Development of Dynamic Integrated Water Quality Modelling Tools in UU and their application for management purposes

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Abstract Integrated Water Quality Modelling (ICQM) approach was applied in AMP4 to a number of river catchments located in the North West of the UK. The application of this approach resulted in better understanding of water quality issues of the watercourses, better identification of the locations were solutions should be implemented to achieve compliance with water quality standards, and a significant savings in terms of the investments required to protect the legitimate use of the receiving waters. Following the successful application of the ICQM methodology in AMP4, studies covering ten river catchments in the North West of UK were included in United Utilities Asset Management Plan (AMP5) delivery. This paper presents an overview of the extent of these studies, the ICQM methodology, the development of the modelling tools, the extent of the river sampling campaign for river models verification, and where the modelling tools developed fit into United Uilities Integrated Asset Planning (IAP) processes. In this paper, the application of the AMP5's modelling tools is illustrated in on the Douglas catchment.

Keywords Integrated water quality modelling, water quality management, urban rivers, AMP5, river water-quality models.

INTRODUCTION TO UNITED UTILITIES PLANNING PROCESS

United Utilities now carry out their long term planning using their Integrated Asset Planning (IAP) Processes. The key elements of the process are:-

- A defined process for the development and implementation of Integrated Asset Plans
- A prioritised comprehensive Integrated Asset Plan is the focal point for business planning.
- Asset plans will be aligned regionally and will look at whole life asset performance and include prioritised plans for operation, maintenance and investment
- Plans will focus on performance and serviceability issues ensuring good compliance performance and an increase in customer service levels.
- It is the process that we use to analyse regulatory drivers and business targets to identify optimum solutions and drive the PR14 business planning process.
- A focus on developing integrated and efficient solutions and ensuring that solutions are not compromised by future regulatory requirements.
- Key Performance Indicators (KPI's) are used to monitor and manage the performance of the IAP's

One of the benefits to this approach is, working in conjunction with the Environment Agency, to drive the PR14 NEP, within a 25 year planning context. It will also guide UU's supply demand and maintenance investment.

A key part of the IAP strategy is the development and use of modelling tools. Buy-in from the Environment Agency is vital to ensure that data sources can be shared and the outputs of the modelling can be used to influence the PR14 business planning process.

The application of modelling tools to a catchment will influence the development of the final business plan for AMP6. Scenarios that will be modelled include the impacts of, changes to final effluent quality parameters, changes to final effluent discharge volumes, closing or opening WwTW, changes to intermittent discharges and analysing the effect on WFD quality objectives. The plans will also be informed by serviceability assessments, surface water management plans and consideration of enhanced levels of service.

To support the development of future investment plans we will use water quality modelling to identify robust, sustainable and future proof investment scenarios. Two tools will be used – Integrated Catchment Water Quality Models (ICQM) and SIMCAT. The ICQM's are the subject of this paper and will be discussed further. United Utilities, in conjunction with the Environment Agency are also developing updated SIMCAT models for the North West of England.

INTEGRATED CATCHMENT WATER QUALITY MODELLING

In AMP4, a number of river impact assessment studies were carried out by MWH for United Utilities using an Integrated Catchment Water Quality Modelling (ICQM) approach. Compared to the simplified river modelling and mass balance approach applied in AMP3, the application of the integrated modelling concept resulted in a better understanding of water quality problems in the river systems, leading to more focussed and cost-efficient solutions (Manache and Squibbs, 2010). The modelling tools applied in AMP4 included InfoWorks CS (Innovyze, 2011) for detailed sewer modelling and MIKE BASIN (DHI Software, Mike Basin User Guide, 2005) for hydrological and river modelling.

Decisions for water pollution management actions and related investments are based on the predictions of river-water quality models. Therefore, the selection of appropriate river model is a key factor for a successful ICQM application. In AMP4's studies, the use of MIKE BASIN to simulate flows and water quality constituents in the river systems was a progression in undertaking river modelling compared to the simplified river modelling applied in AMP3. MIKE BASIN is a steady state model, and therefore, it has some limitations when applied to rivers under unsteady state flow conditions. In order to better represent the dynamic behaviour of the river systems, a model capable of simulating hydraulics and water-quality processes under unsteady-flow conditions would be more appropriate.

In the aim to progress toward fully hydrodynamic river modelling and to identify suitable modelling tools for the AMP5's studies, United Utilities (UU) commissioned MWH to undertake a research study to evaluate other river modelling tools and their suitability as alternatives to MIKE BASIN.

This paper presents the ICQM studies included in UU's AMP5 program and the major work elements in terms of modelling and monitoring. An overview of the tools evaluation and screening study, assessment criteria, and the results of the selection process are also provided in this paper. This paper further illustrates the AMP5's ICQM methodology through its application to the Douglas river catchment and presents some preliminary river modelling calibration and verification results currently obtained.

EVALUATION OF WATER QUALITY MODELS FOR AMP5'S ICQM STUDIES

The number and complexity of models available for use in water quality simulation has grown significantly in the last decades. A number of river water-quality models are available as commercial or as public domain software such as QUAL2E (US EPA; Brown and Barnwell, 1987), QUAL2K (a modernised version of QUAL2E), WASP7 (an enhancement of the original WASP, US EPA; Ambrose et al. 1988), CE-QUAL-ICM (US Army Engineer Waterways Experiment Station; Cerco and Cole, 1995), HEC5Q (US Army Engineer Hydrologic Engineering Centre, HEC 1986), AQUASIM 2.0 (EAWAG, Switzerland; Reichert, 1994), PC-QUASAR (CEH, 1997), MIKE11 (Danish Hydraulic Institute; DHI 1992) ISIS (Halcrow, 1996), InfoWorks RS (Wallingford Software, 2001), DUFLOW (EDS, STOWA, The Netherlands 1992), and others.

A high level assessment of some river water-quality models was carried out based on literature review to investigate their key features. Mainly, the models that are capable to simulate unsteady steady conditions and are widely used in Europe were considered in the high level assessment. Based on the outcome of this review, MIKE 11 (DHI, 2007) and DUFLOW (DUFLOW, 2004) were selected for detailed assessment alongside Mike Basin, which was used in AMP5's ICQM studies. The Mike11 model is widely used in Europe and UK and approved by numerous governmental organisations and had previously been used in UU's UPM studies. However, it is unclear how many of these applications that concern water quality (Arheimer and Olsson, 2003). DUFLOW is a flexible, robust, and low cost water quality model, which was successfully applied in Europe and USA (Manache and Meching, 2004; Manache et al., 2007) and has been widely used by consulting firms and water authorities (Aalderink et al., 1995).

The detailed comparison of the capabilities and applicability of MIKE 11 and DUFLOW to AMP5's ICQM studies was carried out based on their application to a river catchment: the Upper Roch catchment. An ICQM study of the Roch catchment was undertaken in AMP4 using MIKE BASIN. Therefore, to assess MIKE 11 and DUFLOW models against MIKE BASIN, both models were applied to the same catchment and compared throughout their application based on some selection criteria.

For the evaluation of the river models, some criteria were considered. This included suitability of the models for planning purposes, capability to represent complex interrelated water quality processes and their interactions (i.e. BOD, nitrogen Cycle, phosphorous cycle, eutrophication, faecal coliform, bacteria, etc.), capability to evaluate various water pollution management alternatives (i.e. Scenarios/data management facilities), capability of modelling large watersheds, level of modelling expertise and data required, ease of use, input and output aids (i.e. user interface), User support (i.e. documentation and technical support), simulation speed, Robustness, and cost.

The application of DUFLOW and MIKE 11 to the Upper Roch catchment and the comparison of their outcomes against those of MIKE BASIN demonstrated that both models provide similar representation of water quality processes in the river system. The capability of including user defined water quality processes and the possibility to vary water quality parameters and dispersion coefficient over the river reaches make MIKE 11 and DUFLOW more suitable for ICQM studies. In terms of computational requirements, however, the run time required by MIKE 11 was high compared to DUFLOW and MIKE BASIN as illustrated in Table 1.

Table 1. Summary of the computational requirements of MIKE BASIN, DUFLOW, and MIKE 11 models of the Upper Roch catchment.

Simulation settings	**MIKE BASIN**	**DUFLOW**	**MIKE 11**
Time step (hydraulic)	15 min	15 min	15 min
Time step (water quality)	15 min	15 min	1 min
Time step (output)	1 hr	1 hr	1 hr
Simulation period	3 yrs	3 yrs	3 yrs
Number of output locations	41	125	122
Computer characteristics	1*	1*	1*
Run Time	60 min	15 min	10 hours

1*: computer Intel (R) Xeon(R) CPU X54720, 3.00GHz and 2.5GB of RAM

Based on the selection criteria that are relevant to AMP5's ICQM, ranking scores were attributed to each of the evaluated river-water quality models as given in Table 2. An overall score derived from the individual scores (i.e. an average of the individual scores) is then used as an indicator to rank the models from most to least recommend for ICQM studies (1 for the most recommended, 3 for the least recommended).

Table 2. Scores attributed to the evaluated river water-quality models based on relevant criteria for ICQM studies.

Model	**Processes modelled**	**Software code/ user friendly/ flexibility**	**Scenarios generator/ data management facilities**	**Run time**	**Cost**	**Overall evaluation**
MIKE BASIN	3	3	3	2	2	3
DUFLOW	1	1	1	1	1	1
MIKE11	1	2	1	3	3	2

Note: Scores 1 to 3 were used to rank the software in terms of meeting the selection criteria (or recommended software) from strong to weak.

Following the detailed assessment of the modelling tools, the DUFLOW water-quality model was selected for the AMP5 ICQM studies for the following reasons:

1. A fully hydrodynamic model with an integrated hydrological module.
2. Diffusion and water quality parameters can be varied throughout the model. This capability is useful when modelling large systems where variation in hydraulic and water quality conditions can be significant from one river reach to another.
3. DUFLOW was found to be computationally robust with few computational failures encountered over thousands of runs.
4. Successfully applied to several European and USA rivers.
5. Users can define their own water quality processes easily with little skills in programming and this concept makes DUFLOW a very flexible package with which different types of water quality models can be developed.
6. Model build is relatively quick due to a friendly user interface.
7. With the scenario manager in DUFLOW, the user can easily define different model scenarios and compare their results.
8. DUFLOW includes a built in batch run utility that allows the running of multiple scenarios and models.

9. Compatible with Geographic Information Systems.
10. Good documentation and user support
11. Low license cost.
12. Relatively short computational time

Like any computer model, DUFLOW has also some limitations which have been taking into consideration prior to its use:

1. DUFLOW is a one dimensional model and, therefore, not suitable for performing calculations of flows in which an extra spatial dimension is of interest.
2. Although the equations underlying the model are valid in case of supercritical flow, the numerical solution method does not support this.
3. Spot measured data cannot be displayed as scattered points in graphical representation (e.g. calibration against spot samples).
4. When the size of the DUFLOW results files become significant (i.e. greater than 2GB), the results cannot be displayed in graphical or tabular format.

Based on the context of AMP5's ICQM studies in terms of the objectives, budget, and time scale, a one dimensional river model would be adequate. Therefore, the spatial dimension of DUFLOW was not of major concern. The calculation of supercritical flow for hydraulic structures is not a problem in DUFLOW. Therefore, it was possible to mitigate supercritical flow issues by using notional structures where required.

The graphical representation of spot data cannot be considered a major limitation since the simulation results can be exported easily to Excell or other graphical tools to create the plots. For the Uu ICQMs the Mike zero plot composer of DHI software was selected as graphical aid tool.

The DUFLOW results files have a clear and simple structure. Therefore, in order to overcome the memory issues in reading and displaying large results files, a tool was developed by MWH to process the results files outside DUFLOW interface. This allows a significant flexibility and time savings for post data processing.

Taking into account the relatively short run time required by DUFLOW compared to MIKE 11, the scale and extent of the rivers to be modelled, the tight deadlines for the AMP5's studies, and the relatively low cost of DUFLOW compared to MIKE11, the selection of DUFLOW can be considered rational in the context of AMP5's ICQM studies.

EXTENT OF AMP5'S STUDIES AND THE MAJOR WORK ELEMENTS

The integrated catchment modelling studies of the UU-AMP5's program include the Calder, Mersey, Micker Brook, Douglas, Irwell, Mersey, Calder, Darwen, Weaver, Irk, Medlock, and Glaze river catchments (Figure 1). The study area covers about 3,867.66 km² and includes 1,482.87 km of watercourses. The aim of the study is to assess the compliance of the river systems within these catchments against water quality standards (i.e. UPM standards and WFD chemical standards) and to identify, with supporting information on existing river condition, potential locations where intermittent discharge may be contributing to failing watercourses. The results from this assessment will be fed into the UU IAP processes for inclusion in future asset plans.

The ICQM approach applied in AMP5 evolved from the exiting AMP4 approach (Manache and Squibbs, 2010). Hydrologic and sewer modelling tools were applied to characterise the spatial and temporal variations of different discharges to the river system. The modelling tools applied involved the RAM hydrological module of DUFLOW and InfoWorks CS. A fully hydrodynamic river modelling was applied using

DUFLOW to simulate flows and water quality of the river systems under unsteady state conditions and to predict the impact of different pollution sources on the quality of the receiving waters.

To allow successful application of the river water-quality models, calibration and verification processes are required prior to their use as decision-making tools for solutions identification and catchment management. In the AMP5 studies, models calibration was carried out for the recent three years (2007-2009). Flows and water quality data available at the Environment Agency (EA) monitoring sites were used for model calibration. In total, about 140 sites were identified suitable for models calibration. To characterise river water quality conditions during storm events and to further check models consistency in representing the behaviour of the systems under different conditions, the river water-quality models were further verified.

Models verification was carried out against water quality data collected during storm events in addition to dry weather events. Water quality data that were collected in AMP3-UID projects were used. A review of the AMP3 survey data and the location of the sampling sites resulted was undertaken. The review process determined whether or not additional sampling sites were required. To collect a representative number of samples for river water-quality model verification, a new sampling campaign was undertaken in the framework of AMP5's ICQM studies. In total, 32 sampling sites were identified in addition the 62 historic verification sites. The locations of the historic and new sampling sites within the study area are shown in Figure 1.

At each monitoring site, an auto-sampler and a sonde were installed in order to collect spot and continuous water quality data, respectively. Two-dry weather periods and three rainfall events were considered for each sampling site. Taking into consideration the number of sampling sites, the number of samples to be analysed for each event, and the capacity of UU's laboratory, it was not possible to cover all the catchments by one sampling campaign. Therefore, two sampling campaigns were carried out, the first campaign started in August 2010 and covered the Douglas, Irwell, Mersey, Weaver, Miker Brook, and Medlock catchments and the second campaign started in June 2011 and covered the Calder and Darwen catchment.

Overall, the AMP5's ICQM studies carried out by United Utilities include significant amount of modelling and monitoring works. The outcome of these studies will highlight the compliance issues of the rivers if any and will be the basis for preliminary solutions identification and assessment, and subsequent cost estimation for PR14. In this paper, the application of ICQM methodology is demonstrated on the Douglas catchment.

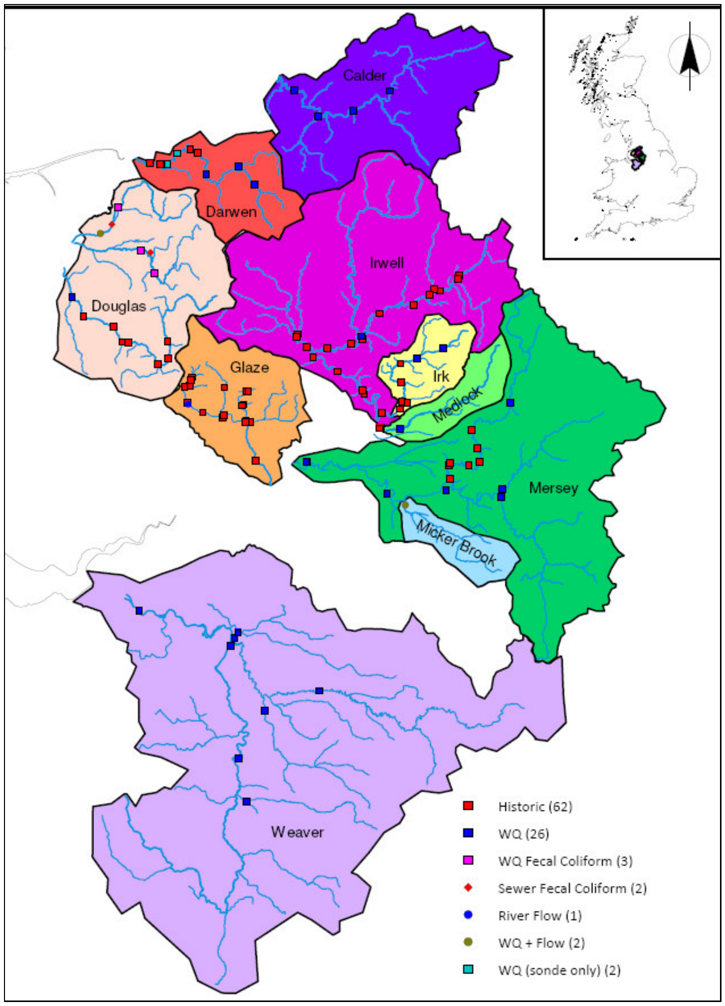

Figure 1. The river catchments included in AMP5's integrated catchment modelling studies

APPLICATION OF ICQM TO THE DOUGLAS CATCHMENT

The Douglas catchment is located in Lancashire in the North West of England and covers an area of approximately 460km^2. The lower part of the catchment is affected by the tides (i.e. about 116km^2). The main rivers in the catchment include the Douglas and its two major tributaries, Yarrow and Lostock. Figure 2 shows the Douglas catchment and the extent of the rivers considered in the ICQM study.

Flow measurements were available at three gauging stations within the catchment: Wanes Blade, Croston, and Littlewood Bridge located at the downstream end of the Rivers Douglas, Yarrow, and Lostock, respectively. To estimate flows at the river boundaries and tributaries, rainfall-runoff models for the Douglas, Yarrow, and Lostock river catchments were developed using the RAM module of DUFLOW. The models were calibrated against flow measurements at the previously mentioned flow gauges for the period 2007-2009 and verified for the period 1999-2009.

To better represent the distribution of rural runoff over river reaches, the Douglas catchment was divided into 18 main sub-catchments, which were further divided into smaller sub-areas. In total, 62 sub-areas were considered. The calibrated RAM model was run for the period 2007-2009 using historic rainfall to simulate the flows from each sub-area. In total, 62 time series of flows were generated and, subsequently, used as rural runoff inputs to the river model. Water quality at the Rivers boundaries and tributaries (i.e. rural runoff quality) were generated statistically from historical data collected at the EA monitoring sites.

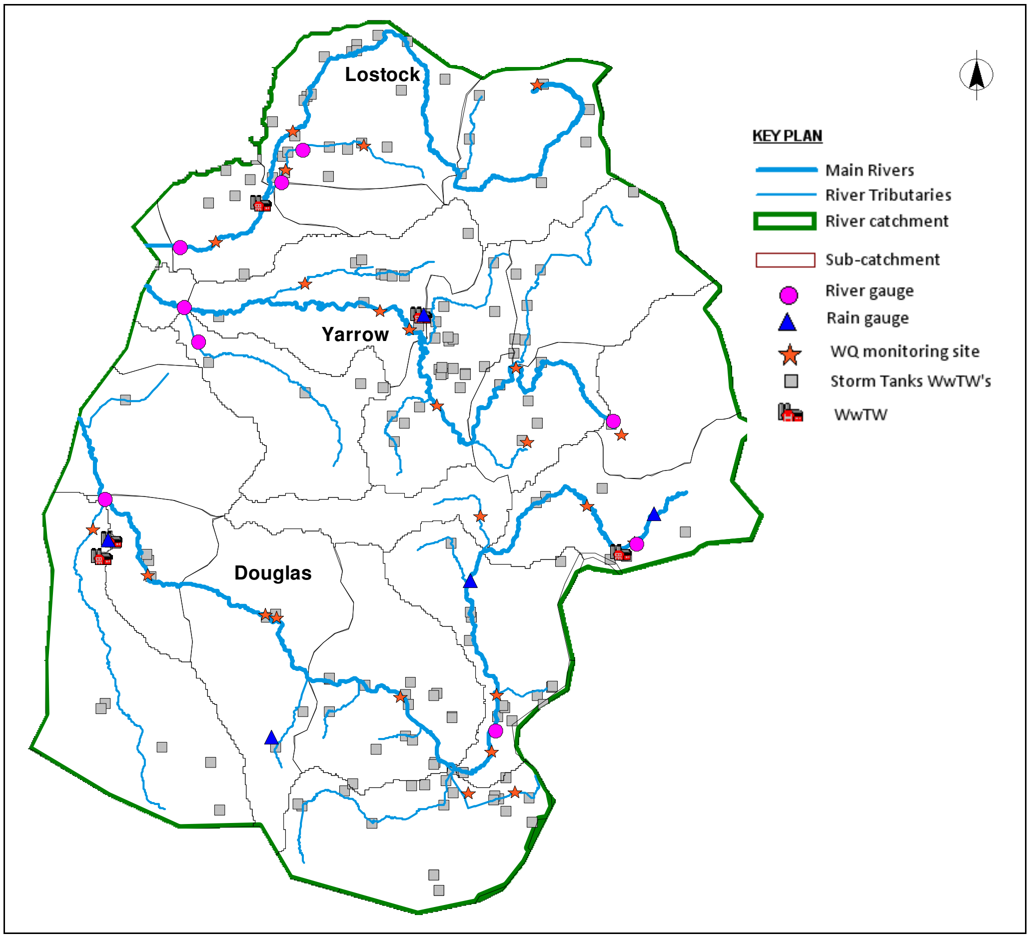

Figure 2. The Douglas catchment and the extent of the rivers considered in the ICQM study.

Sewer modelling was carried out to simulate urban discharges within the catchment (i.e. about 131 CSOs and 5 WwTWs). The CSOs were grouped into a total of 56 groups in order to reduce the number of river model inputs. Water quality of the CSO's discharges was simulated by the sewer model while those of the WwTWs final effluent were generated statistically from historical measurements. Flows and water quality from each CSO group and WwTW's final effluent were used as input to the river model.

Surface water modelling was undertaken using InfoWorks CS to simulate the runoff from urbanised areas for the period 2007- 2009. The simulated discharges from 64 surface water groups were used as inputs to the river models. Water quality of these discharges was estimated based on the event mean concentrations for urban catchments.

DUFLOW was used to represent flow and water quality of the rivers Douglas, Yarrow, Lostock, and their tributaries (i.e. a total of 155 km of river reaches). Discharges and pollutant loads coming from different sources of pollution are used as inputs to the river model. In total, 168 discharge points were included in the Douglas, Yarrow, and Lostock models. A schematic representation of the DUFLOW models including all discharge points is illustrated in Figure 3.

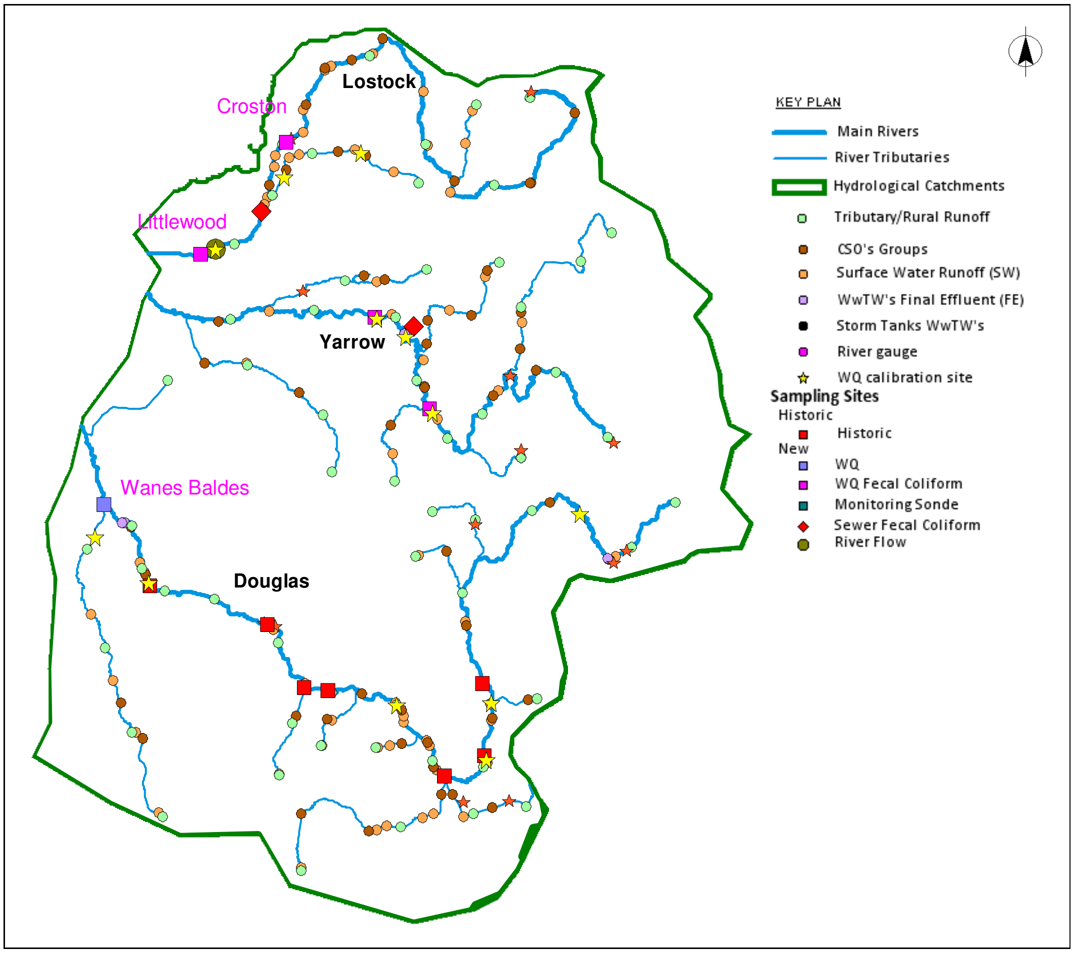

Figure 3. Schematic representation of the river models in the Douglas catchment.

CALIBRATION AND VERIFICATION OF THE DUFLOW MODELS

The river models of the Douglas, Yarrow, and Lostock were calibrated against available flow and water quality measurements (i.e. BOD, ammonia, and dissolved oxygen) within the Douglas catchment for the period 2007-2009. The flow calibration of the Douglas river model was carried at two locations; Wigan and Wanes Blades. The flow calibration of the Yarrow and Lostock models was carried out at Croston and Littlewood Bridge, respectively. The statistical index of model efficiency (Ef) defined by Nash and Sutcliffe (1970) was used to check model efficiency. The Nash-Sutcliffe model efficiencies obtained for Wigan, Wanes Balde, Croston, and Littlewood Bridge were in the range 75%-80%, which indicate good models performance. An example of the flow calibration at Wanes Blade is shown in Figure 4.

Thirteen EA monitoring sites were suitable for the calibration of the river water-quality models. The location of these sites is shown in Figure 3. The calibration results obtained at these locations was quite satisfactory. A good fit was obtained between measured and simulated BOD, ammonia, and dissolved oxygen concentrations at almost all sites for the calibration period (i.e. 2007-2009). Taking into account the overall fits of the models, it can be considered that the models provided a reasonable representation of the water quality processes in the rivers of the Douglas catchment. An example of

BOD, ammonia, and dissolved oxygen calibration at one EA monitoring site on the River Douglas (i.e. Martland bridge) for the year 2007 is shown in Figure 5.

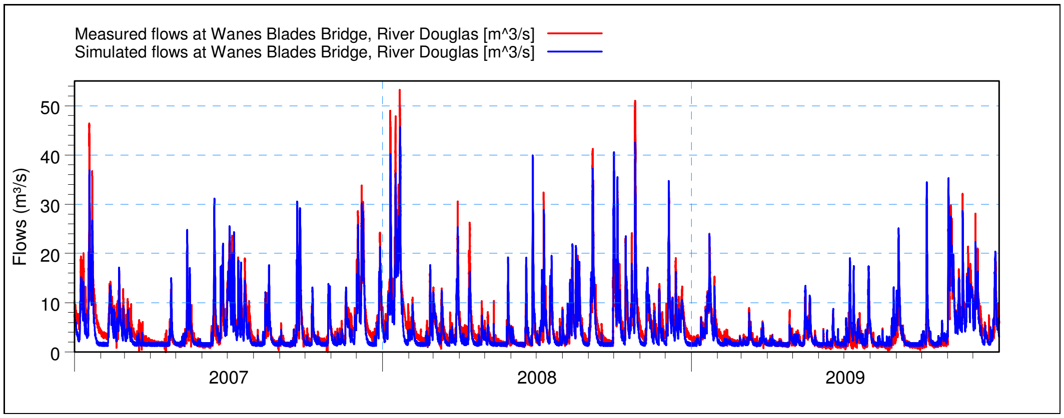

Figure 4. Simulated and measured flows at Wanes Blades for the period 2007-2009.

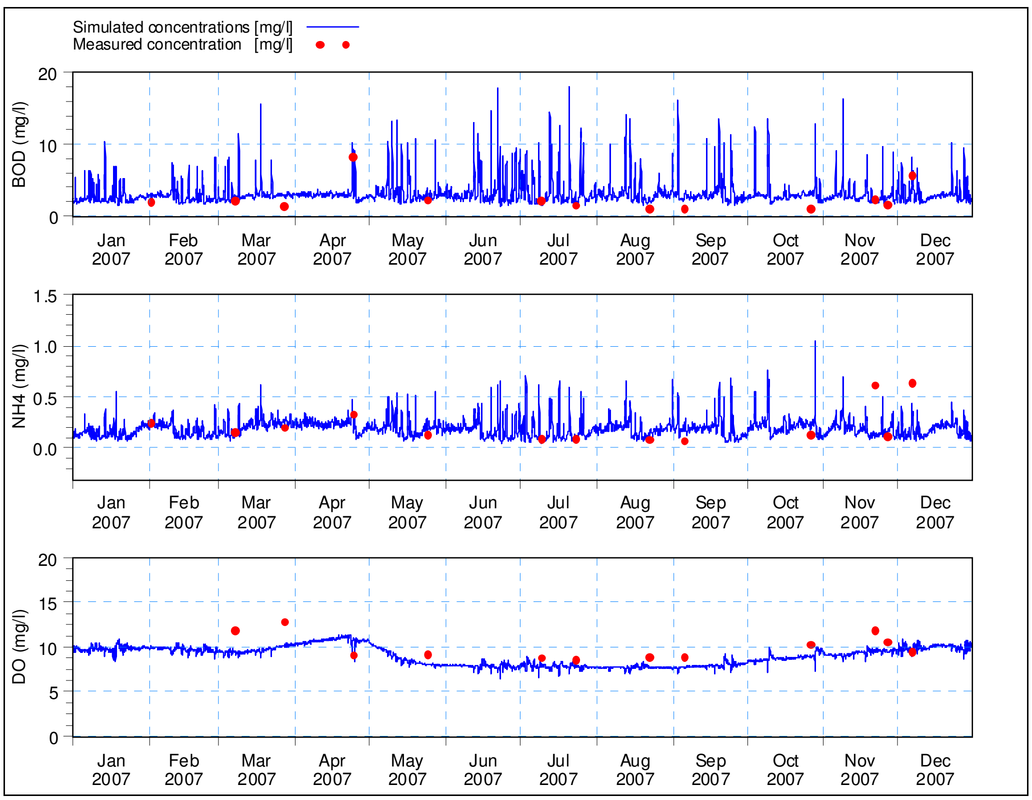

Figure 5. Calibration results at Martland bridge on the River Douglas for 2007

The calibrated water-quality models were further verified against historic and current measurements of BOD, ammonia, and dissolved oxygen. For the River Douglas, historic data collected at seven locations on the river were used for model verification. The data covered two dry and four wet weather events during the period May-October, 2000. In the sampling campaign carried out in AMP5, one monitoring site was considered on the River Douglas downstream of the WwTWs (Figure 3). The data collected at this site during three dry and three wet weather events for the period September-October, 2010 were also used for additional model verification.

For the Rivers Yarrow and Lostock no historic data were available. Therefore, the verification of the models was carried out against the data collected in AMP5. These data covered six events (3 dry and 3 wet weather events) and collected at two monitoring sites on each river (Figure 3) for the period August-November, 2010.

Figures 6 and 7 show an example of the verification results obtained for the Douglas model against historic and current measurements at Martland Bridge, and Leyland Mill Bridge, respectively.

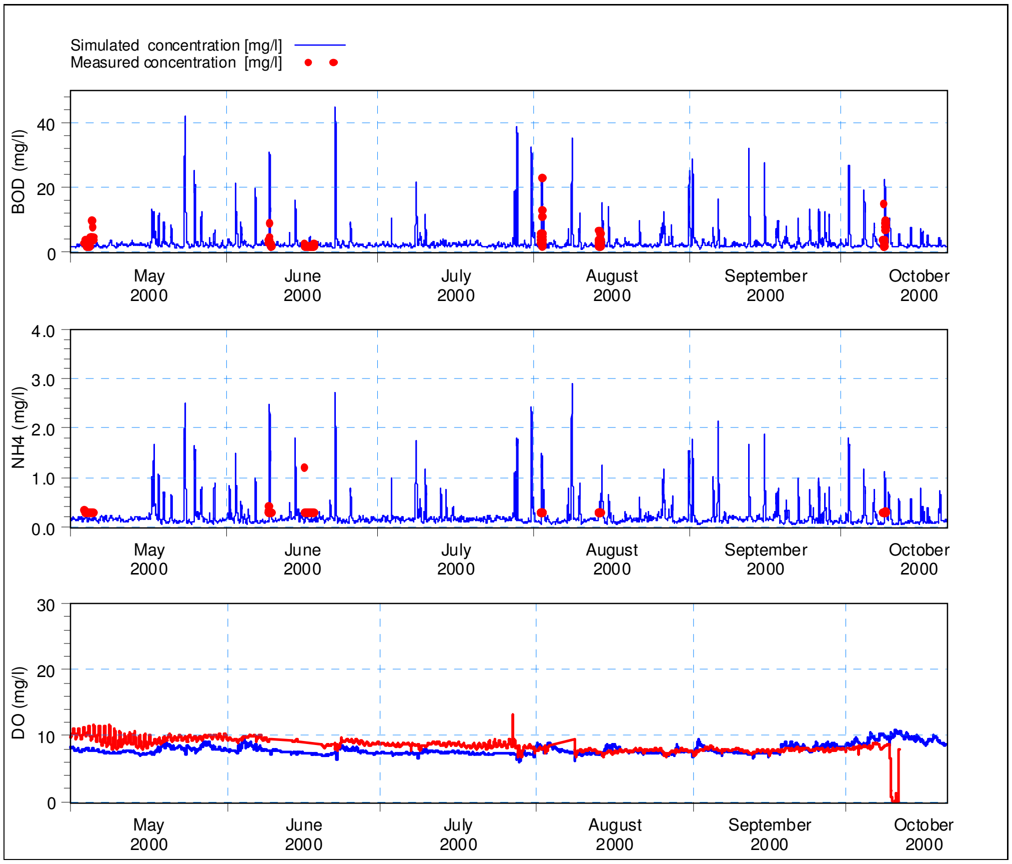

Figure 6. Verification results at Leyland Mill Bridge Lane on the River Douglas for the period May-October 2000.

In general, a good match between simulated and measured BOD, ammonia, and dissolved oxygen concentrations were obtained at most of the verification sites. Nevertheless, in few cases, the match between simulated and measured data was poor. This can be explained by either 1) the quality of the measured data, 2) the uncertainty of the models that simulate the historic behaviour of the urban drainage system, and 3) the uncertainty of the rainfall data used and considered spatial distribution (i.e. the effect of the local storms that cannot be detected by using the available rainfall data).

Overall, the results obtained so far demonstrate hat wit a reasonable level of confidence that the water quality models developed for the Douglas, Yarrow, and Lostock represent adequately water quality processes in these rivers.

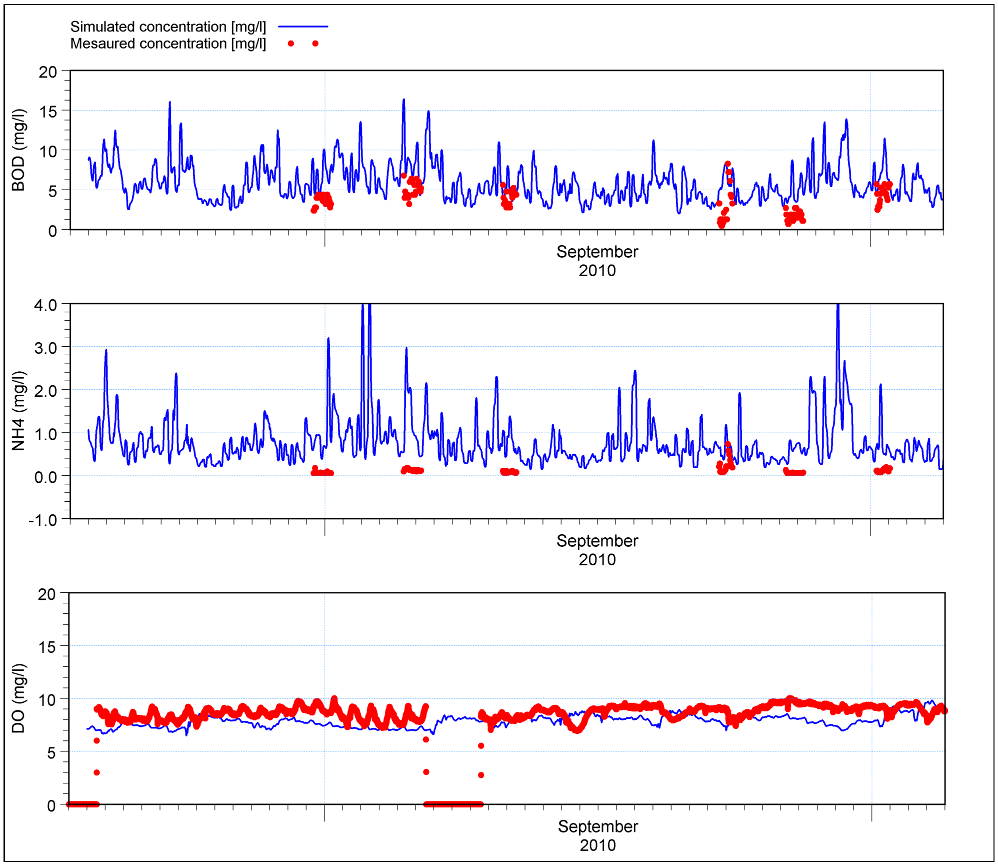

Figure 7. Verification results at Wanes Blades on the River Douglas for the period August-September 2010.

CONCLUSIONS

The ICQM studies undertaken by United Utilities in AMP5 include a significant amount of modelling and monitoring work. The results of these studies will provide insight about the locations of the intermittent discharges that contribute to failing the rivers water-quality standards. These locations will be, consequently considered in the UU's IAP processes in future plans, in conjunction with current river ecological status. Prior to undertaking the AMP5 studies, an investigation of the suitable modelling tools was carried out based on which the DUFLOW water-quality model developed in the Netherlands was selected as suitable tool for the AMP5's ICQM studies

It should be noted that the selection of the modelling tool should be project specific. The use of a too simple or too complex model will not yield reliable predictions. Therefore, the selection of a water-quality model for management purposes should be based on a good balance between three elements: model complexity, model uncertainty, and available amount of information.

The modelling work of the AMP5 studies included hydrological modelling (about 20 hydrological models), sewer modelling (about 120 WwTW catchments) and river modelling (about 1,482.87 km of watercourses). Data collection and analysis was also a major element of work in this project. Data from about 70 river gauges, 45 rain gauges, and 260 water quality monitoring sites were collected and analysed in order to identify their suitability as input or for calibration and verification. In addition to river hydrometry and water quality data, existing river models were provided by the EA in order to make use of the existing surveyed river cross sections. The provision of this data was valuable since it saved cost and time for the project.

The preliminary results obtained at the calibration and verification sites for different periods demonstrate that the river water-quality models for the Douglas catchment reasonable reproduce the dynamics of BOD, ammonia, and dissolved oxygen in the river systems. The quality of the calibration and verification is under improvement in order to provide enough confidence of the models as tools for future management in the catchment.

Taking into account that the river models that will be developed in this study will be used as decision making tool for future investments and to assess different solution scenarios, special attention was given to model calibration and verification. The preliminary calibration and verification results obtained at this stage can be considered acceptable. However, more work is ongoing to improve model calibration and increase the level of confidence regarding model capability to simulate river dynamics and water quality process. For the calibration of the river models within the AMP5's river catchments, data from 140 EA monitoring sites and 90 verification sites within the study area will be used, respectively.

The outcome of AMP5's ICQM studies will provide UU with an integrated and flexible modelling tool for the 10 previously mentioned catchments. It will allow the planners to evaluate future watershed-related water quality management issue, policies and operational improvements.

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