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River basin management using Hydroinformatics Tools

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Synopsis

In recent years, there has been growing public concern about the impact of flooding and water quality in U.K. rivers, and particularly after the autumn 2000 floods. In 2001 the Government invited the President of the Institution of Civil Engineers to establish a commission to review the technical approaches to flood risk management in England and Wales. The need for a new approach to flood inundation modelling will be discussed using state-of-the-art hydroinformatics tools, together with considerations of water quality and diffuse source pollution. Finally, an example of the Ribble River Basin will be introduced to highlight the challenges between flood risk management and maintaining ever-increasing levels of riverine water quality.

Keywords: flood management, hydroinformatics, diffuse source pollution,water quality

Introduction

In recent years many countries have experienced considerable changes in their climate and meteorological conditions that have led to increased river flood levels and an increased frequency in flooding. For example, in the autumn of 2000, the U.K. experienced the wettest autumn for over 270 years (Environment Agency, 2001). Many parts of the country were severely disrupted by the floods; many homes were flooded, possessions lost, businesses closed and transport systems brought to a standstill. Lessons were learnt from previous floods in 1998 and flood defences and warning systems undoubtedly reduced flood damage. However, the cost to the U.K. insurance industry, etc., was still estimated to be £1 billion (Environment Agency, 2001).

Flooding is a phenomenon that cannot easily be prevented. However, flood protection and improved flood forecasting can reduce the impact of floods. Following these recent extreme floods in the U.K., the Minister for Flood Management within the U.K. Government's Department for Environment, Food and Rural Affairs, commissioned the President of the Institution of Civil Engineers to carry out an independent review of the technical approaches to flood risk management in England and Wales (Institution of Civil Engineers, 2001). In parallel with this study, the U.K. government's Department for Environment, Food and Rural Affairs (previously the Ministry of Agriculture, Fisheries and Food) and the National Assembly for Wales have introduced Catchment Flood Management Plans (CFMPs). These are intended to provide a large-scale planning framework for integrated management of flood risk to people and the developed and natural environment in a sustainable manner.

This strategy of adopting a catchment based, more holistic approach, is aimed at reducing flood risk by:

- encouraging the provision of adequate and cost-effective flood warning systems;
- encouraging the provision of adequate technically, environmentally and economically sound and sustainable flood defence measures; and
- discouraging inappropriate development in areas at high risk from flooding.

In addition to the well known problems associated with flooding, in terms of damage to property and, in extreme cases, loss of life, more recent concerns have also focused on diffuse source pollution and the increasing problems of water quality during flood flow conditions. Under storm flow conditions agricultural waste which has accumulated on land may be readily transported by streams and riverlets to rivers and, in due course, to coastal waters. This, in turn, leads to relatively high pollutant and sediment transport levels in rivers, estuaries and coastal waters, which leads to increasing difficulties in complying with current EU Directives, such as the EU Bathing Water Directive, and will lead to even greater problems in the future in the U.K. complying with the EU Water Framework Directive.

This increasing awareness of flooding and hydro-environmental issues relating to flood mitigation measures and agricultural pollution etc. have led to a marked broadening of the role and responsibilities of river engineers, local authority planners and other stakeholders involved in the planning and assessment of flood mitigation and environmental impact assessment studies for water quality considerations. For example, the river engineer or planner involved in a feasibility study to determine the impact of a flood mitigation scheme on a river, or the impact of diffuse source pollution on the hydro-ecology of a river basin system, is increasingly expected to use sophisticated hydoinformatics tools and then to interpret the results of complex flow, sedimentary, biological and geo-chemical processes simulated using these tools. Such tools therefore need to be embedded as much as possible within easy-to-use geographical information systems.

Hydroinformatics Model Details

The type of computational flow models commonly used by environmental engineers and water managers to assist in flooding and environmental impact assessment studies generally involve solving the following equations:

1. For flow modelling:

- The continuity (or mass conservation) equation – including source inputs from outfalls, etc.
- The momentum equations in 1, 2 or 3 co-ordinate directions – including the effects of the Earth's rotation (for 2-D and 3-D flows), wind stress, bed friction, turbulence and (where appropriate) barometric, density or salinity variations. In these equations the wind stress is generally represented using a quadratic friction law and a constant friction coefficient at the air-water interface – with this in itself being a gross over-simplification of a complex phenomenon (Falconer and Chen, 1991). For the bed friction a coefficient is used, together with a quadratic relationship linking the friction to the velocity and fluid depth. Similarly, for the turbulence processes complex relationships are used which are highly dependent upon empirical constants.

2. For water quality modelling:

- The pollutant or sediment transport equation – including source load inputs from outfalls, etc., bed and/or surface inputs or outputs and kinetic transformation rates.

  In terms of the water quality parameters included in such models, these generally include various indicators from the following lists:

- Physical – including: suspended solids, turbidity, temperature, radioactivity and colour.
- Chemical – including: dissolved oxygen, biochemical oxygen demand, nitrogen, phosphorous, chlorides and metals.
- Biological – including: pathogens and algae.

3. Modelling technique:

   The equations referenced above are then generally solved using the finite difference technique or similar. This method requires that in general a regular mesh of square grids is set up over the region of interest and the governing equations are re-formatted using a mathematical technique referred to as the Taylor's series; i.e. they are solved for each grid square of side Δx, as illustrated in Figure 1. Thus, for each grid square, there are four or more equations, including the equations of continuity (or mass conservation), momentum in the x, y and z directions, and solute transport for each solute φ_i (Falconer and Chen, 1996). The number and size of the grid squares will vary with the size of the domain. The local depth below datum is included at the centre of the side of each grid side and the bed roughness height is specified at the centre of each grid square. The equations are then solved for each grid square, at every time step. Model simulations are generally undertaken for many days or weeks of real time. The water elevation, velocity components and the pollutant levels or sediment transport rates are then evaluated at the centre, or mid-sides, of each wet grid square, and for each time step.

Application to Ribble river

The principle of using hydroinformatics models as river basin management tools has undertaken for the Fylde Coast and Ribble River Basin in the U.K., where major concerns have arisen in recent years as a result of the coastal receiving waters failing to meet the European Union (EU) Bathing Water Directive mandatory standards, particularly during times of flood.

The Ribble river basin is situated along the North West coast of England, near the town of Blackpool - one of the U.K.'s largest seaside towns and a key tourist centre. At the mouth of the estuary, there are two well-known seaside resorts, namely Lytham St. Anne’s and Southport, and both have been designated EU bathing waters (see Figure 2). The area has three main centres of population, namely the towns of St. Anne’s and Southport, located on the north and south coasts of the Ribble estuary, and the town of Preston that straddles the Ribble near the tidal limit. In order to improve the water quality, North West Water has invested over £500M along the Fylde coast and in the Ribble river basin over the past 10 years. Examples include upgrading various wastewater treatment works from primary to UV disinfection. Storm discharges have been reduced by construction of 260,000m^3 of additional storage.

Although the decrease in the input of bacterial loads has resulted in a marked reduction in the concentration of bacterial indicators, elevated coliform counts are still encountered, particularly during flood conditions, and the bathing waters frequently continue to fail to comply with the EU Bathing Water Directive (1976) mandatory standards. The mandatory coliform standards given in the directive to assess compliance require that there be no more than 2,000 faecal coliform counts per 100ml. For bathing waters to comply with this directive then 95% of samples must meet these standards. The water quality failures have become a major threat to the local tourist industry. Considerable fieldwork has been undertaken by the Environment Agency and North West Water to investigate flooding issues and how these relate to adverse water quality conditions. The main objective of the study was to quantify the flooding impact on various sewerage infrastructure inputs into the Ribble river basin and the receiving coastal waters.

In undertaking a comprehensive hydroinformatics model study of the basin, studies were undertaken using Cardiff University’s Environmental Water Management Research Centre's 1-D and 2-D hydro-environmental models, namely FASTER and DIVAST. The FASTER model is a 1-D model for simulating flow, water quality and sediment transport processes in well-mixed rivers and narrow estuaries. The model solves the governing equations of motion using a finite volume approach with a varying grid size (see Falconer et al, 2001). In this application the model was used to predict water elevations, discharges, salinity, total and faecal coliform levels and suspended sediment loads.

Likewise, the 2-D computer model DIVAST is based on a finite difference formulation of the governing depth averaged equations of mass, momentum and pollutant and suspended sediment transport, with details of the solution procedure being given in Falconer and Chen (1996). The model simulates the two-dimensional distribution of currents, water surface elevations, various water quality indicators and sediment transport fluxes in the model domain.

The main area of interest in this study was from the outer seaward boundary, of length 41.2km, to the tidal limit of several rivers, with a width at the limit of typically less than 10m. Such a difference in the modelling scale made it almost impossible for either a 1-D or 2-D model to be used alone. Therefore a linked 1-D and 2-D modelling approach was used, with the domain being divided into two sub-domains. This required using a 1-D model to simulate water elevations, discharges and solute levels in the river channels and a 2-D model to simulate water elevations, velocity components and concentration levels in the estuarine and coastal waters. In order to increase the accuracy of the computer model and, at the same time, reduce the effort required to run two separate models, a complex approach was used to link the two models into a single model.

An initial problem with the model study was the absence of recent bathymetric data of the basin. Data were acquired by the Environment Agency using a variety of methods, including: (i) data collected by conventional surveying techniques, used in the rivers Ribble and Douglas; (ii) LIDAR (Light Induced Direction And Range) was used for the floodplains in the outer estuary, where there were significant changes in the bathymetry; and (iii) sidescan sonar was used in the permanently wet regions of the estuary and the coastal waters.

In order to ensure that the integrated model could be used to predict accurately the impact of future improvement works and climate changes on the river basin, the model was calibrated for elevations, currents, salinity, suspended solids, faecal and total coliforms and faecal streptococci against six datasets. Three of the datasets were used for initial calibration and the other three were used for model verification. The six sets of velocity and water quality data were collected during winter and summer, and for flood and dry weather conditions. Measurements were also taken for different tidal ranges, including neap and spring tides, and at the tidal limits of the rivers and the seaward boundary, to provide boundary conditions at the weirs for the model. Measurements were also taken within the basin at several sites, including: 11 milepost, 7 milepost, 3 milepost and Preston Bullnose (see Figure 2).

The 1-D model contained 5 reaches and 922 cross-sections, with the distance between consecutive cross-sections being generally less than 50m. For the 2-D model the grid size was chosen to be 66.7m. Faecal coliform was used in the study as the main water quality indicator. Since faecal coliform is influenced by many factors, calibration of a water quality model is generally more difficult than for a hydrodynamic model. The calibration not only depends upon the accuracy of the velocity predictions and the quality of the measured data, but also on the decay rates of the indicator organisms which are controlled by external factors. The intensity of light, temperature, salinity, toxic substances, settling of organism populations after floods, re-suspension of particles associated with floods are all known to influence the decay rate (see Auer and Niehaus, 1993). In this study different decay rates were used for day and night times, for flood and drought conditions and for sea and fresh water conditions across the catchment.

For the calibration tests excellent agreement was obtained between the flow and faecal coliform predictions for the river basin, with typical examples of comparisons being shown in Figures 3 and 4. It can be seen that the elevations and velocities were in close agreement with the measured data (see Figure 3). Similarly, comparisons of the predicted and measured faecal coliform levels at all of the calibration points showed that the model was able to predict this water quality indicator satisfactorily. The calibrated flood event values of T_{90}(time for the constituent to decay by 90%) for the 2-D and 1-D regions were 72 and 85 hours for day-time, and 106 and 142 hours for night-time conditions. For dry weather conditions the corresponding calibrated T_{90} values were 37.3 and 50.1 hours for day-time and 80.8 and 132.2 hours for night-time conditions respectively. The measured and predicted coliform indicator levels at all of the calibration points were found to be much greater for flood events, in comparison with dry flow events. It was also interesting to note that for all flood events the coliform inputs from the catchments into the upstream reaches of the Ribble and Darwen rivers were significantly larger than for the corresponding dry weather loads.

Finally, a series of baseline simulations was undertaken for a range of river flows, tidal conditions and meteorological conditions. In addition to these baseline simulations, a number of scenario simulations were also undertaken to establish the impact on the coastal receiving waters of further investments in the wastewater treatment works (such as UV disinfection) at a number of sites along the rivers. The results showed that, whilst UV disinfection and storage tanks would undoubtedly reduce the effluent coliform inputs from the sewage works, the diffuse source inputs from the catchment were significant during flood (or wet weather) conditions and little could be done to reduce the adverse impact. Comparisons of the predicted faecal coliform levels for dry and wet weather conditions are shown in Figures 5 and 6 respectively, highlighting that non-compliance at the coastal monitoring site was significantly influenced by diffuse source pollutants.

Conclusions

In recent years there has been a significant increase in public awareness of a wide range of flooding and hydro-environmental issues. Hydroinformatics tools provide wide scope for use in coastal zone and river basin management and can provide valuable and extensive information for environmental water engineers and managers. However, it is important to appreciate that these modelling tools rely heavily on data and have limitations, primarily governed by our lack of understanding of some complex flow and bio-chemical processes.

Details are given of such a model study, namely for the Ribble River Basin, where it was found that the faecal coliform levels in the receiving coastal waters were highly dependent upon the flow rates in the rivers and the corresponding inputs from diffuse source pollutants – mainly in the form of agricultural inputs. It was found that when the river flows were in flood the bathing waters at Lytham St. Anne's were predicted to fail to comply with the EU Bathing Water Directive, whereas under low (or dry) flow conditions non-compliance was not predicted to be an issue. These results were confirmed by field measurements undertaken by the Environment Agency and also highlighted the importance of accurate and reliable data and the use of geographical information systems for such hydro-environmental studies.

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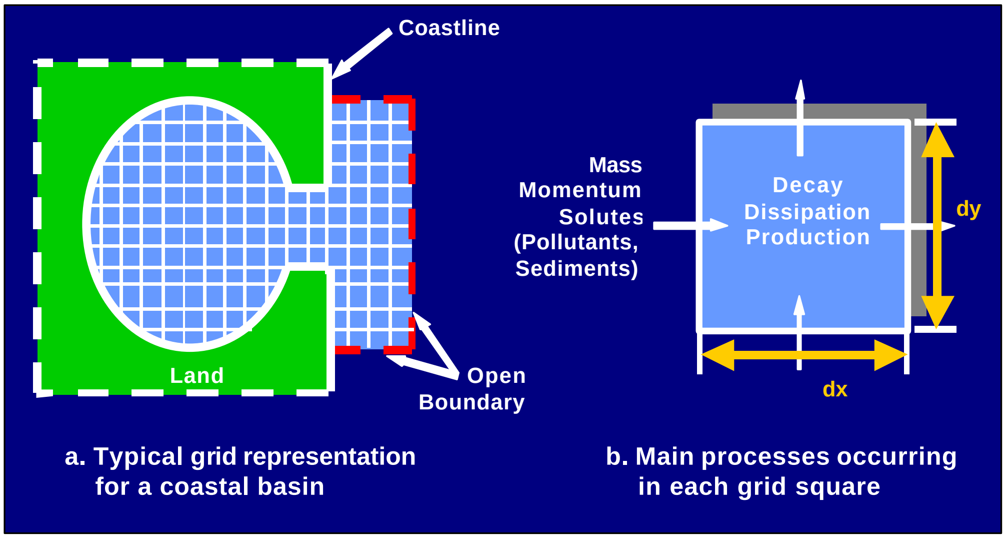

Figure 1 Schematic Illustration of Modelling Principles

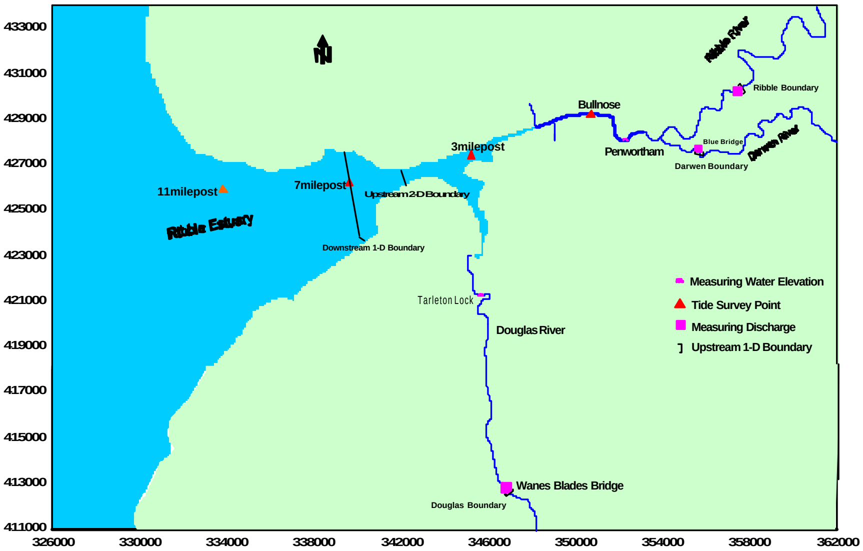

Figure 2: Schematic Illustration of Ribble River Basin

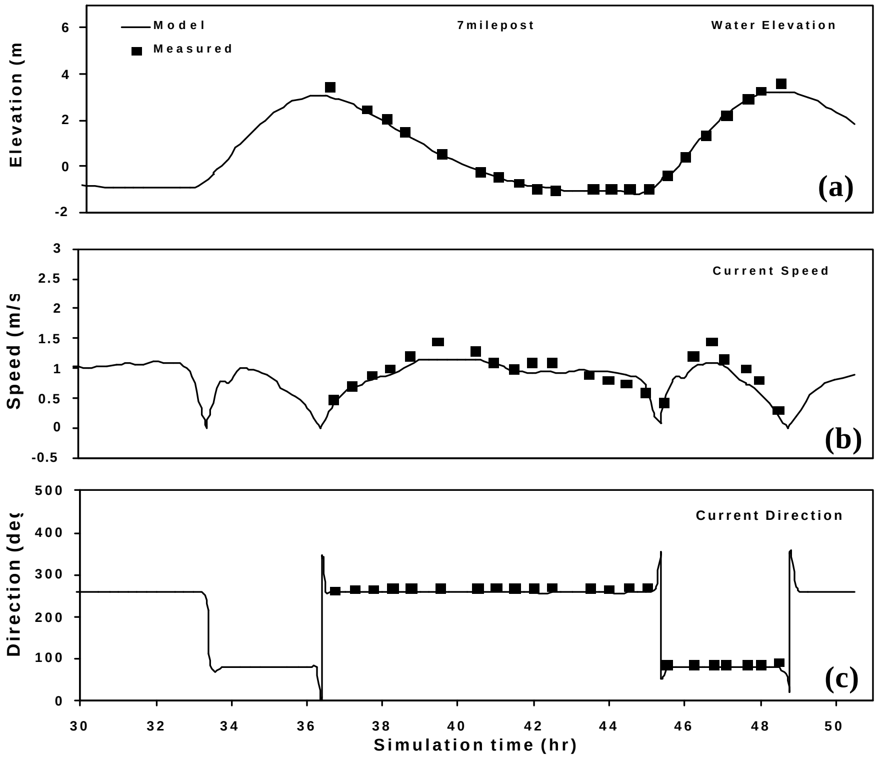

Figure 3: Comparison of predicted and measured: (a) water level (b) current speed and (c) direction for flood conditions at 7 Milepost in June 99

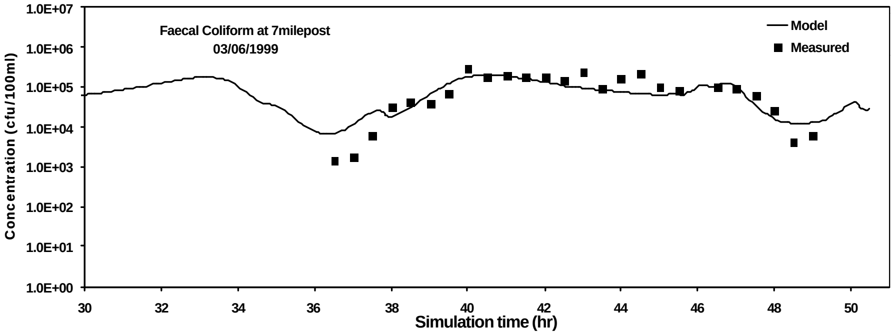

Figure 4: Comparison of predicted and measured faecal coliform levels at 7 Milepost in June 99

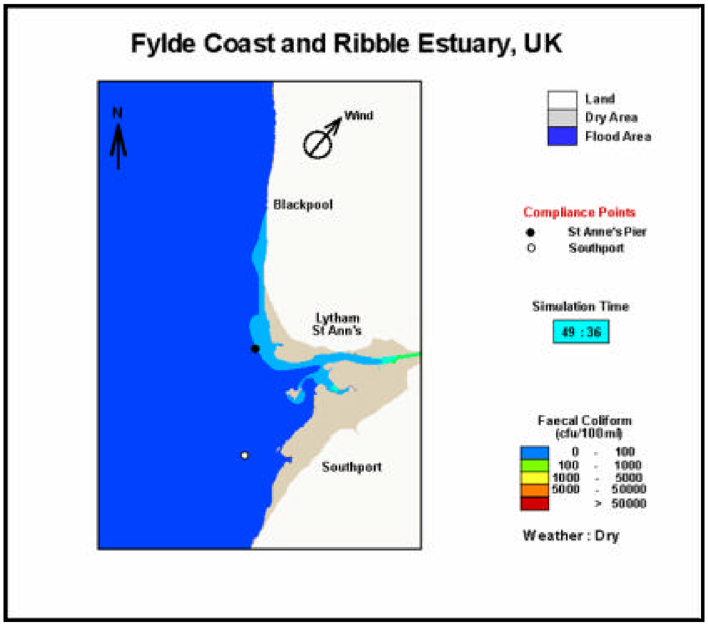

Figure 5 Computed faecal coliform levels for dry weather river flows

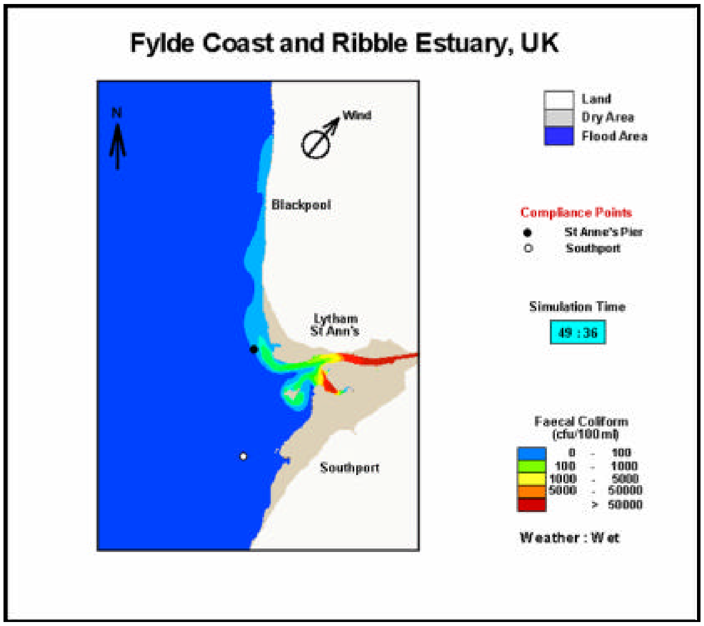

Figure 6 Computed faecal coliform levels for wet weather river flows