UNDERSTANDING AND MANAGING HYDROLOGICAL EXTREMES IN THE LOUGH NEAGH BASIN

By Adrian K Bell[+], Noel Higginson[#], Stephen Dawson[#], Grace Glasgow[+], Bjoern Elsaesser[+]
[+] RPS Consulting Engineers, Belfast
[#] DARD Rivers Agency, Northern Ireland

INTRODUCTION

In 2004 DARD Rivers Agency contracted RPS Consulting Engineers to undertake a comprehensive hydrological and meteorological study of the Lough Neagh / Lower Bann combined catchment and to examine ways of improving control and operation of water levels in the Lough and levels and flows in Lower Bann River. At present the statutory water levels are exceeded on a regular basis in winter months and during dry summers the water level falls below the lower statutory level. The primary objective of the study was to ascertain if with a better understanding of the catchment and more detailed status information could improve control of the water level within the existing limits.

BACKGROUND

The Lough Neagh and Lower Bann catchment covers 5775 km^2 of catchment area, which accounts for 42% of Northern Ireland land surface. The majority of the inflow reaches the Lough via eight rivers. Lough Neagh is approximately 30km long, 12 km wide, has a surface area of 385 km^2 and an average depth of 9.5m. It is the largest fresh water lake in the British Isles.

The Lough Neagh and Lower Bann system has been modified in the past to accommodate navigational and agricultural interests. Improvements date back to 1620, when the Lower Bann was deepened at Coleraine, Portna and Portglenone. Between 1846 and 1856, five locks and weirs were built along with additional rock excavations. In 1942 three of the weir structures were replaced with sluice gates and the water level in Lough Neagh was lowered by 2 feet. In 1952 the Lough Neagh control level was further reduced by 6 inches.

Currently the water level in the Lough is controlled by five sluice gates at Toome, where the water enters the Lower Bann. As far as is practical, it is maintained within an operational band of 150mm. Under low flow conditions the gates are all closed and a flow of at least 10 m^3/s is maintained through the fish bypass. The river level in the Lower Bann itself is controlled by two additional weirs and two sluice gate structures. The Lower Bann is part of the Irish waterway system with five locks to permit navigation and is of great importance with regards to commercial and leisure fishing.

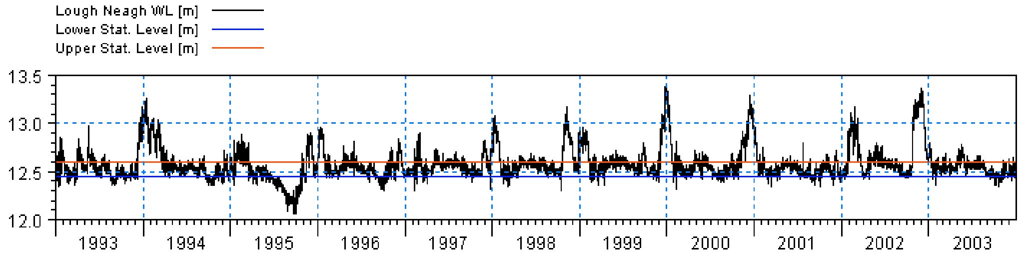

Figure 1: Water level in Lough Neagh between 1993 and 2003

In the past six winter periods the water level in Lough Neagh exceeded its upper statutory level by 0.5m. In October 2002 to December 2002 a water level of 13m (0.4m higher than the upper statutory limit) was exceeded for 47 days causing flooding of the hinterland for a prolonged period in some areas. In contrast, in summer 1995 the water level dropped below the lower statutory level for 4 months, this is illustrated in **Figure 1**.

Due to the size and shallowness of Lough Neagh, strong winds can cause significant surges resulting in seiching in the lake. An example is given in **Figure 2**. The gauge measuring the shown water level is located at the northern end of the Lough near the sluice gates. The seiching results in water level oscillations in this case of up to 0.5m, which is far beyond the statutory range. Other events have been recorded with water level differences close to 1m. While these oscillations are of only short duration (the initial surge may be building over 12 hours and the seiching has a period of around one hour), they pose some difficulties with regards to controlling the Lough, since the decision on opening or closing the gates is at present based on the Lough's water level.

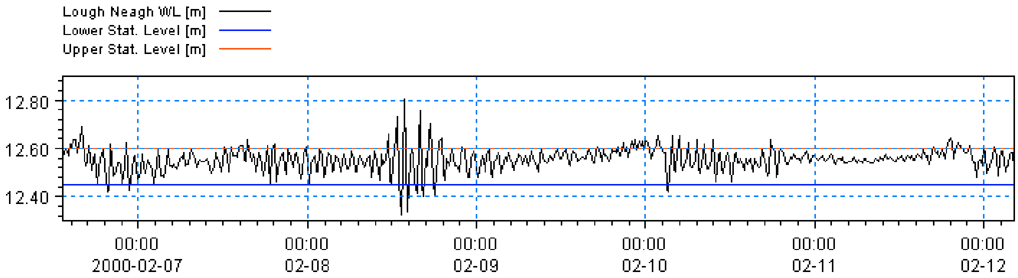

Figure 2: Water level variation due to wind in Lough Neagh in February 2000

In order to assess the present behaviour of the catchment basin and to investigate ways of improving control and operation of water levels in Lough Neagh and Lower Bann, a hydrological model for the entire system has been developed. The model incorporates:

- The hydrological behaviour of the associated catchments by utilising the available physical, hydrometric and hydro-meteorological data
- The behaviour of Lough Neagh including effects from seiching, evaporation and water abstraction
- The natural flow and water levels in the relevant rivers and channels
- The operation of structures and flow in rivers and channels

MODELLING THE LOUGH NEAGH AND LOWER BANN BASIN

The modelling system chosen for this project comprises three different models, which are combined under one software shell:

1. A hydrological model (MIKE 11 NAM) to describe the runoff pattern in the catchments and the inflow to the river.
2. A river model (MIKE 11 HD) to describe the flows in rivers and channels
3. A two-dimensional lake model (MIKE 21 HD) to describe the flow in Lough Neagh

All three models are fully dynamically linked. In particular the Lough model and the river model have a two-way connection, thus high Lough water levels affect the inflow of the tributary in addition to the outflow through the sluice gates. In reality, changes in water levels due to seiching in the Lough can result in negative flows in the tributaries, whereas the outflow from the rivers takes immediate effect on the Lough level. Having all modelling combined and coupled is very important for the solution of these hydrological conditions. This combined approach also makes it easier to execute the modelling system.

The modelling tools and the implementation of these in the project are now discussed in further detail.

THE HYDROLOGICAL MODEL

The MIKE 11 rainfall-runoff module comprises of the continuous rainfall-runoff model NAM. A schematic diagram of the module is shown in **Figure 3**. The rainfall-runoff model is fully and automatically coupled to the hydrodynamic model: the linkage dynamically simulates the routed runoff from the dry areas and the direct effective rainfall from flooded areas taking evaporation into account on the flooded areas. NAM simulates the rainfall-runoff by continuously accounting the moisture content in four different interrelated storages representing the physical elements of the catchment as follows:

- Snow layer
- Surface zone - vegetation, small channels and lakes

- Root zone - the depth from which plant roots draw water
- Ground water

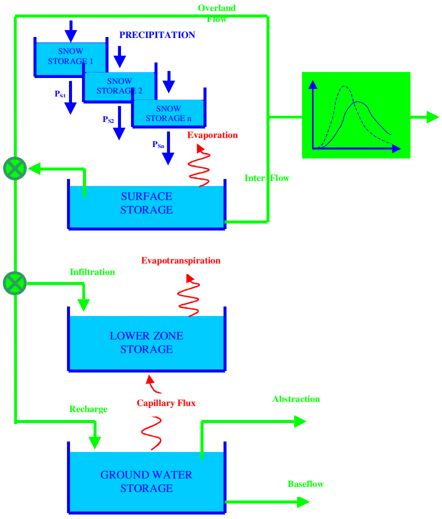

Figure 3: Schematic diagram of rainfall run-off model

Where runoff from the sub-catchments can be defined and has been gauged, the rainfall runoff model has been calibrated by adjusting the response parameters. In the Lough Neagh Basin flow data was available from high quality gauging records for 10 gauged catchments / subcatchments could be selected which had high quality river gauging records. Rainfall and evaporation data were obtained for the relevant period from the UK Met Office and the catchments were calibrated over a period of 11 years.

Initially only daily rainfall data was used, as most of the catchments have response times in excess of 24 hours and the aerial coverage using daily rainfall data is much higher compared to higher resolution data. The UK Met Office offers a gridded data set of daily rainfall data for Northern Ireland covering the full extent of the model area with a resolution of 5km x 5km. The data is generated from point measurements using all available data including some stations in the Republic of Ireland. Long-term averages are calculated for all available stations and the daily rainfall is calculated as the deviation from the average rainfall as a fraction of the daily rainfall. This is interpolated on the grid using all rainfall stations within a radius of 50km and the actual rainfall is recalculated. As a result any errors caused by orographic effects can be minimised.

By merging the gridded rainfall data set and shape files of the relevant catchments, average daily rainfall was derived for each catchment as an input to the model. However, for a number of catchments daily rainfall was not sufficient in terms of temporal resolution and the data required further enhancement. The key difficulty lies in the fast response of the catchment, this was found to apply to catchments smaller than 300km^2 in the project area. Although, this was also seen to be dependant on the catchment characteristics. Fortunately there are two rainfall gauging stations recording sub-hourly rainfall in the Lough Neagh Basin providing 10 years of data which was used to weight the daily time series to 5 minute time series. MIKE 11 offers an algorithm to allow the data to be weighted such that the accumulated rainfall remains the same compared to the daily rainfall data, the time distribution however was weighted similarly to the sub-hourly rainfall station nearby.

Having prepared precipitation, evaporation and run-off data-sets for the catchments the rainfall run-off model was calibrated for a period of up to 11 years. The NAM model has an auto-calibration function, which derives a set of 12 parameters based on the correlation factor between measured and simulated run-off. This is undertaken using a specialised interpolation scheme with up to 2000 steps but takes only a few minutes for reasonably sized catchments. An example result file of the auto-calibration is shown in **Figure 4** and **Figure 5**. These show the instantaneous flow at a gauging station (observed red, calculated black) and the water balance over the calibration period.

The example catchment has a size of 280 m^2. A correlation factor of 0.85 was achieved in this calibration, which is satisfactory taking the uncertainty of the rainfall data and the flow gauging data into account. Overall the water balance was within 5% of the gauged run-off for most of the calibrated catchments. In addition the calibration can be optimised for peak flows or low flows, depending on the scope of the simulation.

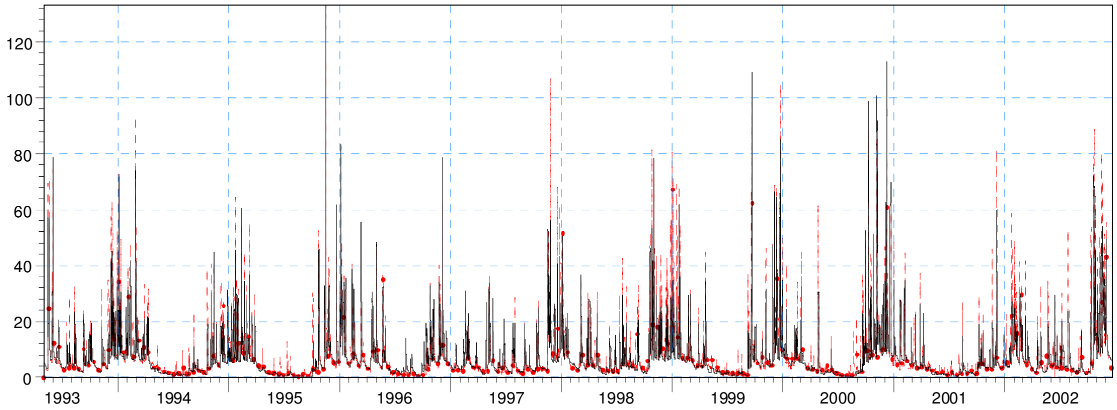

Figure 4: Correlation between simulated and observed run-off

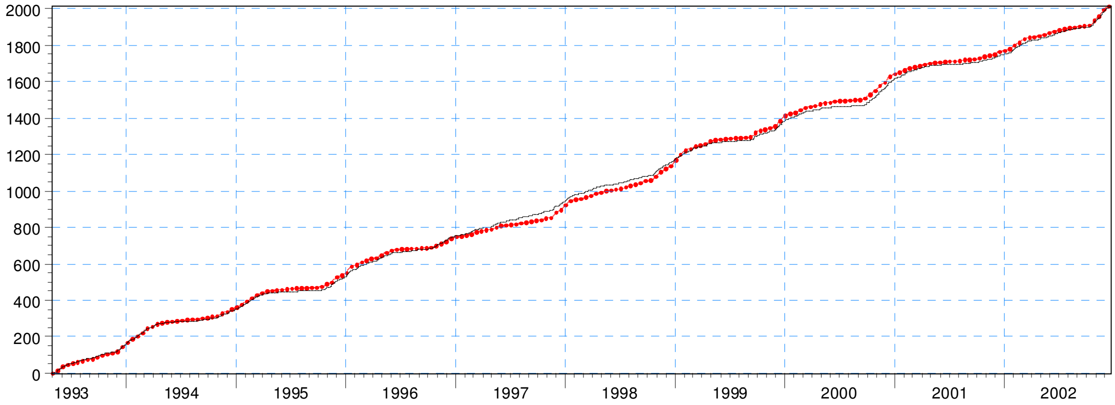

Figure 5: Correlation of water balance between simulated and observed run-off

Figure 6 shows the delineation of the Lough Neagh Basin into the sub-catchments from which the model generated run-off time series from the rainfall and evaporation data. In the sub-catchments marked P the runoff contributes as point inflow to the rivers, while in the sub-catchments marked L the runoff contributes as lateral inflow to the lake model. The directly calibrated run-off model covers 67% of the simulated area excluding Lough Neagh and direct drainage areas.

In order to derive the parameters for the un-gauged sub-catchments and those catchments draining as lateral inflow into the river and lake, the parameters from the calibrated catchments were transferred. Relevant information for this transformation is commonly provided by GIS tools with information on catchment topography, land use and soil characteristics. Parameters such as the average distance between point source or line source and catchment boundary, average slope of the topography and the ratio of poorly drained and well drained areas provide guidance on choosing the correct time constants for overland and interflow. Base geology, land use and HOST soil characteristics provide information on groundwater, root zone and surface storage. Based on this range of information, the run off model parameters were selected and finally checked against water balance considerations.

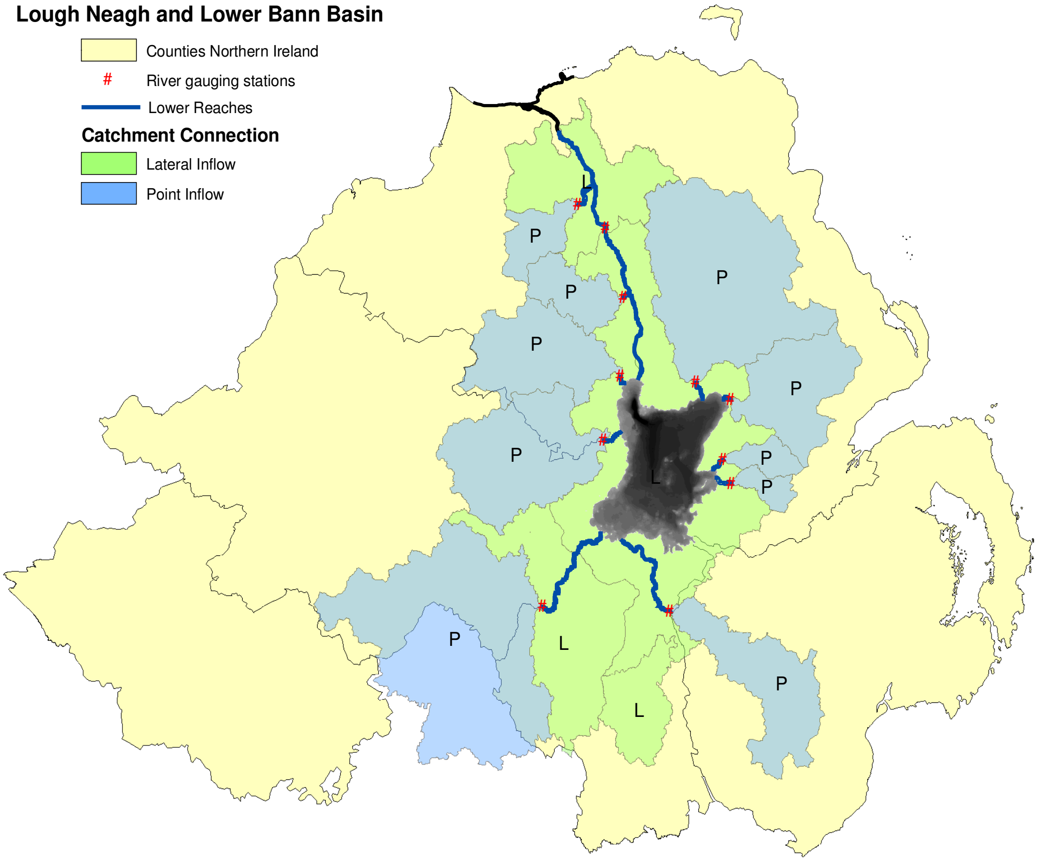

Figure 6: Catchment delineation, river model and lake model

THE RIVER MODEL

The hydrodynamic component of MIKE 11 was set up on the river network as shown in **Figure 6** (river network shown with thick blue lines). The river branches in the upstream catchments contribute with inflow to the lake model. Eight catchments feed as point sources into the river sections. Further two run-off models feed into the Upper Bann and the Blackwater. A total stretch of 22km of the River Blackwater was included in the model. Rivers Agency held detailed cross section information in their own model, which could be directly imported into the Mike 11 river model. In addition 19km of the Upper Bann was included in the model, which utilised detailed cross section information held by RPS Consulting Engineers. All of the other six major tributaries were included with shorter river sections ranging between 4km and 1.8km.

Two larger rivers, the Agivey and the Claudy, feed the Lower Bann and are included in the simulation. Both inputs consist of rainfall runoff models and a river stretch with 7km (Agivey) and 2km (Claudy) length. The Lower Bann itself is Northern Ireland's largest river in terms of flow and a primary inland navigation system. It stretches 50km between the Lough Neagh at Toome and the tidal section at Coleraine. Because of the number of control structures, river crossings, the low flow through Lough Beg, the lock gates and navigation channels, fish bypasses and various salmon fisheries (illustrated in **Figure 7**), the Lower Bann sets a challenge in its own right with regards to numerical modelling. Initially it was considered to use cross section information held by Rivers Agency together with detailed information on the structures for the simulation of the Lower Bann Branch. However as the river was the key element in this model and the data was of varying quality and partially outdated, a new survey of the Lower Bann was commissioned as part of the study.

The hydrodynamic module was calibrated against historical water level and discharge measurements within the rainfall-runoff period calibration with varying characteristics: magnitude, season, type of rainstorm, etc. The calibration ensured that the output from the model correlated with the observations. For this purpose a number of years of lock keeper logs were converted into digital format. This also highlighted some inaccuracy in river gauge datum, which was subsequently rectified.

Figure 7: The Cutts near Coleraine on the Lower Bann with sluice gates, disused fisheries and navigation canal (right hand outside picture)

Initially each river branch was calibrated separately, however towards the end of the calibration the river branches were combined into one model. The hydrodynamic model allowed definition of global and local bed resistance parameters, higher order, fully dynamic wave approximation and the inclusion of structures such as: weirs, culverts, bridges, control structures and local energy losses. In order to model the three sluice gate structures 13 different control structures were included in the model, each sluice gate on the river having its own control definitions. Initially historic records of the gate opening set the control definition. Once the calibration was complete a number of evaluation simulations were carried out. In these specific control and target points were set and the model controlled the actual opening width of the sluice.

THE TWO-DIMENSIONAL LAKE MODEL

Lough Neagh was modelled as a full two-dimensional model (MIKE 21 HD) in order to describe the depth and velocities correctly. The general lake model is shown in **Figure 8**. Using a two-dimensional model made it possible to simulate variations of water level under different meteorological conditions.

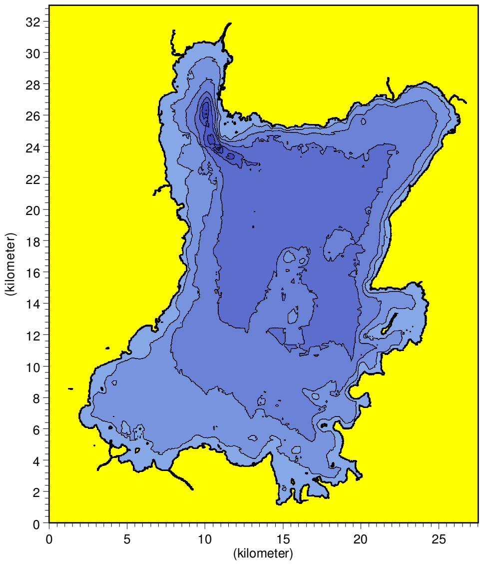

Figure 8: Extent of Lough Neagh implemented in the model and bathymetry

It also enabled testing for the best location of additional water level gauges, which is one proposal to obtain better status information on the system. Furthermore the model includes the simulation of precipitation and evaporation on the lake in addition to water abstraction, as the lake is used as water supply for the Greater Belfast area.

The combined model is outlined in **Figure 9**. The different model components are coupled under MIKE FLOOD. Coupled modelling systems make it feasible to model reservoirs in 2D while at the same time modelling the 1D river, with the inclusion of the hydraulic systems and structures like culverts, bridges and weirs in a structure model. The coupled model used in this project links the hydrodynamic engines (conservation of momentum and mass) in conjunction with the advection-dispersion engines (i.e. linked models include water quality, suspended sediment etc.).

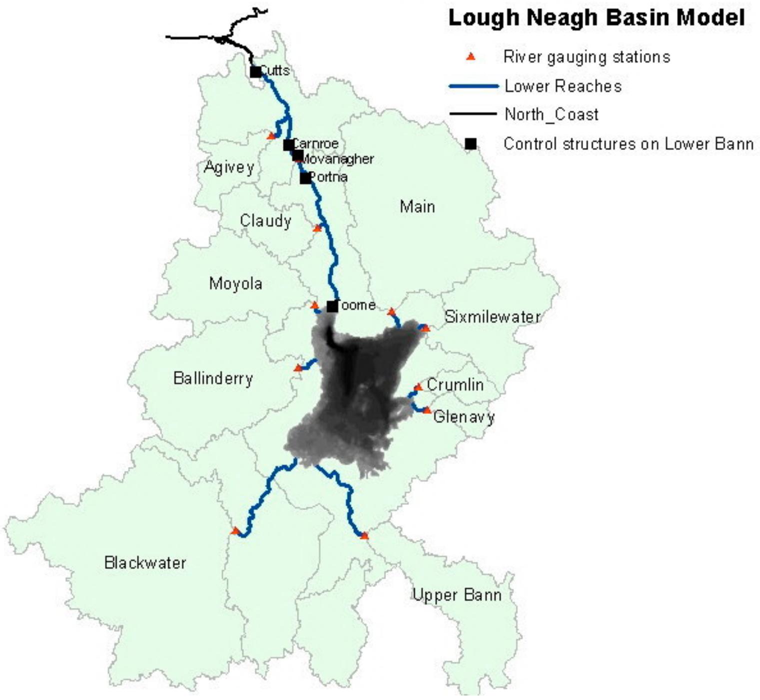

Figure 9: Lough Neagh Basin Model

PROPOSED ALTERNATIVES

The Lough water level is currently managed on a reactionary basis, with limited use of hydro-meteorological information. Water level and flow control is achieved by venting flows from the Lough through sluices at Toome into the Lower Bann River. The daily control of gate openings at Toome is determined by Rivers Agency Area Office staff based in Coleraine. The existing operational actions are based on water level measurements taken at Toome and Oxford Island and by consideration of prevailing weather conditions. Currently the sluice gates are opened and closed manually and the water levels at the lock gates on the River Bann are recorded by hand. Rivers Agency is currently managing another project to investigate the motorisation of the gates, which will offer different alternatives to the water level management. In this study there are three options being considered for controlling the gates:

- Control by staff on site, who open or close gates once a day
- Remote control by staff from the Area Office during normal working hours
- Computer control by model/ software

There are also a number of alternatives to provide guidance on the control strategy. At present it is proposed to retain the current statutory levels. By providing high quality status information on the catchment the Area Office staff can control the gates more in advance of the water level peak, hence reducing the flood periods.

Three different scenarios are currently being considered:

- Provision of additional water level information for Lough Neagh, as the current gauge locations are highly affected by surge causing over- or under-estimation of the actual water level
- Use of gauging information on the three largest upstream catchments, namely Blackwater, Upper Bann and Main to provide details about inflow. As a result water can be drained from Lough Neagh prior to the water level actually starting to rise because of increasing inflow from the rivers
- Utilisation of rainfall radar and rainfall station information for the prediction of runoff before it reaches the larger flow gauging station. This would enable the area office staff to look at the overall water balance in the catchment area and make decisions on regulating the outflow in advance.

The latter two options require a real time forecasting system, which would incorporate the Lough Neagh Basin model described in the previous sections. With the forecasting system in place it would be possible to predict water levels easily and test various scenarios and operation of the system using historical data. It will also be possible to use the model by applying data from the telemetric network, where the real time capabilities of the system can be tested and improved. The forecasting system would be based on MIKE (FLOOD) WATCH, which is a complete decision support system used in real time forecasting (for floods as well as for low flow). MIKE FLOOD WATCH is a client-server based database application, fully integrated into GIS, using a relational database for internal storage of all data such as time series data, model, scenario and job definitions and simulation results.

CONCLUSIONS

As part of a study to investigate the water management of the surface water in the Lough Neagh Basin a numerical model has been implemented in order to improve management of water levels and flows in Lough Neagh and the Lower Bann River. The model combines a hydrological model of the entire catchment area, one-dimensional river models of all tributaries to Lough Neagh and the Lower Bann and a two-dimensional model of Lough Neagh itself.

Key limitations in implementing the model have been found in obtaining sufficient boundary data and network information. In particular rainfall data with higher time resolution and sufficient information on water abstraction and the river network (cross sections and structures) would improve the correlation between observed and simulated run off and flows in the smaller catchments.

The model has improved significantly the understanding of the surface flows in the basin. It provides a relationship between rainfall depth and duration and the resulting inflows into Lough Neagh. It links the entire system together and enables the assessment of water levels and flows on a foresighted approach rather than an *ad hoc* basis. The model can be used to test different scenarios and the best location for additional monitoring equipment. Even the separate parts of the model enable a better understanding of the catchment. The rainfall run-off model for example provides direct insight into the time constants for surface flows, interflow and baseflow.

In addition the model allows the simulation of climate change scenarios, by using projected precipitation and evaporation patterns. This is vital in getting a high quality model as it reduces additional uncertainties when transforming the existing outflows to projected outflows. By applying the combined hydrological / hydraulic model this uncertainty is removed and the projected meteorological conditions can be used directly as boundary conditions.

With increasing concern of the impact of climate change on our daily live and since the basin supplies water to nearly 1/3 of Northern Irelands population numerical modelling such as shown in this paper will become more important. Further the model allows easy expansion for the simulation of water quality processes. This provides great potential in relation to requirements under the EU water framework directive.