CASE STUDY: RIVER QUALITY MODELLING FOR URBAN POLLUTION MANAGEMENT

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1. INTRODUCTION

Finham Sewage Treatment Works (STW), which serves the Coventry urban drainage catchment, is to undergo a major capital scheme to meet a number of requirements, namely:

- phosphorus removal as required by the Urban Wastewater Treatment Directive;
- a tighter ammonia consent to secure compliance of the River Avon with the EC Fisheries Directive;
- asset renewal of the secondary treatment processes.

The River Avon is believed to be vulnerable to summer storms under the existing flow regime and is a very sensitive river. There is a record of fish kills in recent years in the reach of the River Avon downstream of the confluence with the River Sowe into which Finham STW discharges. The role of discharges from Finham STW is considered to be an important factor in this situation.

A study has been undertaken using Urban Pollution Management (UPM) models and techniques to investigate the present and post upgrading situations at Finham STW and the associated rivers.

2. OBJECTIVES OF THE UPM STUDY

A scoping study was carried out which identified the broad aims of the project to be to identify the impact that the proposed changes at Finham STW have on the quality of the receiving waters, and to identify whether any further improvements to Finham STW will be necessary.

These broad aims were translated into the following specific objectives:

1. To quantify the changes in flow and loads discharged from Finham STW.
2. To predict how long-term water quality, expressed in percentile terms, in the Rivers Sowe and Avon may change (using SIMCAT[1]).
3. To make a comparison between minimum dissolved oxygen (DO) levels for storm events under summer river flow and quality conditions using a river quality model (MIKE11).
4. To identify the relative magnitude during storm events of the inputs from Finham STW compared to other urban inputs further upstream on the Finham Brook and River Sowe.

This user note considers the third objective of the UPM study and describes how the river quality model was used to carry out this investigation.

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[1] The Environment Agency's catchment scale consent setting model

3. MODELLING METHODOLOGY

The scoping study identified the appropriate types of models for use in the various parts of the project, together with an outline methodology for addressing each of the four specific project objectives. The modelling tools considered to be appropriate for the investigation into DO levels were:

- an historic rainfall record for the Finham STW site;
- a SIMPOL[2] model(s) of the combined sewer systems draining to Finham STW.
- STOAT[3] models of the Finham STW representative of both the pre and post reconstruction configurations;
- a MIKE11 model covering the study area from upstream of the STW inputs on the River Sowe and Finham Brook down to Saxon Mill on the River Avon.

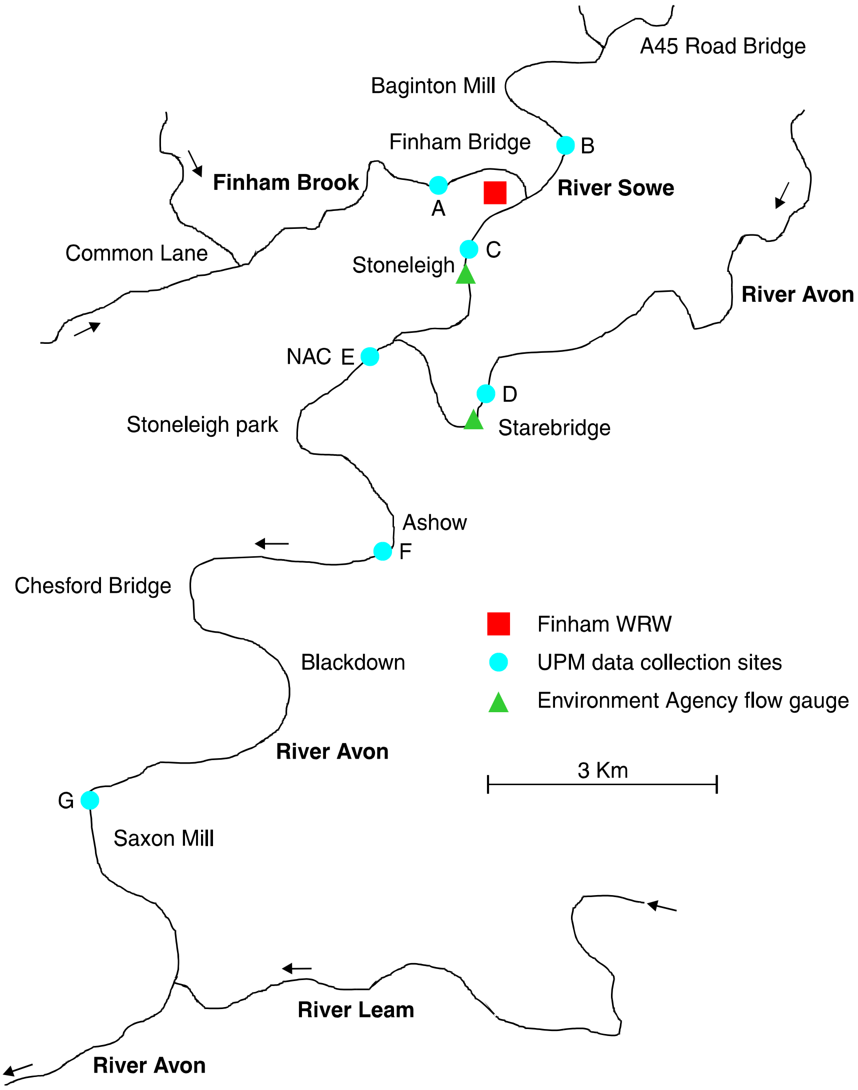

Figure 1 **Extent of river quality model and key locations for data collection**

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[2] WRc's simplified spreadsheet sewer system model
[3] WRc's Sewage Treatment Works model

4. RIVER IMPACT MODELLING

The extent of the River Sowe and River Avon covered by the river model is shown in Figure 1. The data requirements to build, calibrate and verify the Finham river quality model were identified to be as follows:

- Cross sectional information on the Rivers Sowe and Avon and Finham Brook at all significant points of change;
- Descriptions of river structures; weirs, bridges, culverts, etc.
- Time of travel and dispersion characteristics for each river reach at 3 flow rates relevant to the summer flow conditions;
- Flow and quality data, at the locations indicated above, at 1 hour intervals for 3 dry weather periods of 24/48 hours duration;
- Flow and quality data at 15 minute intervals for 2 storm events at the same locations.

Data were collected for a period of three separate dry days and four storms events to fully calibrate and verify the river quality model. This data gave good coverage of the quality of the river during critical periods for aquatic life, i.e. summer low flow conditions and sudden urban storm responses.

The river quality was modelled using the full quality processes available in software. This includes oxygen processes, immediate and delayed oxygen demand, nitrification and denitrification and sediment transport. Data were required at each upstream boundary and all inputs to rivers for the following determinands:

- dissolved oxygen
- temperature
- ammonia (total)
- nitrate
- dissolved BOD
- suspended sediment
- BOD attached to suspended sediment
- Bed sediment.

The determinands were input as time series at the upstream boundaries (Finham Brook, River Sowe and Avon) and at the final effluent and both storm tanks. The results can be output at each calculation point, as time series plots or text. There are just over 100 calculation points in the model.

5. MODEL CALIBRATION AND VERIFICATION

All models require some form of validation or calibration and verification. This ensures that the models can represent reasonably accurately the conditions under which they are being used. The Finham river quality model had to be calibrated in a number of ways to allow greater confidence in the results. Therefore, calibration data were also required at several intermediate points within the model; on the River Sowe below the treatment STW input; on the River Avon immediately downstream of the confluence with the River Sowe; at a point mid-way down the reach at Ashow and at the downstream boundary at Saxon Mill. The relative locations of these points are illustrated in Figure 1.

The MIKE11 software is modular and each module has to be calibrated separately. The modules required for a UPM study are: hydrodynamic, advection dispersion and water quality. Calibration and verification were carried out by simulating data through each module and comparing model results with observed data in the river.

A data collection programme was designed to collect specific data for this purpose covering three dry weather flow days and three storm events. However, four storms were eventually collected, including two good storms which resulted in spill from the storm tanks. These two more significant events were used in detail for model calibration and verification, the remaining storm data were used as validation data. The data from the two dry days and one storm event were used to calibrate the water quality process rates under both dry and storm weather conditions. Once a good match had been achieved, the results were then verified by running the model with the remaining dry and storm data. However, because the data collection period extended over a period of several months, it was not possible to fully verify the dissolved oxygen calibration, because different sets of parameters were required to represent the changing processes which were dependent on the time of year.

The hydrodynamic module was calibrated by matching levels and discharges at key locations down river. The correct river velocities were calculated by simulating the movement of a plug of dye down the river. This was done using the advection dispersion module together with the results from the hydrodynamic model. The same module and data were also used for calculating the in-river dispersion by observing the spread of the dye. The water quality module runs simultaneously with the advection dispersion module and uses the results from the hydrodynamic model. It was calibrated by making reasoned adjustments to the water quality process rates.

Advection Dispersion Module

The advection/dispersion model describes how a plug of pollution travels through the modelled river section in terms of movement downstream (advection) and spreading (dispersion).

The correct advective characteristics of the river were calculated by the Time of Travel data which showed the concentration of a dye plug moving downstream. The model was then calibrated by selecting the most appropriate roughness values that gave correct river velocities, shown by matching the predicted and observed peaks. The shape of that plug was also modelled and matched, to ensure the correct representation of the in-river dispersion. The dispersion calibration required iterative adjustments of the dispersion coefficient until satisfactory matches were obtained with observed data.

The dye was injected at Baginton Mill, upstream of the first data collection point (B) on Finham Brook. The predicted and observed times of the peak dye concentration were compared arriving at several locations down river. The three surveys were carried out between September and November 1996. A number of simulations were carried out to determine the most appropriate roughness coefficient, but because the survey period extended over a time when the channel roughness was changing due to the die back of vegetation, the resulting Mannings ‘n’ for each survey was found to be different.

The Mannings ’n’ value is relatively high, particularly in the lower reaches of the Avon in September, when the excessive weed in the river is at its densest. The shallow river depths, particularly in Finham Brook and in the River Sowe above the Finham works, allow the channel roughness and extra weed growth to exert a greater influence on the velocity of the flow, hence Mannings ‘n’ was higher for lower flows, though the value is still within expected ranges. Site visits and cross reference with literature tables also confirmed that an appropriate roughness was chosen.

Dispersion Calibration

The parameter in the MIKE 11 model governing the dispersion of the dye plug as it moves downstream is the dispersion coefficient. This coefficient is governed by the dispersion factor and the exponent, in the form;

$$D = f.V^{ex}$$

where; D = the dispersion coefficient (m^2/s)
f = the dispersion factor (m^2/s or m dependent on value of ^{ex})
V = flow velocity (m/s)
^{ex} = the exponent.

Typical values for dispersion factors in rivers would be 5-15. However, this could increase to 100, depending on the nature and location of the river. Initially, the dispersion factor was set at 12 and the exponent set to zero, giving a dispersion that is independent of flow velocity.

The dispersion factor was adjusted until a good match was obtained with the observed dye peak. A good match was achieved without having to change the value of the exponent. The resulting appropriate dispersion factor, shown in Figure 2, was optimised as f=1.

The results of the Advection Dispersion modelling showed that the River Sowe and Avon dispersive characteristics can be simulated using low dispersion factors. The roughness value was within expected ranges given the hydraulic conditions, where very low flows allow the bed roughness to become a more significant factor in determining the flow velocities.

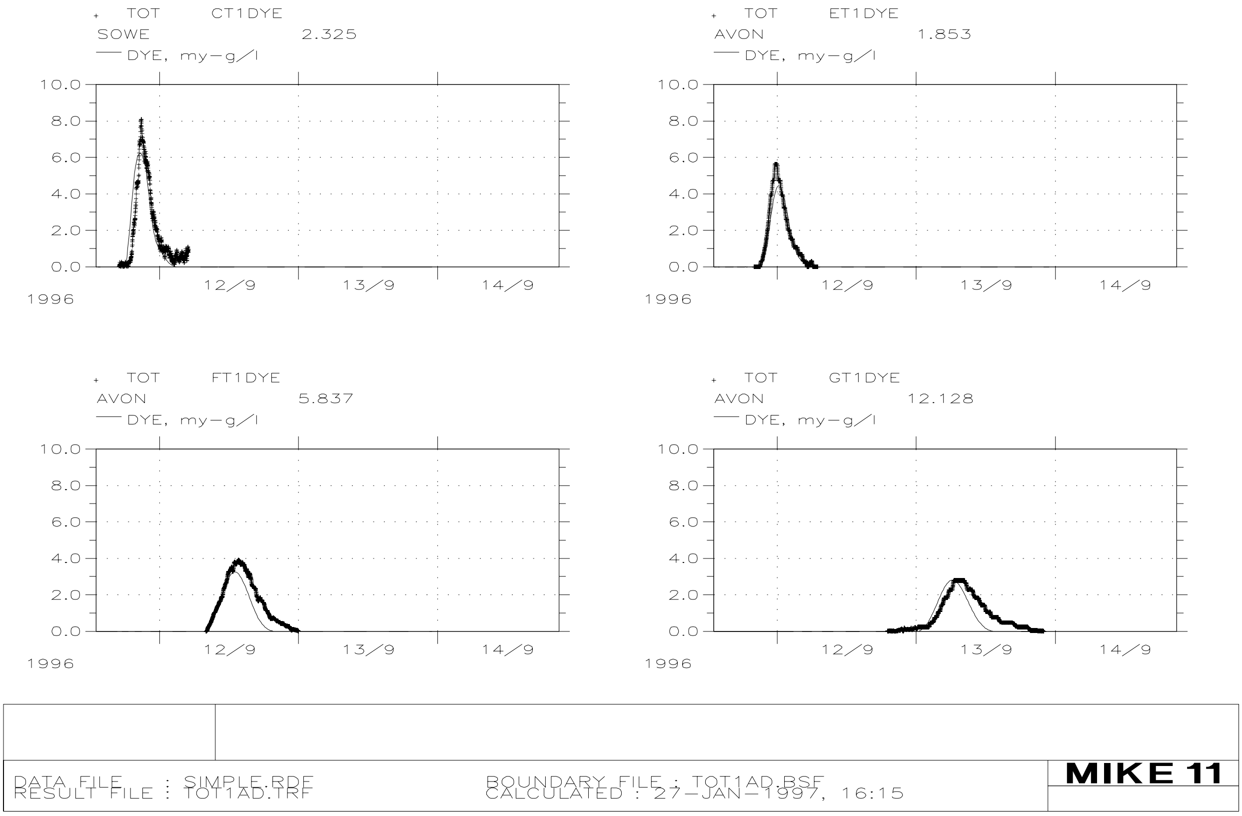

Figure 2 Dye event of the 20 November 1996 illustrating the dye plug at Sites C, E, F and G with a dispersion coefficient of 1

Hydrodynamic Module Calibration

The purpose of hydrodynamic calibration and verification is to ensure that the correct volume of flow is routed down the river system at the correct velocity. This is demonstrated by comparing observed river levels, discharge rates and times of travel data with model predictions over a range of steady and unsteady flows

The data requirements for hydrodynamic model calibration and verification are as follows:

- Time of Travel data derived from dye tracing studies collected over a range of river flows,
- flow and depth data collected over a number of days, a minimum of three dry days and one storm event are recommended. Three dry days and four storm events were collected for this study.

The flows predicted by the river quality model for the dry weather and storm events were compared with the Environment Agency flow gauge at Stoneleigh. There was a good match on the flow peak, which verified that the model was reproducing the correct river flow velocities. The amplitude of the diurnal variation was greater in the observed data. This was considered to be a function of the timestep at which the data were measured. The final effluent data used as model input had a timestep of 1 hour, whilst the flow data measured at Stoneleigh was recorded at a 15 min timestep. Consequently, the observed data was picking up the variations in flow that the averaged hourly data effectively smoothed.

Water Quality Module Calibration

Environmental conditions and biochemical process rates vary considerably depending on season. It was necessary to produce several water quality models, since it was not possible to achieve a good fit for all events with a single set of parameters. This was not unexpected as the data collection phase extended over a four month period. The differences between the models were levels of photosynthesis and respiration. The final models used for the solution appraisal were those which represented the summer period.

The process of calibration and verification produced best fit models for all determinands for the range of summer, autumn and winter conditions. The results of modelling the three dry weather and the two more significant storm events are described below. The process rates used to obtain these results are illustrated below in Table 1.

Process rate	**DWF1**	**DWF2**	**DWF4**	**STM5**	**STM7**
General reaeration equation	User defined				
Dissolved BOD decay (1/day)	0.25	0.25	0.25	0.25	0.25
Suspended sediment BOD decay	0.1	0.1	0.1	0.1	0.1
Bed sediment decay	0.75	0.75	0.75	0.75	0.75
Ammonia decay (1/day)	1.54	1.54	1.54	1.54	1.54
Nitrate decay (1/day)	0.1	0.1	0.1	0.1	0.1
Adsorption of BOD to bed (1/day)	0.0	0.0	0.0	0.0	0.0
Ratio of ammonia release by BOD decay	0.29	0.29	0.29	0.29	0.29

Table 1 Rates and processes used to calibrate the model

The user defined reaeration equation was developed by making appropriate adjustments to the variables within the reaeration expression until a match was obtained with the observed data. The resulting equation was:

$$K_2 = 0.5 \times u^{0.1} \times h^{-1.5}$$

where; K_2 = reaeration constant at 20^oC (1/day)
0.5 = coefficient in the reaeration expression (proportionality factor)
u = flow velocity (m/s)
h = water depth (m)

Photosynthesis and respiration processes were calibrated using the rates shown in Table 2.

	Photosynthesis ($g\ O_2/m^2/d$)		**Respiration ($g\ O_2/m^2/d$)**	
	Global	**Local**	**Global**	**Local**
DWF1	5	-	4	-
Chainage 6.043		15		4
12.174		20		4
DWF2	5	-	4	-
DWF4	3.5		3	
STM5	3.5	-	3	-
STM7	0	-	0	-

Table 2 Photosynthesis and respiration rates used for the calibration and verification events

Temperature and Dissolved Oxygen

One of the most important aspects of the quality model is an accurate assessment of the photosynthesis and respiration rates. The correct choice of these rates enables accurate modelling of the dissolved oxygen regime in the river. They should adequately represent the prevailing conditions in the river, during both dry and storm weather events. However, the photosynthesis and respiration are not the same throughout the year, as seasonal influences, such as aquatic plant growth, will have a marked influence on dissolved oxygen regimes.

The processes affecting the temperature and oxygen levels in the water column are described by a number of parameters and constants in the water quality model.

A reasonable fit of dissolved oxygen data was achieved under most circumstances. The differences are due to natural variations in dissolved oxygen which are difficult to model precisely or are due to transitory effects such as cloudy days, reducing the diurnal cycle. Errors were also associated with some of the dissolved oxygen monitors themselves. However, it was clear that there were a number of different rates affecting the DO along the length of the river. Table 2 shows the final photosynthesis and respiration rates used to produce a match with observed data. It can be seen that the photosynthesis rate increases towards Saxon Mill. It is not uncommon for plant matter to have differing photosynthesis and respiration rates at different locations, as this would depend on the nature and quality of the local aquatic conditions. Equally, it is possible that the two rates would not be in balance, particularly if the biomass was stressed due to its proximity to an outfall.

BOD, Ammonia and Nitrate

BOD was modelled as both dissolved and attached to suspended sediments. Comparisons are made between model results and those obtained from the laboratory analysis of the river water samples.

Calibration of the BOD, ammonia and nitrate process rates for the rivers within the modelled area was achieved by adjustments to the default rates in the software.

Sediments

In UPM applications of MIKE 11, polluted sediments are modelled using the advection/dispersion module rather than through the sediment transport module. This allows BOD fraction attached to sediments to be modelled within a combined advection dispersion / water quality simulation.

Sediments can be defined as either cohesive or non-cohesive, according to size and behaviour. Those occurring in this study area were classified as non-cohesive. The physical characteristics needed to be described for all sediments types specified in MIKE11.

Data for sediment modelling were available from the following three sources;

- survey of river and identification of sediment deposits,
- detailed laboratory analysis of bed sediment samples,
- detailed laboratory analysis of the partitioning of the suspended and dissolved phases of BOD within the liquid sample of suspended sediment

Suspended Sediment

The suspended sediment with any attached BOD were modelled as time series inputs. The sediment characteristics (size, specific gravity and potency factors) are detailed in the advection dispersion model.

Analysis of the survey data showed that suspended sediment had very little attached BOD during dry weather. However, some attached BOD was observed during the storm events. The modelled suspended sediment showed good agreement with observed values under dry weather conditions and one storm event, but the sediment flush of the second storm event was unpredicted.

Bed Sediments

Bed sediment samples were taken at five locations along the river and analysed for particle size, density, porosity and potency. The results show that the bed sediment was relatively unpolluted, with increased levels of attached BOD towards Saxon Mill.

Parameter values

Table 3 shows the parameter values used in the final calibration of the non-cohesive sediments. Two different grain sizes were modelled.

Parameter	Non-cohesive sediment
Transport equation	Engelund – Fredsoe
Mean grain size - suspended sediment	0.01 mm
Mean grain size - bed sediment	0.1mm
Calibration Factor 1	1.0
Calibration Factor 2	1.0
Volume of bed sediment	0.005 m^3/m
Potency	0.04 - 0.60 gBOD/kgsed

Table 3 Non-cohesive sediment calibration parameter values

6. MINIMUM IN-RIVER DISSOLVED OXYGEN

Once calibrated and verified, the model could be used to assess the minimum dissolved oxygen levels in the river. The model was run with a set of typical summer water quality conditions, i.e. low flows and high temperatures. A storm was selected which approximated to a one year return period and run through the sewage treatment works models of the pre and post reconstruction works to give final effluent and spill flows and concentrations. These results were then run through the river quality model to determine the impact on river quality.

Figures 3 and 4 below show the DO profile, at the downstream boundary of the model at Saxon Mill, as a result of the storm inputs generated for the pre and post reconstruction works. For the current works, the DO level seems to average around 3.0mg/l, with the DO sag at a depth of 0.5mg/l. When the post reconstruction works are simulated, the dissolved oxygen sag reaches the same depth of approximately 0.5mg/l as the current works.

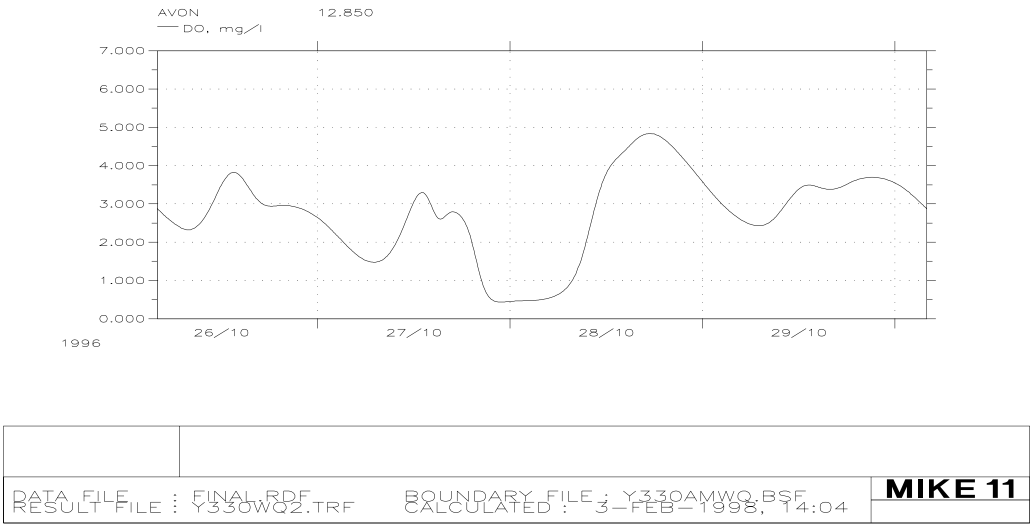

Figure 3 Dissolved oxygen time series at Saxon Mill for the pre reconstruction works after a 1 year return period storm

The major difference is the occurrence of a second substantial sag the following day. A similar sag is hinted at in some of the results for the current scenarios, but for the post reconstruction works, the second sag is significant with minimum dissolved oxygen levels approaching 1mg/l under worst case conditions. A further feature is that for any given discharge condition, the dissolved oxygen levels return to higher peaks between and after the sags for post upgraded works than is the case for the current works. The cause of the second sag phenomenon must be attributed to the extra ammonia load discharged on the second day, as a result of the additional stored volume of storm sewage being returned to the treated effluent stream. Much of the ammonia load is being passed, untreated through the works before being nitrified in the river.

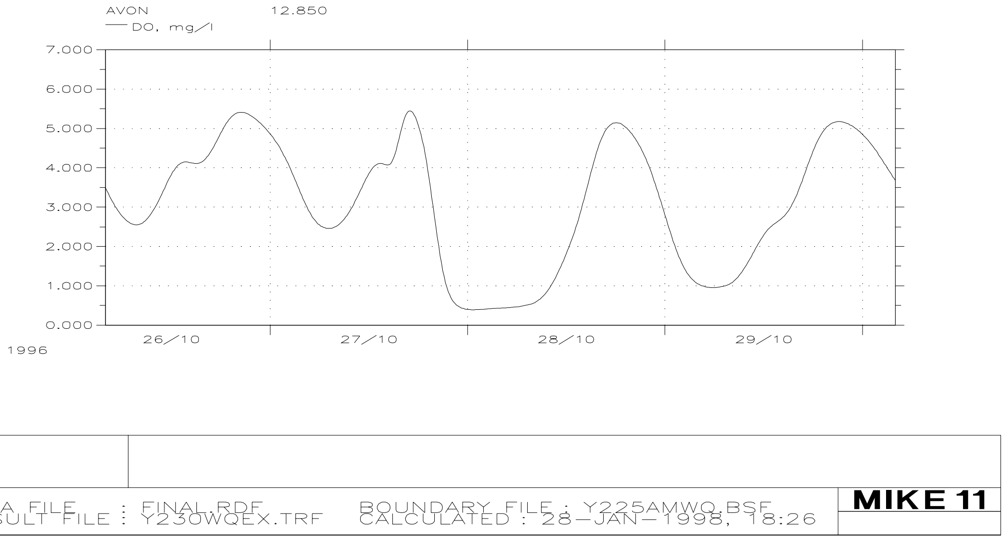

Figure 4 Dissolved oxygen time series at Saxon Mill for post reconstruction works after a 1 year return period storm

7. CONCLUSIONS

Detailed river impact modelling has shown that the upgraded works is likely to produce DO sags of a similar depth as the current works. In addition, the upgraded works produces a second sag the following day, which is likely to have a significant impact on the river ecology. However, the results also indicate that due to the reduced pollutant loading in the river, via an improved final effluent, the DO, under dry weather conditions, is likely to be improved in the downstream region of the river.

Overall, the study has shown that a complex interdependent set of circumstances can be examined successfully using modelling tools, which in turn gives both the discharger and regulator greater confidence in the development and subsequent construction of capital works designed both to provide treatment of wastewater more efficiently and help protect the aquatic environment.

8. REFERENCES

Finham UPM Study Final Report. WRc Report No. UC 2973, March 1998

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AMENDMENTS

Ver	Description	Date
1.	First Published	February 1998
2.	Editorial Amendments	March 2009