Application of integrated water quality modelling for efficient management of water quality in the River Irk with cost-effective investment

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Abstract To meet water quality standards in urban rivers, significant investments in urban drainage systems are required. For future investments in sewerage infrastructure to be cost-effective, an integrated approach at river basin scale should be adopted in evaluating future water quality management issues, policies, and operational improvements. This paper illustrates the benefit of adopting such an approach through the application of integrated catchment modelling (ICM) to the Irk catchment. Hydrologic, hydraulic, and water quality modelling was applied to assess the impact of catchment runoff, combined sewer overflows (CSOs), surface water outfalls (SWOs), and final effluent from the wastewater treatment works on the River Irk. The compliance of the River Irk was assessed against UPM standards based on the use of a river water-quality model which was developed and calibrated in the framework of the ICM approach. In order to enhance the water quality of the river Irk, solutions for the critical CSOs discharging at the river system were identified. Compared to previous solutions identified using a mass balance approach and simplified river model, the application of the ICM approach resulted in a significant decrease in the total storage volume required to achieve compliance with the standard and better identification of the locations where solutions should be implemented. Overall, the results obtained demonstrate that the application of the ICM approach allows significant savings in terms of the wastewater structures needed to protect the legitimate uses of the receiving waters.

Keywords Integrated water quality modelling, water quality management, urban rivers, catchment, water quality standards.

INTRODUCTION

The impact assessment of United Utilities' assets on the downstream part of the River Irk and Moston Brook was previously undertaken in AMP3. The study was based on the application of the UPM mass balance approach to a simplified river model. The downstream part of the River Irk between Boothroyden weir and the confluence with the River Irwell was divided into four reaches. For each reach, a mass balance analysis was performed including the combined sewer overflows (CSOs) located on the upstream reach. Boundary conditions at Boothroyden weir were applied at the upstream reach. Based on the impact assessment results, the study predicted the requirement for a total storage volume of 10,650m^3 and screening across a number of unsatisfactory intermittent discharge (UID) sites.

In AMP4, a new river impact analysis study was carried out using an Integrated Catchment Modelling (ICM) approach. In this approach, detailed river water quality modelling was applied to the entirety of the River Irk and its tributaries taking into account all urban and rural discharges within the river catchment and their interactions. Hydrologic, sewer, and surface water modelling were applied to characterise the spatial and temporal variation of urban and rural discharges and to predict their impacts under current and future water quality conditions. The application of the integrated model to assess the compliance of the River Irk and its tributaries against water quality standards resulted in significant reductions in catchment storage requirements compared to the solution identified in AMP3 study. Moreover, the study highlighted that water quality compliance issues were caused by the discharges upstream of the original boundary of the AMP3 work.

In the 1990s, with the increased concern about sustainable integrated water-quality management on a river basin scale, modellers started to integrate sewer, wastewater treatment plants, and river quality models and apply them as decision support tools for the management of pollution (e.g., Fronteau et al., 1996; Fronteau, 1999; Bauwens et al., 1995; Rauch and Harremoes, 1995; Clifforde et al., 1999; Schütze et al., 1996). within the UK, the management of sewerage systems and their interaction with receiving waters was set up in the Urban Pollution Management (UPM) approach (FWR, 1994), which essentially consists of the application of water quality models in an integrated way for the management of pollution on a river catchment scale.

This paper aims to (1) present the ICM methodology applied by United Utilities and MWH in the context of water quality management; (2) demonstrate its application on the Irk catchment; and (3) illustrate the advantages obtained in terms of water pollution management efficiency and cost-effective compliance with the standards.

INTEGRATED CATCHMENT MODELLING METHODOLOGY

The integrated approach followed in this study is based on the application of modelling tools to represent the different components of the catchment in terms of quantity and quality. These include rural runoff, combined sewer overflows (CSOs), surface water outfalls (SWOs), discharges from wastewater treatment works (WwTWs) and storm tanks, and the assimilation capacity of the river system.

To estimate rural runoff (i.e. inflows at river boundaries and from ungaged tributary watersheds), hydrological modelling is applied. The NAM rainfall-runoff model (DHI, MIKE BASIN user guide 2005) was used in this study. Following model development, calibration, and verification, the model was applied to generate flow time series at the river boundaries and tributaries. Water quality at the river boundaries were derived from statistical distribution based on historic data collected at the Environment Agency (EA) monitoring sites. More specifically, from the monitoring sites located upstream of urban wastewater discharges.

Sewer modelling was applied to simulate discharges from combined sewer overflows, storm tanks, and final effluents of wastewater treatment works. A majority of sewer models within the North West area of the UK are available. For the existing models, auditing and amendments were carried out as necessary prior to use in the ICM study. For missing models, new models were built for significant catchments and verified prior to their use. Continuous simulations were carried out with all sewer models within the catchment using historic rainfall data to generate time series of CSO spills and final effluent discharges. The advantages of using historic continuous rainfall data is that the concurrent flow data can be used to reflect corresponding river discharges conditions and that statistical analysis can be performed on the simulation results. Water quality of CSO discharges were simulated by the sewer models while water quality of the final effluents was derived from the statistical distribution of the historic measurements.

To estimate the surface water runoff from the urban areas, simple surface water models were built in this study based on the surface water area take-off for each sub-catchment. The surface water models were run continuously with the historical rainfall to simulate the runoff from urbanised areas. Water quality of urban runoff was estimated based on event mean concentration values, which were available in form of a 200m grid GIS map.

River modeling was carried out to simulate the hydraulic behaviour of the river system and to represent in river water-quality processes. The river water-quality model MIKE BASIN model (DHI Software, MIKE BASIN User Guide, 2005) was used in this study. Discharges and pollutant loads from different sources (i.e. sub-catchment runoff, CSOs, SWOs, and WwTw's final effluent), which were simulated by the hydrologic, sewers, and surface water models, were used as time series inputs in the river model. The model was calibrated against flow and water quality measurements available for a period of 3 years (01/01/2005-31/12/2007) and verified against historic and/or recent data collected during wet weather events. The calibrated river water-quality model was used as a tool to analyse water quality problems in agreement with the applied water quality standards and to evaluate mitigation measures. A flow chart illustrating the steps followed in the application of ICM methodology in river impact analysis is shown in Figure 1.

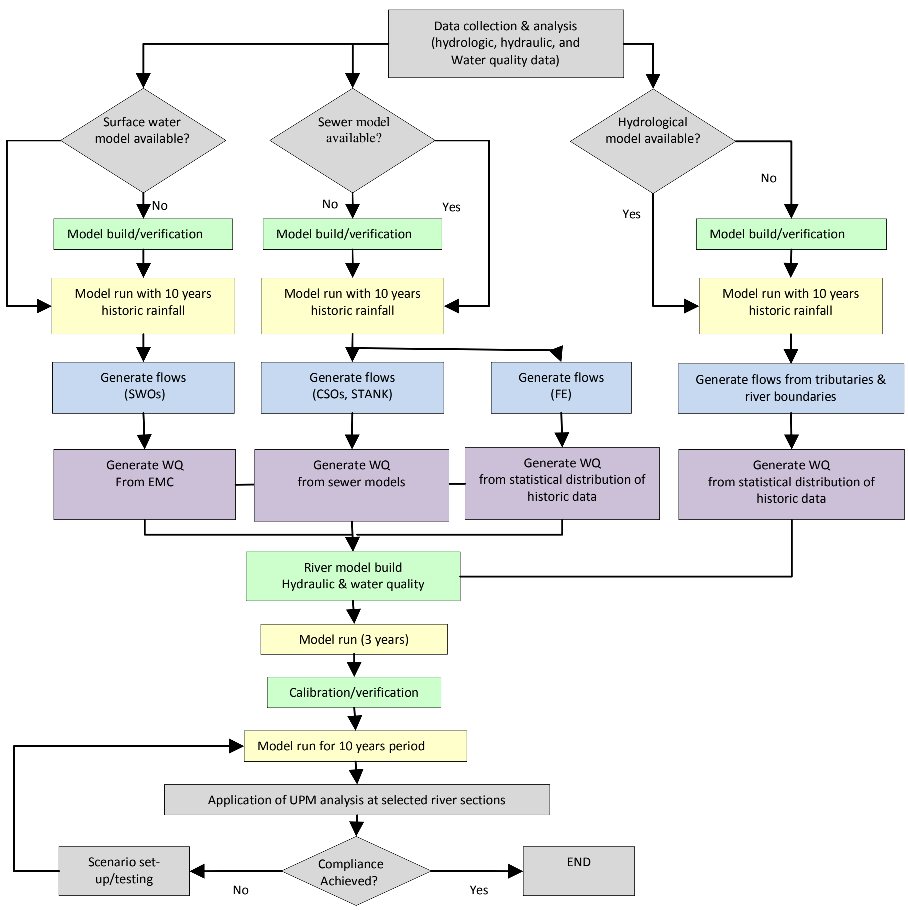

Figure 1. Integrated catchment modelling approach applied in river impact analysis

APPLICATION OF ICM TO THE IRK CATCHMENT

In this paper, the application of ICM approach is demonstrated on the Irk catchment. The catchment is located in the Manchester area in the North West of England. It is predominantly urban and covers an area of approximately 73.47 km^2. The River Irk from its sources to the confluence with the River Irwell was considered in this study in addition to the main tributaries, Whit Brook, Luzely Brook, Wince Brook, and Moston Brook. The Irk-ICM study area is shown in Figure 2.

Flow measurements were available at one gauging station (i.e. Collyhurst weir) located downstream of the catchment. To estimate flows at the river boundaries and tributaries, a rainfall-runoff model for the Irk River catchment was developed using the NAM Rainfall-Runoff of MIKE BASIN and calibrated against flow measurements at Collyhurst weir for the period 01/01/2005-31/01/2007. The Irk catchment was divided into 15 main sub-catchments and some of the sub-catchments were further divided into smaller sub-areas to better represent the distribution of rural runoff over the corresponding river reaches. In total, 33 sub-ctachments and sub-areas were considered.

The calibrated NAM model was run for the period 01/01/2005-31/12/2007 using historic rainfall to simulate the flows from the rural areas for each sub-catchment. A 15-minutes time step was considered for model run and 1-hour time step for the model output. In total, 33 time series of flows were generated and, subsequently, used as rural runoff inputs to the river model.

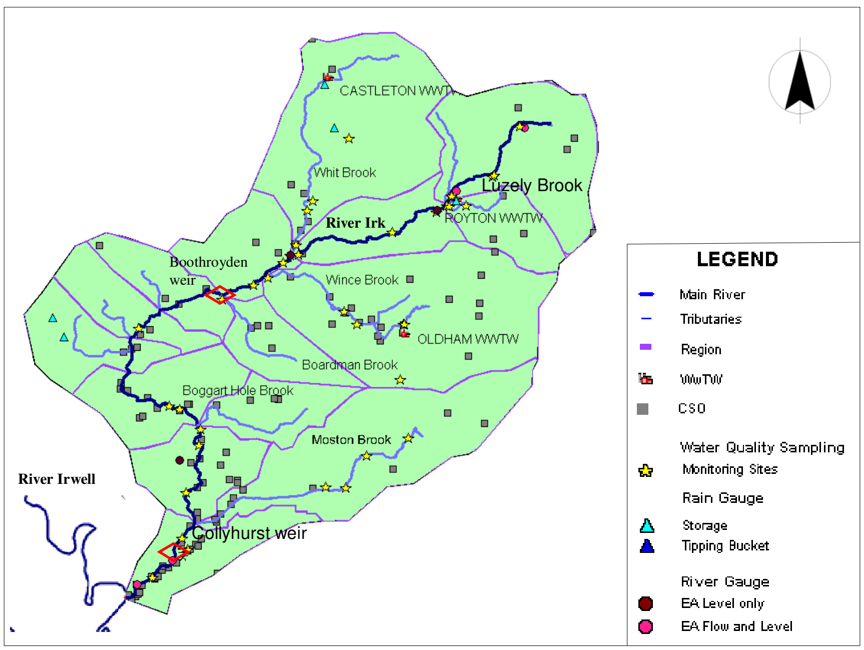

Figure 2. The Irk Catchment and the extent of the rivers considered in the ICM study.

Water quality at the river Irk boundaries and tributaries (i.e. rural runoff quality) were generated from historical data collected at the EA monitoring sites that are not affected by wastewater discharges. Only one monitoring site was found to match this criterion. Mean and standard deviation of Biochemical Oxygen demand (BOD), ammonia, dissolved oxygen (DO), pH, and temperature were computed from the historic water quality measurement at this site for summer and winter periods. These statistics were used to generate rural runoff quality input to the river model for the period 01/01/2005-31/12/2007.

Six Infoworks sewer network models were available for the urbanised areas in the Irk catchment and include 98 CSOs, Castleton, Royton, and Oldham WwTWs and storm tanks. The InfoWorks sewer models of the Irk were run with the 3-years rainfall data measured at Heaton Park and Royton raingauges to generate discharges from the CSOs. In this study, the CSOs were grouped in 22 groups based on their proximity and their location within the Irk sub-catchments. Flows and water quality from each CSO group were aggregated to 1-hour interval time series and used as input to the river model. The aim of CSO grouping was to reduce the number of input points to the river model and keep it manageable.

The WwTW hydraulics was modelled as part of the sewer models. The simulated flows from the WwTW's final effluents were used as hydraulic inputs to the river model. The load of the final effluent was characterised by the statistical distribution derived from historical data of BOD and ammonia available for Royton, Oldham, and Castleton WwTWs. Mean and standard deviation of BOD and ammonia were computed from historical data. A series of hourly water quality input that cover the period 01/01/2005- 31/12/2007 were randomly generated from the assigned distributions and used in the river model to represent BOD and ammonia loads from Castleton, Royton, and Oldham wastewater treatment works.

Simple surface water models were built in this study and run with the historical rainfall to simulate the runoff from urbanised areas for the period 01/01/2005-31/12/2007. The simulated discharges from the 17 outfalls in the model were aggregated to 1-hour interval time series and used as inputs to the River Irk model. To estimate the ammonia and BOD loads coming from the surface water, event mean concentrations for urban catchments were applied. These values were then used to generate time series of BOD and ammonia input to the river model for the period 01/01/2005- 31/12/2007.

Hydraulic and water-quality modelling of the River Irk and its tributaries (about 42.6 km of river reaches) was undertaken using the MIKE BASIN computer model. In the MIKE BASIN model, the River Irk and its tributaries were divided into a number of computational reaches, each of which is limited by two nodes. Discharges and pollutant loads from different sources were given as time series inputs at the model nodes. In total the model included 118 nodes, 117 reaches and 65 discharge points. The MIKE BASIN model network of the River Irk is shown in Figure 3.

The MIKE BASIN model of the River Irk was calibrated to the available flows and water quality measurements (i.e. BOD, ammonia, and dissolved oxygen) for a period of 3 years (01/01/2005-31/12/2007). Six locations on the river Irk and its tributaries were considered for the model calibration (Figure 3). Simulated flows at the outlet of the Irk catchment were verified against available flow measurements at Collyhurst Weir for the period 01/01/2005-31/12/2007. The statistical index of model efficiency (E_f) defined by Nash and Sutcliffe (1970) is used to assess model performance. A 78% Nash-Sutcliffe model efficiency was obtained for the considered calibration period indicating a good model performance. The difference in total water balance between measured and simulated flows for the calibrated period based on the MIKE BASIN results was 4%, which indicates a good flow calibration results.

Calibration of the simulated BOD, ammonia, and dissolved oxygen concentrations against measured data at the six considered monitoring sites was also satisfactory. A good fit was obtained between measured and simulated BOD, ammonia, and dissolved oxygen concentrations at almost all sites for the calibration period. Overall the model provided a reasonable representation of the water quality processes in the River Irk and its tributaries.

Further to model calibration, the model was verified against flow and water quality data collected during three wet weather events in 1999 at five locations (Figure3). This data was collected for the original UPM study. The verification results showed that the calibrated model was adequate to represent flows and water quality of the River Irk and, thus, can be used with a reasonable level of confidence to assess the compliance of the river to water quality standards and to identify adequate solutions (e.g. storage volumes required at key CSO locations).

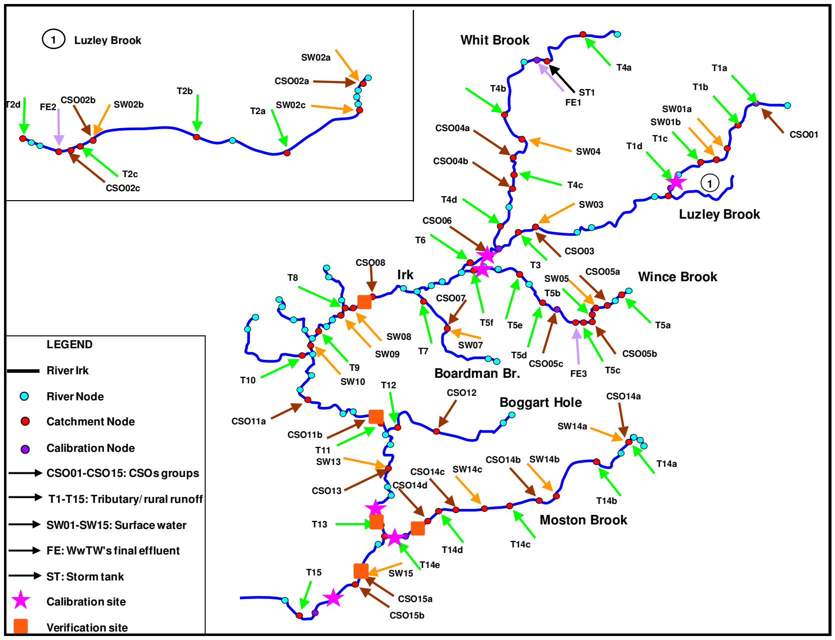

Figure 3. Schematic representation of the MIKE BASIN model of the River Irk.

RIVER IMPACT ASSESSMENT AND SOLUTIONS

Based on the river quality objectives for BOD, ammonia, and dissolved oxygen, the River Irk and its tributaries are classified as RE4 class sustainable cyprinid fishery. The standards against which water quality of the River Irk was assessed are the 99-percentile standard (HPS) and the fundamental intermittent standard (FIS). Continuous simulations were carried out with the different models for a period of ten years (01/01/1998 to 31/12/2007) to determine performance against water quality standards.The river impact assessment was carried out on the river model output (i.e. hourly concentrations of BOD, ammonia, and dissolved oxygen for 10 years) at 82 locations along the River Irk and its tributaries. The River Impact Optimisation Tool (RIOT) developed at MWH was used in this study to analyse the outputs from the MIKE BASIN model.

The compliance assessment results based on HPS standards demonstrated that water quality of the River Irk from the confluence with Luzely Brook to the confluence with the River Irwell does not comply with the applied BOD standard. For the River Irk tributaries, the results obtained showed that the water quality of Whit Brook complies with HPS standards while Luzely Brook and Wince Brook fail in meeting HPS for BOD as illustrated in Figure 4.

The sections of Luzely Brook and Wince Brook that fail in meeting the standards extends from Royton and Oldham WwTW's final effluents and storm tanks to the confluence with the River Irk, respectively. The comparison of the river impact assessment results obtained at the downstream end of Luzely Brook and Wince Brook with those obtained for the Irk just upstream of the confluence with these tributaries highlighted the impact of the Royton and Oldham wastewater treatment works on the quality of the River Irk. For Moston Brook, the compliance assessment results obtained showed that the Brook fails to meet HPS standards for BOD from the upstream end to its confluence with the River Irk. This is mainly due to the discharge from the one combined sewer overflow in addition to the poor background quality of this Brook due to issues with leachate from former landfill sites.

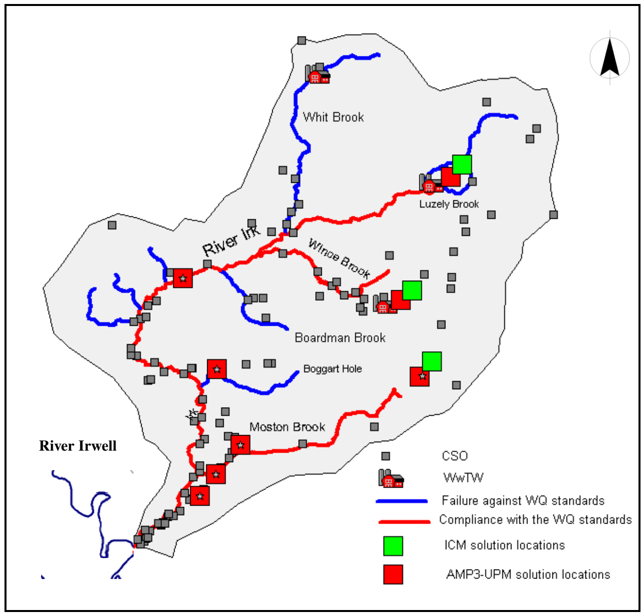

Figure 4. Extent of the river reaches failing the compliance against HPS standards and location of identified solutions

The compliance assessment based on the FIS standards for summer conditions (i.e. May-September of the 10 considered years) showed that all locations on the River Irk and its tributaries meet the standards.

Based on the river impact analysis results, solutions for the critical CSOs discharging to the River Irk and its tributaries were identified. The comparison between the solutions identified with the ICM study and those obtained with the AMP3 UPM study demonstrated that the storage volumes identified at the downstream part of the River Irk with AMP3 UPM analysis were revealed to be not necessarily required. The ICM solution resulted in a total storage volume of 2000m^3 at a single site against 10, 650m^3 at six sites identified with the AMP3 UPM methodology, plus further work required at Oldham and Royton storm tanks.

The ICM study showed that the water quality of the River Irk is driven by the quality of the tributaries Luzely Brook and Wince Brook to which Royton and Oldham WwTWs discharge, respectively. Therefore, solutions at these locations are required. It should be pointed out that a preliminary assessment of the storage volumes for Royton and Oldham storm tanks was undertaken in this study but they will be refined prior to their implementation by undertaking further detailed analysis in AMP5.

CONCLUSIONS

The impact assessment of 98 combined sewer overflows (CSOs) on the downstream part of the River Irk was undertaken in AMP3 using the UPM approach. The study predicted the requirement for storage tanks at six CSOs locations with a total volume of 10,650m^3. To review investment requirements identified in AMP3 study, a new river impact analysis was carried out in AMP4 on the Irk catchment using the ICM approach. The main findings and conclusions obtained from the application of the ICM approach to the Irk catchment can be summarised as follows:

1. The use of hydrological modelling to derive flows at river boundaries and ungauged tributaries resulted in better representation of river flows than those applied in AMP3 UPM study (i.e. randomly generated from available statistics). Moreover, the consideration of the runoff from about 33 sub-catchments within the Irk river-basin allowed better consideration of the variation of river flows along the studied reach and, thus, better representation of river dilution.

2. By accounting for the spatial distribution of pollution sources and the first order decay of the contaminants in the river model, the impact of individual pollution sources on the quality of the River Irk could be identified.

3. The use of continuous simulation and historical rainfall to drive all run-off sources allowed a more representative analysis to be made.

4. With the detailed modelling approach, more locations along the River Irk were considered in the river impact analysis. This allowed examination of the compliance of more sections than the four reaches considered in AMP3 UPM study (i.e. 82 river sections were assessed in the ICM study).

5. Since the AMP3 UPM study was focused on the downstream part of the Irk using the boundary conditions at Boothroydon weir, the real impact of Royton and Oldham WwWTs on the River Irk could not be identified. The use of ICM approach and the analysis of the whole watercourse was allowed these upstream inputs to be better understood and presented potential for adaptive capital works.

Overall, the results obtained from this study demonstrated that the application of the ICM approach allowed a better understanding of water quality issues within the watercourse, leading to more focussed solutions. The experience gained from this ICM study and the previous ICMs carried out by MWH for United Utilities (Rossendale, Rochdale and, Manchester Ship Canal) will be of help in future studies. Due to the success of these earlier studies, a number of ICM studies covering ten river catchments in the North West of the UK are included in AMP5 and being carried out by United Utilities. The outcome of these studies will demonstrate whether integrated modelling would be an optimal approach to achieve sustainable, cost-effective management of urban drainage systems.

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