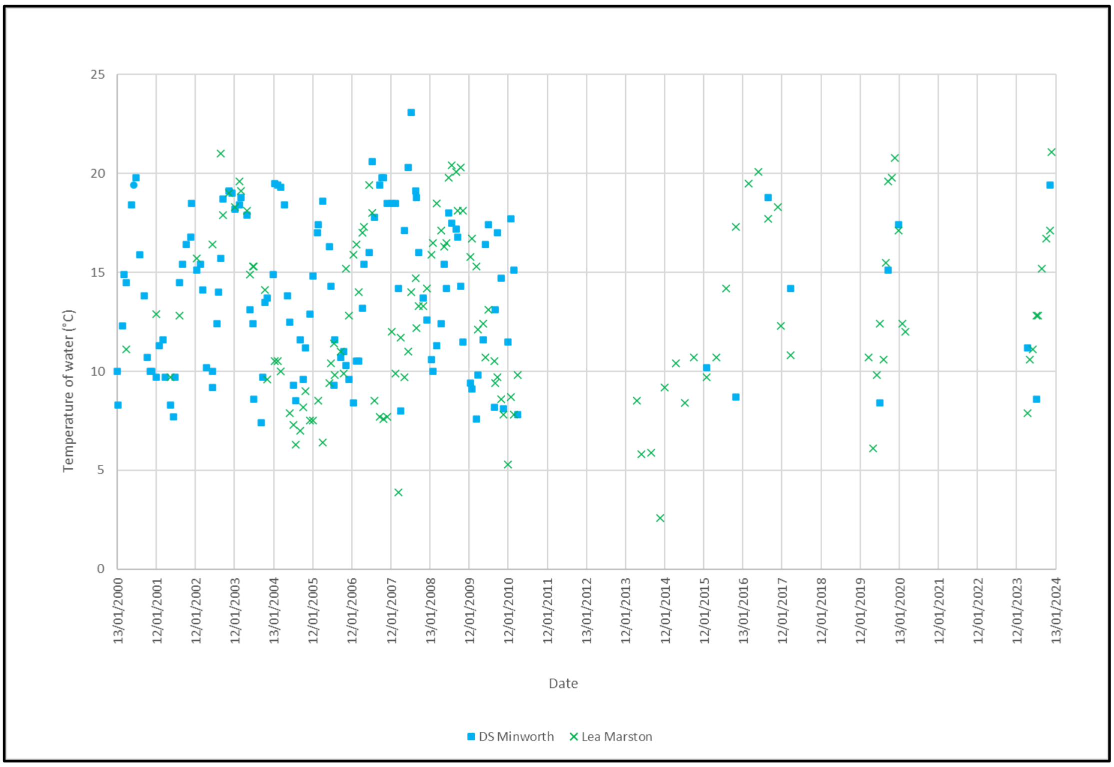

Plate 22: Water temperature (°C) across the monitoring period 2000-2024 at the DS Minworth and Lea Marston sampling points

Dissolved Oxygen (% Saturation)

2.4.5 The recorded DO saturation at the sample points on the River Tame tributaries are shown in **Plate 23**. There is higher variability in DO in the River Cole than at other locations but a high degree of similarity between the DO saturation recorded at the Rivers Blythe and Bourne. **Plate 24** shows the recorded DO saturation in the River Tame; there is a reduction in maximum saturation between 2000 and 2008, after which DO levels at more constrained to between 60% and 100%.

2.4.6 The 10th percentile values of DO (% saturation) over the whole monitoring period in the River Cole, River Blythe, River Bourne, DS Minworth, and Lea Marston sampling points are 75.0%, 72.6%, 84.0%, 71.0% and 68.6%, respectively. The values at the River Blythe, DS Minworth, and Lea Marston sampling points exceed the Water Framework Directive Environmental Quality Standard (EQS) minimum 10th percentile value of 64% that is required to achieve 'moderate' status in salmonid rivers. However, only the 10th percentile values at the River Cole and River Bourne sampling points exceed the EQS value of 75% that is required to achieve 'Good' status in salmonid rivers (Ref. 12).

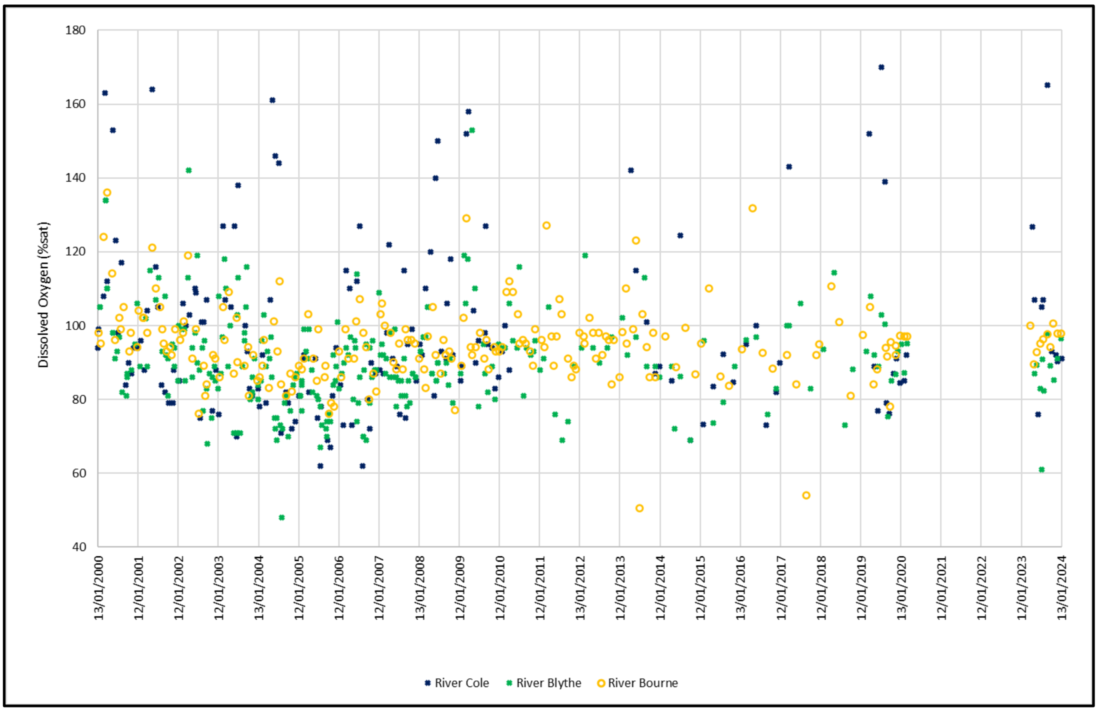

Plate 23: DO (% saturation) across the monitoring period 2000-2024 at the River Cole, River Blythe, and the River Bourne sampling points

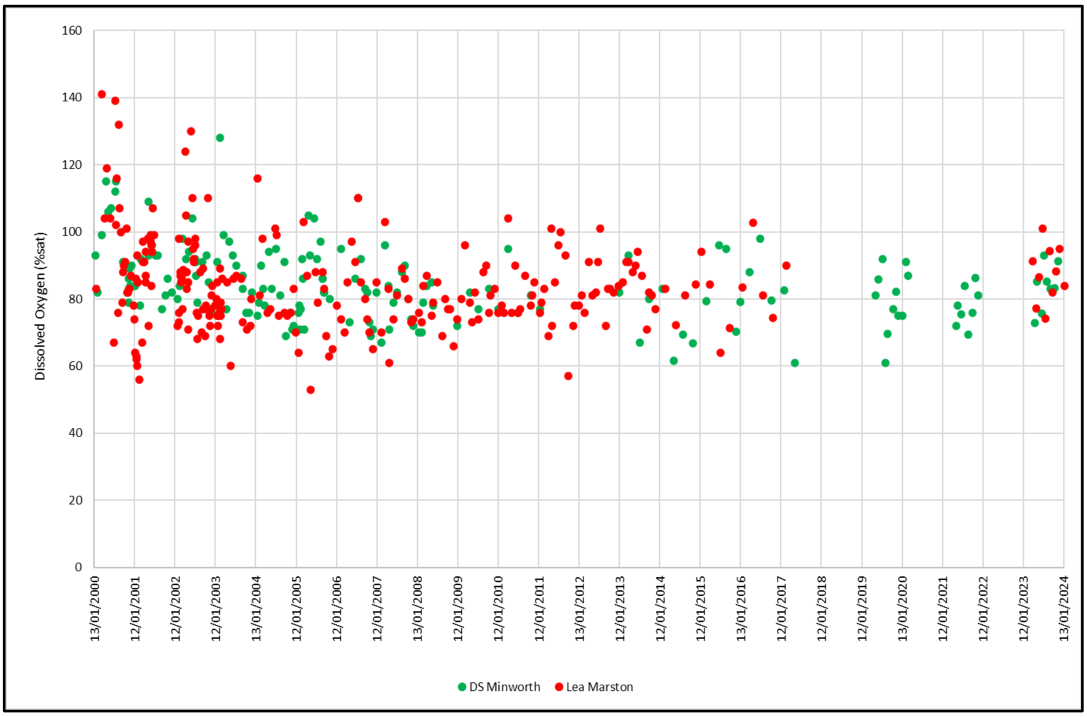

Plate 24: DO (% saturation) across the monitoring period 2000-2024 at the DS Minworth and Lea Marston sampling points

Orthophosphate

2.4.7 The recorded orthophosphate concentrations at the sample points on the River Tame tributaries are shown in **Plate 25**. There are no clear trends in orthophosphate concentrations in the Rivers Cole and Bourne, however there are significant reductions in orthophosphate concentrations in the River Blythe after 2008. Reductions are also seen in the River Tame at both Lea Marston and DS Minworth (**Plate 26**) up to 2015.

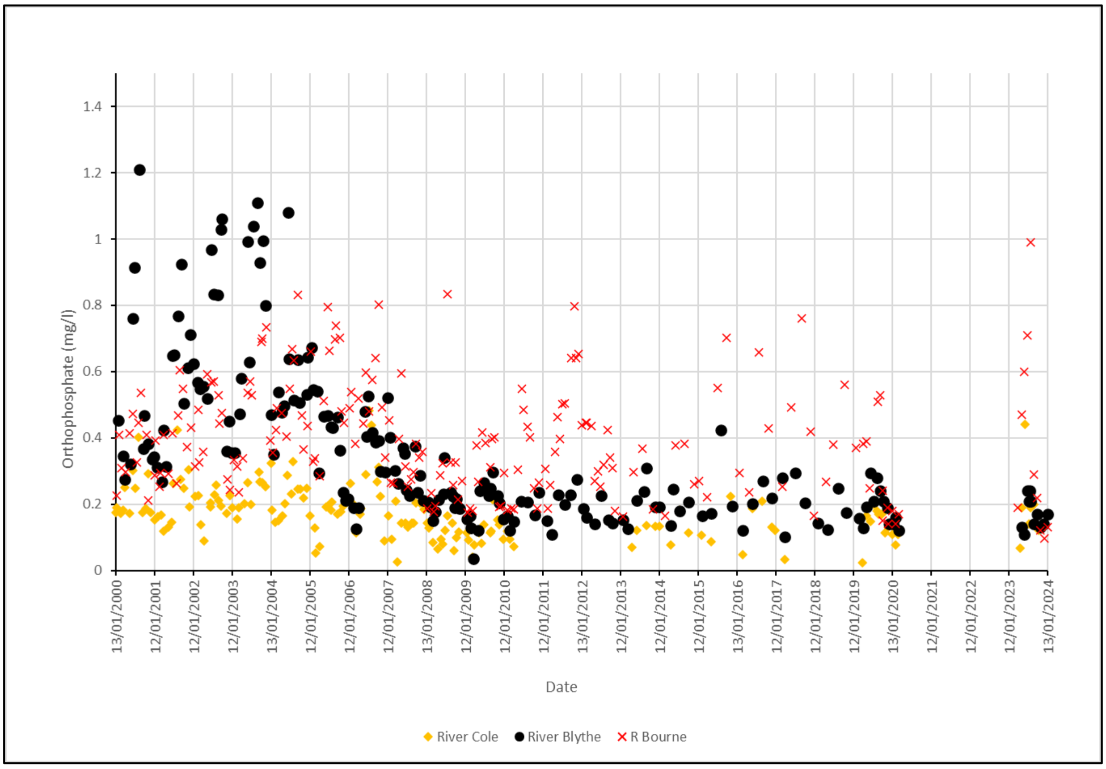

Plate 25: Orthophosphate (reactive as P) (mg/l) across the monitoring period 2000-2024 at the River Cole, River Blythe, and the River Bourne sampling points

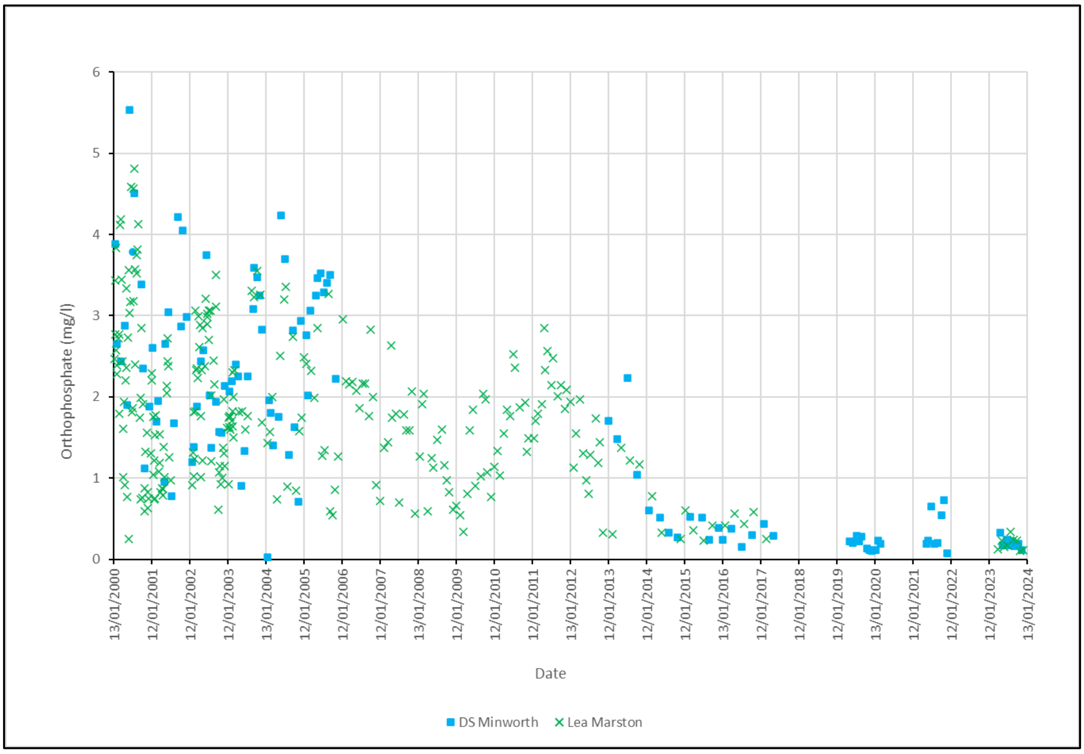

Plate 26: Orthophosphate (reactive as P) (mg/l) across the monitoring period 2000-2024 at the DS Min worth and Lea Marston sampling points

Ammoniacal Nitrogen

2.4.8 The ammoniacal nitrogen concentrations at the sampling points on the River Tame tributaries are shown in **Plate 27**. There are no clear changes in the ammoniacal nitrogen concentration at the River Cole, River Blythe and River Bourne sampling points.

2.4.9 **Plate 28** shows that there was a reduction in ammoniacal nitrogen concentrations in 2010 at Lea Marston and a possible reduction at DS Minworth, although there is less available data at this point. This reduction is likely associated with the upgrade works to Minworth WwRC in 2009 which included an enlarged activated sludge plant and additional storm tank capacity.

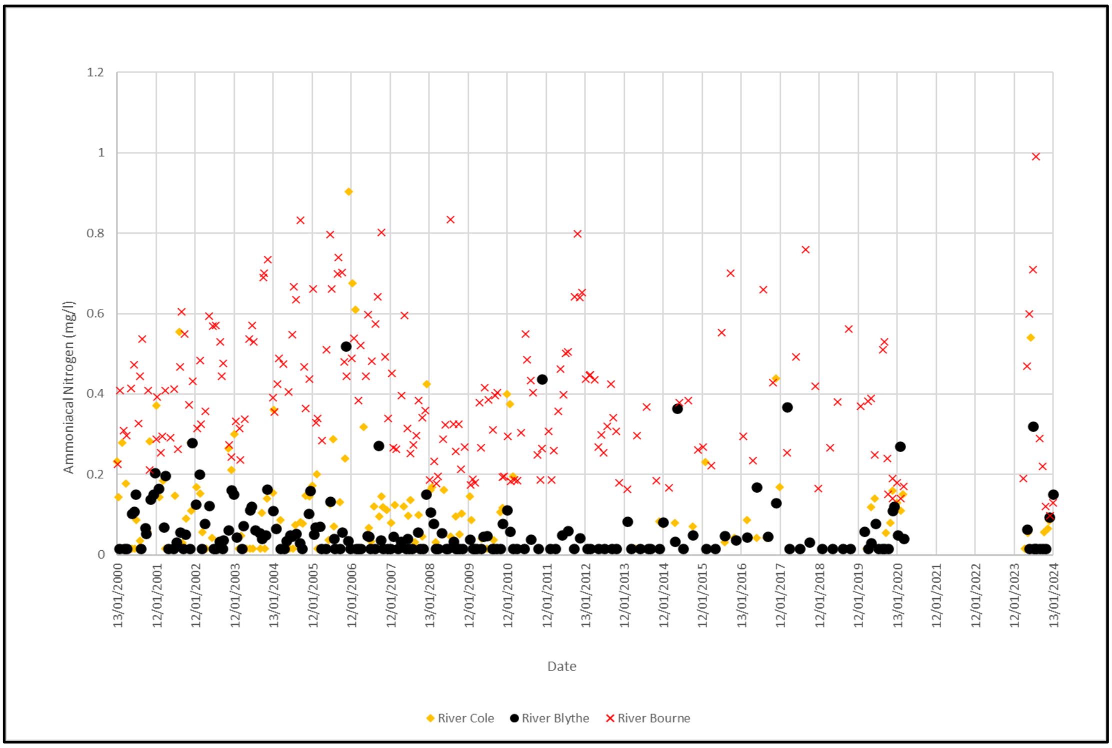

Plate 27: Ammoniacal nitrogen (mg/l) across the monitoring period 2000-2024 at the River Cole, River Blythe, and the River Bourne sampling points

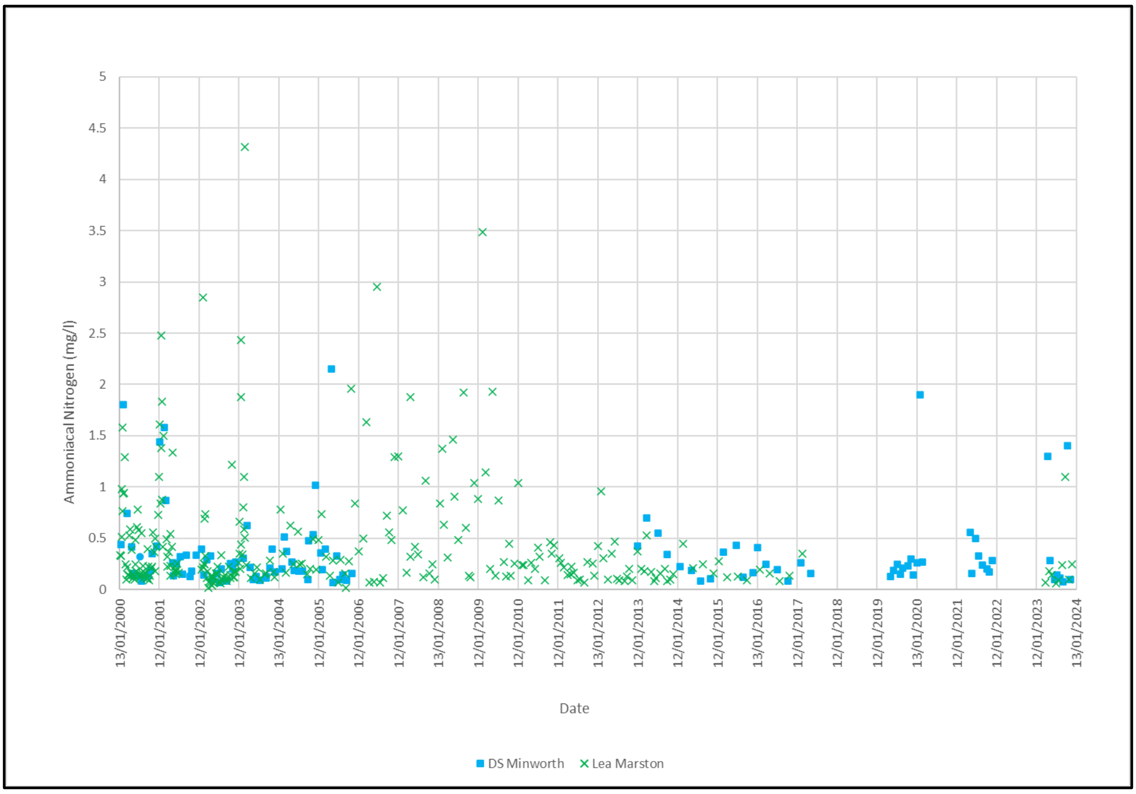

Plate 28: Ammoniacal nitrogen (mg/l) across the monitoring period 2000-2024 at the DS Minworth and Lea Marston sampling points

2.4.10 It is worth noting the following limitations to the Environment Agency data:

a. The data has been collected at specific points in time and therefore may not reflect short-term or diurnal fluctuations in water quality variables; for example, DO can be influenced by daily fluctuations in air temperature, photosynthesis and respiration;

b. The data has been obtained from four discrete locations and therefore may not accurately capture spatial variability within DO values that may be influenced by factors such as shading by overhead trees, point sources of contaminants and turbulence near sudden changes in bathymetry; and

c. There are gaps in temporal coverage in the Environment Agency data for the four water quality variables at the five sampling locations.

Discharge Consents

2.4.11 It is important to establish if there are any discharge consents in the Pilot Model Reach, as these may influence the internal processes relating to DO. A list of environmental permits authorising discharges of potentially polluting liquids into the River Tame within the Pilot Model Reach has been collated through consultation of the Environment Agency website (Ref. 13) and is provided in **Table 3**. There are two discharge consents (permit numbers MI/T/16/35595/T/001 and MI/T/16/35497/T/001) within the Pilot Model Reach, which are both solely for the drainage of surface water runoff.

2.4.12 This investigation relates to the impact of changes in river DO levels on fish populations in hot, dry weather conditions. The two consented discharges are unlikely to be operational during such atmospheric conditions are and therefore do not need to be accounted for or represented within the TUFLOW FV water quality model.

Table 3: List of environmental permits authorising discharges of potentially polluting liquids into the River Tame within the Pilot Model Reach

Permit Holder Name	Permit number	Site Coordinates (Latitude, Longitude)	Status of Consent	Composition
BMW Hams Hall Motoren GMBH	MI/T/16/35595/T/001	52.528356, -1.6940956	Issued in August 2001.	The Discharge shall consist solely of site drainage. Suspended solids, dried at 105^{0}C, shall not exceed 100 milligrams per litre. There shall be no visible oil or grease in the receiving watercourse.
Forterra Building Products Limited	MI/T/16/35497/T/001	52.529085, -1.6977757	Issued on 13 August 1993. Parts of consent related to discharge of treated sewage effluent and trade effluent consisting of vehicle wash water revoked on 6 October 2000.	The Discharge shall consist solely of site drainage. Suspended solids, dried at 105^{0}C, shall not exceed 100 milligrams per litre. The pH value shall not be less than 6 or greater than 9. There shall be no visible oil or grease in the receiving watercourse.
Marley PLC	MI/T/16/22574/T/002	52.529085, -1.6977757	Revoked in 2000.	Not Applicable.
Marley PLC	MI/T/16/22574/T/001	52.529085, -1.6977757	Revoked in 2000.	Not Applicable.
Severn Trent Water Limited	MI/T/16/12113/R/001	52.538074 , -1.6977140	Revoked in 2001.	Not Applicable.

Sonde Data

2.4.13 To support the development and calibration of the TUFLOW FV 2D model, two sondes were installed on the River Tame at the upstream end (Ladywalk Reserve) and downstream end (Lea Marston) of the Pilot Model Reach. The sondes were installed in February 2024 and set up to record water temperature and DO concentrations at 15-minute intervals throughout the spring and summer of 2024. The sonde installations are shown in **Plate 29**– these photographs were taken on the day of installation.

Plate 29: Sondes installed at Lea Marston (left) and Ladywalk Reserve (right)

2.4.14 The water temperature timeseries is shown in **Plate 30**. Water temperature is similar at both sites and shows a day-night variation of the order 1°C. The water temperature reached a maximum of 22°C in June and July 2004 and a minimum of 13°C in September 2024.

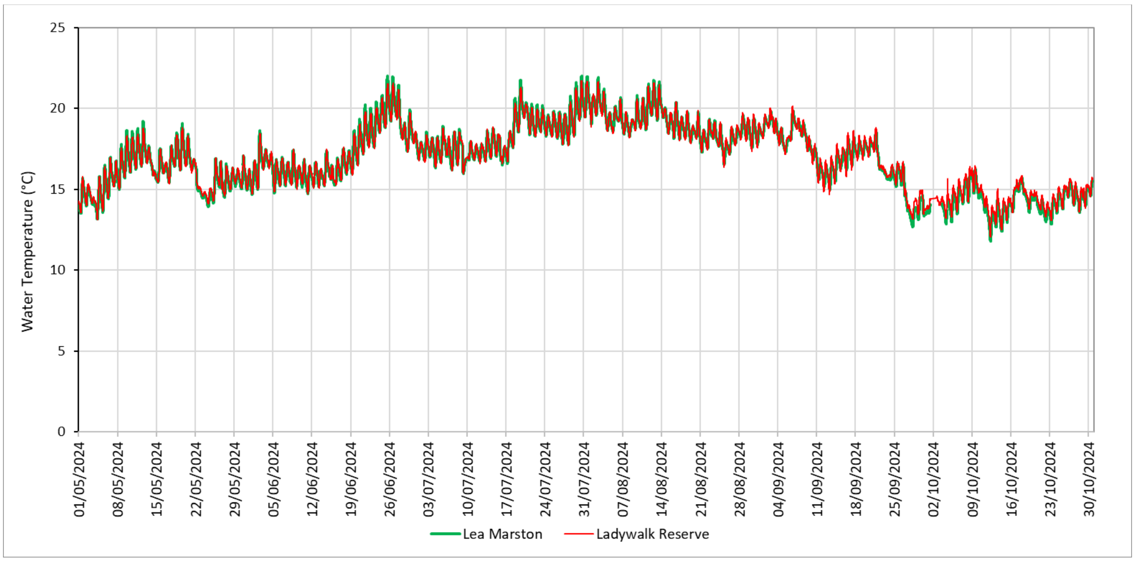

Plate 30: River Temperature Timeseries for at Ladywalk Reserve and Lea Marston (May - Oct 2024)

2.4.15 The timeseries of DO concentrations (mg/l) recorded by the sondes is shown in **Plate 31**. There is noise in the data and individual high or low values occurring at only one sonde and not being sustained should not be considered realistic. In addition, the data quality is impacted by difficulties encountered during the survey and the data have been colour-coded in **Plate 31** to distinguish between reliable and unreliable data periods.

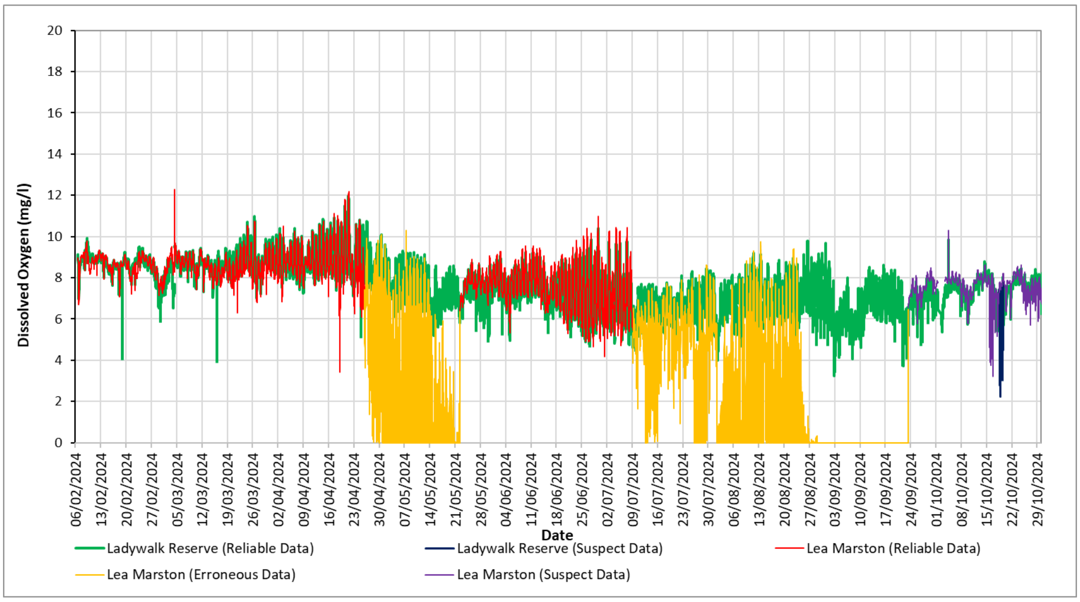

Plate 31: Dissolved Oxygen Monitoring data at Ladywalk Reserve and Lea Marston

2.4.16 Significant problems arose with DO monitoring at Lea Marston in April 2024, and this sonde did not produce reliable data for most of May 2024. Following recalibration and careful maintenance, the sonde provided reliable DO concentration records from 22 May 2024 to 9 July 2024, after which the data once again became erroneous. Access to the sonde for further maintenance was attempted but was made impossible due to extensive vegetation over the approx. 500 m distance between the survey vehicle and the sonde installation (**Plate 32**). Attempts were made to access the sonde via boat, with plans to potentially relocate the sonde, however this was impossible to do safely due to the presence of the toxic and invasive species Giant Hogweed becoming established along the riverbank. The sonde failed entirely between 28 August and 23 September 2024. The landowner was contacted to request removal of the vegetation from June 2024 onwards, however this was not actually carried out until April 2025. The sonde began reporting data again on 23 September without intervention and the data were reasonably consistent with the information recorded at Ladywalk Reserve, although given that maintenance could not be carried out, the data are still considered to be suspect. A short section of suspect data was also recorded at Ladywalk Reserve in October 2024.

Plate 32: Attempted Vegetation Clearance to Allow Access to the Lea Marston Sonde

Use in DO Modelling

2.4.17 The time series data for nitrate, ammoniacal nitrogen and orthophosphate obtained from the Environment Agency Water Quality Archive has been used to generate water quality boundary conditions for nutrients within the Pilot Model Reach. The data have been taken from the monitoring location at Lea Marston, the downstream end of the Pilot Model Reach, and are applied at the upstream end of the Reach. This assumes that there is no change in nutrient concentrations through the Reach, which is an acceptable approach as there is little difference between nutrient concentrations at Lea Marston and DS Minworth, significantly further upstream (**Plate 26** and **Plate 28**). Mean concentration values have been used based on data which are representative of the current conditions for orthophosphate, nitrate and ammonia, recognising the changes in observed water quality over time.

2.4.18 The sonde monitoring data is required to provide a suitable upstream boundary information for DO and water temperature for the water quality model (Ladywalk Reserve) and to provide end-of-reach observed data against which the model could be calibrated (Lea Marston). Given the problems with the monitoring at Lea Marston, the only data period which can be used in the calibration is the period 22 May 2024 to 9 June 2024. The timeseries for this period is shown in **Plate 33**. Three one-week periods of data have been selected which capture the lowest recorded dissolved oxygen concentrations at both sondes. Two weeks (15 to 22 June and 22 to 29 June) were used as calibration events and the third week (1 July to 8 July 2024) was used in model validation. These periods include warm water temperatures of up to 22°C at both sondes and the data show significant reductions (approximately 2°C fall) in river temperature at night. The water temperature at both sondes is essentially the same, showing no significant heating or cooling of water through the Pilot Model Reach.

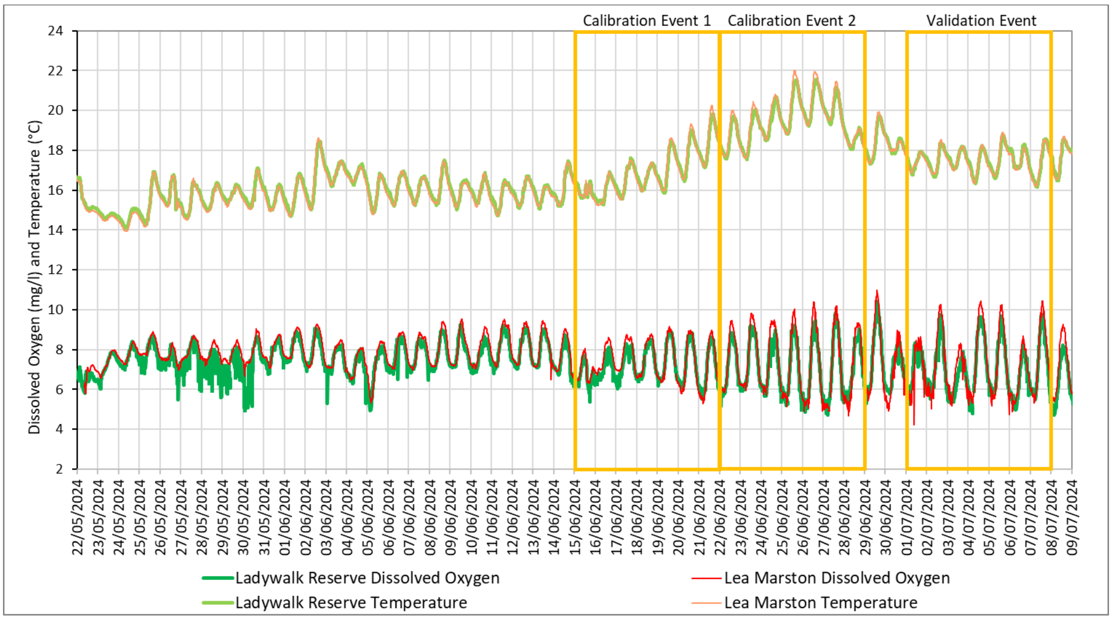

Plate 33: Calibration and Validation Model Run Periods Observed Temperature and DO Data

2.4.19 The record shows that DO concentrations increase during the day and fall at night, and that the daytime peaks at Lea Marston are slightly higher than at Ladywalk Reserve. This indicates that there is a net generation of DO through the Pilot Model Reach during the day. Given the pronounced daily variation in DO, this production is attributed to photosynthesis.

2.4.20 The sonde data was also used in scenario testing, with changes to the specified air temperature and river flow conditions (section 5.1).

2.5 River Flow Data

Available Data and Review

Environment Agency Data

2.5.1 Flow time series data with a time series interval of 15 minutes was obtained over the period 1991-2024 for the Lea Marston Lakes gauge from the Environment Agency Hydrology Data Explorer website (Ref. 14). The gauge is located at the inlet of the Lea Marston Lakes complex, the downstream limit of the Pilot Model Reach. The daily averaged flow timeseries is shown in **Plate 34** and the long term monthly averaged flow is shown in **Plate 35**. The daily averaged flows are typically within the range of 10 m^3/s to 100 m^3/s, however mean flow values below 6 m^3/s were recorded in September 2011, June-July 2017, November 2017, and August 2018. The range of flow is generally stable and there is no evidence of a long-term trend of reducing or increasing flow at this gauge. The highest flows area recorded between October and March and the lowest flows between July and September.

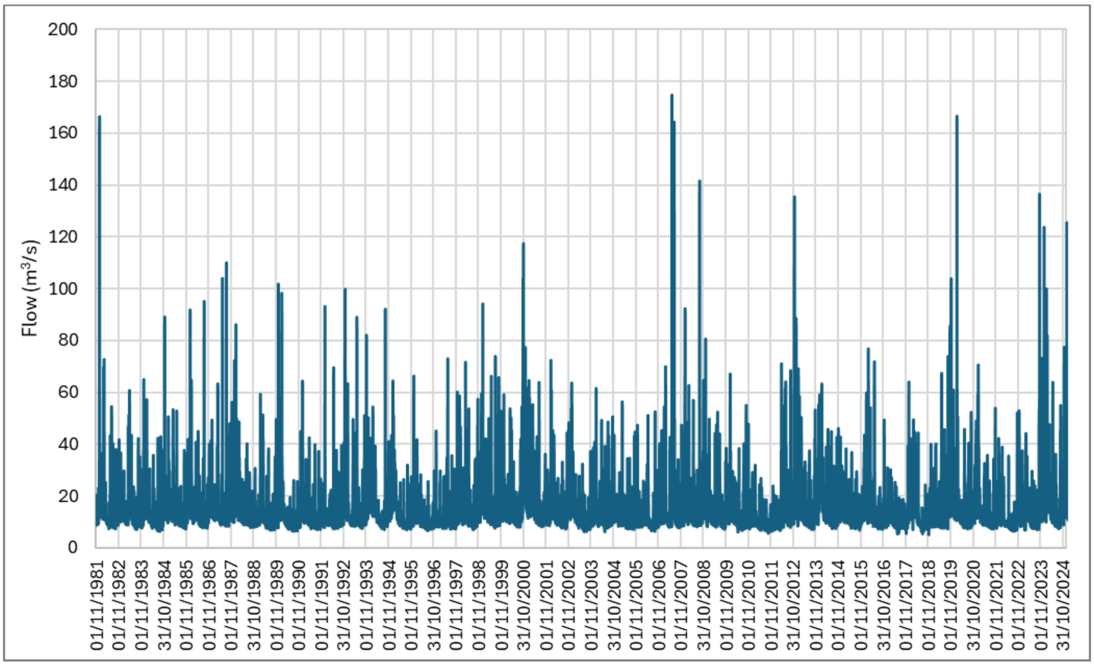

Plate 34: Daily Mean flows (m^3/s) for the period 1991-2024 recorded at the Lea Marston Lakes gauge.

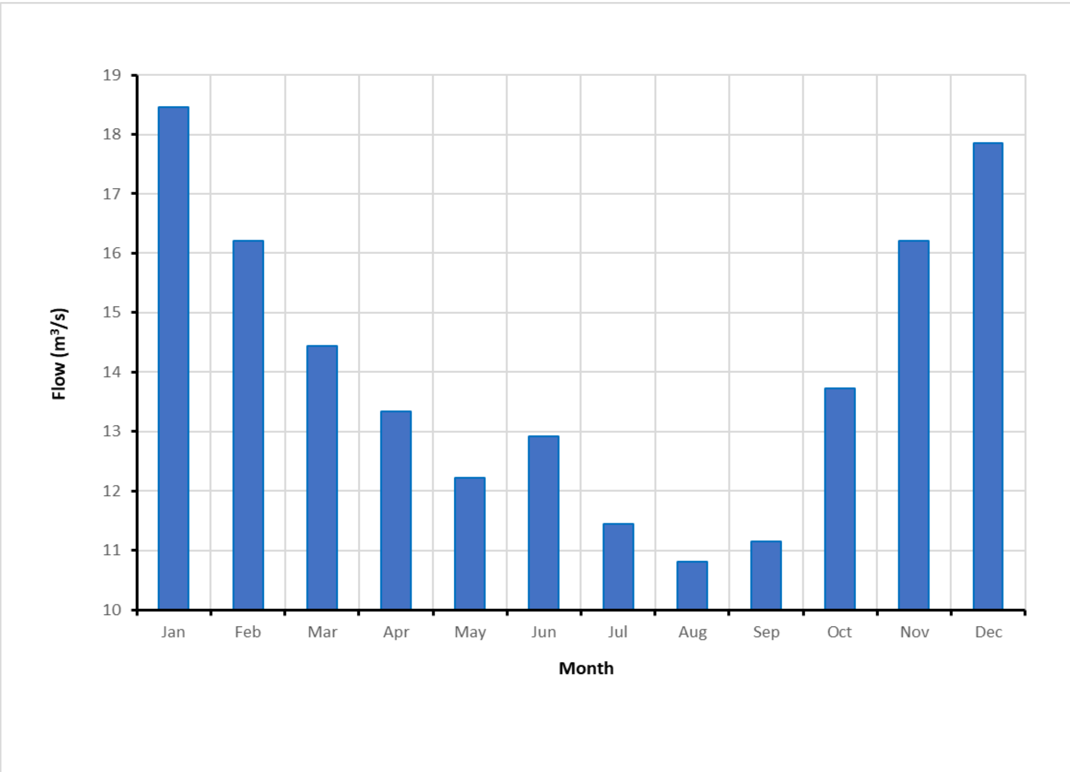

Plate 35: Average flow (m^3/s) for each month of the year recorded at Lea Marston Lakes gauge over the period 1991-2024

2.5.2 A flow duration curve has also been calculated using the entire daily mean flow record (**Plate 36**). The mean, Q_{10}, Q_{95}, and Q_{99} flow conditions are as follows:

a. Annual Mean Flow: 14.10 m^3/s;
b. Q_{10}: 24.10 m^3/s;
c. Q_{95}: 7.40 m^3/s; and
d. Q_{99}: 6.79 m^3/s.

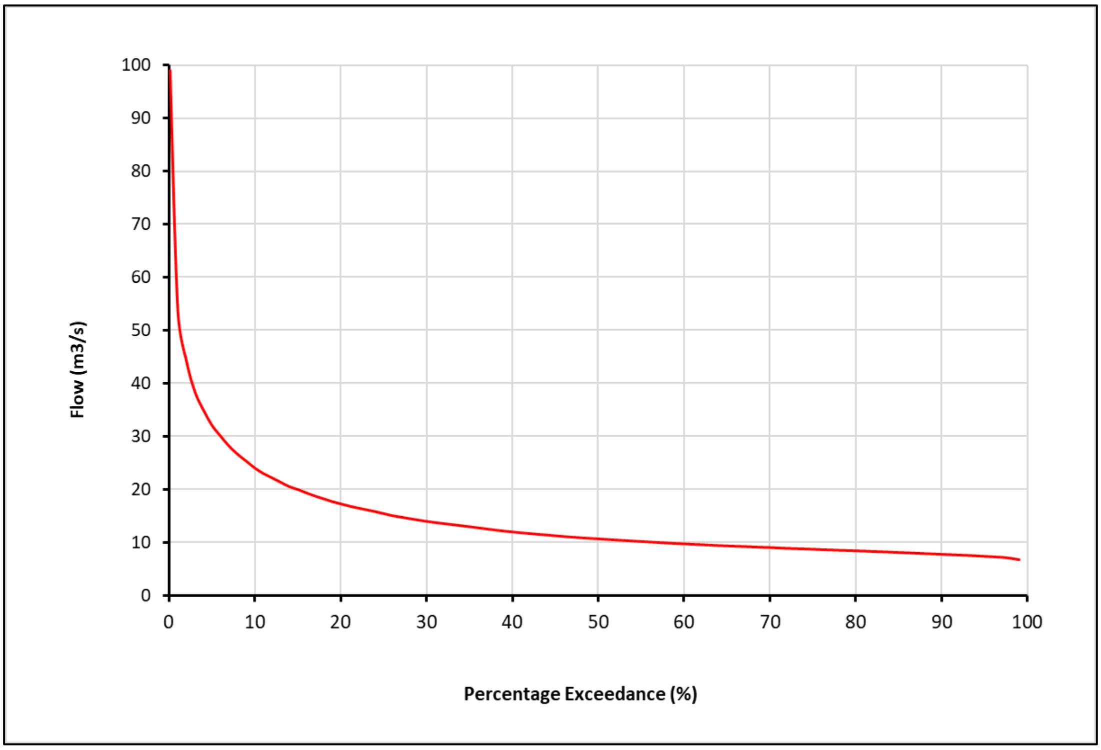

Plate 36: Flow duration curve for daily averaged flow (m^3/s) over the period 1991-2024 recorded at the Lea Marston Lakes gauge

2.5.3 A summer flow data timeseries (10/07/2022-12/07/2022) and winter flow data timeseries (15/12/2016-17/12/2016) are presented in **Plate 37** based on the 15-minute flow record at Lea Marston Lakes gauge. This clearly shows that, for both the summer and winter profiles, the 15-minute flows exhibit pronounced diurnal variability. This is attributed to changes in the rate of release of wastewater into the River Tame by the Minworth and Coleshill WwRC.

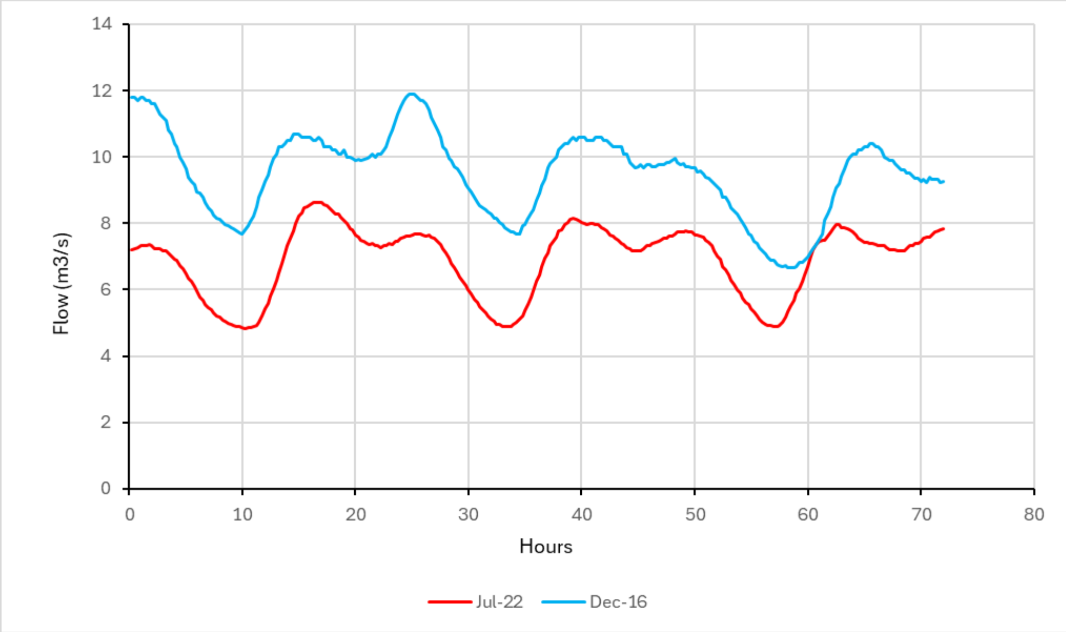

Plate 37: 15-minute flows (m^3/s) recorded at Lea Marston Lakes gauge for three day periods in summer 2022 (10/07/2022-12/07/2022) and in winter 2016 (15/12/2016-17/12/2016)

Aquator Modelling

2.5.4 Additional hydrological modelling is being carried out (and reported elsewhere) to simulate the effects of climate change and SRO operation on river flow using stochastic data sets. The outputs of this modelling have been used in the DO model to provide adjusted river flow for scenario testing. A range of climate change scenarios have been simulated in Aquator and two scenarios have been selected from two Representative Concentration Pathways (RCP) (Ref. 15) to account for different future emissions scenarios and likely temperature change ranges:

a. RCP6.0 – representing a change in temperature range of 2.0°C to 3.7°C by 2100; and

b. RCP8.5 - representing a change in temperature range of 3.2°C and 5.95°C by 2100.

2.5.5 The RCP 8.5 dry estimate mode (RCP 8.5 RCM 13) was used to represent the impacts of climate change on river flow in the Pilot Model Reach. The model outputs were used to generate a predicted future summer low river flow conditions (Q_{95}) as well as an extreme low flow (ELF) estimate which gave a good match to the worst-case drought low flows recorded in 1990 and 1996 at gauging stations on the River Tame. The ELF scenario is equivalent to a 20% reduction in the simulated Q_{99} flow in the River Tame catchment.

Use in DO Modelling

2.5.6 The 15-minute river flow timeseries data for the Lea Marston Lakes gauge has been obtained for the DO model calibration and validation periods (**Plate 38**) and used to specify the river inflow timeseries for these events. The river flow was relatively high during the start of Calibration Event 1, reaching 35.87 m^3/s (Q_4) on 15 June 2024. However, flows rapidly reduced through this event and varied between 6.88 m^3/s (Q_{99}) and 10.43 m^3/s (Q_{53}) from 18 June to 22 June with daily variation. River flows during Calibration Event 2 varied between 6.20 m^3/s (below Q_{99}) and 10.43 m^3/s (Q_{53}) and river flows during the Validation Event increased from 6.17 m^3/s (below Q_{99}) to 16.84 m^3/s (Q_{21}) over the course of the event. All three Events therefore include periods of extreme low flow for present day conditions.

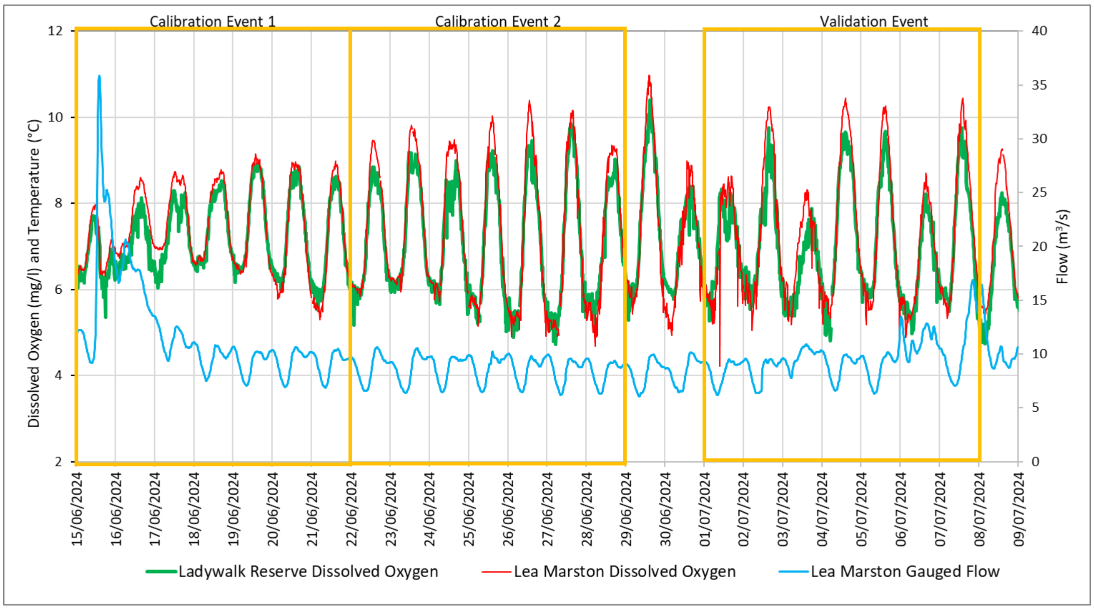

Plate 38: 15-min flows (m^3/s) for the period May-September 2024 at the Lea Marston Lakes gauge

2.5.7 Initial checks were made prior to model calibration to establish the importance of river flow for DO concentrations. Recognising the extent of sub-daily variation in river flow, the model was used to examine the variation in DO along the Pilot Model reach for a summer and winter 48-hour period, assuming either continuous river flow at the gauged mean flow of 14.0 m^3/s, or at an ELF flow of 5.4 m^3/s (the current gauged Q_{99}, reduced by 20%). Additional checks were also made using a climate-change adjusted mean flow of 13.3 m^3/s and an adjusted ELF of 5.3 m^3/s. The outcomes of these initial tests are discussed in section 4.

2.5.8 Following model calibration, the calibrated and validated model was run using finalised ELF and Q_{95} estimates derived from the Aquator model outputs for the RCP 8.5 RCM 13 climate change scenario. These flow estimates have been entered as a time-invariant flows at the upstream boundary of the model and are presented in **Table 4**. The ELF has been used to model a synthetic drought, representing a potential future worst case scenario.

Table 4: Flow estimates for the RCP 8.5 RCM 13 climate change scenario

Scenario	Flow Event	Flow estimate (m^3/s)
RCP 8.5 RCM 13 Baseline	Q_{95}	6.7
Synthetic ‘Drought’ – Potential Worst Case Scenario	ELF	5.3

2.6 Sediment Data

Available Data and Review

2.6.1 As part of the initial morphological modelling undertaken by AECOM in 2022, a number of field reconnaissance surveys were completed in which the River Tame was split into reaches. The Pilot Model Reach falls within ‘Reach 3’ and the findings of these surveys were summarised in section 4 of the ‘Environmental Assessment for the Trent Strategic Resource Options, Appendix E: Sedimentation’(Ref. 16). Four locations were visited and photographed within the Pilot Model Reach, as shown in **Plate 39**.

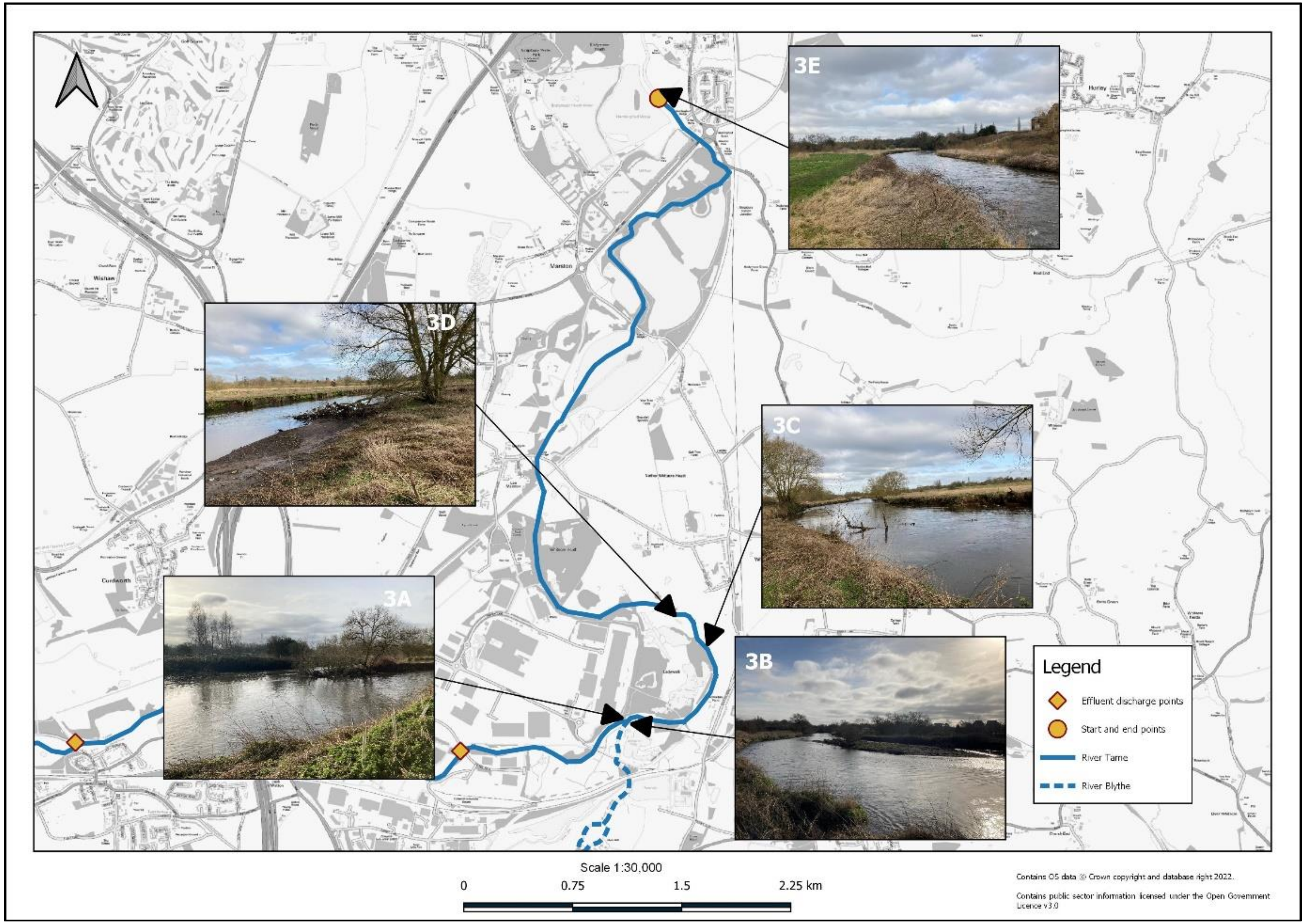

Plate 39: Locations photographed by AECOM during field reconnaissance surveys in 2022 as part of Gate 1 morphological modelling

2.6.2 Section 4 within Appendix E of the Environmental Assessment for the Trent SRO report (Ref. 17) identifies gravel bar formation at locations 3A and 3B where the River Blythe joins the River Tame. This is indicative of both watercourses depositing coarse sediment from upstream at this convergence point. No evidence of deposition was observed at location 3C, however the visit was conducted during relatively high flow conditions and it is possible that gravel features at the channel margins were submerged. Significant deposition was noted at location 3D with a fine sediment berm/bar present on the inside bend of the meander. It was suggested that gravel likely existed at this location but was covered by excess fine sediment. Given the close proximity of locations 3C and 3D, similar sediment conditions are expected at both sites.

2.6.3 Within section 3 of Appendix E of the Environmental Assessment for the Trent SRO report (Ref. 17), it is also highlighted that there is a large amount of excess fine sediment within the river system, much of which is contaminated. The unnaturally high quantities of fine sediment within the catchment are the result of catchment-scale modifications such as channel deepening and the construction of floodplain embankments which disconnect the mainstem channel from floodplain deposition zones, as well as activities such as scour protection, channel dredging, and channel realignment which deplete the system of coarse sediment.

Use in DO Modelling

2.6.4 The sediment information has two uses in the TUFLOW FV model, one in the benthic oxygen flux calculations and one to inform the Manning’s n roughness coefficients. The information collected at by AECOM in 2022 indicates that much of the Pilot Model Reach is likely to be covered by fine sediment. Therefore, the rate of benthic oxygen consumption and the Manning’s n roughness coefficient have not been varied for the channel bed within the model.

2.6.5 Benthic surveys and detailed sediment surveys have not been carried out to establish the actual oxygen demand of sediment within the Pilot Model Reach. The values used for the sediment parameters are based on high-level information (see **Table 6**) and sensitivity testing has been carried to understand the importance of the values used on the model results (see section 4).

3. Model Build

3.1 Software

3.1.1 TUFLOW FV is a flexible mesh hydrodynamic model that can be used to solve the 1D, 2D and 3D non-linear shallow water equations on both structured fixed resolution grids and unstructured grids comprised of triangular and/or quadrilateral elements. TUFLOW FV also includes a number of optional modules. The optional water quality module is treated as an external component with which TUFLOW FV interacts over the course of the simulation. Based on the commands provided by the user, TUFLOW requests the number of water quality constituents (for example DO) from the water quality files at initialisation and sets up the corresponding number of tracers (one each for computed variable) within the simulation. TUFLOW FV communicates with the water quality module at a user specified time step so that the module can perform non-conservative calculations on the tracers and then return revised concentrations of these to TUFLOW FV. Between these timesteps TUFLOW FV implements conservative advection and dispersion on these tracers based on initial and boundary conditions. TUFLOW FV also provides the options to switch on the modelling of salinity, temperature and heat fluxes, with or without density coupling enabled.

3.1.2 The TUFLOW FV Water Quality Module is arranged in a nested structure, with the individual parts being, in order, simulation classes, model classes, and constituent models. This investigation has used the Inorganics Simulation Class which consists of the model classes and constituent models shown in **Table 5**.

Table 5: List of model classes and constituent models in the Inorganics Simulation Class

Model Class	Constituent Model
Oxygen	O2
Silicate	Si
Inorganic Nitrogen	AmmoniumNitrate
Inorganic Phosphorus	FRPhs FRPhsads
Phytoplankton	Basic Advanced

3.2 Model Mesh

3.2.1 The 2024 bathymetric and topographic survey described in section 2 has been used to form the geometry of the model. A 2D flexible mesh has been generated in Aquaveo SMS 13.3, which is comprised of individual cells that are used to solve the non-linear shallow water equations at each timestep. A longitudinal spacing between rectangular cells has been specified, whilst the number of cross-channel segments has been specified as 7.

3.2.2 The use of a flexible mesh resolution allows a range of a spatial scales to be modelled without the need for nested elements and allows the mesh to neatly align around curves in the river channel. The vertices have been distributed evenly along the banks and river centreline to control the number of mesh cells. Rectangular or quadrilateral elements were deemed more suitable to represent the Pilot Model Reach than triangular elements as the geometry of the system is primarily comprised of linear and smoothly curving features. A rectangular mesh with a typical cell widths and lengths of 8 m has been constructed for the TUFLOW FV water quality model, an illustrative section of which is shown in **Plate 40**. As the channel width within the reach is generally 25-30 m, this has resulted in 3-4 cells across the width of the wet channel with additional cells within the floodplain.

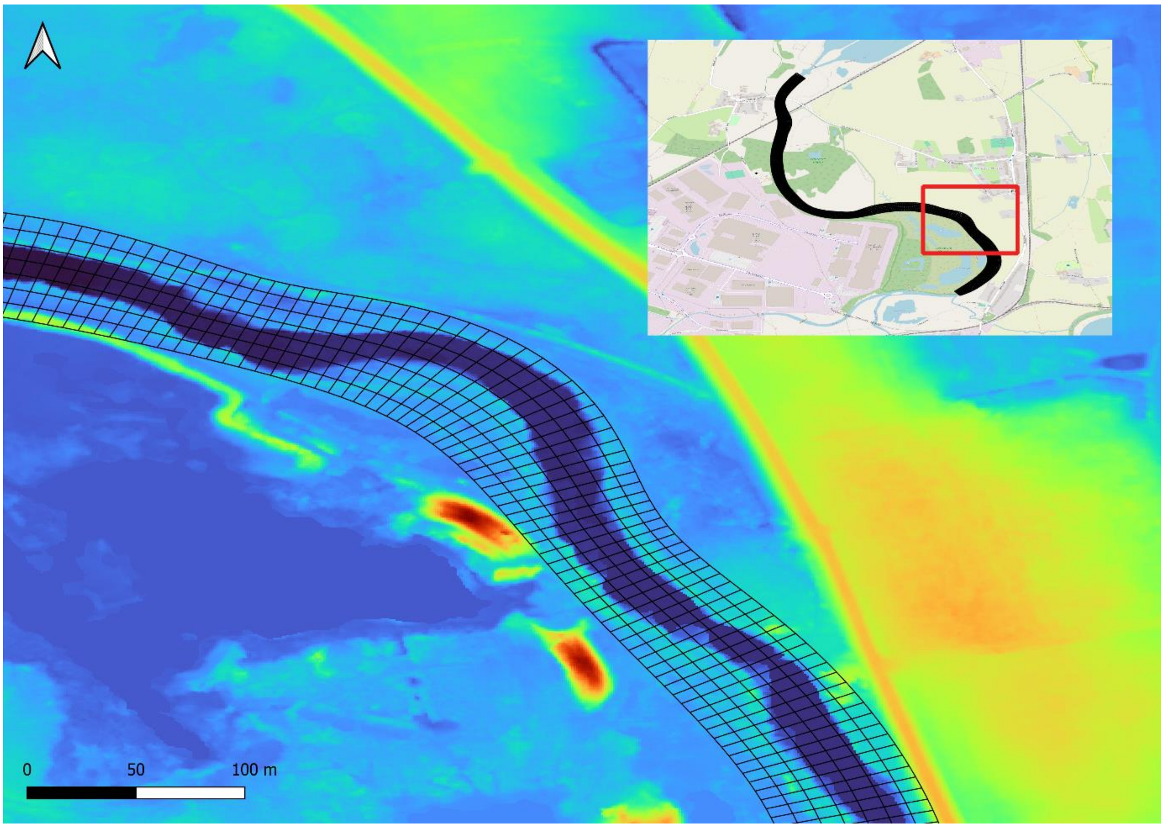

Plate 40 Illustrative section of 2 m TUFLOW FV mesh used in water quality model (Ref. 18)

Map data © OpenStreetMap contributors.

3.3 External Boundary Conditions

3.3.1 The available data discussed in section 2 have been used to determine the external boundary conditions applied to the TUFLOW FV model. No additional inflows have been applied to the model to represent the three minor tributaries, as it is assumed that during the summer these do not contribute significant flows to the River Tame. The river flow values specified were initially used in model sensitivity testing to understand the impacts of river flow variation on in-reach DO concentrations, as described in section 4.1. The river flows used in assessing the potential water quality impacts of the SRO (section 5.3) were limited to climate change scenarios based on the outcome of that analysis.

Table 6: External boundary conditions for DO modelling.

External Boundary Parameter	Description	Scenario	Input Value & *Source*
River Inflow	Constant inflow into the upstream boundary of a model using a QT boundary	Present Day Average Present Day Worst Case Drought Present Day Worst Case Drought (1 SRO) Present Day Worst Case Drought (2 SROs) Climate Change (2080s) Summer Climate Change (2080s) Summer (1 SRO) Climate Change (2080s) Summer (2 SROs) Climate Change (2080s) Synthetic Drought Climate Change (2080s) Synthetic Drought (1SRO) Climate Change (2080s) Synthetic Drought (2SROs)	14 m^3/s (*Mean flow at Lea Marston Lakes gauge)* 5.3 m^3/s *(ELF from Aquator modelling)*(Ref. 19) 3.97 m^3/s *(ELF from Aquator modelling, minus SRO at 115 Ml/d)* 2.64 m^3/s *(ELF from Aquator modelling, minus SRO at 230 Mld)* 6.70 m^3/s *(Q_{95} from Aquator modelling)* 5.38 m^3/s *(Q_{95} from Aquator modelling, minus SRO at 115 Ml/d)* 4.50 m^3/s *(Q_{95} from Aquator modelling, minus SRO at 230 Ml/d)* 5.30 m^3/s *(ELF from Aquator modelling)* 3.97 m^3/s *(ELF from Aquator modelling, minus SRO at 115 Ml/d)* 2.64 m^3/s *(ELF from Aquator modelling, minus SRO at 230 Ml/d)*
River Outflow	Downstream Flow Boundary	All	A QN normal flow condition with a slope of 0.0007 has been used to derive a downstream water level. *The slope value was approximated from the Survey Solutions (2024) bathymetry data.*
Manning's N roughness	Channel Roughness	All	Three roughness values have been used for all simulations: 0.1 (weedy reaches) 0.04 (clean, straight with stones and weeds) 0.03 (clean, winding, some pools and shoals) *Manning's n roughness values selected through reference to table of indicative Chow (1959) values provided on Oregon State University website.*
Nutrients (Nitrate, Ammonium & Filterable Reactive Phosphorus (FRP)		All	Summer mean nitrate = 11.61 mg/l Summer mean ammonium = 0.28 mg/l Summer mean FRP = 2.37 mg/ *EA Water Quality Archive data at Lea Marston, applied as time invariant inputs at the upstream boundary of the model*
Weather conditions	Mean sea level pressure Wind speed and direction Shortwave and longwave radiation Air temperature Relative humidity	Present Day Scenarios	ERA5 time-series data for the atmospheric variables, applied to the model in gridded NetCDF format for the duration of the simulation periods. Wind speed reduced by 50% to account for vegetation cover and river banks.
		Climate Change (2080s) Scenarios	ERA5 time-series data for the atmospheric variables, applied to the model in gridded NetCDF format for the duration of the simulation periods. Wind speed reduced by 50% to account for vegetation cover and river banks Air temperature increased by 5.95^0C *in line with the latest UK CP 18 projections for mean annual temperature and mean summer temperature in the emissions scenario RCP 8.5 90th percentile over the time horizon 2070-2089 for the West Midlands* (Ref. 20).

3.3.2 Water temperature and DO concentrations at the upstream end of the model reach were specified for the calibration periods based on the timeseries recorded at the Ladywalk Reserve sonde. For scenario testing, a single initial upstream water temperature value of 17.68°C has been specified (**Table 6**) which is a normal summer water temperature for the River Tame in this location, based Environment Agency data, and in the range of water temperature measurements in the sonde data during the calibration and validation periods (**Table 6**). The river water can then warm further through the reach in response to atmospheric heat exchange. Since a single air temperature adjustment factor is applied to simulate climate change effects, using a single initial water temperature though the scenario test allows for a clearer demonstration of the vulnerability of the Pilot Reach to water heating and DO loss under low to extreme low flow conditions.

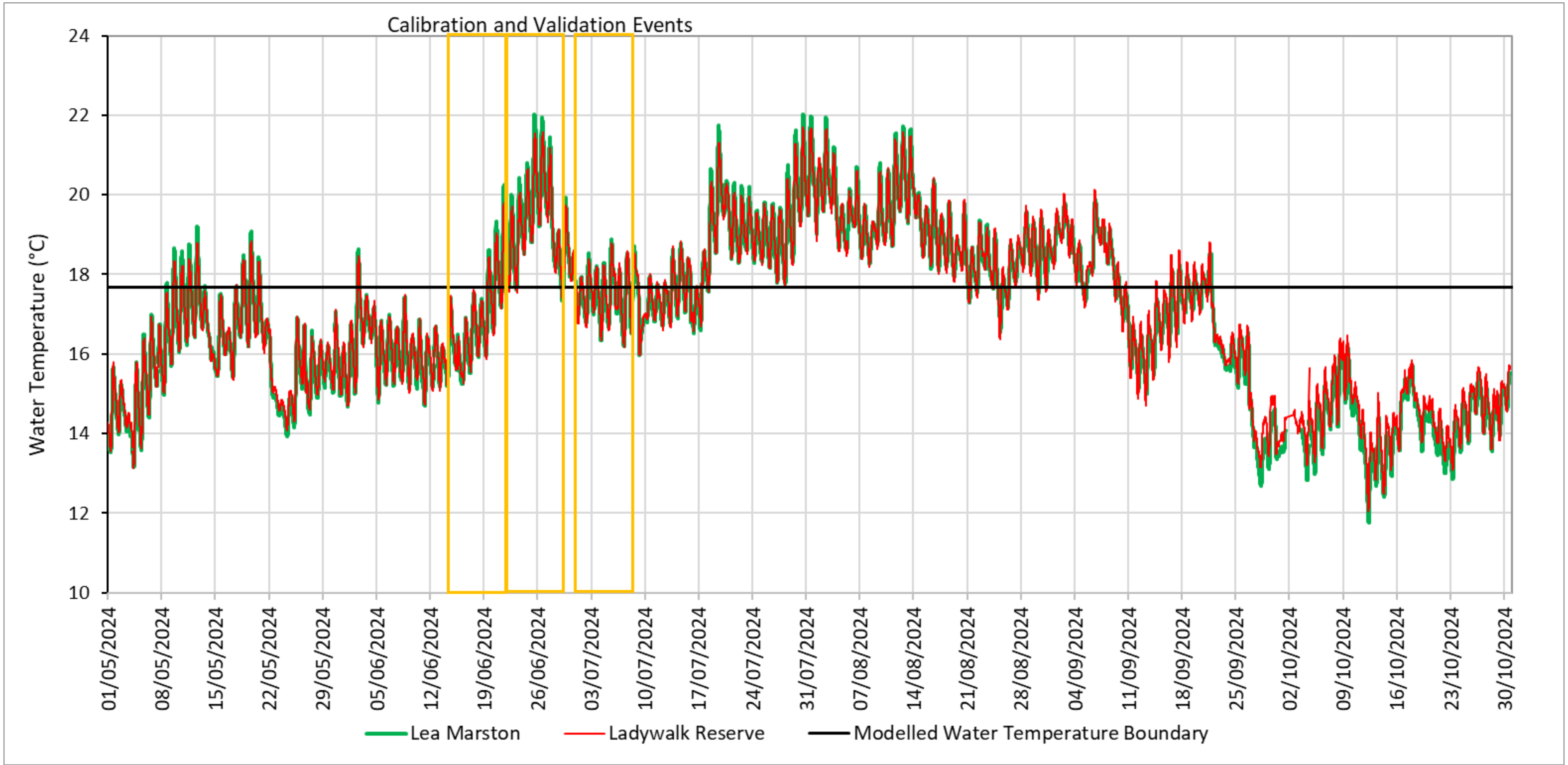

Plate 41: Water Temperature Data and Boundary Condition Value Used in Scenario Testing

3.3.3 Similarly, a single upstream DO concentration boundary condition has been specified in scenario testing of 8.37 mg/l. This is the mean summer value given by Environment Agency data recorded at Lea Marston and is consistent with values recorded in the sonde data (**Plate 42**). Using a single value allows for a clear illustration of the extent to which in-reach DO concentrations are reduced under each flow condition due to heating and in-reach processes. The model calibration results in section 4 show that the upstream boundary condition is the most important control on in-reach DO concentrations. In section 5, The level of reduction in DO through the Pilot Reach simulated for each flow condition has been subtracted from the observed range of upstream DO concentrations at Ladywalk Reserve to estimate the impacts of reduced river flow on DO fall probability, duration and extent. This makes maximum use of the observed upstream data, recognising the limitations on the reliable downstream sonde data.

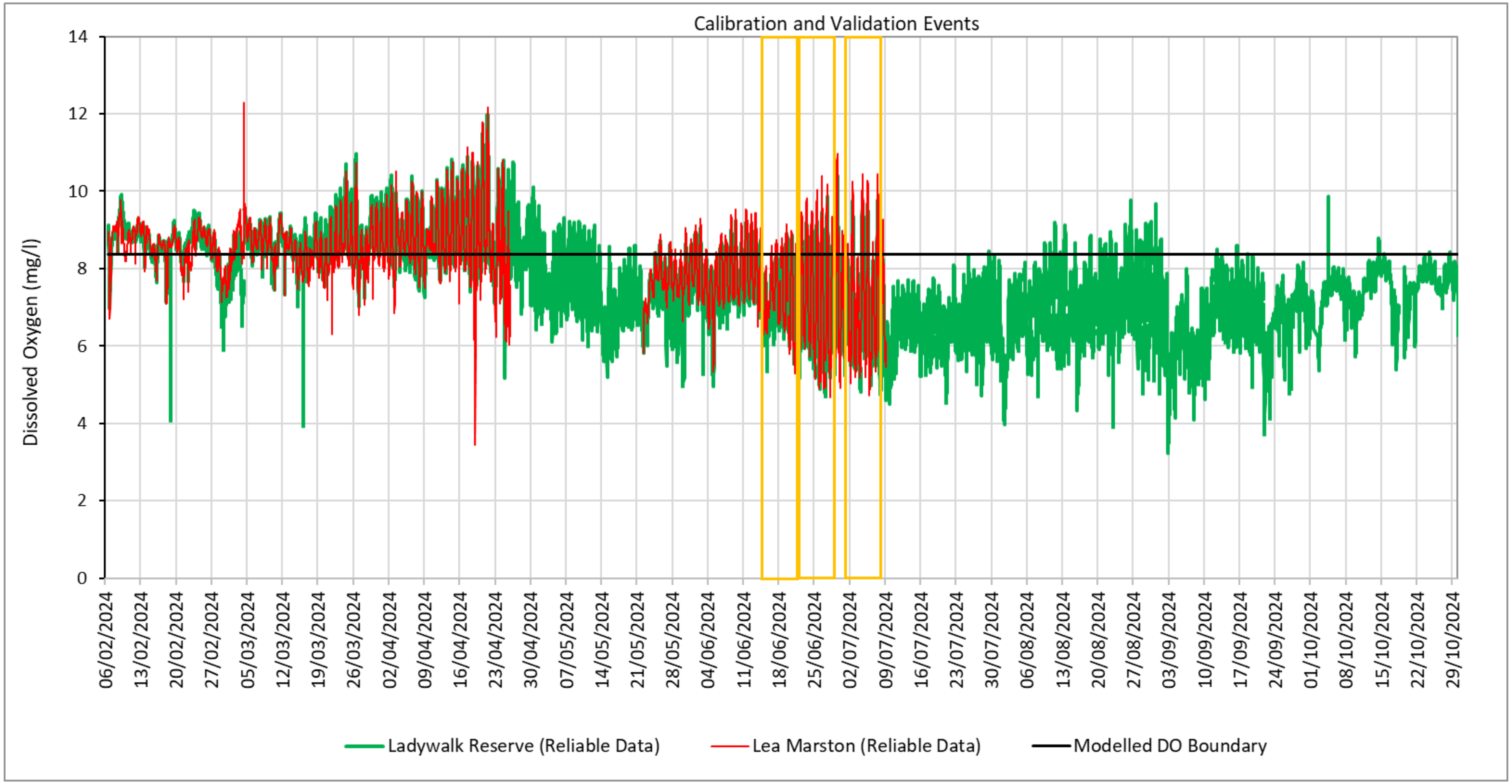

Plate 42: Dissolved Oxygen Data and Boundary Condition Value Used in Scenario Testing

3.4 Other Parametrisations

3.4.1 Other parameters that are specified in the TUFLOW FV control (.fvc) and water quality control (.fvwq) files are described in **Table 7** and **Table 8**. These are used in the calculation of the internal fluxes and some parameters were specified as other than default values following sensitivity analysis and model calibration (section 4). Edited values have been identified in the description where this applies.

Table 7: Values and descriptions of parameters specified in the TUFLOW FV control file

Parameter Name	Value	Description/Explanation
Start time and finish times (duration)	See description	Normal air temperature scenarios: 24/04/2023 10:00 - 26/04/2023 10:00 (48 hours) High air temperature scenarios: 08/09/2023 10:00 - 10/09/2023 10:00 (48 hours) Calibration 1: 15/06/2024 00:00 – 22/06/2024 21:00 (189 hours) Calibration 2: 23/06/2024 00:00 – 30/06/2024 21:00 (189 hours) Validation: 01/07/2024 00:00 – 08/07/2024 21:00 (189 hours)
CFL	0.8	Courant–Friedrichs–Lewy Number Stability Criterion.
Timestep Limits	0.1 (min), 1.0 (max)	Timestep limits in seconds
Momentum Mixing Model	Smagorinsky	Sub-grid scale eddy viscosity model
Global Horizontal Eddy Viscosity	0.2	Smagorinsky coefficient in m^2/s. Default value used.
Global Horizontal Eddy Viscosity Limits	0.05, 99999	
Include Salinity	1,0	Salinity turned on but density effects resulting from salinity ignored on the basis that the Pilot Model Reach consists of a freshwater fluvial environment exhibiting minimal stratification.
Include Temperature	1,0	Temperature turned on but density effects resulting from temperature ignored (for water density but not DO calculations) given that a comparatively shallow waterbody with minimal thermal stratification is being investigated.
Include Heat	1	Heat switched on to enable the full simulation of atmospheric heat exchange processes, which modify water temperature depending on the computed net heat flux. The net heat flux is the sum of the outgoing and incoming shortwave radiation heat, longwave radiation heat, latent heat, and sensible heat fluxes.
Cell Water Quality Depth	0.05	Minimum depth, in metres, at which water quality calculations will be undertaken.
Cell wet/dry depths	0.01, 0.02	Cell Wet/Dry Depths (in metres). Updated following a model review conducted by BMT (Ref. 21). Cell wet/dry depths were not set for the hydrodynamic calculations and therefore the defaults were being used, causing significant computational expense for little relative gain.

Table 8: Values and descriptions of parameters specified in the TUFLOW FV water quality control file.

Parameter Name	Value	Unit	Description/Explanation
Simulation class	inorganics		
wq units	mgl		Milligrams per litre
Wq dt	600		The timestep (seconds) at which the water quality module is called by the hydrodynamic model.
Oxygen Model			
Oxygen min max	min = 0 max = 16	mg/L O_2	Minimum and maximum dissolved oxygen concentration values in milligrams per litre selected through reference to grab sample data collected over the period 2000 to 2024 at Lea Marston. The minimum and maximum measured dissolved oxygen values at Lea Marston over this period were 5.3 mg/l and 14.8 mg/l.
Oxygen benthic	K^{O2}_{sed-O2} = 4.0 θ^{O2}_{sed} = 1.05	mg/L O_2 temp coefficient	K^{O2}_{sed-O2} is the dissolved oxygen concentration for which the computed sediment oxygen flux is half the user specified rate, at 20^0C. 4.0 (default) for all simulations. θ^{O2}_{sed} is the coefficient to account for temperature effects on oxygen sediment flux. A value of 1.0 will remove the effect of temperature. A value of 1.05 for K^{O2}_{sed-O2} has been selected through reference to Table 3-23 in the 1985 United States Environmental Protection Agency (US EPA) manual (Ref. 22) to rates and constants for surface water quality modelling.
Oxygen piston model	Wanninkhof92		This command instructs TUFLOW to use either the Wanninkhof (1992) model or the Ho et al. (2016) model to calculate the oxygen piston velocity (gas transfer velocity). The Wanninkhof (1992) model has been selected here as this excludes the thickness of the uppermost computational layer of water from the equation.
Silicate Model			
Silicate benthic	K^{Si}_{sed-O2} = 4.0 θ^{Si}_{sed} = 1.0	mg/L O_2 temp coefficient	K^{Si}_{sed-O2} is the dissolved oxygen concentration for which the computed sediment silicate flux is half the use specified rate, at 20^0C. 4.0 (default) for all simulations. θ^{Si}_{sed} is the coefficient to account for temperature effects on silicate sediment flux. A value of 1.0 will remove the effect of temperature. The default value of 1.0 has been selected.

Parameter Name	Value	Unit	Description/Explanation
Silicate min max	min = 0.0 max = 140.0	mg/L Si	The minimum and maximum allowable silicate concentration. Set at the minimum and maximum of the recommended range.
Oxygen	On		
Inorganic Nitrogen Model			
Ammonium benthic	K^{NH4}_{sed-O2} = 4.0 θ^{NH4}_{sed} = 1.0	mg/L O_2 temp coefficient	K^{NH4}_{sed-O2} is the dissolved oxygen concentration for which the computed sediment ammonium flux is half the use specified rate, at 20^0C. 4.0 (default) for all simulations. θ^{NH4}_{sed} is the coefficient to account for temperature effects on ammonium sediment flux. A value of 1.0 will remove the effect of temperature. The default value of 1.0 has been selected.
Nitrate benthic	K^{NO3}_{sed-O2} = 4.0 θ^{NO3}_{sed} = 1.0	mg/L O_2 temp coefficient	K^{NO3}_{sed-O2} is the dissolved oxygen concentration for which the computed sediment nitrate flux is half the use specified rate, at 20^0C. 4.0 (default) for all simulations. θ^{NO3}_{sed} is the coefficient to account for temperature effects on nitrate sediment flux. A value of 1.0 will remove the effect of temperature. The default value of 1.0 has been selected.
Ammonium min max	0.0, 98.0		The minimum and maximum allowable ammonium concentration. Set at the minimum and maximum of the recommended range.
Nitrate min max	min = 0.0 max = 98.0	mg/L NH_4-N	The minimum and maximum allowable nitrate concentration. Set at the minimum and maximum of the recommended range.
Nitrification	R^{NH4}_{nitrif} = 0.5 $K^{NH4}_{nitrif-O2}$ = 4.0 θ^{NH4}_{nitrif} = 1.1	/d mg/L O_2 temp coefficient	R^{NH4}_{nitrif} is the rate at which ammonium is nitrified to nitrate at 20^0C excluding the influence of ambient dissolved oxygen concentration. A value of 0.0 will switch off nitrification. A value of 0.5 has been selected to ensure nitrification is switched on. $K^{NH4}_{nitrif-O2}$ is the dissolved oxygen concentration for which the computed nitrification rate is half the user specified rate, at 20^0C. The default value of 4.0 has been selected. θ^{NH4}_{nitrif} is the coefficient to account for temperature effects on nitrification. A value of 1.0 will remove the effect of temperature. The value of 1.1 has been selected to ensure temperature has an effect on nitrification.
Denitrification	Michaelis Menten, R^{NO3}_{denit} = 0.2	/d mg/L O_2	Michaelis Menten R^{NO3}_{denit} is the rate at which nitrate is denitrified to nitrogen gas N_2 at 20^0C excluding the influence of ambient dissolved oxygen and nitrate concentrations. A value of 0.0 will

Parameter Name	Value	Unit	Description/Explanation
	$K^{NO3}_{denit\text{-}O2\text{-}MM}$ = 4.0 θ^{NO3}_{denit} = 1.0	temp coefficient	switch off denitrification. The value of 0.2 has been selected to ensure denitrification is switched on. $K^{NO3}_{denit\text{-}O2\text{-}MM}$ is the dissolved oxygen concentration for which the computed denitrification rate is half the use specified rate, at 20^{0}C and with no influence of ambient nitrate concentration. θ^{NO3}_{denit} is the coefficient to account for temperature effects on denitrification. A value of 1.0 will remove the effect of temperature. The default value of 1.0 has been selected.
Diss nitrate reduction to ammonium (DRNA)	R^{NO3}_{drna} = 0.01 $K^{NO3}_{drna\text{-}O2}$ = 4.0	/d mg/L O_2	R^{NO3}_{drna} is the rate at which nitrate is reduced to ammonium at 20^{0}C excluding the influence of ambient nitrate concentrations. A value of 0.0 will switch off DRNA. A value of 0.01 has been selected to ensure DRNA is switched on. $K^{NO3}_{drna\text{-}O2}$ is the oxygen concentration for which the computed reduction of nitrate to ammonium would be half the corresponding rate. The default value of 4.0 has been selected during model calibration.
Anaerobic oxidation of ammonium	k^{N2}_{anmx} = 0.1 $K^{N2}_{anmx\text{-}NH4}$ = 4.0 $K^{N2}_{anmx\text{-}NO2}$ = 1.0	mg N/L/d mg/L NH_4-N mg/L NO_2-N	k^{N2}_{anmx} is the rate at which ammonium is oxidised to nitrogen gas N_2 at 20^{0}C excluding the influence of ambient ammonium and nitrate concentrations. A value of 0.0 will switch off anammox. A value of 0.1 has been selected to ensure anammox is switched on. $K^{N2}_{anmx\text{-}NH4}$ is the ammonium concentration for which the computed consumption of ammonium due to anaerobic oxidation would be half the corresponding anaerobic oxidation rate, excluding the influence of nitrite. A value of 4.0 has been selected. $K^{N2}_{anmx\text{-}NO2}$ is the nitrite concentration for which the computed consumption of ammonium due to anaerobic oxidation would be half the corresponding anaerobic oxidation rate, excluding the influence of ammonium. A value of 1.0 has been selected during model calibration.
Atmospheric deposition	$[TN]_{rain}$ = 0.0 $R^{TN}_{atm\text{-}dry}$ = 0.04 f^{NO3}_{TN} = 1.0	mg/L N mg/m^2/d N fraction (see description)	$[TN]_{rain}$ is the concentration of total inorganic nitrogen in rainfall. As this model does not include rainfall, a value of 0.0 has been selected. $R^{TN}_{atm\text{-}dry}$ is the rate of atmospheric fallout of dry inorganic nitrogen. The UK's Source Apportionment from GIS (SAGIS) model (Ref. 23) calculates broad scale information on diffuse nutrient inputs to watercourse based on land use and other relevant geographic information. This source gives an average atmospheric deposition of nitrate

Parameter Name	Value	Unit	Description/Explanation
			of 2.5 mg/km^2. Given the catchment area to which this applies, the equivalent deposition rate is 0.04 mg/m^2. f^{NO3}_{TN} is the fraction of N that is nitrate in atmospheric deposition. A value of 1 (0) will set wet and dry deposition to be purely nitrate (ammonium). A value of 1 has been selected to set wet and dry deposition to be purely nitrate as the SAGIS model shows no significant atmospheric deposition of ammonia.
Oxygen	On		
Inorganic Phosphorus Model			
Frp benthic	K^{FRP}_{sed-O2} = 4.0 θ^{FRP}_{sed} = 1.0	mg/L O_2 temp coefficient	K^{FRP}_{sed-O2} is the dissolved oxygen concentration for which the computed sediment FRP flux is half the use specified rate, at 20^{0}C. 4.0 (default) for all simulations. θ^{FRP}_{sed} is the coefficient to account for temperature effects on FRP sediment flux. A value of 1.0 will remove the effect of temperature. The default value of 1.0 has been selected.
Frp min max	min = 0.0 max = 50.0	mg/L PO_4-P	The minimum and maximum allowable silicate concentration.
Atmospheric deposition	$[FRP]_{rain}$ = 0.0 $R^{FRPads}_{atm-dry}$ = 0.0	mg/L P mg/m^2/d P	$[FRP]_{rain}$ is the concentration of FRP in rainfall. As this model does not include rainfall, a value of 0.0 has been selected. $R^{FRPads}_{atm-dry}$ is the rate of atmospheric fallout of adsorbed FRP. A value of 0.0 has been selected as the SAGIS model (Ref. 23) shows no significant atmospheric deposition of phosphorus.
Oxygen	On		
Phyto Model			
Min max	min = 0.01 max = 40.0	µg/L Chl *a*	The minimum and maximum allowable group phytoplankton concentration. The minimum has been set at the minimum of the recommended range and the maximum has been set at twice the phyto concentration specified throughout the calibration model runs.
Temperature limitation	Standard T^{phy}_{std} = 22.0 T^{phy}_{opt} =25.0 T^{phy}_{max} = 35.0	°c	Standard is a generic but customisable temperature limitation function. T^{phy}_{std}, T^{phy}_{opt}, T^{phy}_{max} are used to compute shape of temperature limitation function. Values have been selected during model calibration to ensure temperature is not a limiting factor for the entirety of the model run.

Parameter Name	Value	Unit	Description/Explanation
Salinity limitation	None		The model includes no salinity limitation to either of the computed primary productivity or respiration rates.
Light limitation	Chalker $Ke^{phy} = 0.0$ $I_{K\text{-}cha} = 350.0$	 /(µg Chl *a*/L)/m W/m^2	The Chalker light limitation model has been selected as it includes phytoplankton light limitation with no photoinhibition, as per Chalker (1980). Ke^{phy} is the rate at which light is attenuated by phytoplankton. A default value of 0.0 has been selected. $I_{K\text{-}cha}$ is used to compute the Chalker light limitation function. A value of 350 has been selected following sensitivity testing conducted as part of calibration.
Settling	Constant $V^{phy}_{settle} = -1$	 m/d	Phytoplankton settling is set to a constant value. V^{phy}_{settle} is the constant settling velocity applied to phytoplankton. A value of -1 has been selected following the BMT Model Review (Appendix A) to represent settling within the model.
Nitrogen limitation	$[N]^{phy}_{min} = 0.01$ $K^{phy}_{lim\text{-}N} = 1.0$	mg/L N mg/L N	$[N]^{phy}_{min}$ is the minimum N concentration at which uptake of nitrogen by phytoplankton can occur. A default value of 0.01 has been selected. $K^{phy}_{lim\text{-}N}$ is the concentration of N that, when added to the specified minimum, sets the nitrogen limitation function to a value of 0.5. A default value of 1.0 has been selected.
Phosphorus limitation	$[P]^{phy}_{min} = 0.001$ $K^{phy}_{lim\text{-}P} = 0.1$	mg/L P mg/L P	$[P]^{phy}_{min}$ is the minimum P concentration at which uptake oh phosphorus by phytoplankton can occur. A default value of 0.001 has been selected. $K^{phy}_{lim\text{-}P}$ is the concentration of P that, when added to the specified minimum, sets the phosphorus limitation function to a value of 0.5. A default value of 0.1 has been selected.
Uptake	$x^{phy}_{N\text{-}C\text{-}con} = 4.75$ $x^{phy}_{P\text{-}C\text{-}con} = 0.66$	mg N/mg Chl *a* mg P/mg Chl *a*	$x^{phy}_{N\text{-}C\text{-}con}$ is used to compute the uptake of nitrogen during growth in the model. A default value of 4.75 has been selected. $x^{phy}_{P\text{-}C\text{-}con}$ is used to compute the uptake of phosphorus during growth in the model. A default value of 0.66 has been selected.
Carbon chla ratio	$x^{phy}_{cc} = 27$	mg carbon	x^{phy}_{cc} is the ratio of carbon to chlorophyll *a* in the cellular biomass of a phytoplankton group. A default value of 27 has been selected.

Parameter Name	Value	Unit	Description/Explanation
Primary productivity	R^{phy}_{prod} = 2.0 θ^{phy}_{prod} = 1.1	/d factor (see description)	R^{phy}_{prod} is the phytoplankton primary productivity (growth) rate at 20^{0}C with no light, temperature, salinity, silicate or nutrient limitation. A value of 2.0 was selected during the model calibration. θ^{phy}_{prod} is the factor to which (***T***-20) is raised to account for temperature effect on phytoplankton growth in the standard temperature limitation function. A value of 1.0 will remove the effect of temperature. A value of 1.1 has been selected during the model calibration to ensure the model considers the effect of temperature.
Respiration	R^{phy}_{resp} = 0.1 θ^{phy}_{resp} = 1.1 $f^{phy}_{true\text{-}resp}$ = 1 $f^{phy}_{excr\text{-}loss}$ = 0.1 f^{phy}_{exud} = 0.1	/d temp coefficient fraction fraction fraction	R^{phy}_{resp} is the phytoplankton respiration rate at 20°C with no temperature or salinity limitation. A value of 0.1 has been selected during the model calibration. θ^{phy}_{resp} is the factor to which (***T***-20) is raised to account for temperature effect on phytoplankton respiration. A value of 1.1 has been selected during the model calibration. $f^{phy}_{true\text{-}resp}$ is the proportion of consumed carbohydrates that are converted to energy, as opposed to waste matter. A value of 1 has been selected during the model calibration. $f^{phy}_{excr\text{-}loss}$ is the proportion of combined excretive and mortality losses that are excretive. If set to 1 then this parameter has no effect. A value of 0.1 has been selected during the model calibration. f^{phy}_{exud} is the proportion of primary productivity that does not generate retained cellular carbon biomass, but it lost through exudation. A value of 0.1 has been selected during the model calibration.
Fluxes			
Oxygen flux	F^{O2}_{sed} = -3000	mg/m2/d	F^{O2}_{sed} is the rate at which dissolved oxygen is exchanged between the sediments and overlying water column at 20^{0}C excluding the influence of overlying dissolved oxygen concentration. A negative value represents consumption of oxygen by sediments. A value of -1500 mg O_2/m^2/d is the average value from sampling in 21 English Rivers specified in Table 3-25 of the 1985 US EPA water quality modelling manual for all Gate 3 simulations. A value of -3000 mg O_2/m^2/d has been selected during the model calibration.

Parameter Name	Value	Unit	Description/Explanation
Silicate flux	F^{Si}_{sed} = 35	mg/m^2/d	F^{Si}_{sed} is the rate at which silicate is exchanged between the sediments and the overlying water column. A value of 35 has been selected during the model calibration, which is approximately 25% of the typical range.
Ammonium flux	F^{NH4}_{sed} = 35	mg/m^2/d	F^{NH4}_{sed} is the rate at which ammonium is exchanged between the sediments and the overlying water column. A value of 35 has been selected during the model calibration, which is approximately 25% of the typical range.
Nitrate flux	F^{NO3}_{sed} = 35	mg/m^2/d	F^{NO3}_{sed} is the rate at which nitrate is exchanged between the sediments and the overlying water column. A value of 35 has been selected during the model calibration, which is approximately 25% of the typical range.
FRP flux	F^{FRP}_{sed} = 39	mg/m^2/d	F^{FRP}_{sed} is the rate at which FRP is exchanged between the sediments and the overlying water column. A value of 39 has been selected during the model calibration, which is approximately 25% of the typical range.

4. Model Calibration and Validation

4.1 Pre-Calibration Model Checks

4.1.1 Prior to model calibration, the following tests and checks were made to ensure that the model set-up and selection was appropriate to the setting, and to inform model calibration:

a. A Tracer Test was used to determine how long water remains within the model domain, since this will determine the relative importance of boundary conditions compared to in-model processes (section 4.2);

b. Sensitivity testing was carried out to modelled river flow, to establish whether the observed sub-daily variations river flow would have implications for the use of time-invariant inflow boundaries (section 4.1). These checks also informed selection of scenarios tested using the calibrated model (section 5);

c. Sensitivity testing was carried out for model parameters which are difficult to quantify with certainty (wind speed and sediment oxygen exchange, section 4.1). These tests acted as a guide to model calibration and also showed whether gaps in the available data would reduce confidence in model results; and

d. A mass balance analysis was carried out following the model calibration, which focused exclusively on quantifying the cumulative fluxes of DO within the Pilot Model Reach (section 4.3).

4.1.2 The outcomes of these tests are set out below.

4.2 Tracer Test

4.2.1 In order to understand the residence time of water within the Pilot Model Reach and establish how long water with low DO concentrations would remain within the model domain, a ‘tracer’ test was carried out prior to model calibration. The present day Q_{95} flow was applied as a constant inflow at the upstream boundary and the model was allowed to run for an 11-hour period from a starting time of 10:00 hours. The upstream input of DO was maintained at 0 throughout the simulation, with the exception of a single ‘pulse’ of 15 mg/l at 13:00 hours which would act as the ‘tracer’. The time taken for this ‘pulse’ of DO to reach the downstream boundary was approximately 2-3 hours (**Plate 43**).

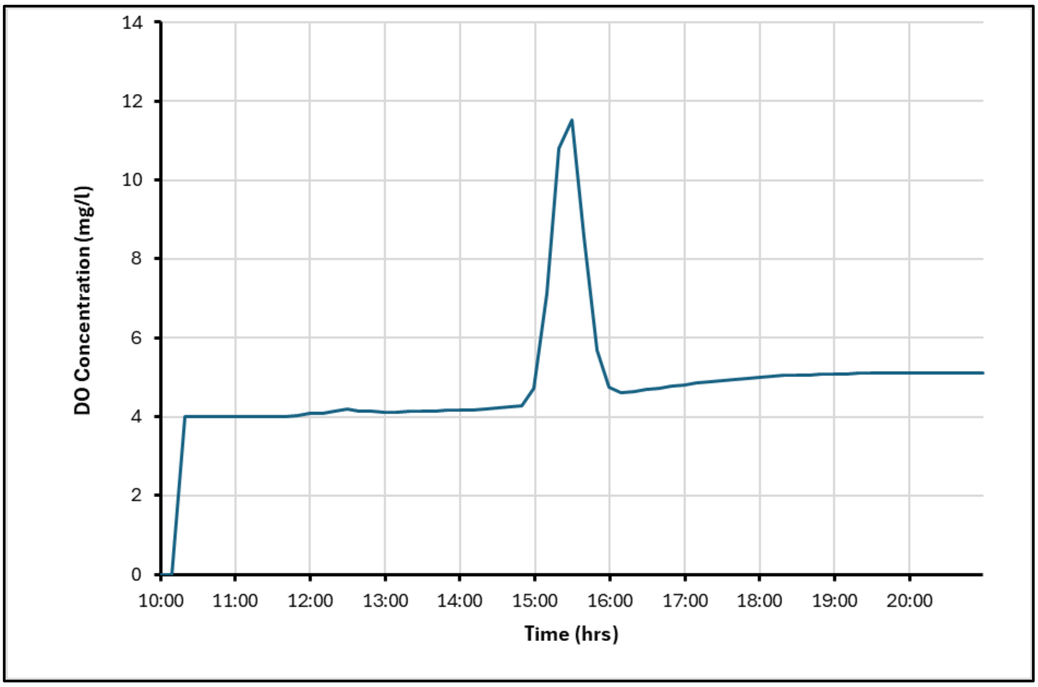

Plate 43: Time series of DO concentrations (mg/) at downstream boundary in Q_{95} Tracer Analysis Test

4.2.2 The short residence time of the water in the Pilot Model Reach would be insufficient to permit the development of thermally stratified layers, and would intensify mixing, which would serve to hinder the formation of chemical and thermal gradients within the water column. Selection of the 2D modelling approach is justified in this context.

4.2.3 Additionally, the residence time of 2-3 hours indicates that biochemical processes which operate over timescales of days rather than hours are unlikely to play a significant role in the consumption and production of DO within the Pilot Model Reach. Boundary conditions will dominate in-reach DO concentrations, and this is confirmed by the sonde data in section 2.4 which shows that concentrations of DO at Ladywalk Reserve and Lea Marston are generally very similar.

Model Sensitivity to River Flow

4.2.4 In order to test the importance of assumed river inflow values, the uncalibrated model was run for various combinations of present day and climate change adjusted scenarios using various steady-state inflow conditions based on gauged flows at Lea Marston. These tests show whether using a single constant river flow gives rise to a potential risk of averaging out the extreme flow minima and maxima in river flow that vary at sub-daily timescales from the gauged flow data (**Plate 37**) with resulting implications on modelled DO. As this is particularly pertinent to this study given its focus on low flow conditions during the summer months and the impact of releases from Minworth WwRC, Q_{99} flow estimates were derived for both the daily averaged gauged flows at Lea Marston and the preprocessed 15-minute time series of gauged flows at Lea Marston. These Q_{99} flow estimates were then reduced by 20% compute the respective ELF flow estimates. The calculated flow values were as follows:

a. Q_{99} (Daily averaged) = 6.78 m^3s;
b. Q_{99} (15-minute time series) = 5.40 m^3/s;
c. ELF (Daily averaged) = 5.30 m^3/s; and
d. ELF (15-minute time series) = 4.20 m^3/s.

4.2.5 The 15-minute flow data give Q_{99} and ELF values which are 1.38 and 1.10 m^3/s lower than the flows given using the daily mean flow data. **Table 9** lists the river flow conditions used in initial model tests to determine whether the DO model results were sensitive to changes in flow of this scale. The flow conditions were selected based on current gauge data and assumptions on SRO operation, and the flows were tested with current average and current summer air temperatures, as well as summer air temperatures increased by 2°C to account for the impacts of climate change (in line with UKCP18 projections for mean annual temperature and mean summer temperature in the emissions scenario RCP 6.0 over the time horizon 2030-2049 for the West Midlands (Ref. 24)).

Table 9: River Flow and Atmospheric Conditions Used in Initial Model Test Runs

SRO Representation	River Scenario	River Flow (m^3/s)	Atmospheric Condition
None	Present Mean	14.0	Current Average
None	Present ELF	5.4	Current Summer
None	Climate Change Mean	13.3	Increased Summer
115 Ml/d	Climate Change Mean	12.0	Increased Summer
230 Ml/d	Climate Change Mean	10.6	Increased Summer
None	Climate Change ELF	5.3	Increased Summer
115 Ml/d	Climate Change ELF	4.0	Increased Summer
230 Ml/d	Climate Change ELF	2.6	Increased Summer

4.2.6 The initial model test runs showed that the simulated DO concentrations in the Pilot Model Reach were not sensitive to changes in river flow at the tested scale. In the most extreme tested scenario, in which both SROs were represented as being in operation, the ELF river flows were used and summer air temperatures were specified and increased to simulate the impacts of climate change, the minimum DO concentrations fell from 8.40 mg/l at the upstream end of the Pilot Model Reach to 8.10-8.20 mg/l at the downstream boundary. For all tested SRO scenarios, the minimum DO percent saturation across the Pilot Model Reach varied between 88% and

92%. Given the very small variations in DO seen in the initial model tests, using a single river flow condition throughout the model run period was considered to be an acceptable approach. The river flow estimates derived from the daily averaged gauged flows are also considered suitable for use in the present-day scenarios because the use of daily mean flow is more common in water quality impact simulation and ecosystems, including fish populations, will be far more impacted by DO reductions lasting an entire day compared with impacts lasting less than one hour.

4.2.7 The initial model runs also show that DO concentrations are unlikely to fall significantly within the model reach unless river flows are very low and air temperatures are very high. None of the testing showed significant reduction in DO through the Pilot Model Reach for the present day mean flow or ELF scenarios. Scenario testing in section 5 have therefore focus on the modelling of SRO impacts which account for the combined impacts with climate change.

Model Sensitivity to Internal Parameters

4.2.8 Sensitivity testing was undertaken to assess the impact of three variables, wind speed, K^{O2}_{sed-O2} , and F^{O2}_{sed}, on modelled minimum DO concentrations and DO saturation values. These variables were selected as there is most uncertainty in their values. The sensitivity testing showed that the results were not sensitive to changes in wind speed and $K^{O2}_{sed-O2m}$, but had some sensitivity to changes in F^{O2}_{sed}. Increasing the value of F^{O2}_{sed} from 1500 mg/m^2/d to 10,000 mg/m^2/d reduced minimum DO concentrations at the downstream boundary of the Pilot Model Reach from 8.10 mg/l to 6.50-7.10 mg/l for the lowest river flow condition in **Table 9**. This variable, together with assumptions on primary productivity, was a focus when calibrating the model.

4.3 Model Calibration

Input Data

4.3.1 The model was run with observed river flow data and upstream DO concentrations for the two calibration events and one validation event shown in section 2.4. The model also uses average concentrations of nutrients based on the Environment Agency data in section 2.4.

4.3.2 Atmospheric data from the ERA5 model could not be obtained for the observed data periods and therefore the TUFLOW GetAtmos tool has been used to download hourly gridded atmospheric data generated by the National Centres for Environmental Prediction (NCEP) Climate Forecast System Version 2 (CFSv2) model (Ref. 25). The CFSv2 is an operational forecast model with a horizontal resolution of approximately 100 km. Atmospheric data has been downloaded from the CFSv2 model for the period June to July 2024 using a bounding box with coordinates ranging from 0 degrees longitude to -2 degrees longitude, and from 52 degrees latitude to 54 degrees latitude.

4.3.3 The CFSv2 data for air temperature and wind speed are compared with observed data from the Coleshill Weather Station in **Plate 46**, **Plate 47** and **Plate 48**. The CFSv2 data do capture the variation and daily fluctuation in air temperature but have a tendency to underestimate the absolute air temperature value. The CFSv2 data also underestimates wind speed, although the underestimate of wind speed is unlikely to be important as the model is less sensitive to this boundary forcing. Direct comparisons between observed shortwave radiation and CFSv2 shortwave radiation is not possible because the Coleshill weather station provides observations of total radiation only. Overall, the CFSv2 data are considered to provide an acceptable approximation for important atmospheric variables during the calibration and validation events, although underestimates of air temperature and any underestimate of shortwave radiation may result in an underestimate of DO generation by photosynthesis.

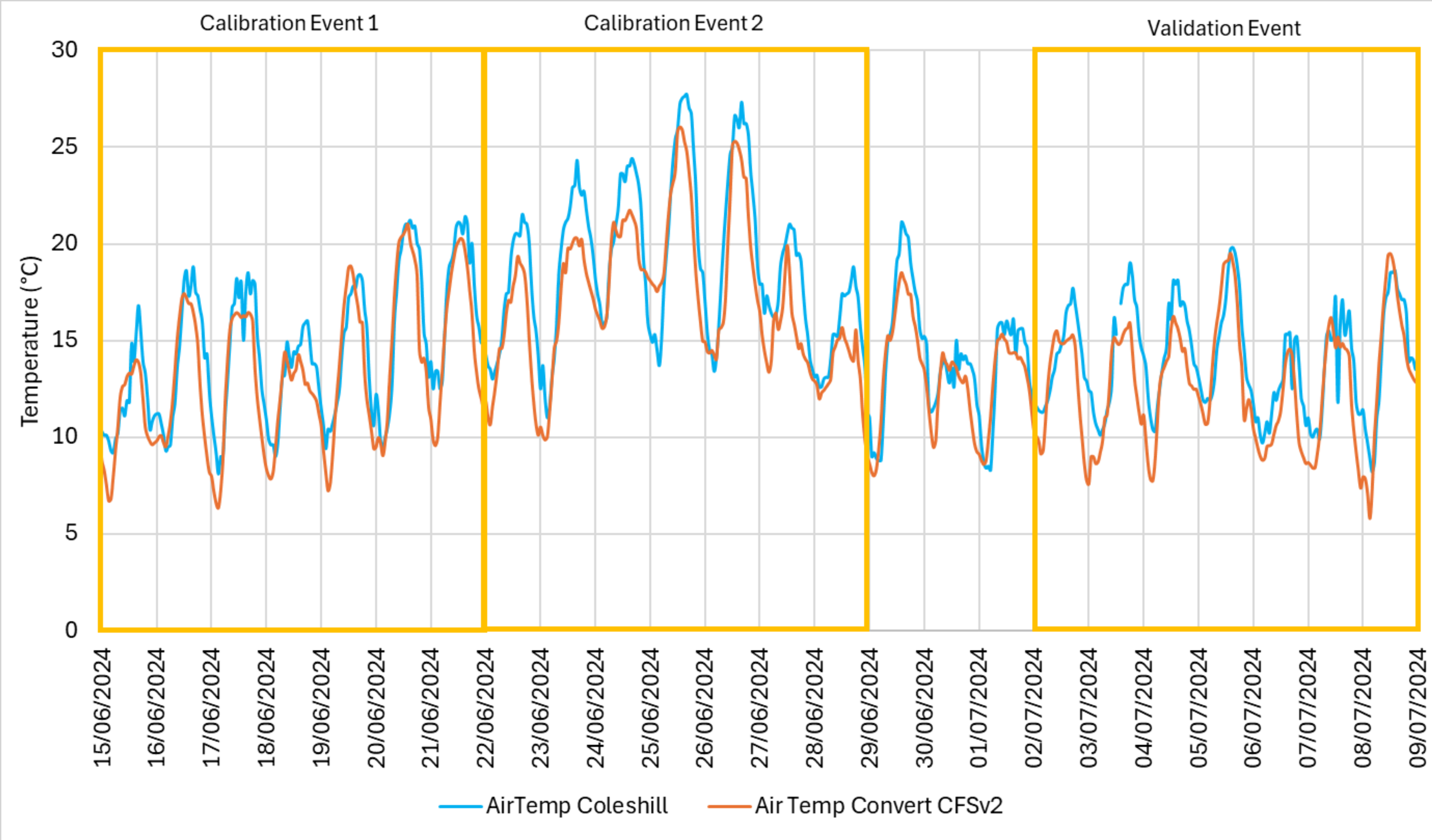

Plate 44: Comparison Between CFSv2 and Observed Air Temperature for Model Calibration and Validation Events

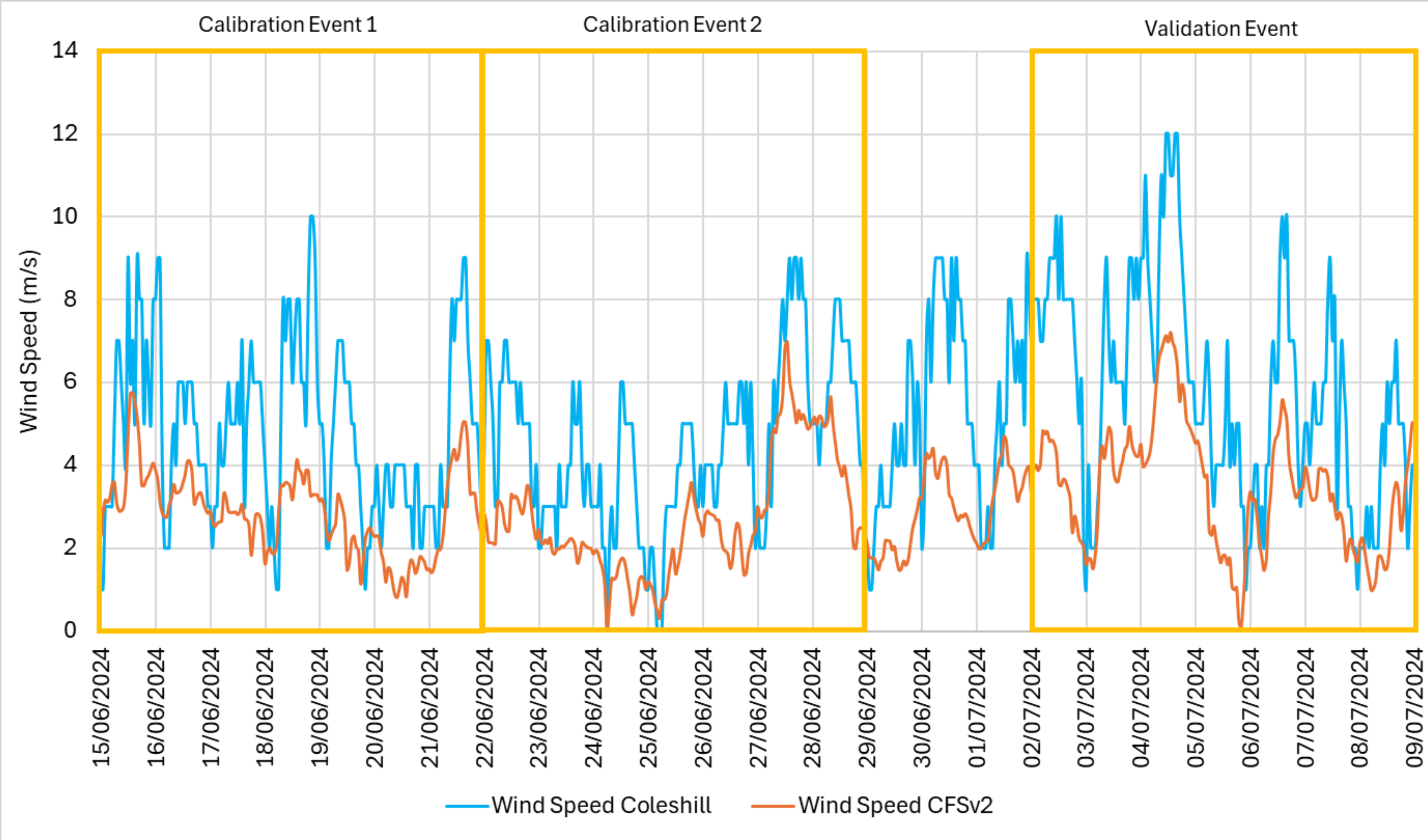

Plate 45: Comparison Between CFSv2 and Observed Wind Speed for Model Calibration and Validation Events

Changes to Model Parameters

4.3.4 Initial model runs showed that the model was able to closely reproduce the concentrations of DO measured by the Lea Marston sonde during most conditions but was not able to reproduce the increase in peak daytime DO seen at this sonde in comparison to the record at Ladywalk Reserve and also overestimated minimum concentrations. Checks of the model parameters showed that the phytoplankton primary productivity rate within the reach was being limited by temperature. The temperature limitation parameters were subsequently updated within the model to rectify this and allow respiration to occur at higher temperatures. In addition, following consultation with BMT (see section 0), the parameters outlined in **Table 10** were updated.

Table 10: Model parameters updated in Model Calibration

Parameter Name	Description/Explanation
Silicate, ammonium, nitrate and FRP sediment flux	Previously all values of 0, updated to 25% of their typical range (see **Table 8**).
Diss nitrate reduction to ammonium (DRNA)	Updates to inorganic nitrogen model, see **Table 8** for more detail.
Anaerobic oxidation of ammonium	
Atmospheric deposition	
Settling	Updates to phyto model, see **Table 8** for more detail.
Primary productivity rate	
Light limitation	
Respiration rate	

4.3.5 Following the updates outlined in **Table 10**, and review of the mass balance analysis in section 4.4, the parameters outlined in **Table 11** were checked and revised where required.

Table 11: Model parameters tested following a mass balance analysis

Parameter Name	Description/Explanation
Oxygen benthic	K^{O2}_{sed-O2} is the dissolved oxygen concentration for which the computed sediment oxygen flux is half the user specified rate, at $20^{0}C$. This value was updated to 6.0 following the mass balance analysis, however this change had little impact on the model results and therefore was reverted back to 4.0. θ^{O2}_{sed} is the coefficient to account for temperature effects on oxygen sediment flux. A value of 1.0 will remove the effect of temperature. This value was updated to 1.15 following the mass balance analysis, however this change had little impact on the model results and was revised back down to 1.05.
Oxygen sediment flux	This value was updated from -1500 to -3000 and a downward shift in dissolved oxygen was observed which allowed for better representation of minimum DO concentrations at Lea Marston.

Parameter Name	Description/Explanation
Nitrification	R^{NH4}_{nitrif} is the rate at which ammonium is nitrified to nitrate at 20°C, excluding the influence of ambient dissolved oxygen concentration. This value was updated to 1.5 following the mass balance analysis, however this change had little impact on the mode results and therefore was reverted back to 0.5.
Light limitation	The Chalker light limitation was updated to 0, 350. A drop in minimum DO was observed throughout the reach while maintaining the peaks.

4.3.6 All parameters utilised within the final model calibration runs are outlined in **Table 7** and **Table 8**.

Calibration Model Outputs

4.3.7 A time series of DO has been extracted from the downstream end of the calibrated model and has been compared to observed DO data from the Ladywalk Reserve and Lea Marston sondes. Results from Calibration Event 1 are presented in **Plate 46**, Calibration Event 2 are presented in **Plate 47** and the Validation Event are presented in **Plate 48**. All three periods indicate daily variation in DO, with levels rising with increased light in the morning and falling overnight. The model generally reproduces the minimum DO concentrations overnight, although it somewhat underestimates the peaks in daytime DO. This may be due to underestimates of the daytime maximum air temperature or shortwave radiation value which drives primary productivity, or it may be due to underestimates of phytoplankton concentration in summer. Prediction of maximum DO concentrations is not as important as prediction of minimum concentrations for this project, and therefore it is considered that an adequate calibration has been achieved for the purposes of the project.

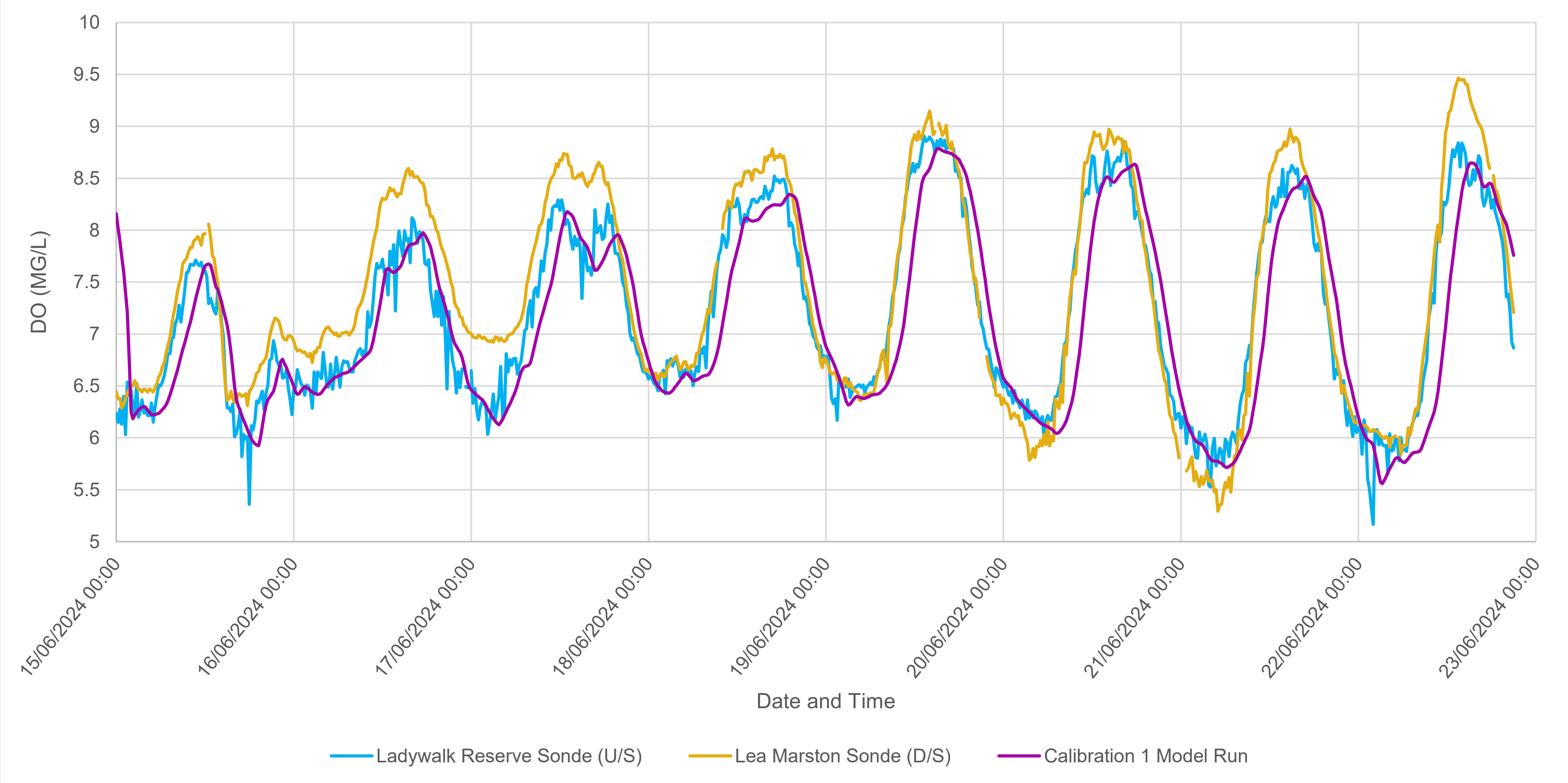

Plate 46: A comparison of recorded DO (mg/l) concentrations from Ladywalk Reserve (upstream sonde) and Lea Marston (downstream sonde) against modelled DO (mg/l) concentration extracted from the downstream of the reach for Calibration Period 1

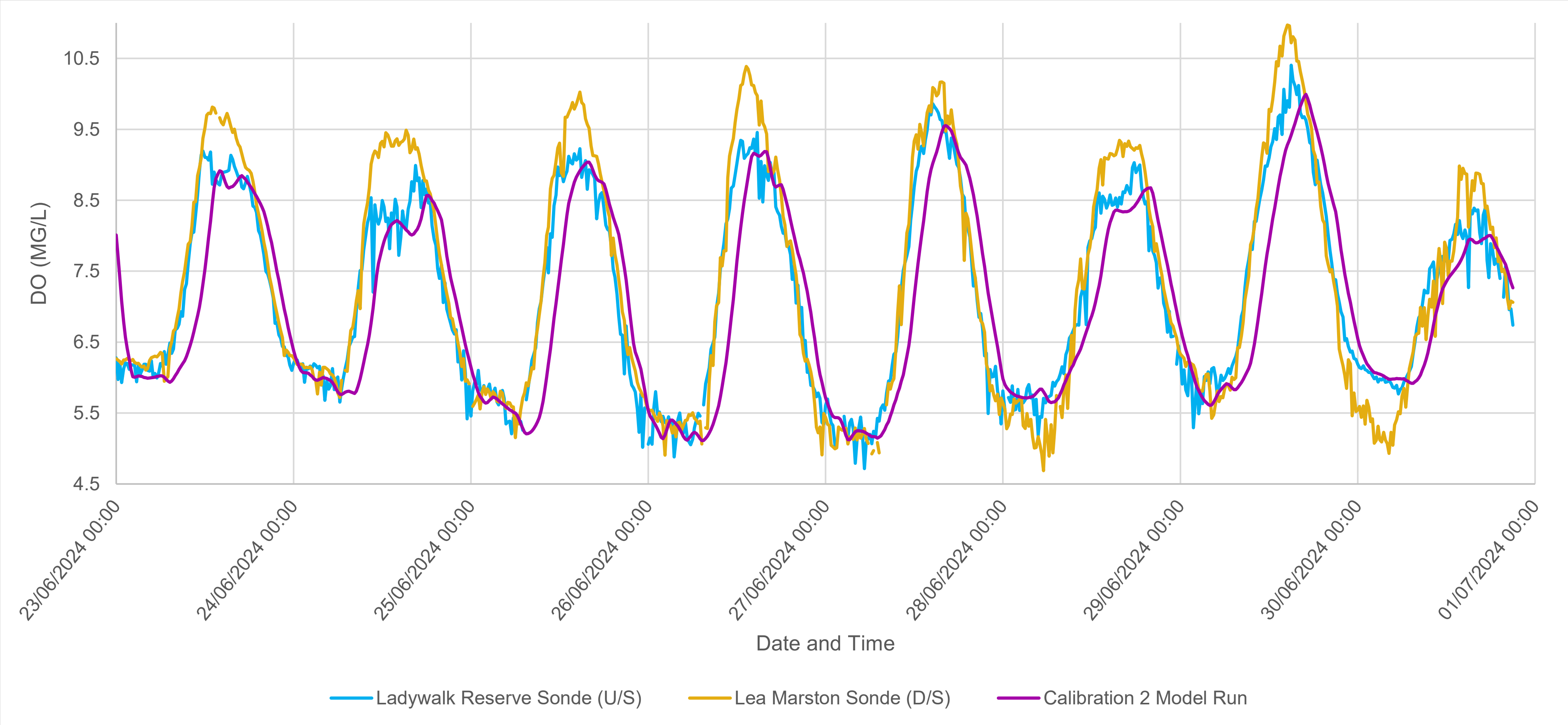

Plate 47: A comparison of recorded DO (mg/l) concentrations from Ladywalk Reserve (upstream sonde) and Lea Marston (downstream sonde) against modelled DO (mg/l) concentration extracted from the downstream of the reach for Calibration Period 2

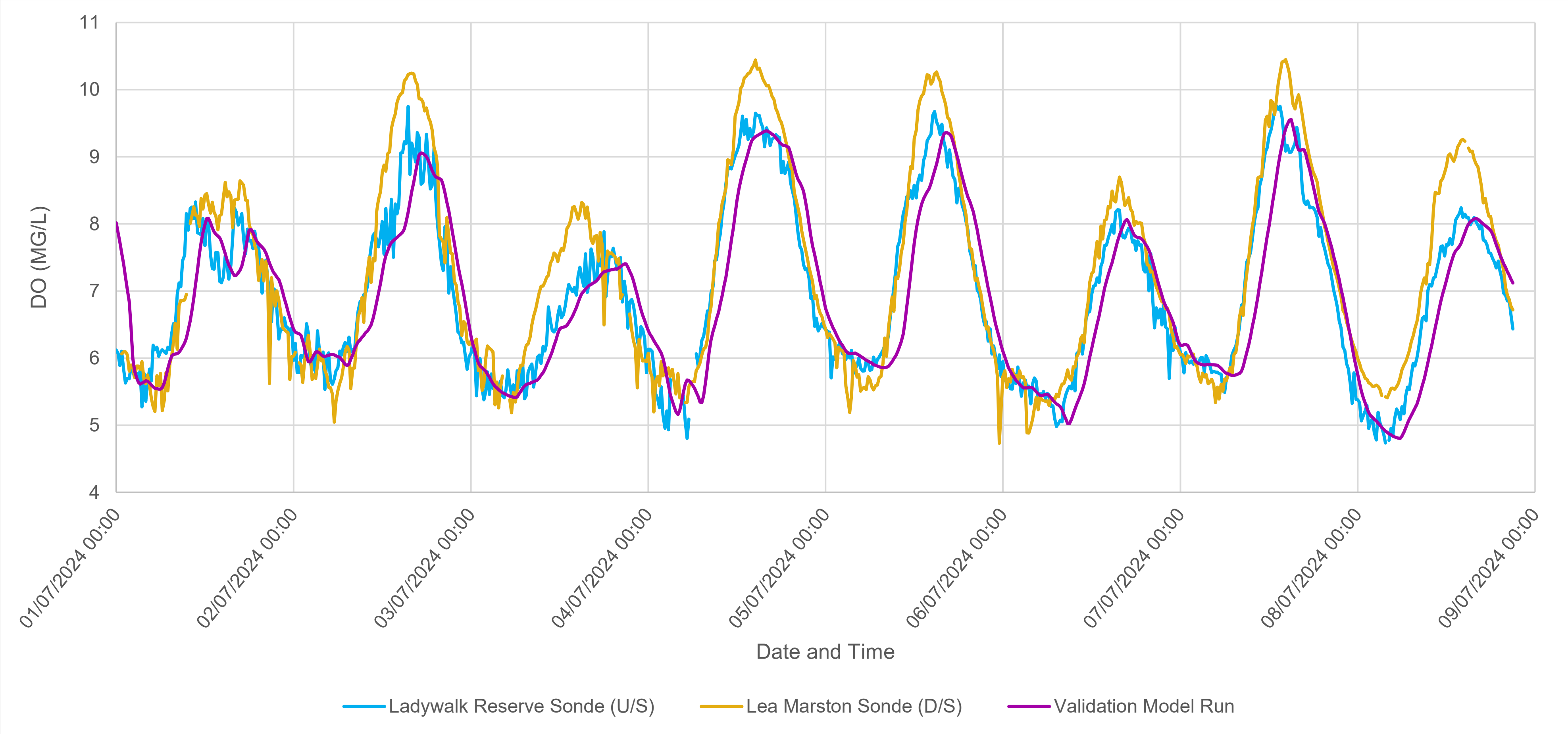

Plate 48 A comparison of recorded DO (mg/l) concentrations from Ladywalk Reserve (upstream sonde) and Lea Marston (downstream sonde) against modelled DO (mg/l) concentration extracted from the downstream of the reach for the Validation Period

4.4 Mass Balance Analysis

4.4.1 An abridged mass balance has been undertaken internally by AECOM following the model calibration, which focused exclusively on quantifying the cumulative fluxes of DO within the Pilot Model Reach. The model run used a Q_{95} river flow, adjusted for climate change, and summer air temperatures which were also increased. The model was run over a 48-hour period.

4.4.2 The flux of DO arising from the processes of phytoplankton primary productivity have been calculated in kg and are presented in **Plate 49**. The model correctly predicts diurnal variations in DO consumption by respiration and DO production via photosynthesis. DO consumption by respiration shows noticeable peaks during night-time hours and then sags during daylight hours, whereas DO production by photosynthesis peaks in daylight hours and then declines to 0 at night. This is an appropriate representation of primary productivity controls on DO.

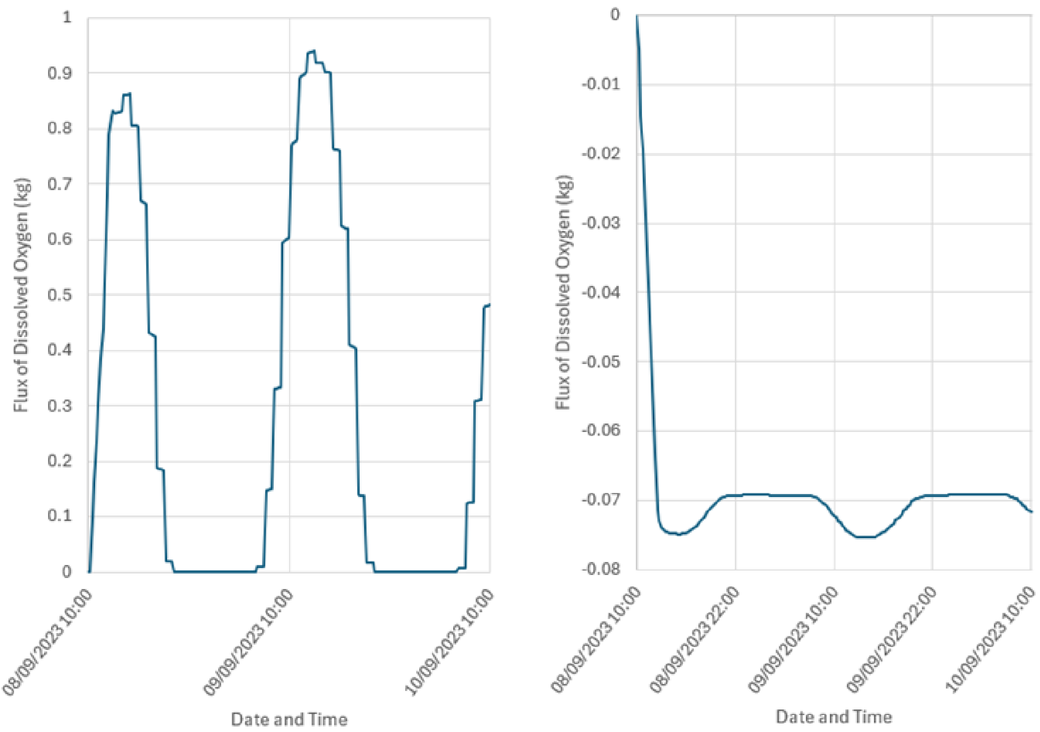

Plate 49: In-Model Primary Productivity DO Flux (Left: Modelled DO Production by Photosynthesis, Right: Modelled DO Consumption by Respiration)

4.4.3 The cumulative fluxes of DO for all sources and sinks of DO within the Pilot Model Reach have been calculated and are presented in **Plate 50**. The flux of DO resulting from sediment consumption (a DO sink) is significantly greater than those associated with primary productivity, respiration, nitrification and exchange with the overlying atmosphere.

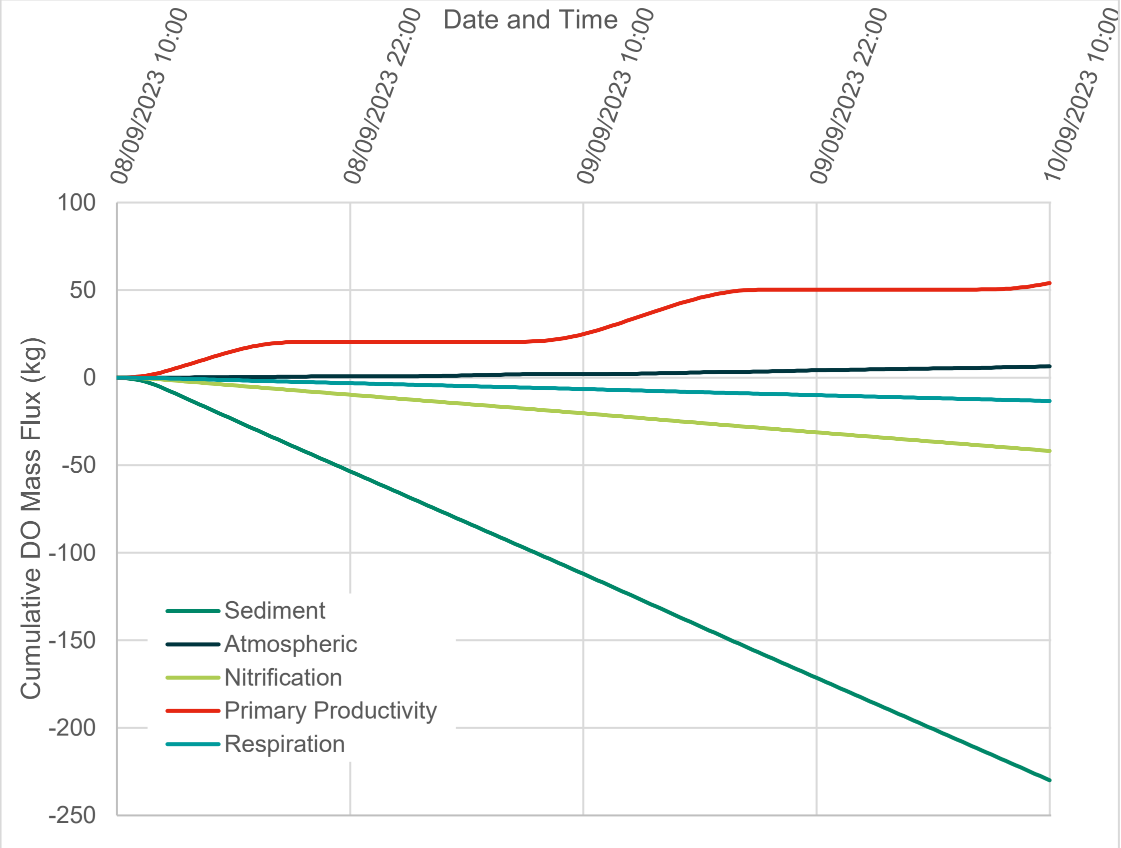

Plate 50: Cumulative fluxes of DO (kg) for DO sources and sinks within the Pilot Model Reach

4.4.4 The cumulative fluxes of DO resulting from the upstream boundary conditions specified for DO and flow have also been computed at the upstream and downstream ends of the DO model and are presented in **Plate 51.** The results suggest that the DO model is effectively a conservative system, as the cumulative fluxes of DO entering the reach at the upstream end are closely balanced by the fluxes of DO leaving the reach at the downstream end. Cross-comparison of **Plate 50** and **Plate 51** shows that the fluxes of DO within the model are dominated by the upstream boundary conditions specified for flow and DO, which is to be expected given the short residence times (of the order of 2-3 hours) within the Pilot Model Reach. These findings closely align with the small changes in DO observed between the sondes at the upstream and downstream ends of the Pilot Model Reach, as described in section 2.4. The model is therefore providing a realistic representation of DO exchange and fluxes within the Pilot Model Reach and is suitable for scenario testing.

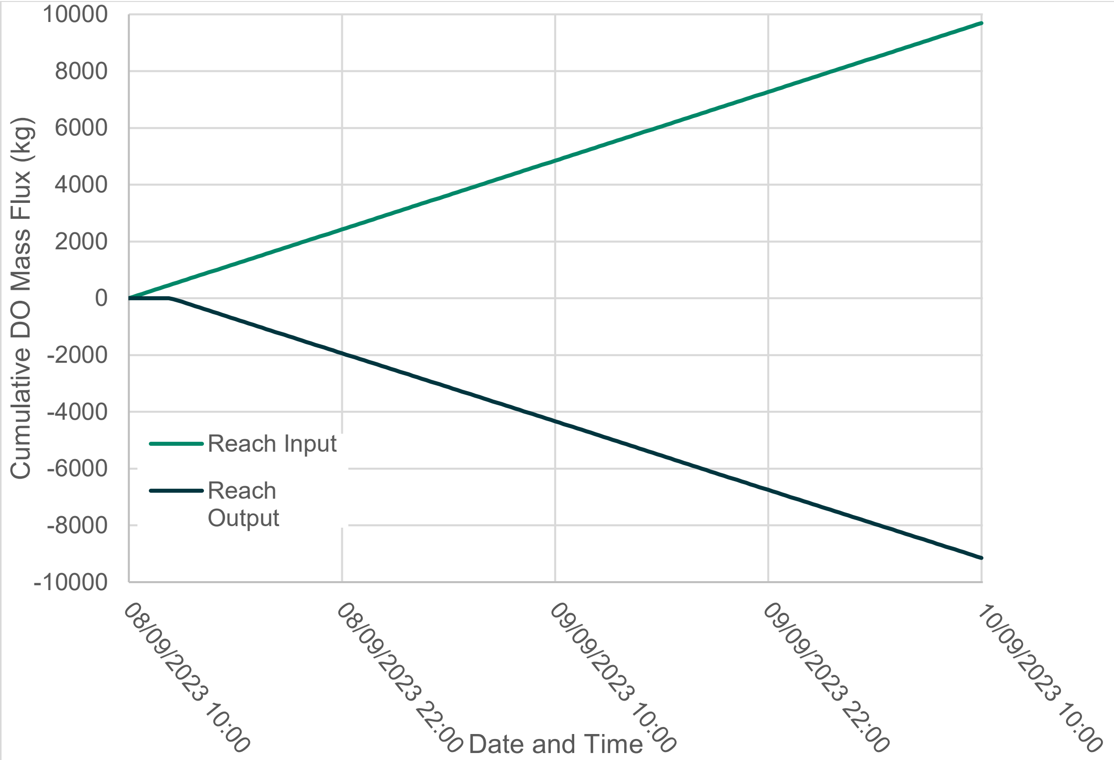

Plate 51: Cumulative boundary fluxes of DO (kg) within the Pilot Model Reach

Model Quality Peer Review

4.4.5 The uncalibrated and calibrated TUFLOW FV models were sent for independent peer review by BMT, the software developers for TUFLOW FV. The quality review reports can be viewed in Annex 22-1 (uncalibrated model) and Annex 22-2 (calibrated model). The reports do not identify any problems with the calibrated model which would preclude the use of the model in scenario testing.

5. Scenario Testing

5.1 Model Inputs

5.1.1 The model build, testing and validation process in section 4 demonstrated that the model would not simulate significant reductions in DO through the Pilot Model Reach for any present-day river flow scenario (reductions of less than 0.2 mg/l). The scenario testing therefore focussed on simulating the maximum potential impacts of the SRO operation, with the river flows set at Q_{95} or ELF only, and adjusted for climate change based on the Aquator Modelling. All models were run for the summer condition only (weather data as specified in the ERA5 model for 08/09/2023 to 10/09/2023, a 48-hour period commencing a 10am) with air temperature increased by 5.95°C in line with the latest UK CP 18 projections for mean summer temperature in the emissions scenario RCP 8.5 90th percentile over the time horizon 2070-2089 for the West Midlands. The list of modelled scenarios is set out in **Table 12**.

Table 12: Scenario Testing Model Runs

Run Name	SRO Representation	River Scenario	River Flow (m^3/s)	Atmospheric Condition
RT_G4_8m_FD_HT_BL_Q95	None	Climate Change Q_{95}	6.70	Climate Change Summer
RT_G4_8m_FD_HT_SA_Q95	115 Ml/d	Climate Change Q_{95}	5.38	
RT_G4_8m_FD_HT_SB_Q95	230 Ml/d	Climate Change Q_{95}	4.05	
RT_G4_8m_DR_HT_BL_ELF	None	Climate Change ELF	5.30	
RT_G4_8m_DR_HT_SA_ELF	115 Ml/d	Climate Change ELF	3.97	
RT_G4_8m_DR_HT_SB_ELF	230 Ml/d	Climate Change ELF	2.64	

5.2 Model Outputs – Water Temperature

5.2.1 The model outputs have been interrogated to establish the likely degree of additional water heating arising from the reduction in river flow due to the SRO operation under the future Q_{95} and ELF flow scenarios. The models were all run with an upstream boundary condition water temperature of 17.68°C and water warms through the model reach due to atmospheric heating.

5.2.2 Maximum water temperatures along the model reach through the model run time are shown in **Plate 52** for the Q_{95} scenario and **Plate 53** for the ELF scenario. The degree of water heating along the river channel is slight in all scenarios, although individual model cells along the edge of the channel, where the river is particularly shallow, can show higher temperatures. Under these conditions, the heating will be gradual and fish would migrate to areas of cooler water as the water warms.

5.2.3 Significant increases in river water temperatures are only visible in the most extreme modelled scenario, i.e. use of the SRO at 230 Ml/d during ELF conditions. The river water warms to between 19 and 20°C through the Pilot Model Reach (an increase of 1.32 to 2.32°C), with the greatest increase in temperature seen at the downstream end. A timeseries of water temperature has been extracted for each scenario from the central area of the channel close to the downstream limit and is presented in **Plate 54**. The timeseries show an increase in water temperature under the Q_{95} condition of 0.2°C in response to SRO operation at 115 Ml/d, increasing to 0.5°C if the SRO is operated at 230 Ml/d. This is a very small increase and will not, in itself, have acute impacts on fish populations. Operating the SRO at 115 Ml/d during ELF conditions also results in an increase in river temperatures of 0.2°C above the ELF baseline, and operating the SRO at 230 Ml/d during the ELF condition results in an increase in river temperature of 0.8°C. The changes in DO concentration in response to this degree of heating is discussed in section 5.3.

Plate 52: Temperature Profile Along Pilot Model Reach (Q_{95} Conditions and Climate Change and without SRO (Left), with SRO at 115 Ml/d (Centre) and with SRO at 230 Ml/d (Right))

Plate 53: Temperature Profile Along Pilot Model Reach (Climate Change & ELF Conditions without SRO (Left), with SRO at 115 Ml/d (Centre) and with SRO at 230 Ml/d (Right))

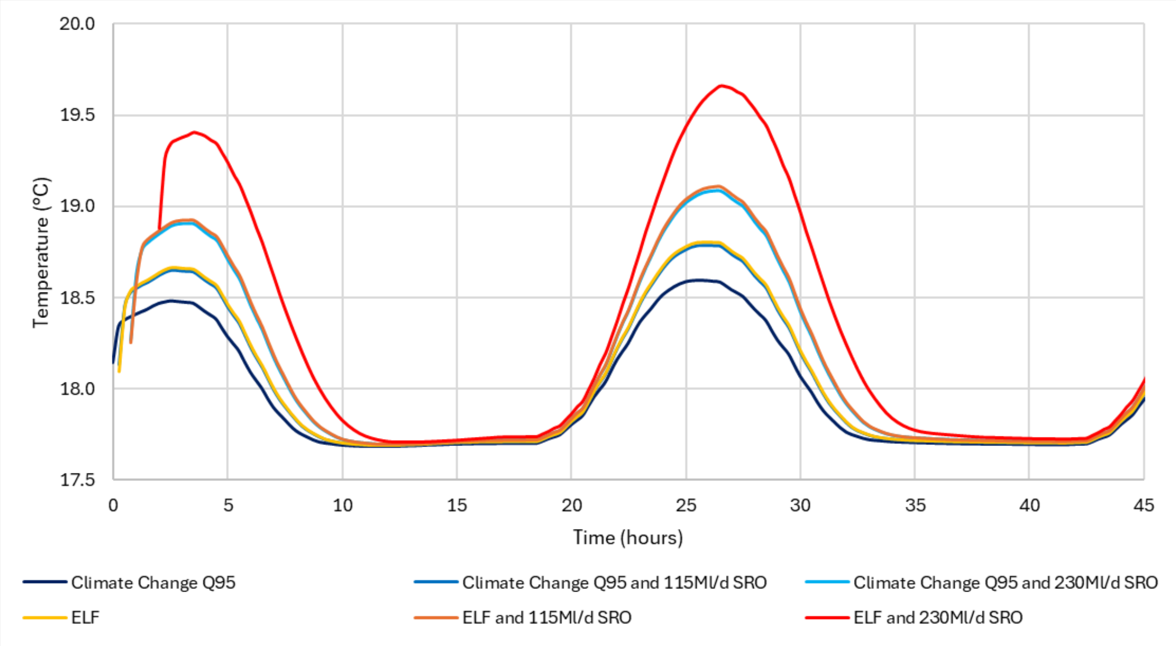

Plate 54: Timeseries of River Water Temperature at the Downstream End of the Pilot Model Reach (Climate Change with Q_{95} and ELF Scenarios)

5.3 Model Outputs - DO Concentrations

5.3.1 The model outputs have been interrogated to simulate the loss of DO from the River Tame through the Pilot Model Reach in response to the increase in river water temperature. **Plate 55** shows the minimum DO concentration simulated over the 48-hour run time, based on an upstream concentration of 8.37 mg/l, assuming climate change Q_{95} flow rate. The results are presented without the SRO and for the SRO operated at 115 and 230 Ml/d, and equivalent results are shown in **Plate 56** for the ELF scenarios.

5.3.2 The results for all model scenarios show a gradual reduction in DO through the Pilot Model Reach in response to water heating, and the model shows that the greatest reductions are in shallow water areas. The DO loss increases as modelled river flow reduces, however the maximum DO loss is small in all scenarios, at less than 0.5 mg/l. **Plate 57** shows the timeseries of DO concentration at the downstream end of the model reach for all scenarios.

Plate 55: Dissolved Oxygen Profile Along Pilot Model Reach (Climate Change & Q_{95} Conditions without SRO (Left), with SRO at 115 Ml/d (Centre) and with SRO at 230 Ml/d (Right))

Plate 56: Dissolved Oxygen Profile Along Pilot Model Reach (Climate Change and ELF Conditions without SRO (Left), with SRO at 115 Ml/d (Centre) and with SRO at 230 Ml/d (Right))

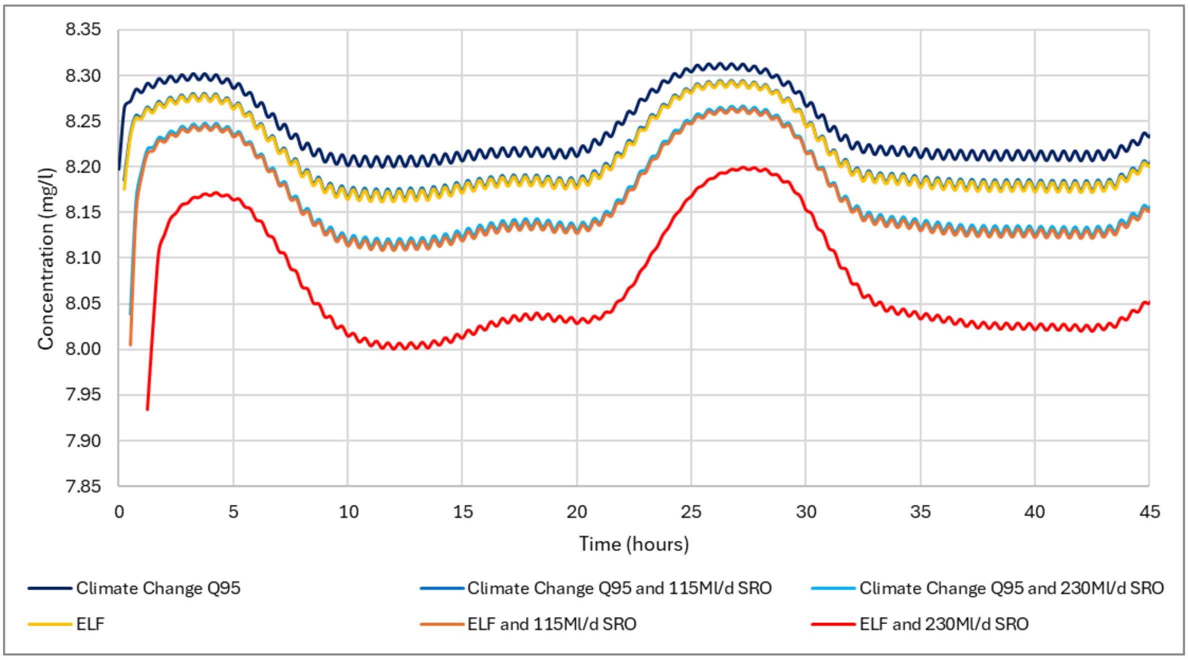

Plate 57: Timeseries of River Water Temperature at the Downstream End of the Pilot Model Reach (Climate Change Q_{95} and ELF Scenarios)

Impact Assessment

5.3.3 The minimum DO concentrations across the Pilot Model Reach are set out in **Table 13** and were small, at less than 0.5 mg/l during extreme drought and high temperature conditions. Since the Pilot Model Reach was selected as being potentially sensitive to warming due to loss of wetted perimeter as river flows reduce, impacts on DO at other less sensitive locations are expected to be insignificant, and extension of the model to areas outside the Pilot Reach is not required.

Table 13: Comparison of minimum DO concentrations (mg/l) for modelled scenarios at the Downstream End of the Pilot Model Reach

Flow Scenario	Minimum DO Concentration (mg/l)	Change in DO Concentration (mg/l)
Climate Change Summer Q95 Conditions	8.20	-0.17
Climate Change Summer Q95, 115 Ml/d SRO Conditions	8.16	-0.21
Climate Change Summer Q95, 230 Ml/d SRO Conditions	8.04	-0.33
Future ELF Summer Conditions	8.16	-0.21
Future ELF Summer, 115 Ml/d SRO Conditions	8.00	-0.37
Future ELF Summer, 230 Ml/d SRO Conditions	7.93	-0.44

5.3.4 The sonde data demonstrate that the upstream DO concentrations in the Pilot Model Reach show considerable daily variation, well in excess of the level of reduction in DO simulated by the model in response to in-reach atmospheric and solar heating during times of low river flow. The minimum DO concentration recorded at Ladywalk Reserve during the 2024 survey period occurred over the night of 02-03 September 2024, during which observed DO concentrations fell to 3.14 mg/l. The sonde at Lea Marston was not recording reliable data during this time.

5.3.5 The model results have been combined with the sonde data to investigate the significance of the simulated reduction in DO at the downstream limit of the Pilot Model Reach, where maximum reductions occur, in the context of the observed range of data at the Ladywalk Reserve sonde. The simulated reduction values in **Table 13** have been applied to the entire reliable record from the Ladywalk Reserve sonde to generate estimated timeseries of DO under future warm weather conditions (adjusted for climate change), future estimated Q_{95} and future ELF, under the two SRO utilisations scenarios. The estimated timeseries can then be interrogated to understand the impact of the SRO on the frequency and duration of low DO values in the Pilot Model Reach. This type of analysis gives a very worst-case indication of impacts as the very low flows simulated in the DO model will not be sustained over long periods. In addition, the maximum reduction in DO occurs only at night and the reduction in DO during the day is partly offset by increased photosynthesis. The Ladywalk Reserve sonde measured DO in shallow water at the edge of the River Tame channel and DO concentrations may fall more at this location than in deeper water. Finally, the frequency of DO concentrations below 4 mg/l in **Table 14** is also calculated with inclusion of single values shown in the sonde data which are likely to be spurious values due to sensor variation.

Table 14: Impact of Climate Change, River Flow and SRO Operation on the Frequency and Duration of Low DO Concentrations at Lea Marston

Scenario	% of values below 4 mg/l
Observed Sonde Data	0.09
Climate Change Summer Q_{95} Conditions	0.16
Climate Change Summer Q_{95}, 115 Ml/d SRO Conditions	0.17
Climate Change Summer Q_{95}, 230 Ml/d SRO Conditions	0.21
Future ELF Summer Conditions	0.17
Future ELF Summer, 115 Ml/d SRO Conditions	0.24
Future ELF Summer, 230 Ml/d SRO Conditions	0.27

5.3.6 **Table 14** shows that 0.09% of DO values recorded at Ladywalk Reserve were below 4 mg/l between February and October 2024. Applying the simulated level of DO reduction to the observed upstream data, DO concentrations below 4 mg/l would be expected to occur at the downstream end of the model reach for less than 0.3% of the time assuming the extreme worst-case combinations of conditions. Use of the SRO at flows of 115 Ml/d or 230 Ml/d has minor impact on the results for both tested river flow conditions.

5.3.7 This level of impact is not considered to be significant for fish populations due to the very low frequency of low DO concentrations, and the fact that, given the caveats above, the indicated level of impact will be overestimated. In addition, the modelling shows that there are areas within the River Tame and Pilot Model Reach which show less impact compared to the downstream end of the Reach and can act as refuge areas for fish during short periods of reduced DO concentrations.

6. Summary and Conclusions

6.1.1 A TUFLOW FV model has been constructed of the reach of the River Tame between the River Bourne inflow and Lea Marston Lakes. The model was constructed to establish whether flow reductions associated with use of the Minworth SRO would result in additional reductions in DO and acute impacts on fish populations. The model has been calibrated and validated using data collected from Ladywalk Reserve and Lea Marston Lakes and was run to simulate the variation in DO for future climate change scenarios using two river flow conditions (Q_{95} and ELF). The air temperatures were derived from ERA5 Reanalysis gridded climate data and were raised by 5.95°c in line with the latest UKCP18 projections for the emissions scenario RCP 8.5. Flows have been estimated using gauged flows at Lea Marston Lakes gauge and from the Aquator outputs for the RCP 8.5 RCM 13 climate change scenario.

6.1.2 The two SRO scenarios have been tested through flow reductions of:

a. 115 Ml/d - to represent the scenario of supply to the GUC SRO or the STT SRO at their maximum volume individually; and,
b. 230 Ml/d - to represent the scenario of supply to both GUC and STT SROs at their maximum volume together.

6.1.3 The TUFLOW FV model results show that water within the Pilot Model Reach is not significantly heated by atmospheric and solar conditions, even during times of very low river flow and warm air temperatures. In the most extreme tested scenario, in which both SROs were represented as being in operation, the extreme low river flows were used and summer air temperatures were specified and increased to simulate the impacts of climate change, the minimum DO concentrations within the Pilot Model Reach were reduced by less than 0.5 mg/l. This reduction occurred only at the most downstream areas of the reach and in shallow water. This extent of reduction is not sufficient to impact fish populations unless the DO concentration present at the upstream end of the Pilot Model Reach are already very low.

6.1.4 The observed data at Ladywalk Reserve shows that the upstream DO concentrations can vary significantly and can occasionally fall below 4 mg/l under the present-day condition. However, this is very rare, occurring in less than 0.1% of all measurements taken during the spring and summer of 2024 (February to October) at the edge of the channel. Allowing for this range of variation, the maximum duration and frequency of DO concentrations below 4 mg/l in the Pilot Model Reach would be less than 0.3% if both SRO were to be in use during warm weather climate change conditions and during a synthetic drought river flow condition. Given the availability of areas in the Pilot Model Reach with higher DO concentrations, the SRO operation is not expected to have significant acute impact on fish populations, at least from changes in ambient dissolved oxygen concentrations.

6.2 References

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Ref. 17 AECOM Environmental Assessment for the Trent Strategic Resource Options (SRO) Minworth SRO and South Lincolnshire Reservoir (SLR) SRO Appendix E: Sedimentation (April 2022)

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Annex 22-1: BMT TUFLOW FV Model Peer Review (Sep 2024)

Gate 4 DO Model Build and Results Report Peer Review

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Project	TQ23423
Deliverable	
Version	
	9 November 2025

Document Control

Document Identification

Title	Gate 4 DO Model Build and Results Report Peer Review
Project No	TQ23423
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Version No	001
Version Date	9 November 2025
Customer	AECOM
Classification	BMT (UNOFFICIAL)

Author	Dr Duncan Kitts
Checked By	Dr Michael Barry
Certified By	Dr Michael Barry
Approved By	Dr Michael Barry
Project Manager	Dr Michael Barry

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Contents

1 Introduction

AECOM have been commissioned to determine whether the Minworth Strategic Resource Options will impact Dissolved Oxygen concentrations, which may subsequently negatively impact fish populations in the River Tame. A 2D modelling approach, utilising TUFLOW FV, was proposed to allow for simulation of varying impact in the range of flow depths experienced within the study reach. BMT have assisted with multiple stages of the project through the provision of technical training, model specific technical support, detailed mass balance analysis and peer reviews of the uncalibrated and calibrated models. This technical note provides a summary of the latest peer review that BMT were invited to undertake of the final modelling report, titled Gate 4 DO Model Build and Results Report, produced by AECOM for their clients. The latest report documents the data collection, the TUFLOW FV model build and calibration, and the running of sensitivity runs to test the Strategic Research Options and the impact upon Dissolved Oxygen concentrations within the River Tame reach.

2 Model Build and Result Report Peer Review

The latest River Tame 2D TUFLOW FV model build and calibration has been documented by AECOM in the Gate 4 DO Model Build and Results Report. This technical report provides the following information:

- The Minworth Strategic Resource Option (SRO) project background and objectives.
- An introduction to the need for the dissolved oxygen modelling and the modelling process.
- Details of the collation of necessary boundary data (model bathymetry, hydrological, meteorological and water quality) to feed into the TUFLOW FV model as well as observed data for model calibration.
- Details of the TUFLOW FV model, including model setup and parameters.
- A description of the model calibration and validation phase to ensure the TUFLOW FV model reflects reality.
- Scenario option testing to reflect Q95 and Extreme Low Flow options for the present day and into the future.
- Discussion of the model outputs and impact assessment.
- A summary of findings and conclusions.

The report is well structured and provides comprehensive details of the modelling process which allow the understanding of the TUFLOW FV model set up, the calibration/validation process and the resource options testing and findings. There are no major omissions or concerns with the report. There are some suggestions to further improve the technical report which are outlined in the below. As well as the sections below, a marked up copy of the technical report has been provided to AECOM which provides some minor adjustments and comments for consideration.

2.1 Section Titles

Section headings are generally titled appropriately. However, it is suggested that section 2 be renamed Boundary Data to reflect the fact that it includes details of data collation for meteorological, water quality, hydrological and sediment data, discharge consents and sonde data in addition to the bathymetric survey data.

A subheading in section 3 refers to 'Model Grid' which should more accurately be defined as 'Model Mesh'.

2.2 Units

Within multiple parts of the report, but specifically within Table 3-3, there are locations where units could be defined for the defined parameters to aid reader understanding. In a few locations, incorrect units are specified for example, Radiation units of kJ/m^2 are specified when they should be W/m^2 (and is correctly specified as such in section 2.3.3.3). Similarly, the air temperature of the ERA5 dataset is in º Kelvin and converted to º Celsius within the TUFLOW FVC file.

2.3 Figures and Tables

There are a number of figures within the report which could be improved to assist with interpretation. These are as follows:

- Table 3-3: It might of use to include links to the TUFLOW FV Water Quality manual to support the reader's understanding of the various parameters.

  Further improvements to Table 3-3 would be to explain that the order of the 'Description/Explanation' column parameters, matches the order of the specified numbers within the 'Value' column.

  As mentioned in the preceding section, it would be of benefit to the user to include units, possibly within an additional units column.

- Figure 4.1. Remove the zero value from the time series which reflects the initial condition for the test.

- Figure 5.1. It is difficult to determine where the variation of temperature within the modelled reach is with the figures. The colour scale goes from 17-36 degrees Celsius. It would be recommended to reduce the range so that any differences are visually distinguishable.

- Figure 5.4. The scalebar includes zero which causes interpretative difficulties. The precision to 2 decimal places is not required.

- Table 5-2. Percentage changes to the Change in DO Concentrations may assist the users understanding of the magnitude of change.

2.4 Technical ReportTense

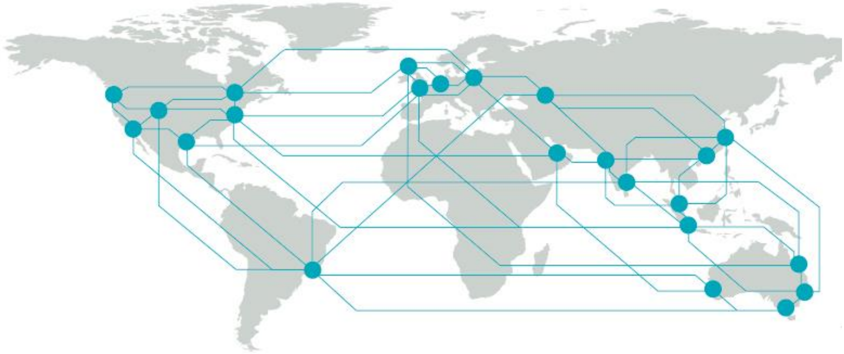
The tense of the report seems to be inconsistent, with it being clear that some sections have been written in advance of calibration and scenario tests being undertaken. It is recommended that this is reviewed further to ensure a consistent tense is used throughout the report to support reader understanding.

2.5 TUFLOW Versions

Section 1.5 mentions previous TUFLOW modelling, which it is assumed was undertaken with TUFLOW Classic or HPC. To avoid any potential confusion, it is suggested to explicitly state the TUFLOW solver used for the various modelling studies, ie, TUFLOW Classic or HPC and TUFLOW FV as appropriate.

3 Summary and Conclusions

BMT have undertaken a peer review of the Gate 4 DO Model Build and Results Report, produced by AECOM, which outlines the modelling approach, outputs and findings for the assessment of how the Minworth Strategic Resource Options will impact Dissolved Oxygen concentrations. The report is considered to provide a comprehensive description of the modelling undertaken and is of high quality. A number of recommendations have been provided by BMT to enhance readability and understanding of some of the modelling approaches and details. These were related to the section titles, addition of parameter units, improvements to figures and tables, consistent tense within the report and minor clarifications. In conjunction with the provision of this report, BMT have also provided a markup of the technical report within some minor modifications.



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Annex 22-2: BMT TUFLOW FV Model Peer Review (July 2025)

TPO079.050 RIVER TAME TUFLOW FV Model Review

TUFLOW FV Model Review

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Author	Dr Duncan Kitts
Checked By	Dr Michael Barry
Certified By	Dr Michael Barry
Approved By	Dr Michael Barry
Project Manager	Dr Michael Barry

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Executive Summary

AECOM have been commissioned to determine whether the Minworth Strategic Resource Options will impact Dissolved Oxygen concentrations, and by extension, fish populations in the River Tame. A 2D modelling approach, utilising TUFLOW FV, was proposed to allow for simulation of varying impact in deeper water compared with shallow or stagnant river sections. The model has been developed and calibrated to observed sonde data. The outputs from the TUFLOW FV model provide a good correspondence with the sonde data and is generally of sound construction. The TUFLOW FV model is dominated by the specification of the input boundary conditions which means that the water quality outputs are generally insensitive to the parameterisation of the water quality model functions.

Contents

1 Introduction

AECOM were commissioned to determine whether the Minworth Strategic Resource Options will impact Dissolved Oxygen (DO) concentrations, and by extension, fish populations in the River Tame. A 2D modelling approach, utilising TUFLOW FV, was proposed to allow for simulation of varying impact in deeper water compared with shallow or stagnant river sections. AECOM have previously undertaken a pilot study where a 2D TUFLOW FV model, including the Water Quality (WQ) Module of the River Tame from immediately downstream of the River Bourne inflow to Lea Marston Lakes, covering a length of 3.3km, was constructed. Following the pilot phase of the study, AECOM were commissioned to calibrate the River Tame TUFLOW FV Water Quality mode using observed sonde data. AECOM have requested that BMT undertake a peer review of the calibrated model with scenarios. This document documents the current peer review.

2 TUFLOW FV Water Quality Model Peer Review

The original River Tame 2D TUFLOW FV model was reviewed as part of the TPO079.000.055 RIVER TAME DISSOLVED OXYGEN MODELLING (GATE 3 PILOT STUDY). Since then, the TUFLOW FV model has been modified and enhanced by AECOM to include:

- An updated simulation period of the 23rd June 2024 to 30th June 2024.
- Updated boundary conditions including specification of an unsteady inflow time-series reflecting the simulation period.
- A spatial distribution of the prescribed hydraulic roughness.
- Changes to the model water quality parameters including benthic oxygen parameters and the phytoplankton model parameters.

The model was run using the TUFLOW FV 2023.1.0 Commercial Release What follows is a review of the updated model, specifically, Cal2_23062024_30062024_SINKSOURCE_026.fvc.

2.1 TUFLOW FV Model Geometry

The River Tame 2D Mesh exists for the selected model reach as shown in Figure 2.1. The original mesh has been maintained and consists of 2667 elements with an average area of 77.8m^2. The channel width within the reach is 25-30m. Typical cell widths and lengths are 9m in length resulting in 3-4 cells across the width of the wet channel with some additional cells within the floodplain.

Figure 2.1 River Tame TUFLOW FV Model Flexible Mesh

The mesh is well formed and exhibits a very smooth and streamwise aligned cell structure.

The Manning's *n* values which were originally uniformly set to 0.04 when previously reviewed are now spatially distributed, as shown in Figure 2.2 but are slightly higher than might be expected in a river with typical values being 0.015 to 0.02. In some areas, a value of 0.1 is used which is generally considered to be a high Manning's *n* value, although it is assigned to river edges only in areas that do look roughened, so this may be considered appropriate.

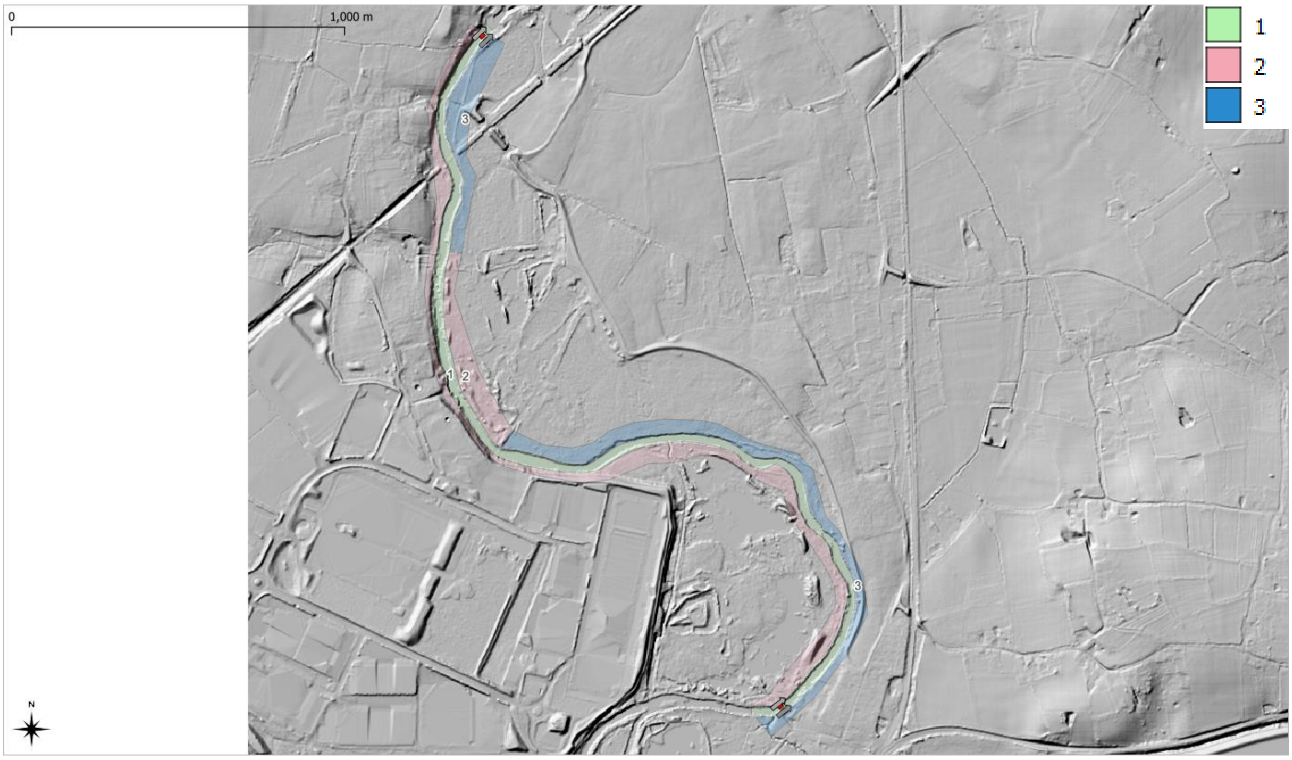


Figure 2.2 Spatially Distributed Roughness. Polygons labelled 1 have a Manning's *n* value of 0.04, polygons labelled 2 have a value of 0.1 and polygon labelled 3 a value of 0.03.

2.2 TUFLOW FV Model Boundary Conditions

At the upstream end of the modelled reach a nodestring boundary has been updated to apply an unsteady inflow condition to the model domain, replacing the original steady state boundary. The upstream boundary inflow is shown in Figure 2.3 as displays a clear daily cycle throughout the simulation time-period. It is understood that this relates to the discharges from the upstream Minworth waste water treatment works during times of low flow.

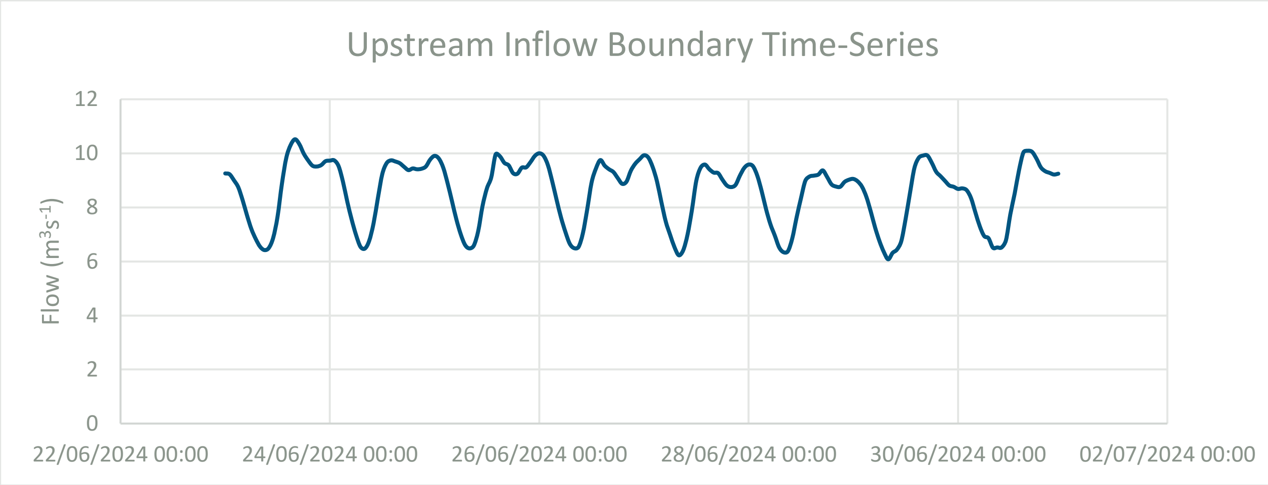


Figure 2.3 River Tame Model Upstream Boundary Inflow

The downstream limit of the modelled reach has a nodestring to define the downstream boundary condition which was originally set as a water level boundary. In this instance, the downstream nodestring has been updated to have two boundary conditions associated with it as shown in the section of the TUFLOW FV control file shown in Figure 2.4. The specified downstream boundaries being both a Q (flow boundary) and QN (Normal Flow boundary based on the calculation of a stage-discharge boundary based on a user defined friction slope).

```
BC == Q, Upstream, ..\bc_dbase\Cal2_23062024_30062024_002.csv                    ! BC Block. Flow boundary and csv input file
  BC Header == Date, Q,sali,temp, DOxy, SiO4, NH41, nitr, frph, green
End BC

BC == Q, Downstream, ..\bc_dbase\Cal2_23062024_30062024_002.csv                  ! BC Block. Water level boundary and csv input file
  BC Header == Date,sali                                               ! Csv headers read to assign time and water level information
End BC

BC == QN, Downstream, 0.0007
End BC
```

Figure 2.4 Two Boundary Conditions associated with the 'Downstream' Nodestring

In this instance, TUFLOW FV applies only one boundary condition.

It is usual practise to apply just a QN boundary on a downstream outflow, with no need for a Q boundary or associated constituent concentrations. This is because water is flowing out of the domain – the constituent concentrations are set by upstream processes rather than an exiting downstream boundary condition. It is suggested this is corrected and that only the QN boundary is applied at the northern end, downstream limit, of the model It is also suggested that there is justification for the selected friction slope of 0.0007 provided as it is a key hydraulic control for the upstream channel dynamics.

Water depths vary throughout the domain but are generally in the order of several metres, and inflows vary between 6 and just over 10 m^3/s. Cell wet/dry depths were not set for the hydrodynamic calculations. The defaults are therefore used (0.000001 and 0.01m) which amount to millimetres causing significant computational expense for little relative gain. They can be thought of as the water depths below which resolving of the environmental processes is not considered important. It is suggested that the Cell Wet Dry Depths are set to 0.01m (drying) and 0.02m (momentum switched off).

```
Cell wet/dry depths == 0.01, 0.02
```

Both values should be less than the cell water quality depth (which is currently set to 0.05m).

Simulated constituents included (all in two dimensions with the exception of the first):

- Water depth,
- Water velocity, salinity and temperature,
- Dissolved oxygen and silicate,
- Ammonium and nitrate,
- Free reactive phosphate,
- One basic phytoplankton group.

Atmospheric heat exchange was activated to support water quality modelling and reviewed as part of the TPO079.000.055 RIVER TAME DISSOLVED OXYGEN MODELLING (GATE 3 PILOT STUDY)- BMT Training and Support TUFLOW FV Model Peer Review. The specified meteorological boundaries were updated to reflect the simulation periods being simulated.

2.3 TUFLOW FV Model Water Quality Setup

The TUFLOW FV model was coupled with the Water Quality module. The Inorganics simulation class was utilised which provides the capabilities to represent advanced dissolved oxygen processes as shown in Figure 2.5 although it should be noted that suspended sediment was not modelled within the River Tame model reach.

The inorganics simulation class provides an intermediate point between more simplified dissolved oxygen modelling without the nutrient cycling associated with organic matter.

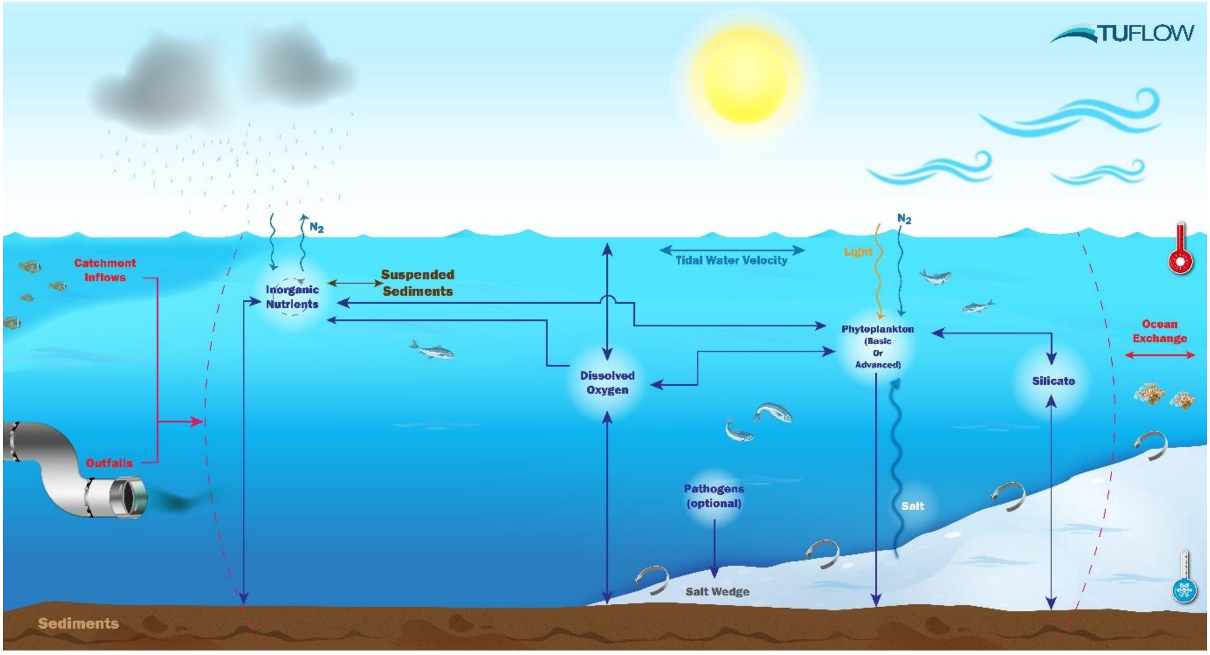


Figure 2.5 TUFLOW FV Inorganics Simulation Class

The inorganics simulation class is made up of oxygen, silicate, inorganic nitrogen, inorganic phosphorous model classes and phytoplankton model class.

Water Quality Boundary conditions were updated and specified at the upstream boundary as per Table 2.1. Temporal inputs of water temperature and dissolved oxygen reflect the daily cycle of inputs from the Minworth waste water treatment works. No water quality boundary conditions were specified for the downstream boundary with the exception of Salinity which was set to 0g/l.

Table 2.1 River Tame TUFLOW FV Upstream Water Quality Boundary Conditions Specifications

Water Quality Parameter	Upstream Boundary Condition Input
Salinity (g/L)	0
Water Temperature (ºC)	Variable (as shown in Figure 2.6)
Dissolved Oxygen (mg/l)	Variable (as shown in Figure 2.7)
Silicate (mg/l)	0
Ammonium (mg/l)	0.28
Nitrate (mg/l)	11.61
Filterable Reactive Phosphorous (mg/l)	2.37
Phytoplankton (micg/l)	20

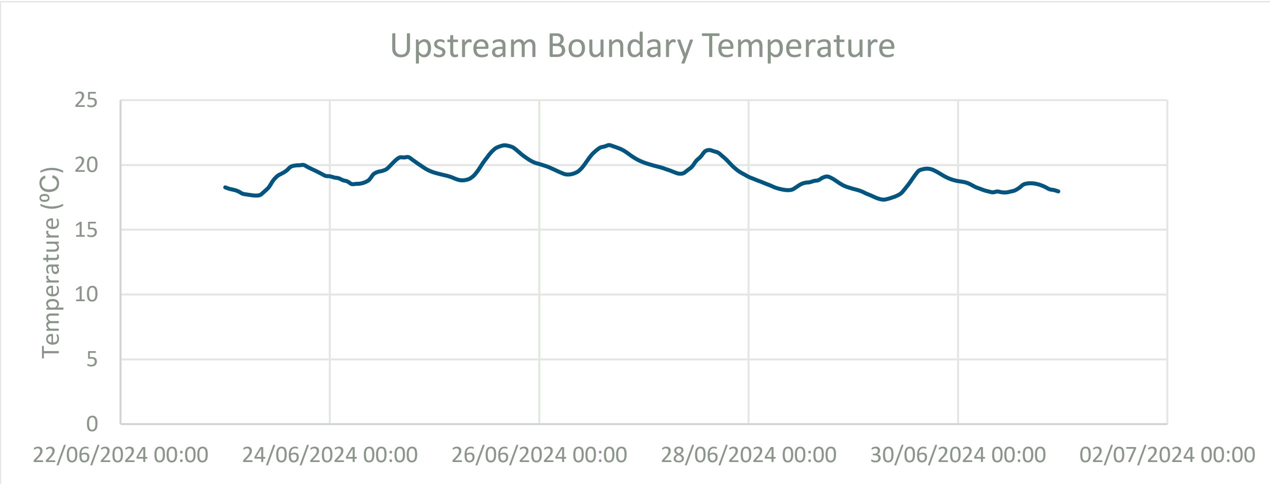


Figure 2.6 River Tame upstream temperature boundary condition

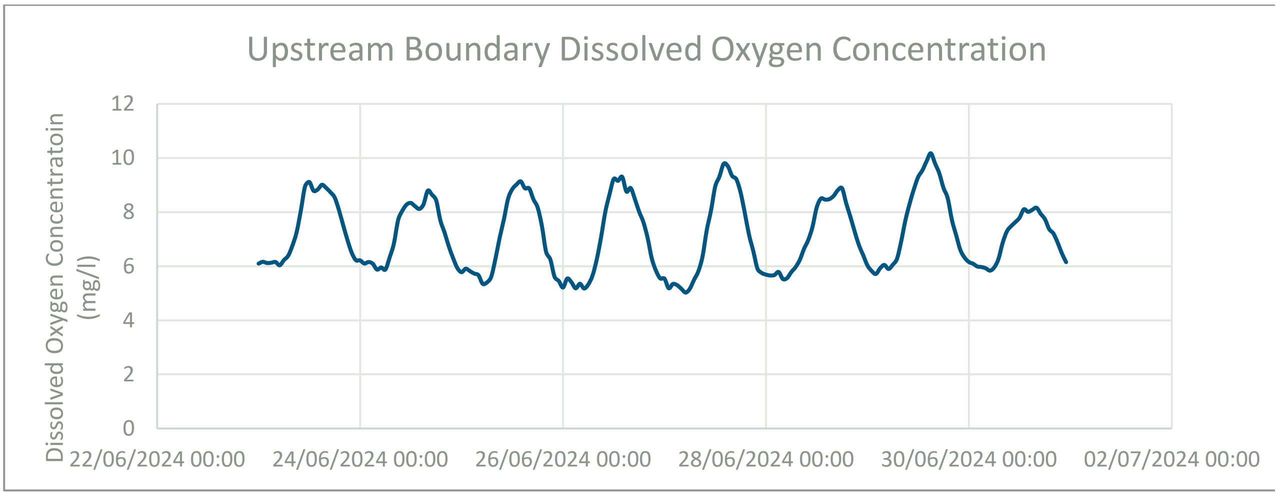


Figure 2.7 River Tame upstream dissolved oxygen boundary condition

2.4 TUFLOW FV Model Initial Conditions

The TUFLOW FV model is set up with an initial water level of 69m AD, an initial salinity of 0g/l a temperature of 17.68 ºC and initial water concentrations as follows:

- Dissolved Oxygen - 6.19mg/l,
- Silicate - 0mg/l,
- Ammonium - 0.28mg/l,
- Nitrate - 11.61 mg/l,
- Filterable Reactive Phosphorous - 2.37mg/l,
- Phytoplankton Concentration - 20micg/l.

Although not mandatory, it is sometimes useful to generate a restart file for a simulation that has considerable dry cells as its initial conditions (such as the current model). The specification of the restart assists with TUFLOW FV's ability to resolve constituent (dissolved) concentrations in cells that are dry: if they are initially dry without having been previously wet, they will be assigned concentration values of zero when re-wet, which can be problematic for temperature and water quality simulation. On the other hand, if the cells have been previously wet during a restart process, then TUFLOW FV remembers the last wet concentrations and applies them on re-wetting (rather than applying zero).

To execute such a restart, simply run the model for a day or so, with an initial water level higher than the highest bathymetric point and set an upstream WL boundary condition so that it gradually decreases over the warmup day to end up as the water level originally required at time zero. Make sure that restart files are generated each hour by TUFLOW FV (using the command Write restart dt == 1.0), and then use the restart time written last as the initial conditions for the simulation proper. The timestamp of the restart file does not matter as the command Use restart file time == 0 will tell TUFLOW FV to ignore the restart timestamp and apply all other fields to the model at the time specified as Start Time in the TUFLOW FV Control file for the full run.

2.5 TUFLOW FV Water Quality Model Parameterisation

The water quality model is generally well constructed, with parameters mostly in range (as specified in the TPO079.000.055 RIVER TAME DISSOLVED OXYGEN MODELLING (GATE 3 PILOT STUDY)-BMT Training and Support TUFLOW FV Model Peer Review report), other than the following:

- **Nitrogen**
  - DRNA is turned off via the diss nitrate reduction to ammonium parameters in the Inorganic Nitrogen model definition. This requires justification.

    - Anammox is turned off via the anaerobic oxidation of ammonium parameters in the Inorganic Nitrogen model definition and (although typically a small flux) should also be justified.
    - Atmospheric deposition of N and P are turned off (set via the atmospheric deposition command) in the Inorganic Nitrogen model definition. This is unlikely to be the case and some values should be entered for these processes.
- **Phytoplankton**
    - Primary productivity, set the via the phytoplankton model Primary productivity parameters is too high – 3.5 d^{-1} is well beyond literature values and general expectation. It should be reduced unless there is strong evidence to the contrary. The values within the TUFLOW FV Water Quality manual are at the very top of the range, for extreme circumstances like sewage lagoons – such a value is unlikely to be justifiable for the River Tame.
    - Respiration is similarly very high – double the maximum recommended in the TUFLOW FV Water Quality manual. It should be reduced by a factor of at least two.
    - The half saturation radiation for light limitation is low (20.0 W/m^2) (set by the Light Limitation parameter in the phytoplankton model specification) and should be justified.
    - Settling is turned off (using the Settling == none command in the phytoplankton model parameters), which is unlikely. A small value (m/d) should be set here.
- **Sediment fluxes**
    - These are all turned off except oxygen, within the material 1 definition in the fvwq and this is likely unrealistic. The River Tame is highly impacted and I would expect that the sediments would release nutrients to a not insignificant extent. Unless there is strong justification to the contrary, these rates should be increased.
- **General**
    - Water is becoming trapped in isolated side cells that are not connected with the main flow domain. This means that there are a large number of cells that are experiencing evapoconcentration and therefore predicting artificially large concentrations. Figure 2.8 present the phytoplankton concentrations for a period of the model simulation period– yellow is high.

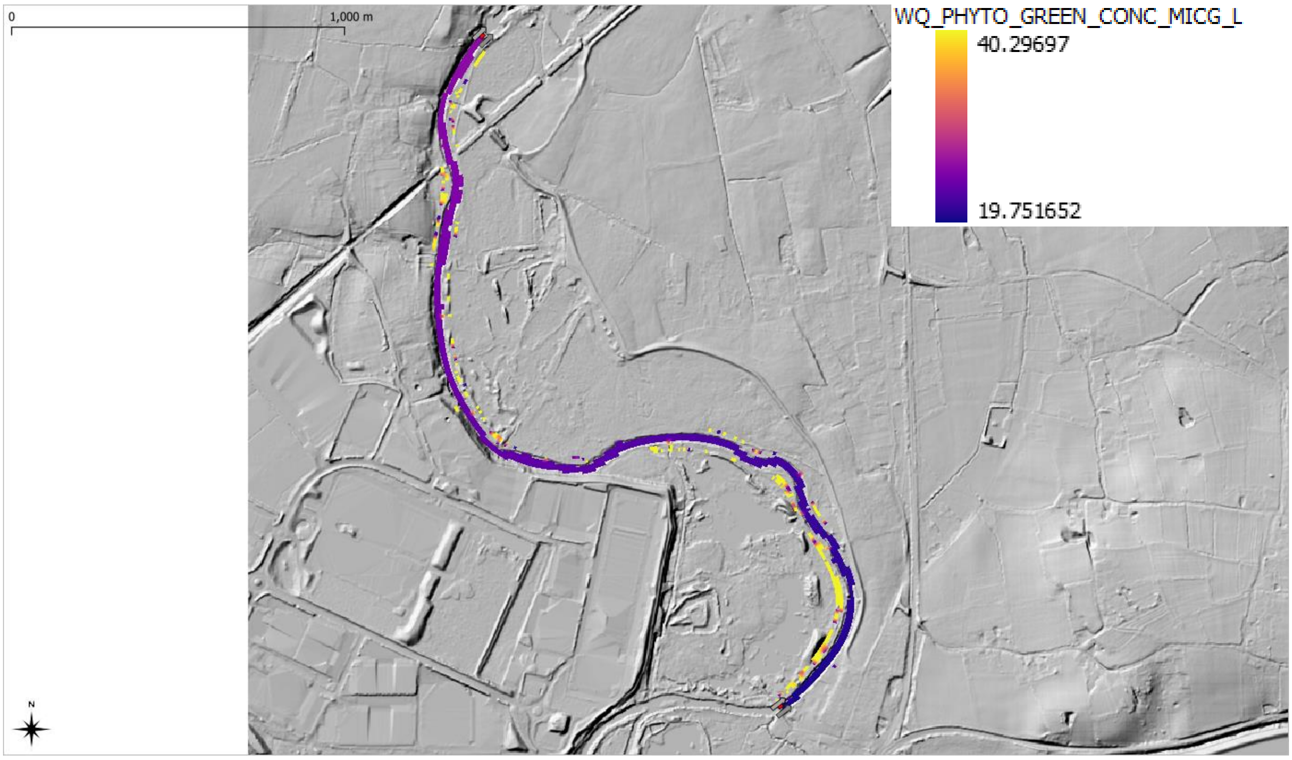


Figure 2.8 Phytoplankton Concentrations showing disconnected regions of high concentrations

As result, the TUFLOW FV Water Quality engine is continually resetting these cells to the specified maximums and sending error messages to the screen and log file. This slows down the simulation and creates unnecessary text within the log file.

```
WARNING: PHYTO_GREEN_CONC =     40.66441     is outside range at  3D cell: 2040. Concentration reset to    40.00000     and mass may not be conserved
WARNING: PHYTO_GREEN_CONC =     40.65993     is outside range at  3D cell: 2041. Concentration reset to    40.00000     and mass may not be conserved
WARNING: PHYTO_GREEN_CONC =     40.68128     is outside range at  3D cell: 2046. Concentration reset to    40.00000     and mass may not be conserved
WARNING: PHYTO_GREEN_CONC =     40.69166     is outside range at  3D cell: 2047. Concentration reset to    40.00000     and mass may not be conserved
WARNING: PHYTO_GREEN_CONC =     40.66076     is outside range at  3D cell: 2065. Concentration reset to    40.00000     and mass may not be conserved
WARNING: PHYTO_GREEN_CONC =     40.66103     is outside range at  3D cell: 2066. Concentration reset to    40.00000     and mass may not be conserved
WARNING: PHYTO_GREEN_CONC =     40.64530     is outside range at  3D cell: 2067. Concentration reset to    40.00000     and mass may not be conserved
WARNING: PHYTO_GREEN_CONC =     40.68511     is outside range at  3D cell: 2069. Concentration reset to    40.00000     and mass may not be conserved
WARNING: PHYTO_GREEN_CONC =     40.73058     is outside range at  3D cell: 2089. Concentration reset to    40.00000     and mass may not be conserved
WARNING: PHYTO_GREEN_CONC =     40.65450     is outside range at  3D cell: 2170. Concentration reset to    40.00000     and mass may not be conserved
WARNING: PHYTO_GREEN_CONC =     40.65563     is outside range at  3D cell: 2171. Concentration reset to    40.00000     and mass may not be conserved
WARNING: PHYTO_GREEN_CONC =     40.66978     is outside range at  3D cell: 2291. Concentration reset to    40.00000     and mass may not be conserved
WARNING: PHYTO_GREEN_CONC =     40.66715     is outside range at  3D cell: 2292. Concentration reset to    40.00000     and mass may not be conserved
WARNING: PHYTO_GREEN_CONC =     40.66203     is outside range at  3D cell: 2293. Concentration reset to    40.00000     and mass may not be conserved
```

Figure 2.9 TUFLOW FV Water Quality Log Warning Messages

It is suggested that either:

- Bathymetry be adjusted so that these cells in the model domain reconnect with the main flow paths and do not evapoconcentrate, or
- Turn off these WQ warnings (Report max min warnings == off in the TUFLOW FV Water Quality file, the fvwq) and accept that mass will not balance in the model. This is not generally accepted as good modelling practice, however.

2.6 TUFLOW FV Water Quality Mass Balance

A high-level mass balance analysis was undertaken of the model as provided. This was affected using the 2025.2.0 Release Candidate TUFLOW FV suite of binaries, which execute this analysis as the simulation progresses and therefore without the need for manual manipulation or post processing. Key outcomes include:

- The volumetric turnover time of the model domain is between one and three hours. This means that water flowing into the domain at the southern boundary exits at the northern boundary within this timeframe. This in turn means that the boundaries dominate the hydrodynamic operation of the model. This finding is consistent with that the findings presented within the TPO079.000.055 RIVER TAME DISSOLVED OXYGEN MODELLING (GATE 3 PILOT STUDY) review. The cumulative volumetric mass balance (shown in Figure 2.10) shows that the inflows balance the outflows, which is consistent with a very short turnover timescale.

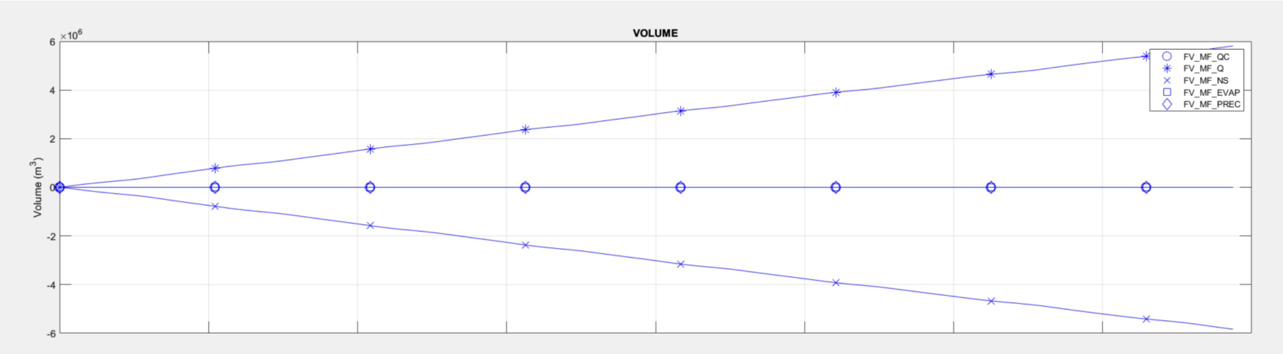


Figure 2.10 River Tame Volume Mass Balance. QC are the fluxes due to QC Boundaries (none within the River Tame model), Q are fluxes due to the upstream Q boundary, NS are fluxes across boundary nodestrings, in this instance the downstream boundary of the River Tame model, EVAP is Evaporative fluxes and PRECUP are precipitation fluxes.

- The cumulative oxygen mass balance (shown in Figure 2.11) reflects the cumulative volumetric balance in that upstream boundary inflow of oxygen essentially equals downstream boundary outflow, with all other processes (including sediment consumption) being of negligible influence. The exception is oxygen production due to primary productivity, and this has a detectable signal. It is noted however that this signal is likely overstated because it is driven strongly by the excessive specified growth rate (3.5 d^{-1}). When this rate is returned to typical ranges this oxygen production will decrease and the balance will likely return to being solely inflow-outflow dominated. This result means that there is little value in calibrating water quality rate parameters for any processes that affect oxygen – these processes are dominated by boundary condition specifications. This outcome may also have implications for when climate change scenarios are executed, and it may be reasonable to expect that unless these scenarios involve changes to boundary conditions, other climate related changes will result in negligible change to model predictions.

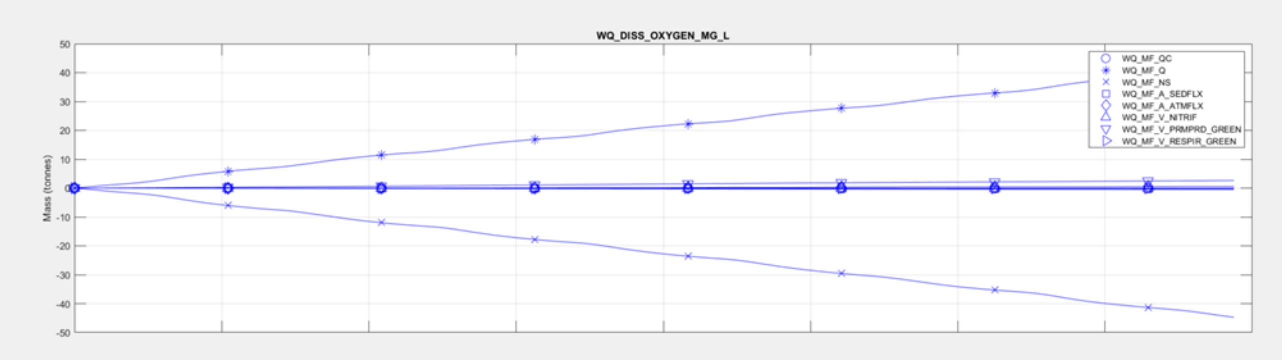


Figure 2.11 Cumulative mass fluxes of dissolved oxygen. QC are the fluxes due to QC Boundaries (none within the River Tame model), Q are fluxes due to the upstream Q boundary, NS are fluxes across boundary nodestrings, in this instance the downstream boundary of the River Tame model, A_SEDFLX are fluxes due to consumption of oxygen via sediment, A_ATMFLX are atmospheric exchange fluxes, V_NITRIF are fluxes due to nitrification, V_PRIMPROD_GREEN, are fluxes due to green phytoplankton primary productivity and V_RESPIR_GREEN are fluxes due to green phytoplankton respiration.

- Similar inflow-outflow balances apply to almost all other simulated quantities, and an example of phytoplankton (noting that primary productivity is overstated and needs correcting in the phytoplankton balance) is shown in Figure 2.12.

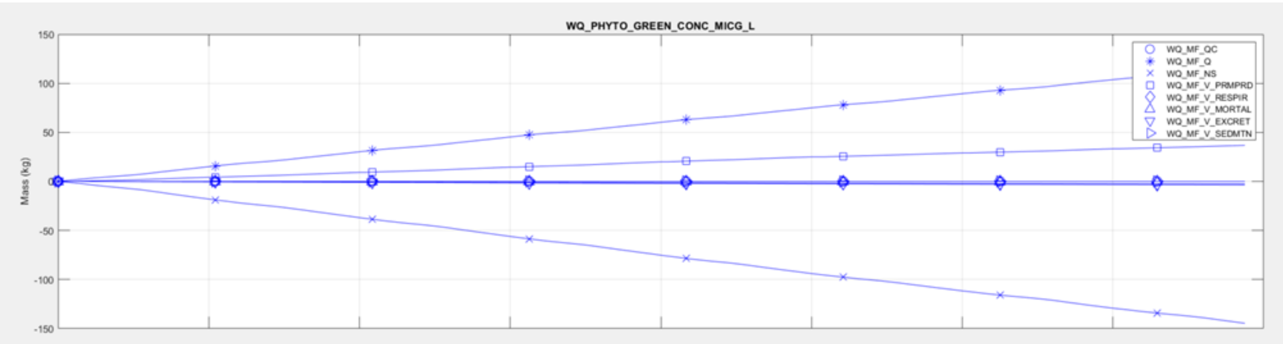


Figure 2.12 Cumulative mass fluxes of green phytoplankton. QC are the fluxes due to QC Boundaries (none within the River Tame model), Q are fluxes due to the upstream Q boundary, NS are fluxes across boundary nodestrings, in this instance the downstream boundary of the River Tame model, V_PRIMPROD are fluxes due to green phytoplankton primary productivity, V_RESPIR are fluxes due to green phytoplankton respiration, V_MORTAL and V_EXCRET and V_SEDMTN are fluxes from green phytoplankton mortality, excretion and sedimentation respectively.

3 Conclusions

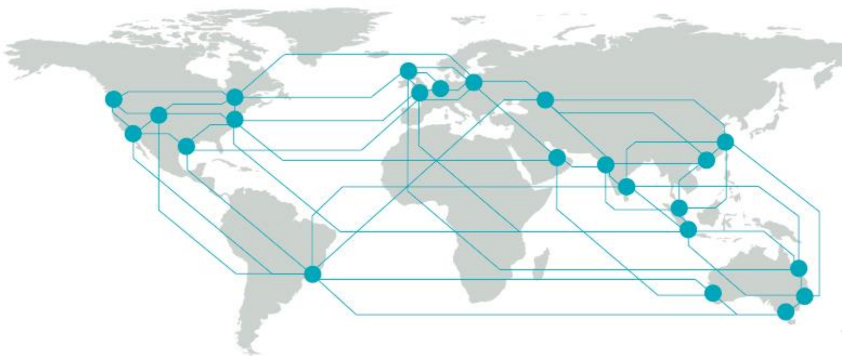
BMT have undertaken a peer review of the updated River Tame TUFLOW FV Water Quality model. The model review suggests that the model water quality is driven by external boundary fluxes and that with a short reach length, there is insufficient opportunity for significant changes to pollutant concentrations due to water quality process. This is demonstrated with the mass balance plots. Therefore, key sensitivity tests should be undertaken on the inflow water quality boundary specifications.

The |TUFLOW FV model is generally well designed although there are a number of improvements which can be made to the model to improve its operation. Specifically, these are:

- Removal of the duplicated boundary condition applied to the downstream boundary nodestring.
- A specification of the Cell Wet/Dry Depths to 0.01m (drying) and 0.02m (momentum switched off) to improve model efficiency.
- Generate a restart file to enable initial hydrodynamic and water quality conditions to be spatially distribute and applied to the whole wetted channel.
- Switch on the atmospheric deposition of N and P and set via the atmospheric deposition command.
- Reduce the phytoplankton primary productivity parameters to acceptable literature ranges.
- Reduce the phytoplankton respiration parameter to acceptable ranges.
- Turn on phytoplankton settling through the specification of a small settling rate.
- Turn on the sediment fluxes for silicate, ammonium, nitrate and filterable reactive phosphorous.
- Mitigation of the water being trapped in isolated cells not connected to the main wetted flow area.

There are some parameter settings which would be worthwhile justifying within the final technical report and these are as follows:

- the switching off of the DRNA process via the diss nitrate reduction to ammonium command.
- the switching off of the Anamox process via the anaerobic oxidation of ammonium command.
- the low parameter value of the half-saturation radiation for light limitation via the light limitation command.



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