West Indian Journal of Engineering Vol. 24, No. 2, (January 2002) Technical Paper (Baban & Foster) 1 - 15

Modelling Water Flow and Water Quality: An Evaluation of the ISIS Model in the River Avon, United Kingdom

S.M.J. Baban*
& I.D.L. Foster**

A conceptual deterministic hydrodynamic-water quality model, ISIS, was used to simulate flow in the Warwickshire River Avon, UK under a range of flow conditions. ISIS was also used to assess the impact of flow on water quality under each flow condition. The mid Avon section receives high nutrients (nitrogen and phosphorous) loads from 3 major sewage treatment works as well as from diffuse sources leading to the growth of planktonic blooms. The approach in this study was based on the assumption that any reduction in river velocity may result in lower dissolved oxygen concentrations and provide opportunities for planktonic blooms. The ISIS model consists of two components, ISIS-Flow and ISIS-Quality. ISIS has a well-established flow routing component and provides an opportunity to examine water quality, sediment and nutrient transport and the biological response of the River Avon to nutrient availability. Furthermore, it enables interactions between bed-sediments and the water column to be predicted.

ISIS-Flow was found to accurately predict flow variations at two stations (Warwick and Stratford) located on the river network. ISIS-Quality output provided a reasonable outcome in terms of predicting DO, BOD, Total Nitrogen. Ammoniacal Nitrogen and Nitrate-N. A sensitivity analysis for ISIS-Quality revealed that only changes in the temperature dependency factor and nitrogen decay parameters had a significant impact on the predicted output of the Dissolved Oxygen module. Evaluations regarding the user friendliness of the model, as well as specific evaluations regarding the ability of the model to predict water quality in the Avon, are also presented.

1. Introduction

Most practicing engineers and scientists view hydrologic models as tools capable of providing the necessary quantitative description of hydrological processes required for water resources and water quality planning and river engineering. Models should be robust, effective and easy to understand and use, yet complex enough to be representative of the system being studied (Anderson and Burt, 1985).

Flow models usually simulate steady-state, one-dimensional flow: the quantities of flow are assigned, and water passage is ideal plug-flow with neither longitudinal dispersion nor lateral dispersion (Hammer and Kichan, 1981). These models are based on the assumption that the hydrological cycle is fundamentally the same in all drainage basins and the magnitude of parameters influencing runoff varies with climate, geology, soils and topography. Hence, concurrent stream-flow and climate records are required for calibration. Many models have been developed to address water flow. These include the Great Ouse Resource Model, which is a semi-distributed model of the hydrological processes within the catchment (Oakes and Keay, 1990). Three hundred and ninety-two (392) reaches, linked together at node points, represent the river system. The inflows and outflows for each reach are calculated then accumulated so that the flows can be determined at every node in the model. The main outputs are flow duration statistics, which synthesise the effects of all upstream changes and summarise alterations to the flow regime. The abstraction and discharge

---

* The Centre for Caribbean Land and Environmental Appraisal Research (CLEAR), Department of Surveying and Land Information, The University of the West Indies, St. Augustine, Trinidad and Tobago, West Indies.

** Geography, School of Science and the Environment, Coventry University, Coventry CV1 5FB, United Kingdom.

Pertinent discussion will be published in January, 2003 West Indian Journal of Engineering if received by November, 2002.

data can be modified for simulating expected future changes. Another example is the ONDA model, which is a mathematical hydraulic model. Open Channels are represented by their cross sections and roughness coefficients, and flows are calculated using the St Venant equations for the conservation of mass and momentum (Gardiner et. al 1987).

Water quality models are usually developed to simulate a specific type of river-quality problem. Examples include simulating dissolved oxygen levels at various points along a river system. This is done by modelling the interactions of physical and biological processes affecting oxygen demand. These models are generally developed for steady-state flow regimes and assume that longitudinal dispersion is insignificant. Examples include QUAL-II, which is mainly based on modelling interactions between biochemical oxygen demand (BOD) and oxygen. It is applicable to well-mixed dendritic stream systems and can predict both the temporal and spatial variations of up to 13 water quality parameters in any combination required by the user (Roesner *et al*, 1981). QUAL-II is suited for scenario testing and was used as a screening model to identify and assess pollutants likely to affect water abstraction from a river (Clark *et al*, 1986).

Water quality models can only function in association with flow models, which usually provide the necessary hydrodynamics. This dependency usually adds a level of complexity to hydrological models. For example, contaminant transport models must be underpinned by reliable modelling of the regional flow to which are added equations representing the advection, dispersion and chemical reaction of the determinand being modelled (Hammer and Kichan, 1981; Fawthrop, 1994). Using these models for managing surface water requires an understanding of how water quality will respond to, and be affected by, various management actions, such as effluent reductions or low flow augmentation.

This study, which was sponsored by the Environment Agency in the UK, aims to use and evaluate the ability of a coupled hydrodynamic-water quality model (ISIS) to simulate water flow in the Mid Avon (Warwickshire, UK) under different conditions and to assess the impact of flow on water quality under each condition within the study area.

1.1 Software Availability

Name of Software:	ISIS
Contact address:	Sir William Halcrow & Partners Ltd. Buderop Park, Swindon, Whltshire SN4 0QD, UK.
Tel:	+44 (0) 1793 812470
Fax:	+44 (0)1793 812089
Platforms required:	PC s or UNIX
Hardware required:	PC 486 (or higher), 40 MB
Software required:	(For PC's) Windows 3.x and DOS 5.0 (or higher) (For UNIX) Windows MOTIF.
Programme size:	10 MB
Availability and Cost:	Contact developer

2. Study Area/Background Information

The Warwickshire River Avon upstream of Evesham drains an area of 2210 km^2. It is located in a lowland (< 150 m above Ordnance Datum), predominantly agricultural area and has a mean annual discharge at Evesham of ca. 15.2 m^3 s^{-1} (1313 million litres per day) (NRA, 1992). Annual rainfall for the basin ranges from 720 mm in the north-east to 599 mm in the south, and average effective rainfall ranges from c. 250 mm to less than 150 mm year-1.

This study was mainly concerned with the Mid Avon section beginning at Stoneleigh and Stare Bridge and ending at Stratford **(Figure 1)**. These reaches receive high nutrient (nitrogen and phosphorous) loads from 3 major sewage treatment works (Finham, near Kenilworth, Rugby, east of Coventry, and Warwick) as well as from diffuse sources (Foster *et al.*, 1996). These reaches also include the first point in the River Avon system (Barford) **(Figure 1)** where planktonic blooms, defined as locations where chlorophyll a concentrations exceed 100mg/m^3, leading to diurnal variations in dissolved oxygen concentrations (Foster *et.al*, 1997).

The approach in this study was based on the assumption that any reduction in river velocity may result in lower dissolved oxygen concentrations and provide opportunities for the inoculation of blue-green algae which

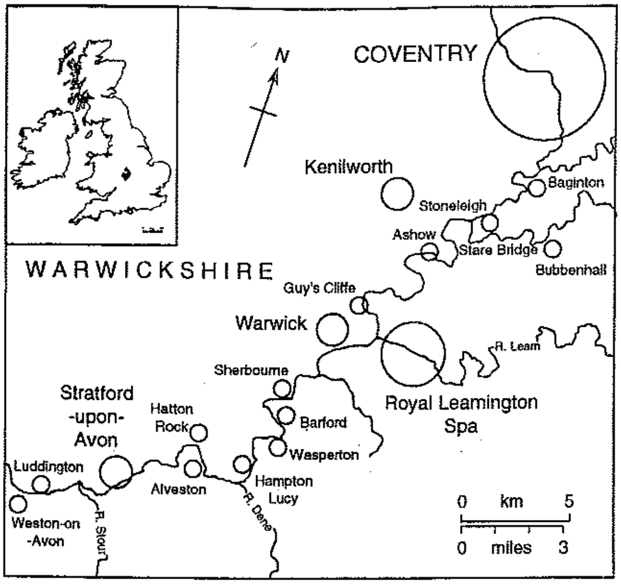


FIGURE 1: *Study Area*

cannot accumulate in large numbers in fast flowing waters (Reynolds, 1994). Dissolved Oxygen was chosen as an indictor for water quality because it is used in the decay of organic matter and the nitrification of ammonia and is added to the river by re-aeration. Moreover, the Biochemical Oxygen Demand (BOD) represents the potential utilisation of dissolved oxygen (DO) by microbes to metabolise organic matter (Shaw, 1983). The rate of oxygen use also depends on the concentration of organic and ammoniacal nitrogen. The ISIS model provides facilities to input all these variables (either measured or estimated) at the upstream boundary of each hydraulic unit within the river (**Figure 1**).

3. The Model

ISIS is a conceptual deterministic hydrodynamic-water quality model, developed by Sir William Halcrow and Partners and Hydraulics Research Wallingford (ISIS-Flow, 1995; ISIS-Quality, 1996). ISIS has a well-established flow routing component and provides an opportunity to examine water quality, sediment and nutrient transport and the biological response of the River Avon to nutrient availability. Furthermore, it enables interactions between bed-sediments and the water column to be predicted.

In the context of management, ISIS has the potential benefits of enabling water managers to predict the consequences of various management scenarios (for example changes in water flow, effluent discharge or urban storm drainage on water quality, nutrient and sediment transport and the biological response of river systems). An added advantage for using ISIS was the fact that ISIS requires and accepts data readily available to the research team without much modification. ISIS has two main components; ISIS-Flow and ISIS-Quality, which are described in detail below (**Figure 2**).

3.1 ISIS-Flow

ISIS -Flow calculates flow depths and discharges in open channel networks using a finite difference solution to the Saint Venant equations, which expresses conservation of mass and momentum in rivers. The river network is represented in the model as a series of hydraulic unit 'cross-sections' that can incorporate a large number of structures, such as weirs, sluice gates, bridges, tributary inputs and bifurcation in the river network. At every point that water flows into the river, termed a 'node', detailed boundary condition data are required. In addition, a downstream boundary condition is required for ISIS-Flow simulations. Both steady and unsteady flow can be modelled. To run an unsteady flow, the initial conditions for every node in the model have to be set. These initial conditions can be obtained by carrying out a steady run at the proposed start time. The solution of the equations within ISIS depends on the definitions of the boundary conditions and the hydrodynamics of the river network. The basic ISIS-Flow output consists of flow, stage, Froude number and velocity.

3.1.1 Conceptual Foundation

Unsteady flows for the hydraulic units are calculated according to the hydraulic equations for each unit, which contain both empirical and theoretical components. The non-linear equations are first linearised and afterwards all the equations are solved by matrix-inversion (ISIS-Flow User Manual, 1995). The discharges are calculated by using a finite difference approximation of the Saint Venant equations that are based on the following assumptions as set out by Cunge *et al.* (1980):

(i) The flow is one dimensional i.e. the velocity is uniform over the cross section and the water level across the section is horizontal.

(ii) The streamline curvature is small and vertical accelerations are negligible, hence the pressure is hydrostatic.

(iii) The effects of boundary friction and turbulence can be accounted for through resistance laws analogous to those used for steady state flow.

(iv) The average channel bed slope is small so that the cosine of the angle it makes with the horizontal may be replaced by unity.

Saint Venant equations handle the conservation of mass and momentum, which establishes a balance between the rate of rise of water level and wedge and prism stages (ISIS-Flow User Manual, 1995). Conservation of mass is expressed by the continuity equation:

$$\delta Q / \delta x + \delta A / \delta t = q \qquad (1)$$

where: Q = flow (m^3/s)
A = cross section area (m^2)
x = longitudinal channel distance (m)
t = time (s)
q = lateral inflow ($m^3/s/m$)

The conservation of momentum is expressed by the momentum equation, which establishes a balance between interia, dispersion, gravity and friction forces;

$$\delta Q / \delta t + \delta / \delta x(\beta Q^2 / A) + gA\,(\delta H / \delta x) - g\left(AQ|Q|\right) / K^2 + q \cos\alpha\left(Q / A\right) = 0 \qquad (2)$$

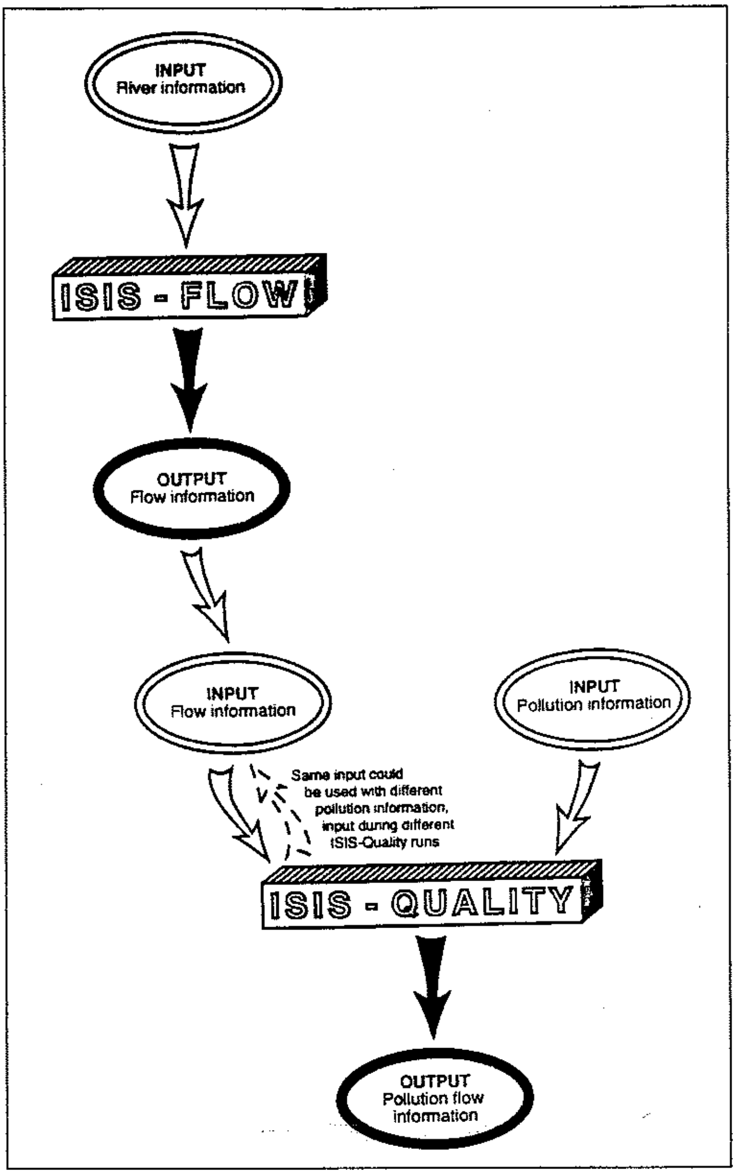


FIGURE 2: *Running ISIS Flow and ISIS Quality*

where:
H = water surface elevation above datum (m)
β = momentum correction coefficient
g = gravitational acceleration (m/s^2)
α = angle of inflow
K = channel conveyance
n = Manning's roughness coefficient
R = hydraulic radius = A/P (m)
P = wetted perimeter (m)

The equations used at junctions between channels are those defining flow continuity:

$$Q_1 + Q_2 + Q_3 + \ldots\ldots = 0 \qquad (3)$$

and the equality of water surface level:

$$h_1 = h_2 = h_3 \qquad (4)$$

3.2 *ISIS Quality*

ISIS Quality has been designed to be used for modelling the water quality in the same open channel network. ISIS-Quality is separate from ISIS-Flow and water quality simulations require the running of ISIS-Quality after an ISIS-Flow analysis has been completed.

ISIS-Quality uses the output from ISIS-Flow as an input to model the concentrations of water quality variables or 'pollutants' within the network. Multiple runs of ISIS Quality can be undertaken using the same input from ISIS-Flow. The pollutant transport mechanism is computed by using a finite difference approximation to what is referred to in the manual as the one-dimensional advection-diffusion equation (ISIS Quality User Manual, 1996). This terminology could be misleading, as the dominant transport mechanism is dispersion and not diffusion. However, it is not unusual to use the diffusion process to represent the process of dispersion within one-dimensional water quality models (Crockett, 1994). A more appropriate term to describe the mechanism is perhaps advection-dispersion.

Although ISIS Quality is a depth averaged model for mud transport and water quality modelling, an individual stream element is divided into four vertical components. **(Figure 3)**;

i) Water column: the main body of water through which dissolved and suspended solids are transported.

ii) River bed: the consolidated mud that has settled out of the water column and can be re-suspended.

iii) Fluffy layer: the layer of mud on top of the consolidated bed, initially receiving settled matter.

vi) Pore water: water trapped within the pores of the bed.

In terms of interactions, the contents of the fluffy layer can interact biochemically with the water column. The material in the bed and pore water can interact but are

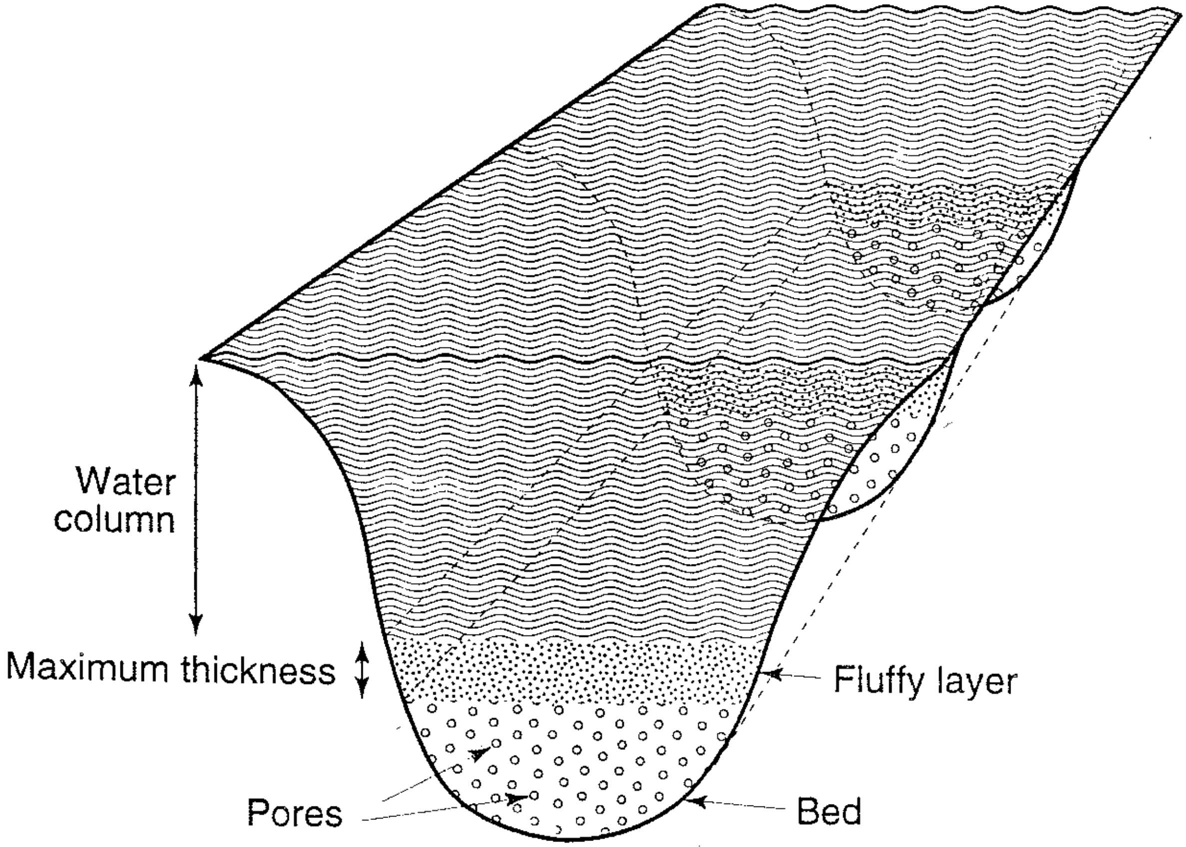


FIGURE 3: *ISIS-Quality Subdivisions of a Channel to Water Column, River Bed, Fluffy Layer and Pore Water (Adapted from ISIS Quality, 1996)*

isolated from the water column until resuspended. Erosion of the fluffy layer and bed material returns their contents and that of the pore water to the water column.

Boundary conditions for modelled water quality parameters, either estimated from literature values or derived experimentally using water and sediment samples, must be entered for each upstream boundary node. ISIS can model a range of water quality parameters and processes simultaneously including; conservative pollutants, decaying pollutants, coliforms, salt, water temperature, sediment, Oxygen balance (ultimate BOD), Phytoplankton, Macrophytes, Benthic Algae and pH.

ISIS-Quality is set up in a modular format, enabling various processes to run separately. However, some variables and processes are interlinked and interact with each other and consequently they will not run in isolation. The Phytoplankton module, for example, cannot be run without the Oxygen module (**Figure 3**).

3.2.1 Conceptual Foundation

The transport of pollutants in the river network is calculated by the one-dimensional convection-dispersion equation (ISIS Quality User Manual, 1996):

$$\delta(CA) / \delta t = -\delta(\mu CA) / \delta x + \delta(DA(\delta C / \delta x)) / \delta x + S \qquad (5)$$

where:
C = pollutant concentration (kg/m^3)
A = cross-sectional flow area (m^2)
u = cross-sectional average flow velocity (m/s)
D = dispersion coefficient (m^2/s)
X = distance (m)
t = time (s)
S = source/sink term; representing decay, growth, erosion, deposition etc. (kg/m/s)

This equation is a statement of the conservation of mass. The first term is the rate of change of pollutant at a point. The second term is the advection mass transport. This is then balanced by the third term, the dispersion term, which represents the flux of a pollutant out of a small unit of fluid travelling with the flow. The equation is one-dimensional and therefore all variables represent cross-sectional averages. Equation 5 is solved numerically (as an effect of variations in the physical configuration of the river network (x) and time (t)). In ISIS-Quality, the saturated dissolved oxygen concentration (DOS) is determined as a function of temperature and salinity and re-aeration is represented by the equation:

$$\delta DO / \delta t = K_{air} (DOS - DO) \qquad (6)$$

where:
DO = dissolved oxygen concentration (mg/l)
K_{air} = re-aeration coefficient (s^{-1})

K_{air} can be approximated as a function of cross-section dimension, temperature and the parameter f^{air}, which represents the rate at which oxygen penetrates the water column:

$$K_{air} = f_{air} B/A \qquad (7)$$

where:
f_{air} = transfer velocity (m/s), it is a function of the temperature
B = water surface width (m)
A = cross sectional area of flow (m^2)

Alternatively, it can be estimated using three empirical equations that consider water depth (d) and velocity (u) (ISIS-Quality User Manual, 1996):

Owen's equation (for $d \leq 2.12$):

$$K_{air} = 5.33u^{0.67} d^{-0.85} \qquad (8)$$

O'Conner and Dobbin's equation

$$K_{air} = 3.93u^{0.5} d^{0.5}$$

$$\text{(for } d \leq 2.12 \text{ and } u \leq 1.68d^{0.3689} - 1.433\text{):} \qquad (9)$$

Otherwise, the Churchill equation is used:

$$K_{air} = 5.02u^{0.969} d^{-0.673} \qquad (10)$$

The decay of organic material is described by first order kinetics:

$$\delta C / \delta t = -KC \qquad (11)$$

Where:

K = reaction rate constant (s^{-1})
C = concentration of organic material (kg/m^3)

The reaction rate is a function of temperature:

$$K_\theta = K_{20} (1 + \alpha / 100)^{\theta - 20} \qquad (12)$$

where: K_θ = rate constant (s^{-1}) at θ^0C

K_{20} = rate constant (s^{-1}) at 20^0C

α = temperature dependence factor.

ISIS calculates the ultimate BOD, which has been divided to fast BOD and slow BOD to account for different rates of metabolism by different types of material, rather than the standard five-day BOD according to the following formula:

$$BOD_U = BOD_5 / (1 - [(1 - \psi) \exp(-5k_f) + \psi \exp(5k_s)]) \quad (13)$$

where: Ψ = proportion of slow BOD
k_f = reaction rate constant for fast BOD
k_s = reaction rate constant for slow BOD

When the oxygen concentration falls below 5% saturation, both nitrate and nitrite can be used as sources of oxygen. The equation for nitrate concentration is:

$$\delta NO_3 / \delta t = -0.35(NO_3 / (NO_3 + NO_2)) \quad (14)$$

The equation for nitrite is:

$$\delta NO_2 / \delta t = -0.58(NO_2 / (NO_3 + NO_2)) \quad (15)$$

The net rate of change in dissolved oxygen concentration is calculated according to the formula:

$$DO / \delta t = K_f BOD_u(fast) - K_s\ BOD(slow) - 3.43K_{am} AM - 1.14NO_2 + K_{air}(DOS - DO) \quad (16)$$

4. Application to the River Avon

4.1 Preparations For and Use of ISIS

In order to reduce the runtimes on the PC platform used (Pentium with 16 MB RAM, 90 Mhz processor and SCSI 1.0 GB hard disk drive) to run ISIS, the study area was divided into two sections. Section 1 included the river Avon between Stare Bridge and Warwick and section 2 included the river section between Warwick and Stratford **(Figure 4)**. These sections correspond to discharge/stage measurement locations. The output obtained at Warwick from the first section serves as an upstream boundary input for the second section.

4.1.1 ISIS-Flow

The Mid River Avon hydraulic unit data consisted of 550 river cross sections which were provided by the Feasibility and Modelling Section of the UK Environmental Agency. In order to evaluate the model under a range of flow conditions, periods representing critical high and low flow conditions were examined. High flow events occurred in January and September while low flow conditions occurred in June. Consequently, three representative periods were chosen for modelling which were; 23.01.1995 to 02.02.1995, 20.06.1995 to 30.06.1995 and 05.09.1995 to 21.09.1995. The first and the last day in each period corresponded with days on which weekly water quality data were available.

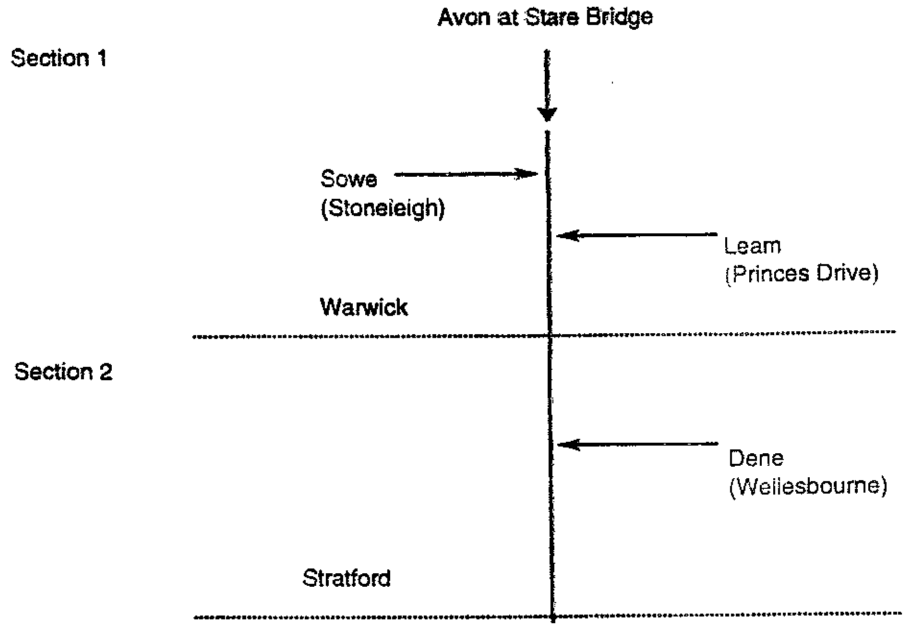
ISIS-Flow requires carrying out a steady state analysis first and results from this run are subsequently used as initial conditions for the unsteady analysis. To carry out an unsteady analysis, the start time and finish time have to be given; this period must be covered in all the boundary node's time series. In addition, a time step has to be selected. This can be problematic, as a smaller time step will extend the run time, whereas a larger time step will result in a poor model convergence. During this project, the recommended time step of 20 seconds was found to be effective. The interval for saving the data can also be set (as a multiple of the time step). The runtime on a PC platform could be very long, depending on the number of nodes and hours involved in each run **(Table 1)**.

TABLE 1: *ISIS-Flow Runtimes on a PC Platform (Pentium with 16 MB RAM, 90 Mhz Processor and SCSI 1.0 GB Hard Disk Drive*

Number of Nodes	Number of Hours	Runtime
140	260	75 min
140	400	90 min
400	260	180 min
400	400	200 min

4.1.2 ISIS-Quality

ISIS-Quality uses the stored hydrodynamic data from the previous flow run. As with a flow run, the start and end time, as well as the time step, has to be chosen in order to run ISIS Quality. The recommended time step of 2 seconds resulted in long run times for the files for which ISIS-Flow was previously run. After experimentation, a time step of 10 seconds was found to be effective. As in ISIS-Flow, the length of runtimes is dependent on the number of nodes and hours involved in each run **(Table 2)**.



Available data at boundary nodes:

Stare Bridge	Continuous discharge	Weekly quality
Sowe	Continuous discharge	Continuous quality
Leam	Continuous discharge	Continuous quality
Warwick	Continuous stage	
Dene	Continuous discharge	Weekly quality
Stratford	Continuous stage	Weekly quality

FIGURE 4: *Simplified Schematic Diagram of the Modelled Mid Avon Reach*

4.2 *Model Validation*

In this project, model validation was defined as the ability of the ISIS model to predict and explain observed variations in water flow and water quality within the studied sections of the Mid River Avon (**Figures 1** and **4**).

4.2.1 *ISIS-Flow*

During the early stages of this research project, a file with 500 nodes was run for a whole month. The stage in the river was measured at Warwick and Stratford stations along the river network. These two points were used to validate the model results from ISIS-Flow. **Figures 5** and **6** show the observed and the predicted river stages at these two points. The statistics for the model fit at Warwick show a very good correspondence between field measurements and predicted values ($r^2 = 0.859$). In fact, the levels of explained variance exceed 85% and the standard error of estimate (rms = 0.013) is small. Therefore, the model emulates reality well and manages to predict river stages in the network with an acceptable degree of success. The occasional periods of model instability at Stratford (**Figure 6**) decreased when the network was divided into smaller parts and the model was run for shorter periods. However the over prediction of stage values remained unchanged.

TABLE 2: *ISIS-Quality Runtimes on a PC Platform (Pentium with 16 MB RAM, 90 mhz Processor and SCSI 1.0 GB Hard Disk Drive*

Number of Nodes	Number of Hours	Runtime
140	260	120 min
140	400	180 min
400	260	210 min
400	400	270 min

4.2.2 *ISIS-Quality*

The following data sets were used directly or indirectly to extract the necessary information for running ISIS Quality in the following way:

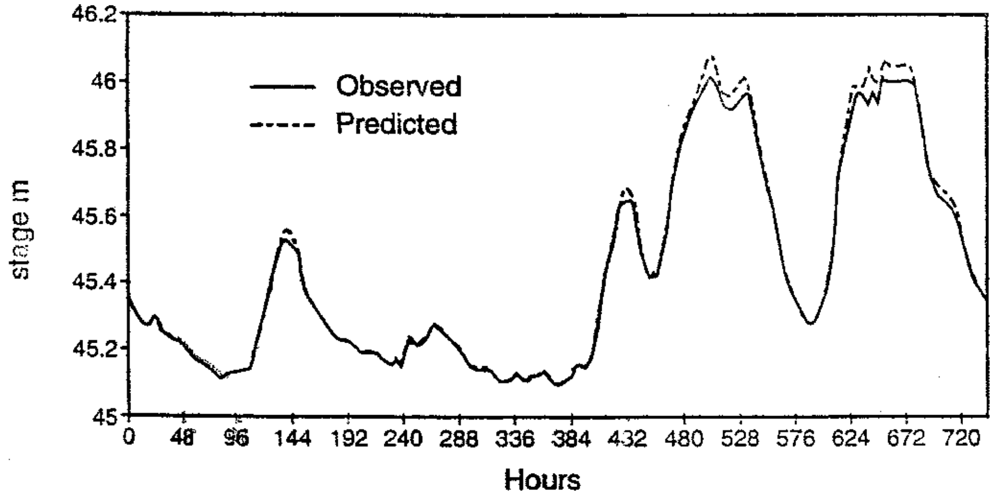


FIGURE 5: *Predicted and Observed River Stage at Warwick*

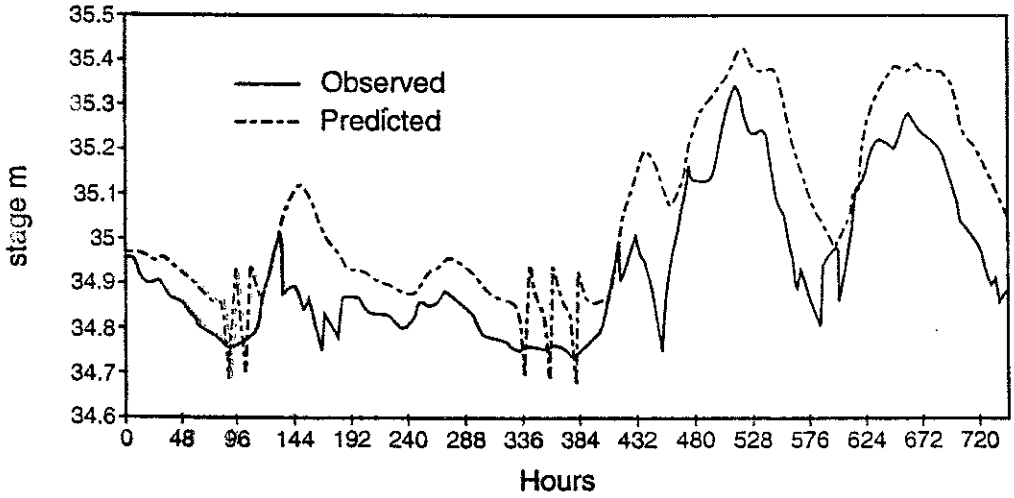


FIGURE 6: *Predicted and Observed Stage at Stratford, showing Periods of Model Instability*

i) Continuous BOD and nitrogen measurements for November 1994 and 1995. As no measurement of either parameter was available for November 1996, the mean value of these parameters in 1994 and 1995 was calculated and used as estimates for November 1996.

ii) No data regarding the River Dene were available. Mean values from previous years were used.

iii) Since no continuous water quality parameters were available for testing and evaluating ISIS quality components, comparisons of predicted DO, BOD, Total Nitrogen, Ammoniacal Nitrogen and Nitrate-N were undertaken at Stratford and Barford for the January 1995 data set, where limited data were available from another project. The results are presented in **Figures 7** and **8**. While it is not appropriate to evaluate these predictions against a single observed data point at Stratford and two points at Barford, the outcome is sufficiently encouraging to suggest that further modelling with continuous data or data derived from more frequent sampling would be worth actively pursuing.

4.3 Sensitivity Analysis for ISIS-Quality

In order to establish a better understanding of the ISIS-Quality performance, a sensitivity analysis was carried out. In this analysis, the impacts of different parameters on the output values of dissolved oxygen from the model were

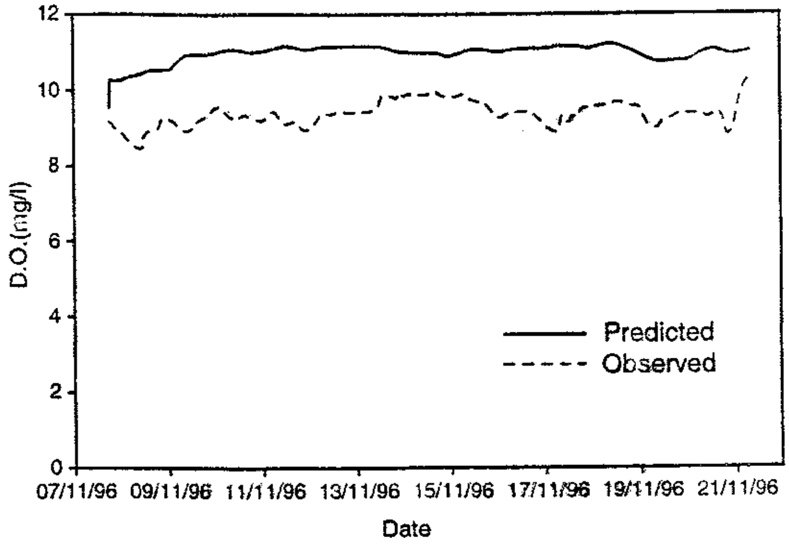


FIGURE 7: *Predicted and Observed Dissolved Oxygen at Stratford*

evaluated. The input values used are general parameters used in dissolved oxygen calculations (**Table 3**). The biochemical oxygen demand (BOD) decay parameter (rkb20) was set to 0.3, the BOD5 decay parameter (sbrate) was set to 0.75 and, the organic nitrogen decay parameter (snarate) was set to 0.75. Next, the input values were changed to maximum and minimum values from available published literature (**Table 3**), and a ± 25% change in the input value was used. The output of a sensitivity analyses for the Oxygen module of ISIS shows that only changes in the value of the temperature dependency factor (alpair) and the rkb20 have a significant impact on the predicted output (**Table 4**). It is important to indicate that this type of analysis does not account for the importance of interactions between variables nor the implications of data inaccuracy with respect to their impact on overall (**Table 3** and **4**) model error. Because the 'sensitivity' of a parameter is low, it may still be important to overall model performance (Anderson and Burt, 1985).

4.4 Model Evaluation

4.4.1 General Evaluation of ISIS-Flow

The User Manual for the model is comprehensive. It gives a clear, though brief, description of the theoretical basis of all the hydraulic units. The steps and choices that have to be taken to run the model are described stepwise in the manual in a user-friendly format.

The model is also supplied with general guidelines for assembling data files, examples illustrating data schematisation and procedures for concluding estimations for various parameters.

4.4.2 Specific Evaluation of ISIS-Flow

A large number of input parameters are needed to run ISIS-Flow for two reasons. First, channel geometry must be measured along the river. Therefore, cross-sections are required at relatively frequent intervals. Secondly, stage or flow has to be measured at every boundary node in the model. Besides these parameters, the parameters under *General System Parameters* that include number of nodes, tolerance parameter for the direct steady state solver and water temperature have to be set. Sufficient information on their values can be found in the hydraulic literature and the User Manual. For most of these parameters the ISIS-Flow model gives useful default values.

The maximum number of hydraulic units in ISIS-Flow is 1000. In order to keep a better overview of the files, it is recommended that the river network is divided into smaller sections. For example, if the model is being used to asses the consequences of different management strategies on a river network, it is recommended that the user isolate the sections that are subjected to these strategies, partition them into smaller sections, analyse them, and use the output from an upstream section as input for the downstream section.

Boundary conditions have to be set at every boundary point. The run times for the model during this project are long (**Table 1**). When aiming to compare different structures in the river network, this is a disadvantage, and it is advisable to use a faster PC or a network. Model evaluation indicates the success of ISIS-Flow in predicting the stage in the river network (**Figure 5** and **Figure 6**). It must be emphasised that building large files containing different

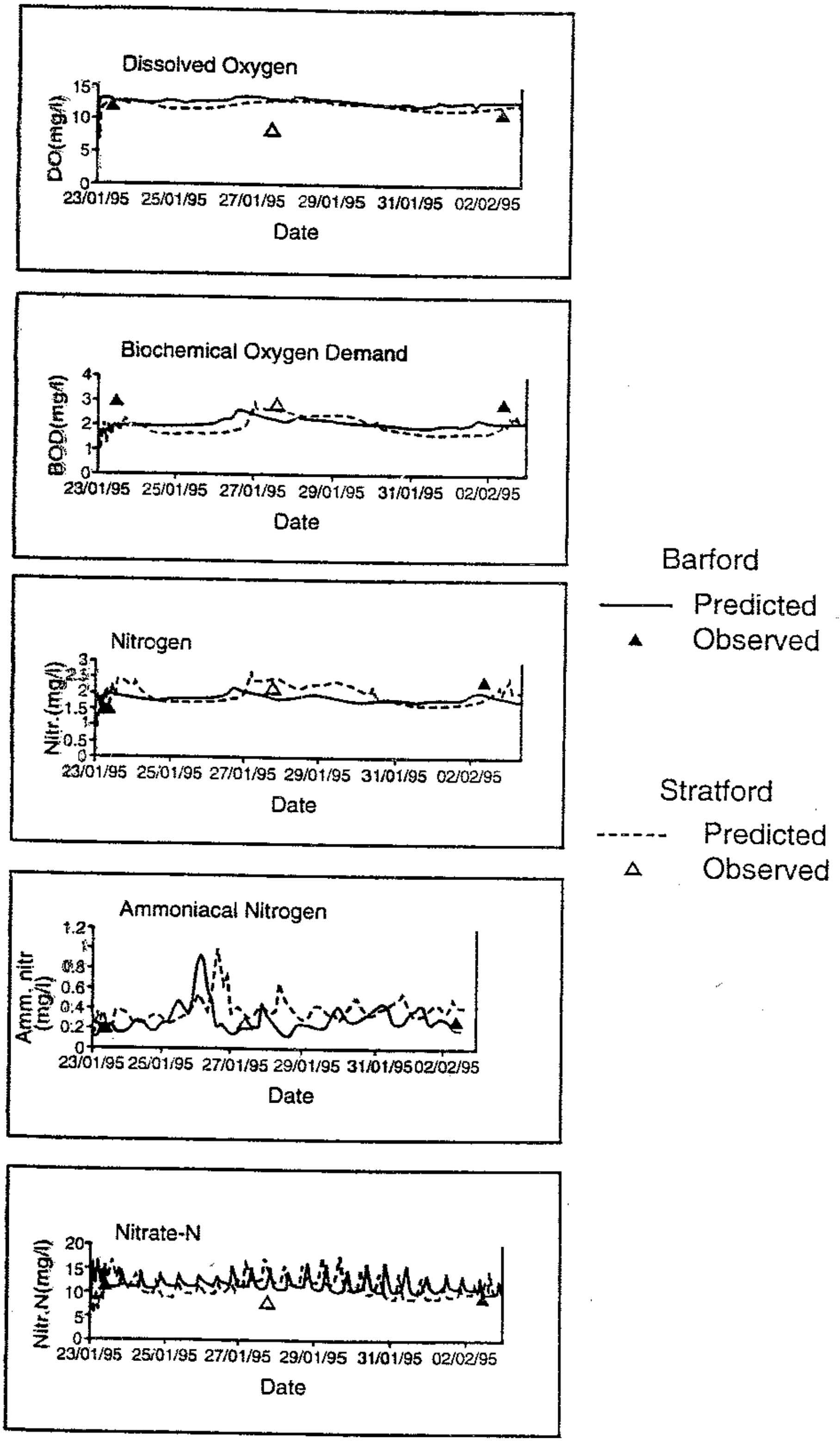


FIGURE 8: *Water Quality at Stratford and Barford in January 1995*

TABLE 3: *General Parameters used in Dissolved Oxygen Calculations based on the Literature*

Parameters	Calculated/Estimated Values
Rearation Coefficient (faircm) m hr^{-1}	Set negative to use empirical hydronamic equations
Temp. Dependency Factor (alpair)	1.008 - 1.047 (2), default 1.024 (l)
Addition Rearation Coefficient used for structures (constc)	0.03
BOD5 Decay Parameters	
Rate constant at 20°C day^{-1} (rkb20)	0.09 - 0.64 (2), 0 - 2.0 (4)
Temperature Coefficient (alphab)	1.047 (3)
Slow rate as fraction of fast rate (sbrate)	0.16 (based on full range of decay rates) -1.0
Organic Nitrogen Decay Parameters	
Rate constant at 20°C day^{-1} (rkb20)	0.04
Temperature Coefficient (alphab)	1.047 (3)
Slow rate as fraction of fast rate (sbrate)	0.16 - 1.0
Ammonia Oxidation Parameters	
Rate constant at 20°C day^{-1} (rkb20)	0.07 - 0.14 (2)
Temperature Coefficient (alphab)	1.083 (3)
Salinity Coefficient	1
Base Salinity	0
Suspended Solids Coefficient	1
Base Suspended Solids (SS)	0
Multiplication factor for base SS	0

types of structure is time consuming. This was not a problem in the current project as large amounts of secondary data were already available.

4.4.3 General Evaluation of ISIS-Quality

The ISIS-Quality model used was a beta release. Occasionally the names of the different parameters are confused in the manual for example, page 7 of the Dissolved Oxygen Module, Chapter 9, the parameter *faircm* is called the rearation coefficient, which is incorrect. This parameter represents the transfer velocity (in meters per hour). The pollutant transport mechanism is referred to as the one-dimensional advection-diffusion equation. This narration could potentially be deceptive as the dominant transport mechanism is dispersion and not diffusion. A more appropriate term to describe the mechanism is perhaps advection-dispertion.

The manual divides the Biochemical Oxygen Demand and Nitrogen into a fast and a slow component on the basis that different types of material are metabolised at different rates (ISIS Quality Manual, 1996). This is simulated in ISIS-Quality by using a fast rate and a slow BOD rate. However, no detailed information on this particular separation is given in the manual. According to the manual, there is an option to leave this differentiation out but this option was not found in the software. The manual needs to be expanded and should provide the user with more guidelines on the different parameters.

4.4.4 Specific Evaluation of ISIS-Quality

ISIS-Quality demands a large number of input values. For example, all the boundary nodes and all the water quality processes and boundary conditions have to be set. The initial conditions for every node also have to be set.

All water quality parameters have to be measured at each boundary node. Different water quality processes require a large number of parameters. Unfortunately, the Manual does not give useful guidelines or references to the published literature for these values.

ISIS-Quality could not provide a solution for a river network containing a large number of structures. Therefore, when planning to run this model after the ISIS-Flow run, it

TABLE 4: *Sensitivity Analysis for the Oxygen Module in ISIS-Quality using Maximum and Minimum Input Values, based on Published Literature, and a ± 25% Change of the Input Values*

INPUT		OUTPUT					
Default values		**DO**	**Fast BOD**	**Slow BOD**	**Fast nitrogen**	**Slow nitrogen**	**Amm. nitrogen**
		11.907	1.171	1.19	0.883	0.839	0.81287
New input values or % change in input values							
rkb20	0.09	**% change**	**% change**	**% change**	**% change**	**% change**	**% change**
rkb20	2.00	0.125	4.434	3.219	0.000	0.000	0.000
sbrate	0.16	-1.126	-29.441	-23.279	0.000	0.000	0.000
sbrate	1.00	0.058	0.000	3.599	0.000	0.000	0.000
snrate	0.16	-0.027	0.000	-1.583	0.000	0.000	0.000
snrate	1.00	0.000	0.000	0.000	0.000	0.399	-0.421
rkam20	0.07	-0.000	0.000	0.000	0.000	-0.170	0.177
rkam	0.14	0.047	0.000	0.000	0.000	0.000	0.732
epsam2	1.00	-0.061	0.000	0.000	0.000	0.000	-0.967
rkb20 2.00 + sbrate 0.16 + rkam 0.14		0.0000	0.000	0.000	0.000	0.000	0.000
alpair	-25%	-1.238	-29.441	-30.558	0.000	0.000	0.732
alpair	+25%	5.838	0.000	0.000	0.000	0.000	0.000
alphab	-25%	-19.352	0.000	0.000	0.000	0.000	0.000
alphab	+25%	-0.007	-0.236	-0.176	0.000	0.000	0.000
rkn20	-25%	0.007	0.228	0.171	0.000	0.000	0.000
rkn20	+25%	0.000	0.000	0.000	0.163	0.127	-0.317
alphan	-25%	-.000	0.000	0.000	-0.165	-0.129	0.317
alphan	+25%	0.000	0.000	0.000	-0.024	-0.019	0.047
alpham	-25%	0.000	0.000	0.000	0.024	0.018	-0.046
alpham	+25%	-0.006	0.000	0.000	0.000	0.000	-0.092
rkno20	-25%	0.006	0.000	0.000	0.000	0.000	0.090
rkno20	+25%	0.001	0.000	0.000	0.000	0.000	0.000
alphn2	-25%	-0.001	0.000	0.000	0.000	0.000	0.000
alphn2	+25%	-0.000	0.000	0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000	0.000	0.000

is advisable to omit those structures, which do not possess a significant influence on the flow in the river. Even after simplifying the network, it was not possible to run files containing *junction* units (these are units containing information on the division of a single channel into several channels or the confluence of many channels into one). This problem was solved temporarily by deleting the file containing the steady state run results and rerunning the unsteady state run.

5. Discussion and Conclusions

It is important to relate all the necessary aspects of an application to ISIS, before starting to build complicated river networks. This can be achieved by answering questions such as; what is the main purpose of modelling the river in ISIS? Which parameters need to be calculated and at which locations? Which part of the river network is of interest? Where can discharge measurements be carried out or where are these measurements already available? Where to plan measurement points for calibration/validation of the model? How to model the hydraulic structures in the river network? How to schematise the actual river network? Where are these cross-sections going to be located and for which time period(s) the model should run? Once these questions have been answered, a clear list of all measured parameters on each sampling point, should be compiled.

The results from ISIS-Flow were validated by using stage measurements at Warwick and Stratford stations along the river network. The summary statistics for the model fit at Warwick shows that levels of explained variance exceed 85% and the standard error of estimate was small. Therefore, the model appears to be predicting flow variations in the river network with a considerable degree of success. Predicted stage at Stratford showed periods of model instability. When using ISIS-Flow, it is recommended that the river network is divided into smaller sections and the model is run for shorter periods. Then, the output from an upstream section can be used as input for the downstream section. This action will also seem to decrease the occasional events of model instability.

In an attempt to gain a general idea about the performance of ISIS-Quality, comparisons of predicted DO, BOD, Total Nitrogen, Ammoniacal Nitrogen and Nitrate-N were undertaken at Stratford and Barford where limited data were available. While it is not appropriate to evaluate these predictions against a single observed data point at Stratford and two points at Barford, the result provides a reasonable outcome. A sensitivity analysis for the Oxygen module of ISIS-Quality shows that only changes in the temperature dependency factor and the nitrogen decay had a significant impact on the predicted output of the Dissolved Oxygen module.

ISIS has the potential benefits of enabling water managers to predict the consequences of various management scenarios (for example changes in water flow, effluent discharge or urban storm drainage on water quality, nutrient and sediment transport and the biological response of river systems).

6. Acknowledgements

The authors would like to thank Dr. Steven Wade and Mrs Ankie Bruens for their contribution while working on the project and The Environment Agency in the UK for funding this research.

References

[1] Anderson M.G. and Burt T.P. (Editors), (1985). *Hydrological Forecasting.* John Wiley & Sons. UK.

[2] Brown, L. C., and T. O. Barnwell, Jr. (1987). *The Enhanced Stream Water Quality Models QUAL2E and QUAL2E-UNCAS: Documentation and User Manual.* EPA-600/3-87/007. U.S. Environmental Protection Agency, Athens, GA. May.

[3] Clark R.M., Grayman W.M. and Goodrich J.A. (1986). *Toxic Screening Models for Water Supply.* Journal of Water Resources Planning and Management, 112, 2, pp.149-165.

[4] Crockett P. (1994). *Water Quality Modelling.* In: Calow P. and Petts G., (Editors), The River Handbook, Hydrological and Ecological Principles. Blackwell Scientific Publications.

[5] Cunge J. A., Holly, F.M. and Verwey, A. (1980). *Practical Aspects of Computational River Hydraulics.*

[6] Foster I., Baban S.M.J., Charlesworth S., Jackson R., Wade S., Buckland P., Wagstaff K. and Harrison S. (1996). *Eutrophication in Controlled Water in Lower Severn Area.* Report to the National Rivers Authority, UK on the Avon Eutrophication Project, April 1996.

[7] Foster I., Baban S.M.J., Charlesworth S., Jackson R., Wade S., Buckland P., Wagstaff K. and Harrison S. (1997). *Nutrient Concentrations and Planktonic Biomass (Chlorophyll a) Behaviour in the Basin of the River Avon, Warwickshire, UK. Freshwater Contamination* (Proceedings of Rabat Symposium S4, April-May 1997). IAHS Pub. No. 243. pp. 167-176.

[8] Fawthrop N.P., (1994). *Modelling Hydrological Processes for River Management.* In: Calow P. and Petts G., (Editors), The River Handbook, Hydrological and Ecological Principles. Blackwell Scientific Publications.

[9] Gardiner J.L., Dearsley A.F. and Woolnough J.R. (1987). *The Appraisal of Environmentally Sensitive Options for Flood Alleviation using Mathematical Modelling.* Journal of the Institute of Water and Environmental Management. 1, 2, pp. 171-184.

[10] *ISIS-Flow User Manual,* (1995). Halcrow & Partners Ltd an HR Wallingford Ltd. UK.

[11] *ISIS-Quality User Manual,* (1996). Halcrow & Partners Ltd an HR Wallingford Ltd. UK.

[12] Shaw E., (1983). *Hydrology in Practice.* Van Nostrand Reinhold, UK. 569 P.

[13] Hammer M.J. and Kichan K.A.M. (1981). *Hydrology and Quality of Water Resources.* John Wiley & Sons, USA. 486p

[14] Jorgenson, S.E. and Gromiec, M.J. (1989) (Editors.) *Mathematical Submodels in Water Quality Systems.* Developments in Environmental Modelling. Elsevier ISBN 0-444-88030-5.

[15] Gromiec, M.J. (1989). Reaeration. In Jorgenson, S.E. and Gromiec, M.J. (Eds.) *Mathematical Submodels in Water Quality Systems.* Developments in Environmental Modelling 14, Ch.3.Elsevier ISBN 0-444-88030-5.

[16] Oakes D.B. and Keay D. (1990). *A Resource Model of the Great Ouse River System.* Report No. CO2504-M. Water Research Centre, Medmenham, UK.

[17] National Rivers Authority (NRA) (1992). *Hydrometric Report and Catalogue (1991).* NRA Severn-Trent Region, Solihull.

[18] Reynolds C.S. (1994). Algae. In: Calow P. and Petts G., (Editors), (1994). *The River Handbook, Hydrological and Ecological Principles.* Blackwell Scientific Publications.

[19] Roesner L.A., Gigure P.R. and Evenson D.E. (1981). *Computer Programme Documentation for the Stream Quality Model QUAL-II. EPA 600/9-81-014.* USEPA Environmental Research Laboratory, Athens.

[20] Tassin, B. and Thevenot, D.R. (1989). In Jorgenson, S.E. and Gromiec, M.J. (Eds.) *Mathematical Submodels in Water Quality Systems.* Developments in Environmental Modelling 14, Ch 12.Elsevier ISBN 0-444-88030-5.