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Design and development of an internet-based flood forecasting system using real-time rainfall, radar and river flow data

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Abstract

Modern flood forecasting systems have developed from simple forecasting engines to sophisticated but user-friendly real-time decision support systems for basin- and region-wide forecasting. Such flood forecasting systems must provide reliable, accurate and timely forecasts for a range of catchments; from small rapidly responding urban areas, to large, more slowly responding fluvial systems, often within the same region. Forecasting of fast response catchments requires rainfall-runoff modelling combined with real-time precipitation data and quantitative precipitation forecasts. In such cases the potential benefits of using weather radar, particularly in terms of increasing forecast lead-time can be substantial. Forecasting of large fluvial systems often requires hydraulic modelling where the use of real-time water level and discharge data for updating is crucial. In this paper a comprehensive regional flood forecasting system for the Anglian Region of the Environment Agency is presented. The design recognises the need to efficiently use and combine real-time data from a variety of sources. For this purpose a flexible data hierarchy structure was developed to ensure the reliability, timeliness and accuracy of the forecasting.. The system, based on state-of-the-art database, GIS and Internet technology, provides a user-friendly real-time operational tool that allows the consistent application of different data, and modelling approaches. Thus the system not only fulfils the Region's needs but also provides an open generic, forecasting framework.

Introduction

Flood warning is only one aspect of floodplain management and protection but it is an important one since it can save lives and substantially reduce flood damages. The key requirement for effective flood warnings is the need for timely, accurate and reliable flood forecasts that make the best possible use of available real-time data, and forecasts. Accuracy implies maximising the probability that flood-threatened areas receive appropriate warnings. Reliability relates to instrument performance (e.g. radar maintenance and down time, reliability of the telemetry system and data collection, reliability of the warning procedures and robustness of the forecasting model to missing and uncertain data. Timeliness refers to the balance between early but less accurate forecasts and high-accuracy forecasts with insufficient "lead time" to provide significant benefits.

The major flooding in the Midlands and East Anglian Regions of England over Easter 1998 highlighted the fact that severe flooding is seldom an isolated event, but often affects many neighbouring catchments and river systems. The hydrological response of a specific catchment depends on a number of essentially static factors such as catchment size, catchments slope, land use, soil type, etc. and dynamic features such as the distribution of rainfall including storm type and direction, catchment wetness, groundwater levels, etc. The optimal strategy for flood forecasting will depend on relating the lead time required to obtain significant benefit from flood forecasting to the time scale of catchment response, see Table 1, and Butts [1]. Provision of timely forecasts in a regional setting requires forecast modelling capable of treating forecasting problems ranging from small rapidly responding urban areas, to large, more slowly responding fluvial systems, often within the same region. Thus a regional forecasting modelling system must provide integrated hydraulic routing and rainfall-runoff modelling using both rainfall observations and quantitative precipitation forecasts.

It is often the case, also, that it is not desirable in a regional setting to treat flood management in isolation from other water resource management problems. A flow forecasting system can also be used as a decision support tool for the operational management of water transfers, river support schemes, abstractions and discharges, such as are used to meet domestic, industrial, agricultural and recreational water needs and to alleviate the environmental consequences of abstraction. This requires continuous rainfall-runoff modelling over the full range of flows.

This paper describes a comprehensive, region-wide flow forecast modelling system - AFFMS (Anglian Flow Forecasting Modelling System) – for the Anglian Region of the Environment Agency. In particular this paper reviews how the system design addresses the above requirements for a regional flow forecasting system while matching the needs of the operational users working in a real-time environment.

The timeliness of forecasts is ensured by designing a system that can use information from a wide variety of sources - both telemetry data and forecast

data - and by using modelling systems capable of using the full range of forecasting strategies in Table 1. An open, generic systems approach was adopted to treat different data sources and different modelling systems within the same forecasting framework. Server replication and the use of a data hierarchy that provides robust, automatic forecasting in the presence of missing or uncertain data ensure reliability of the forecasts. Systematic model calibration, forecast validation and real-time updating ensure accuracy.

Table 1. Recommended forecasting strategy as a function of T_f the forecast lead time required at a particular forecast point and the time to peak at the forecast point (which consists of two components; the hydrological response time T_c and the travel time through the river channels T_r)

Time Scale of Catchment Response	Optimal Forecasting Strategy
$T_f, > T_c + T_r,$ The required lead time is greater than the time of concentration at the forecast point	Precipitation forecasting (by radar, meteorological modelling, synoptic forecasts) and flow forecasting with rainfall-runoff modelling may be required
$T_f, < T_c + T_r, T_c > > T_r$ The time of concentration is dominated by hydrological response and the lead time is less than the lead time	Streamflow forecasts should be based on observed rainfall (from radar or telemetered raingauges) and rainfall-runoff modelling
$T_f, < T_c + T_r, T_c < < T_r$ The catchment response is dominated by the routing time of the flood wave through the channel system	Streamflow forecast can be based on channel routing alone.

Background

The Anglian Region, covers an area of 27,200 square km. This is about 20 per cent of the area of England and Wales and is the largest area of the eight Agency regions. Flooding is predominantly from frontal systems, though convective storms can also cause problems in some areas. There are 26 river catchments, which are characterised as intensively exploited lowland rivers flowing eastwards to the sea. The hydrology of the rivers is varied, ranging from rapidly responding clay headwaters in the west of the Region to extensive areas where interactions with chalk, limestone and drift aquifers dominate. Many of the rapidly responding catchments are along the western edge of the Region and would benefit from the use of rain radar both to provide additional

lead time and to improve the spatial description of the rainfall. However, some key areas of this type, including Northampton, lie at or beyond the limit of quantitative radar coverage. Many of the rivers also drain extensive fenlands along flat, canalised, often embanked, stretches before reaching the sea, and accordingly they are strongly affected by the tidal level. Combined with the variety of artificial influences on the flow regime, this presents a complex and challenging modelling and forecasting problem, requiring the full scope of flood forecasting approaches and modelling tools

As part of the development of AFFMS, two pilot catchments have been selected for inclusion in the first phase of development of forecast models of the region. These are the Welland and Glen catchment, and the Witham, both located in the Northern Area of the Anglian Region. These catchments were selected for their complexity and importance to the regional forecasting operations. They encompass most of the modelling challenges encountered in the Region including long routing reaches and rapidly responding rainfall-runoff catchments and lie partly within and partly beyond the quantitative range of the Ingham radar.

AFFMS – Flow forecast information

The main purpose of AFFMS is to provide a system to forecast flows and levels in the river systems of the Anglian Region. The key elements of the Anglian flood warning system are shown in Figure 1.

The main software components of AFFMS are the user interface, the forecasting database and the forecasting modelling shell, Each of these components acts as an interface for the flow of data and information into and out of the system. The user interface must present forecast and contextual information clearly, and give appropriate access to information for a variety of users, in different geographical locations with different backgrounds and needs. The forecasting modelling shell is designed to provide a flexible and expandable forecasting harness, which is open to and able to run models of various technologies and from a variety of suppliers. The forecasting database must receive, validate and store these real-time data from a variety of external sources and process these via the models into forecasts.

The database system underlying AFFMS comprises both a file-based database, which is useful for managing model data structures and certain types such as radar images and a relational database (Microsoft SQL). Within the Anglian region the collection of data from catchment sensors, and its transmission and real-time database management is carried out by the Anglian Region Telemetry System (ARTS). A radar processing package does the same for rain radar data. At present these are the main sources of real-time data. However to provide an flexible and expandable system the external data interface is built as a generic component to which tailored interfaces can be developed for new data sources, see figure 2.

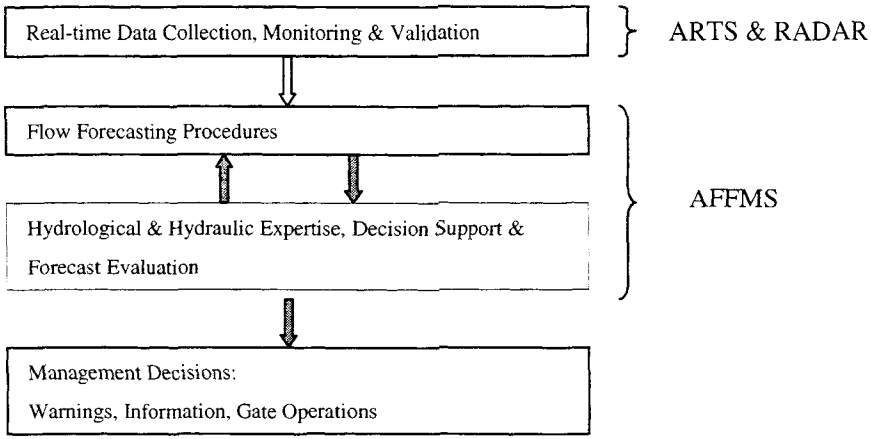


Figure 1 Key elements of the Anglian Flood Warning System

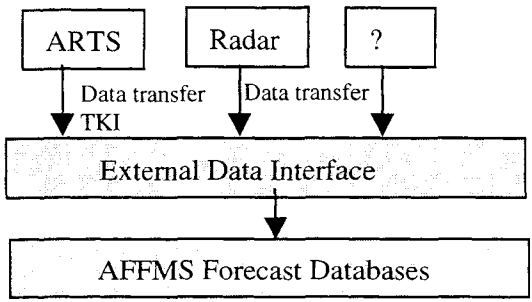


Figure 2 The generic external data interface used in AFFMS

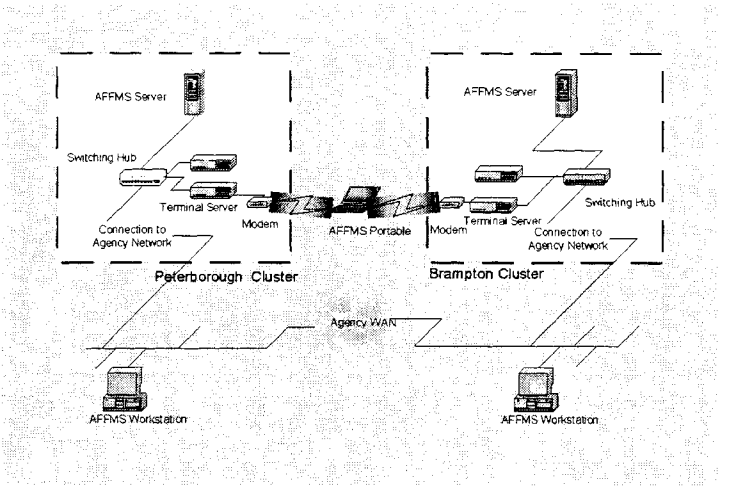


Figure 3 User access to the AFFMS dual server system

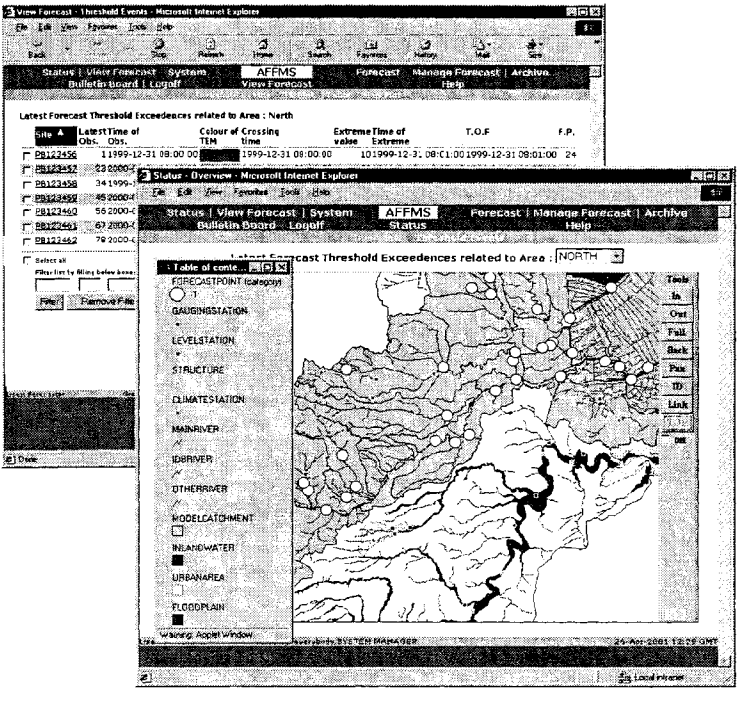


Figure 4 The AFFMS user interface uses Internet technology to present intuitive and readily understood displays for forecast information

User interface

The fundamental architecture of AFFMS is client server. The clients are the user workstations, which provide access to the facilities provided by the servers through use of industry standard internet technology. The servers produce information, forecast results, etc., for the client machines, and the client machines request the information from, or actions of, the server. In AFFMS the client machines can be either personal computers located in any of the Area or Catchment Offices or the Regional headquarters; or portable computers allowing operational staff to view or initiate forecasts wherever they might be at a particular time. File and database replication is used to ensure the data held on both servers are identical, so that in the case of failure of one of the two server groups at either Brampton or Peterborough, the remaining server group will continue to provide function; see Figure 3.

To provide a user-friendly and highly visual display the AFFMS user-interface is based on intranet/internet technology using Microsoft Internet Explorer as the vehicle for navigation and data presentation within the system. This technology is well suited to distributed users requiring access to forecast information from different physical and geographical locations. The widespread use of the Internet also means that most users will readily understand navigation within the AFFMS interface. Forecast information is presented to the operational user graphically using HTML, Active Server Pages, customised graphics and Map Objects to provide map-based displays and GIS functionality. The resulting interface allows rapid access to forecast information in a simple intuitive manner; see figure 4.

Modelling shell

The open system philosophy adopted for the modelling shell ensures that the Region is not dependent on one forecast model supplier and the system can be readily extended to take advantage of new developments in modelling technology. The AFFMS model interface is sketched in Figure 5.

Open model architecture

Since the data requirements and data storage formats vary for different model systems (e.g. MIKE 11, SOBEK or ISIS), tailoring of both model inputs and model outputs is required. This is performed in model specific modules in both the model pre- and post-processing modules. The development and maintenance of these model specific interfaces can therefore be the responsibility of the model suppliers. In this manner the system is future-proofed as versions of the modelling systems used develop and grow. The above design is generic in the sense that all models are treated in the same manner and there are few restrictions on the forecast models that can be used. For example, flood forecasting in a river estuary may require the application of a two-dimensional

hydraulic model from one supplier, while a grid-based hydrological model taking advantage of satellite and radar information from another supplier may be appropriate in another part of the same region.

A central assumption in this design is that the forecasting shell acts as an interface to a modelling system. This reflects the fact that state-of-the-art forecasting models are indeed modelling systems. This has the important benefit That the model systems can be used off-line for the model building and calibration without interfering with operational forecasting.

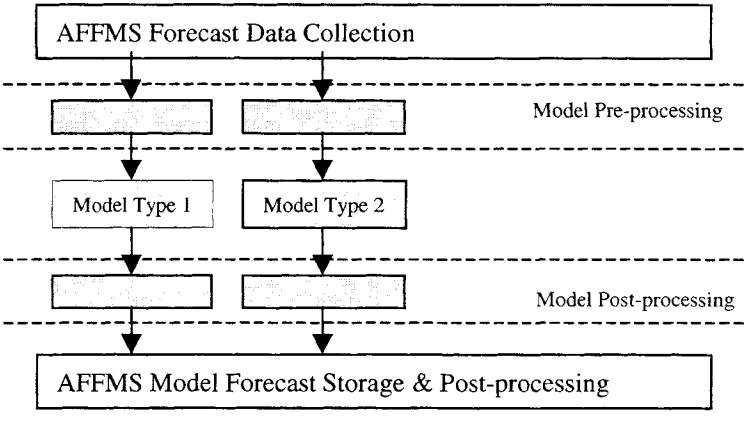


Figure 5 Open and flexible model interface within AFFMS

Data hierarchy for resilience and forecasting scenarios

AFFMS acquires the forecast model data through a data collection module. For a particular model set-up the data required is pre-configured. Prior to any forecast run, a series of data manipulations must be carried out. These include level to flow conversions, the calculation of average areal rainfall etc. In an operational environment, these manipulations must be carried out automatically. These operations are carried out in the model pre-processing modules. Time series data is provided in a generic format for all models based on the generic format used in the European Flood Modelling System (EUROTAS) format.

Within AFFMS a set of tools called the data hierarchy is used to ensure that alternative data sources can be used in flood situations where real-time data becomes unavailable due to instrument malfunction or transmission problems. For example, raingauge data are the preferred choice of rainfall data for the pilot catchments. This is primarily because of long-established trust in the gauge network, the ready availability of data for calibration and the coverage of the entire pilot catchments. If a single gauge is unavailable, neighbouring gauges will be used. If the network is lost, the pre-configured output from the radar processing system will be used. If no data are available, a standard rainfall profile will be used, ensuring that a forecast can be made, though obviously with

some degradation in accuracy. The default hierarchy can be reconfigured off-line to accommodate future developments. For example, improvements in radar data provision are planned. If this includes reorientation of the network to extend quantitative coverage then radar may become the preferred source.

The hierarchy can also be changed, or overridden with manual inputs, in real-time. This allows the forecaster to examine the difference in forecast results arising from exchange of input data sources, or to examine what would happen 'if.'. This allows the forecaster to make some assessment of whether the errors in characterising the rainfall field, arguably the single biggest uncertainty in rainfall-runoff forecasting, have a significant effect on an operational decision.

Welland and Glen Pilot Catchment

A detailed MIKE 11 model has been developed and calibrated which will be used as the basis for the flow forecast modelling. Model features include:

- Continuous rainfall runoff model (MIKE 11 RR) to provide hydrological inputs
- Hydrodynamic routing of flood flows in river and on floodplains
- Advanced structure operation module to describe the operation of tidal sluice gates and retention structures
- Flood forecasting module with updating on either level or discharge using real time data

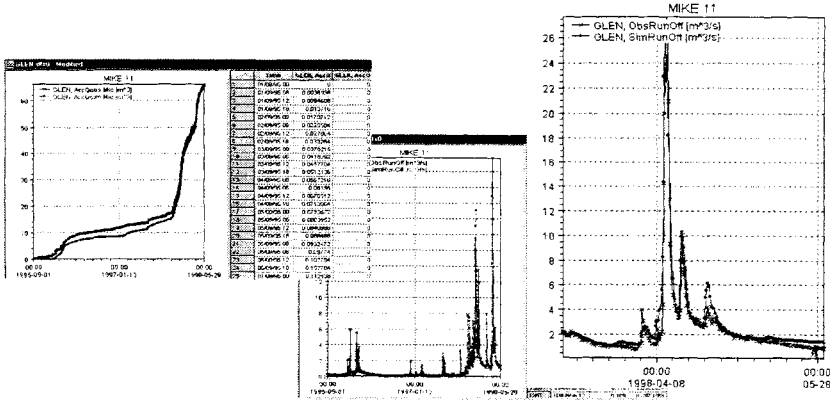


Figure 6 Calibration of the rainfall-runoff model NAM at the Kates Brdige gauge showing the overall water balance, a comparison of the observed and simulated discharge time series and a close up of the major peak

A total of 55 subcatchments (of which 20 are pumped) are used to simulate runoff from the surface, soils and groundwater catchments. Extensive use of the MIKE 11 NAM auto-calibration (Madsen [2]) facility has been made during the model development. The hydrodynamic model extends from the upper reaches of the Welland, Glen and tributaries down to The Wash. A

number of existing design models have been incorporated into the final forecasting model which includes a wide range of structures, including flow measurement weirs, culverts and bridges, siphons, off-stream and in-stream storage reservoirs, tidal exclusion sluice gates and pumps

The model was calibrated for the period July 1996 to June 1998 including the Easter floods of 1998. Once the model was calibrated, it was transformed for use as a real time forecasting model with updating using the MIKE 11 Flood Forecast (FF) module. Model updating involves utilizing water level and discharge measurements available in real time to provide an improved basis for the simulation into the forecasting period. The FF module carries out the updating automatically, and is able to detect and correct for both phase and amplitude errors. (Rungø et al. [3]). As shown in figure 7 real-time updating can improve short-term forecast accuracy where uncertainties in the real-time data cause deviations between the model prediction and observed discharges.

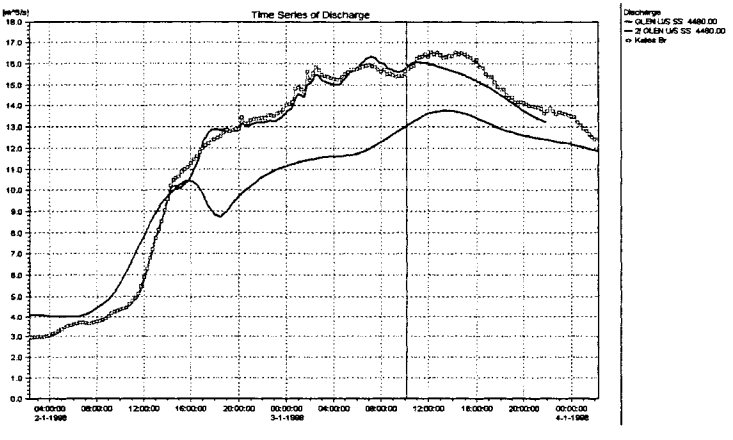


Figure 7 Improvement in short-term accuracy where significant deviations between the model and flow observations arise from uncertain or unreliable input data can be achieved by real-time updating.

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