DEVELOPING FLOOD FORECASTING SYSTEMS: EXAMPLES FROM THE UK, EUROPE, AND PAKISTAN

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Abstract

Provision of early flood warning is an important strategy in reducing flood damage and loss of life. To increase warning lead-time and mitigate impacts more efficiently, flood forecasting systems are increasingly becoming an essential step in the warning process. Development of these has traditionally been initiated by local authorities, and often these systems were no more than a dedicated user interface around hydrological and hydraulic models. Although these have often been proven to be suitable for purpose, the disadvantage of these often bespoke developments is that these are somewhat inflexible to change. Advances in weather forecasting, radar data and on-line meteorological and hydrological data collection, and progress in hydrological and hydraulic models, are requiring an increasing need in developing flood forecasting systems that are flexible to change in the data and models used. In this paper an open shell flood forecasting system is presented that allows for flexible adaptation to changing requirements in terms of data and models, without requiring complete replacement of the forecasting system, and the organisational changes this may require. The shell provides essential generic functionality for handling real-time data, data assimilation and managing forecast runs, while also allowing integration of forecasting modules through an open (XML based) interface. The system has been applied in numerous operational flood forecasting systems. This paper briefly discusses the philosophy and structure of the system, and through its application in the UK, mainland Europe, and Pakistan, the open systems approach is illustrated.

Key words: data integration, flood forecasting, open modelling systems

INTRODUCTION

Flood events across Europe, including the 1993 and 1995 events in the Rhine and Meuse basins, the summer floods of 1997 and 2002 in the Oder, Elbe and Danube basins, the UK floods of 2000/2001 and widespread flooding in the summer of 2005 in Southern Germany, Switzerland, Hungary, Rumania and Bulgaria have raised interest in the provision of flood warning in an effort to reduce losses of property and life due to large floods (De Roo *et al*, 2003). Research in climatic change gives the suggestion that the frequency of large flood events in western Europe may be on the increase (Middelkoop et al, 2001), and together with this possible increase in the occurrence of flood events, public acceptance of traditional engineering measures in providing flood protection is gradually reducing. Alternative strategies in reducing flood risk must therefore be sought. One such strategy is the provision of timely flood warning, the potential of which is broadly accepted (Parker and Fordham, 1996; Hagget, 1998, Grijsen et al., 1992). Whilst the role of flood forecasting in the flood warning process holds a modest position in the chain of detection, forecasting, warning and response (Hagget, 1998), its potential in added effectiveness of warnings through an increase of lead time means its significance is becoming more and more relevant. This lead time can be effectively used to implement measures to reduce either the consequence of flooding through for example evacuation, or reduce flooding itself through mounting of temporary defences. Flood forecasting is typically achieved using some form of hydrological modelling, with a number of model based operational flood forecasting systems in use across Europe and overseas (Grijssen et al., 1992; Bürgi, 2000; Moore and Jones, 1998). With the possible exception of the RFFS system described by Moore and Jones (1998), most of these have developed as an interface around a hydrological or hydraulic model, thus concentrating on the model rather than the data process. Increasing availability of observed data through on-line telemetry and from technologies such as weather radar and quantitative precipitation

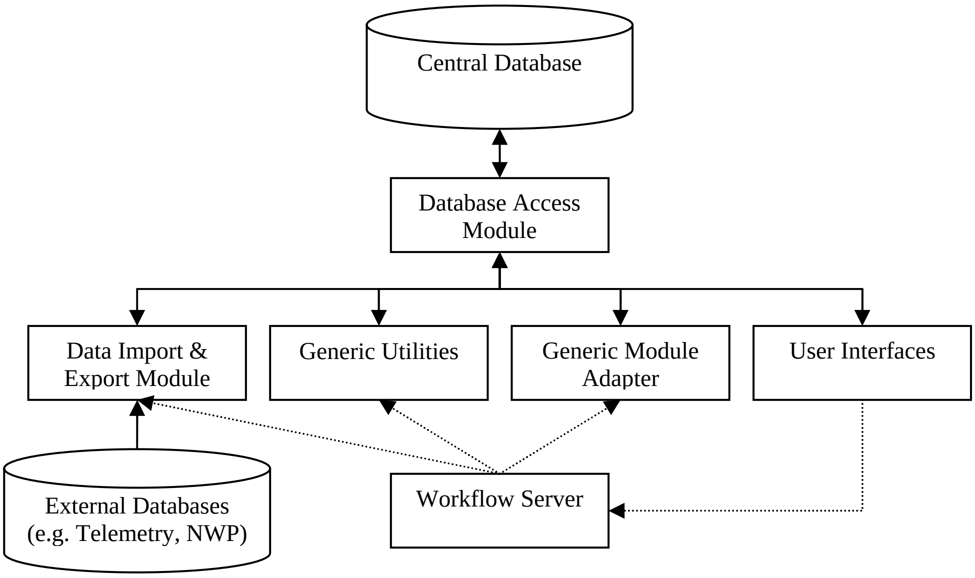

Figure 1 Schematic architecture of the DELFT FEWS forecasting system

forecasting are, however, requiring attention to shift to the complete process of information and data in flood forecasting. In this paper a flood forecasting system is presented that follows the open systems approach to integration of data and models in the flood forecasting process. The advantage of this open approach is illustrated through descriptions of a number of operational flood forecasting systems used in the UK, mainland Europe, as well as for the large river systems of the Indus valley in Pakistan.

FLOOD FORECASTING SYSTEM DEVELOPMENT

Operational flood warning systems are relatively widespread, and there are probably as many different approaches as there are systems. These flood warning systems are typically tailor made to the location(s) for which the warnings are to be provided, ranging from fast responding local warning systems in the headwaters of a river (Krzystofowicz, 1992), to flood warning systems for lower reaches of large river basins (Sprokkereef, 2001) or for all rivers in an administrative region (Moore and Jones, 1998). A list of the elements of a flood forecasting system is given in Madsen et al. (2000), describe the primary elements as being; (i) a real time data acquisition system for observed meteorological and hydrological conditions, (ii) hydrological and hydraulic models for simulation, (iii) a system for forecast and meteorological conditions, and (iii) a system for updating and data assimilation. In many flood forecasting systems, the model component has traditionally taken centre-stage. Whilst this model centred approach has led to many successfully operated flood forecasting systems, rapid changes in real-time modelling capabilities has led to the desire of increased flexibility with respect to the model being used. For forecasting systems that have been developed following the model centred approach, a change of the model used may ultimately result in a complete change of the flood forecasting system. This requires the additional effort of not only establishing a new model, it may also require extensive development or even replacement of the flood forecasting system itself. Additionally, changes in the flood forecasting system may require extensive retraining of operational staff and re-establishing operational procedures. The extensive organisational effort alone then acts as a very effective deterrent to organisations to change a modelling approach, even when more advanced modelling tools are readily available.

Another challenge to developing flood forecasting systems is the increasing operational availability of local and medium-range meteorological forecasting (De Roo *et al*, 2003), with the potential of increasing flood forecast lead time. This has resulted in the focus in development of flood forecasting systems to shift from the models themselves to an integrated process of integration of multiple sources of observed and forecast data, coupled with multiple models, to provide a more complete picture of possible forecast results.

The structure of the flood forecasting system presented here, DELFT-FEWS, takes a different approach than the traditional model centred one. The architecture of the DELFT-FEWS system has been designed to provide an open framework that allows a flood forecasting system to be established to cater to the specific requirements of a forecasting authority. Through its modular structure it can, however, be easily adapted when requirements change. The modular approach has the advantage that many of the components used, such as the underlying models can be exchanged, without the need to change how the forecasting system is operated by its users. This allows for a much more rapid adaptation to advances in modelling techniques, without the added effort in organisational change. The system includes a wide range of modules that deal with generic processing of data in the context of flood forecasting, including data validation, data manipulation, spatial and temporal interpolation etc. An overview of some of the functionality provided is given in the more extensive description of the DELFT-FEWS system in Werner *et al*, (2004). A schematic overview of the different components of the system is given in Figure 1.

CLASSIFICATION OF FLOOD FORECASTING SYSTEMS

To help categorise the various flood forecasting systems described here and the methods and models used, a simple classification of flood forecasting systems is introduced. This compares the desired lead time T_d to the hydrological response time T_p at the location for which the forecast is to be provided. This hydrological response time is further sub-divided into the time that water needs to flow through the river channel (T_c) and the time the water needs to flow from the land phase into the river (T_s). The division between the land phase and the river channel is perhaps somewhat arbitrary, but generally the river channel is considered to be the main river (system), while the response of the land-phase is the response of (sub) catchments before the water flows into the main river system (see Figure 2).

On the basis of these characteristic times, four situations can be recognized (adopted from Lettenmaier and Wood, 1993):

1. $T_d < T_c$ or $T_s << T_c$. The warning will be issued on the basis of water that is already in the main river channel; or the time the water needs to flow from the land phase into the river is insignificant compared to the time the water needs to flow through the main river. This may be the case for forecast point VII in Figure 2, assuming that catchments E and F have only a minor contribution.
2. $T_d < T_p$ and $T_c \cong T_s$. The warning will be issued on the basis of water that is still on the land phase and the response time is determined by the time this water needs to flow from the land phase into the river channel as well as by the time the water will needs to flow through the main river. This may be the case for forecast point IV in Figure 2.
3. $T_d < T_p$ and $T_s >> T_c$. The warning will be issued on the basis of water that is still on the land phase and the response time is mainly determined by the time this water needs to flow from the land phase into the river channel. This may be the case for forecast point I in Figure 2.
4. $T_d > T_p$. The desired lead time is such that warning may be issued on the basis of water that has not yet fallen as rain. In this case also the weather forecast is needed for a timely forecast.

Cases 1-3 are typically applied for short range forecasting in medium and larger basins. Case 4 is typically applied in either medium to long range forecasting in larger river basins or for forecasting in small (flashy) river basins.

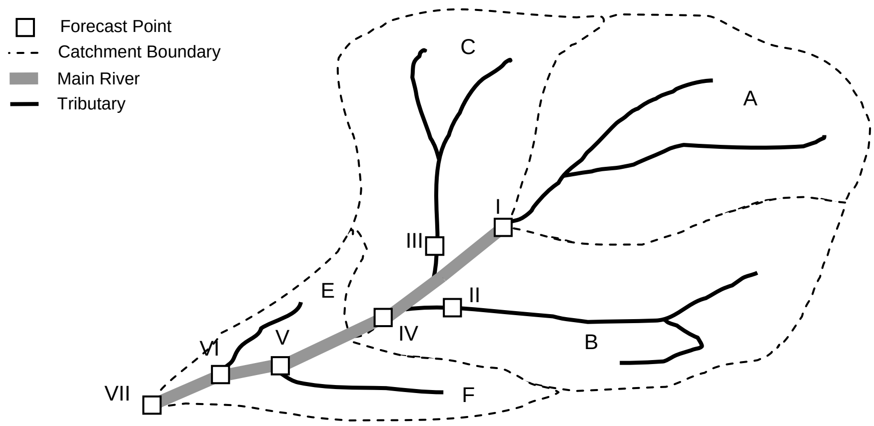

Figure 2 Schematic layout of a catchment, including the main river, tributaries and catchments

EXAMPLES OF FLOOD FORECASTING SYSTEMS

To illustrate the use of the DELFT-FEWS flood forecasting system framework, four examples of flood forecasting systems developed both in Europe and Asia are given. These flood forecasting systems cover all the categories described above, and as a consequence include a wide range of modelling techniques and different approaches in using data. Each of the systems is described briefly, the modelling techniques used are given, as well as specific points of interest with respect to the use of external data, modelling systems, and management of forecast data.

FewsNL – Flood forecasting system for the Rhine and Meuse Rivers (Netherlands)

FewsNL is the operational flood forecasting system used by the Dutch Institute for Inland Water Management and Waste Water Treatment (RIZA), to provide operational forecasts for the Rhine and Meuse rivers. These operational forecasts are provided for the gauging stations located at the borders where the rivers enter the Netherlands. For the Rhine, forecasts are given for the gauging station at Lobith on the Dutch-German border, while for the Meuse forecasts are given at Borgharen-Dorp, just downstream of the Belgian-Dutch border. The system is yet to replace the current operational system for the Rhine, which provides a forecast at a lead time of two days for the station at Lobith. Forecasting at a lead time of two days for the Rhine falls in the first category of flood forecasting systems, with the main source of large floods being upstream of the gauging station at Andernach (Wilke, 1998), which is at a travel time of some two days upstream of Lobith. The requirement to RIZA to extend the lead time for forecasting on the Rhine to four days lead time (Sprokkereef, 2001), has caused a shift towards the second and third category of forecasting system. A further desire to obtain pre-warnings at a lead time of ten days falls into the fourth category of forecasting system. This extension has primarily led to the development of FewsNL (using the DELFT-FEWS framework), with a much more extensive use of data and models than the current operational system.

Observed data

Both the Rhine and the Meuse are good examples of truly trans-boundary rivers. The Rhine catchment in particular is shared by Switzerland, Austria, Liechtenstein, France, Germany, Luxembourg, Belgium, and the Netherlands. Through close cooperation of the hydrological/meteorological agencies of all countries involved, FewsNL is able to use on-line data from the different national hydrological and meteorological agencies. While cooperation in data exchange has been successful, standardisation of data exchange formats has had less success. To cater for this, for each of the formats to be imported, separate plug-in import modules have been developed. This is an example of the advantage of the open architecture approach, with plug-in modules/classes easily added to allow different formats to be imported.

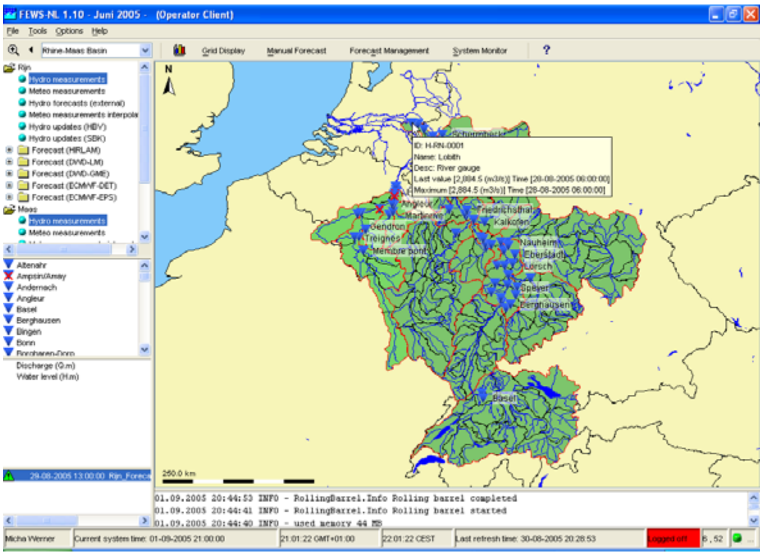

Figure 3 Main user interface for FewsNL, showing the Rhine and Meuse catchments upstream of the border stations of Lobith and Borgharen-Dorp respectively.

External Forecast Data

FewsNL makes extensive use of Numerical Weather Prediction. Rainfall and temperature prediction grids are obtained from various meteorological agencies. This includes the HIRLAM model from the Royal Dutch Meteorological Institute (Resolution ~14km, 1 hour time step, 48 hours lead time, see Figure 4), the LM model from the German Weather Service (Resolution ~7km, 1 hour time step, 72 hours lead time), the GME model from the German Weather Service (Resolution ~40km, 3 hour time step, 7 ¼ days lead time), the deterministic model from the European Centre for Medium Range weather forecasting (ECMWF), with a lead time of 10 days, and finally the ensemble prediction system output from ECMWF. This also has a lead time of ten days, but contains 50 ensemble forecasts, created by perturbing the initial conditions (Buizza and Hollingsworth, 2002). Most of these predictions are provided to FewsNL in the standardised GRIB exchange format used by meteorological agencies worldwide, and are imported using a standard DELFT-FEWS GRIB import module. There are some exceptions which use a propriety format, and here additional plug-in import modules have been developed.

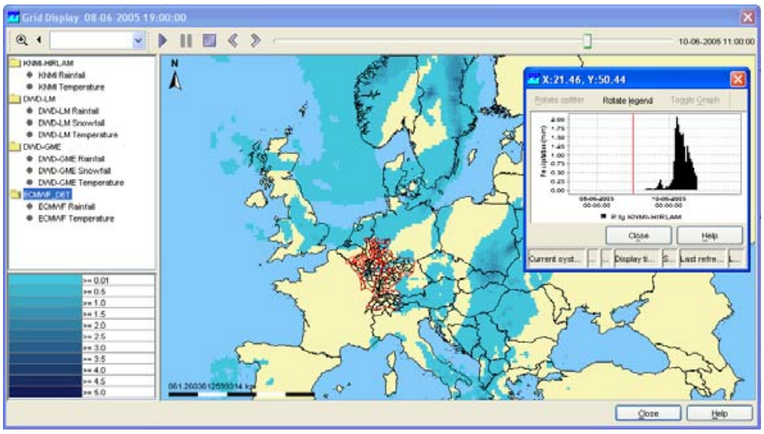

Figure 4 Example of the NWP forecast rainfall across Europe from the HIRLAM model run by the Royal Dutch Meteorological Institute. The forecast was run on the 8th of June, 2005, 18:00 GMT.

Hydrological and hydraulic models

Hydrological models covering the complete Rhine and Meuse basins have been calibrated to model the catchment response to rainfall. The model used is the HBV model from the Swedish Meteorological Hydrological Institute (SMHI). This has been integrated with DELFT-FEWS using the open interface XML format (see for a description of the approach Werner *et al*., 2004). Outflows from the HBV sub-catchment models input to the SOBEK hydrodynamic flow models for the Rhine and Meuse, which routes the discharge to Lobith and Borgharen-Dorp respectively. The SOBEK model is again run in DELFT-FEWS using the same plug-in approach as the HBV model. To reduce errors in estimated flows from the hydrological models, ARMA error correction is applied to these for the larger tributaries prior to introduction in the SOBEK model. A standard error correction module forms an integral part of the DELFT-FEWS system.

Hydrological Forecasts

For comparison purposes, forecasts are run using all the meteorological products available. This includes the ensemble prediction models. Figure 5 gives an example of the output of an ensemble run. When comparing the different forecasts, the hydrological lag time becomes very clear. For the Rhine, where lag times are more significant than in the Meuse, it may take 4-5 days before differences can be seen between the different forecast products. This response is much faster in the Meuse River, where the hydrological lag time can be in the range of 12-24 hours (Figure 5).

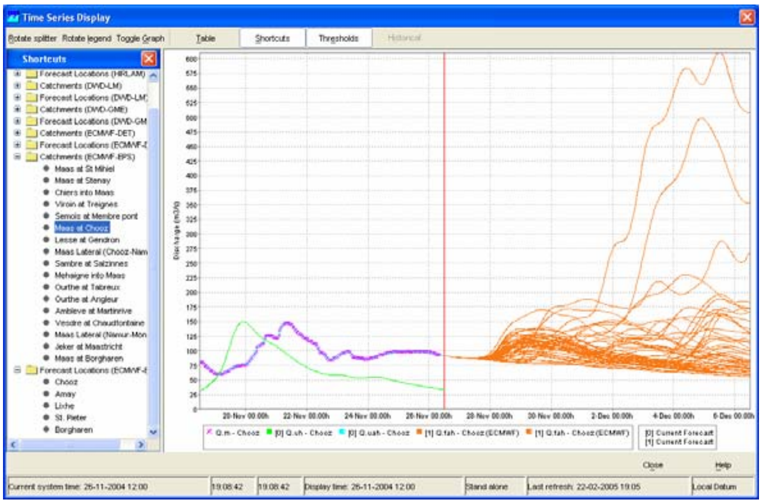

Figure 5 Example of the output of the Ensemble prediction forecast at Chooz in the Meuse basin

FEWS-FOWG – Flood Forecasting System for the Rhine Catchment (Switzerland)

FEWS-FOWG is the flood forecasting system used by the Federal Office for Water and Geology (FOWG) in Switzerland. The system has the same user interface layout as FewsNL (Figure 6), and in fact uses the same hydrological model (HBV). However, despite the hydrological model code not only being the same, but also covering the same area, the model setup and calibration of the HBV model is quite different. Forecasting rainfall-runoff in mountainous areas is a serious challenge (Bürgi, 2002), and has led to the requirement of advanced data handling methods. This includes interpolation of rainfall and temperature data not only in the horizontal plane, but also vertically, to allow for the large gradients of temperature and rainfall and the effects of temperature inversion. Precipitation forecasts are again provided through numerical weather prediction from both the Swiss Meteorological Agency and ECMWF.

In FewsNL a simpler approach is followed to describe the rainfall runoff process in Switzerland, with less detail incorporated in modelling snow cover and effects of temperature gradients on snowmelt.

These differences in model complexity can be understood when considering the travel time from the Swiss-German border to the station at Lobith (in the order of six days), and reflects the different categories of forecasting system. The lead times considered by FEWS-FOWG put this system in the third/fourth category described above. The quick response of some of the basins is, however, reduced by the large lakes in Switzerland, with most of the primary forecasting points being downstream of these lakes.

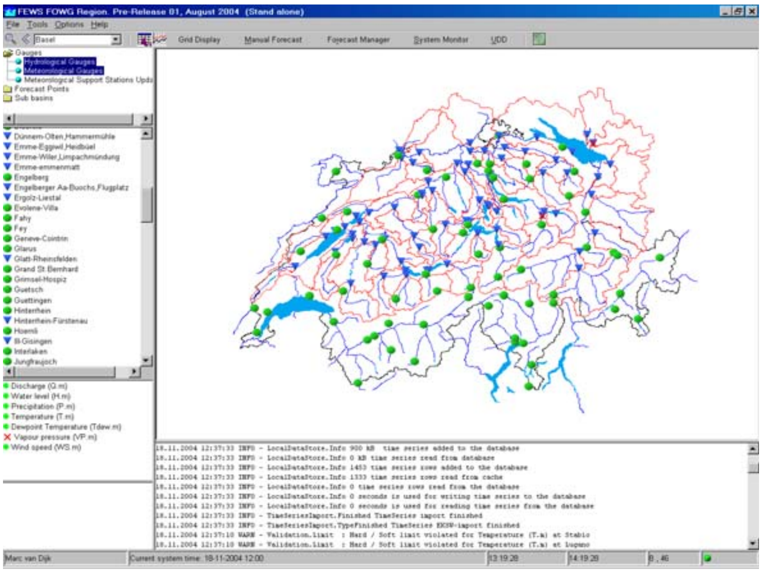

Figure 6 Main user interface for FEWS-FOWG, showing the Upper Rhine catchment in Switzerland.

NFFS– National Flood Forecasting System, Environment Agency, UK

The National Flood Forecasting System (NFFS) is perhaps the most extensive application of DELFT-FEWS to date. Flood forecasting, both fluvial and coastal is organised in eight regions in the UK, each providing forecasts for all fluvial and coastal sites within each region. DELFT-FEWS fulfils the aim of the Environment Agency to standardise flood forecasting practice across the eight regions, which have historically developed independent systems and approaches.

Observed and external forecast data

All data imported to NFFS is provided to the system in a standardised XML or GRIB form. such standardised formats have greatly eased integration of data from numerous sources (Telemetry, UK Meteorological Office, etc.). Data returned from NFFS for publishing in other systems also follows the standardised XML format. Data uses is primarily observed data from telemetry and precipitation forecasts from the NIMROD system (see Golding, 2000), but also includes surge forecasts at numerous sites around the coast. New developments, such as the use of precipitation forecasts derived from numerical weather prediction will also be included, and the use of the standardised XML exchange formats makes adaptation to these sources very simple, without the need of fundamentally changing the system.

Forecasting models

The eight regions responsible for flood forecasting have historically developed their flood forecasting systems independently. As a consequence, a wide range of forecasting models and methods is used. All modules have been integrated as a part of NFFS. This has again been achieved through use of the published XML exchange format between DELFT-FEWS and the third party models (see Werner *et al*, 2004 for details on the approach). The models integrated include hydrodynamic models (ISIS & Mike11), Hydrological routing models (KW, DODO), Hydrological runoff models (PDM, NAM, MCRM, TCM), a number of transfer function models, as well as various lookup table type models used in coastal forecasting.

The wide range of forecasting methods reflects in part the range of response times found for the different river systems across the UK, or even across a single region. For faster responding systems on the western coast development has traditionally focussed on Transfer function type models (category 4 type forecasting points), while for the larger river systems such as the Severn, Trent and Thames the catchment model approach has been followed (category 2-3). The advantage of introducing these models to run under NFFS is that not only are these different models run using similar procedures across the eight regions, there is now much greater opportunity for using appropriate model techniques for different forecasting points depending how the response times and desired lead times compare. Such exchange of methods was not possible prior to the introduction of NFFS simply because of the technical constraint of adapting existing forecasting systems.

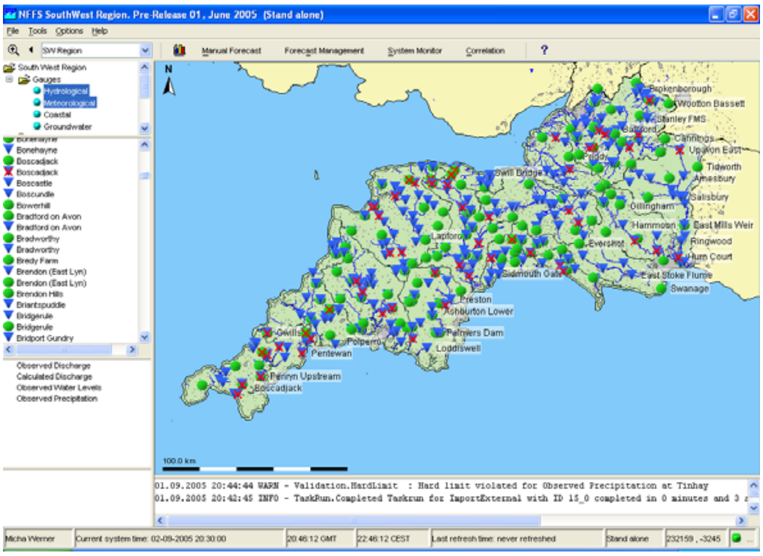

Figure 6 Main user interface for NFFS, as configured for the Southwest region of the UK Environment Agency.

FEWS-Pakistan– Indus flood forecasting system, Federal Flood Commission, Pakistan

The Indus flood forecasting system has been developed to provide flood warning for the Indus river downstream of the Himalaya (below Tarbela dam), and for the four large tributaries of the Indus in Pakistan that form the Punjab basin. Flooding in Pakistan is induced mainly through the effect of monsoonal depressions causing extreme precipitation when meeting the Himalaya mountain ranges, combined with the effect of snowmelt (mainly on the Indus, Chenab and Jhelum rivers, where the main snowmelt season coincides with the monsoon season). Most of the forecasting points in the Indus forecasting system are, however, sufficiently far downstream and warnings can be issued primarily on the basis of observed upstream flows. Table 1 provides an example of typical lead times for the Indus River downstream of Tarbela dam. Lead times for the large tributaries are in the same order. Most of these forecasting points clearly belong to the first category of forecasting system described above.

Table 1 Lead times of flood waves on the Indus

Location	Chainage [km]	Lad times [days]
Tarbela dam	0	0
Kalabagh barrage	210	3
Chashma barrage	268	3.5
Taunsa barrage	505	6
Chenab confluence	665	8 - 10*)
Guddu barrage	794	9 - 11
Sukkur barrage	940	10 - 12
Kotri barrage	1,349	13 - 15

*) first value for floods from Indus, second value for floods from Chenab

Observed data

One of the large challenges in the Indus Flood Forecasting System is the provision of real time data. Observed hydrological data for the rivers in Pakistan is obtained from various national agencies, and include levels and flows at gauges and barrages at regular intervals along the Indus and its tributaries. The Indus and its tributaries are also truly trans-boundary rivers, with most of the catchment area falling in India, Pakistan and Afghanistan. In contrast to the Rhine basin, cooperation in terms of data exchange has been a significant challenge. Most precipitation data for Pakistan is provided through the online rain gauge and synoptic networks of the Pakistan Meteorological Department. Two weather radar systems have been installed to provide estimates of rainfall in the Indian catchments. These estimates are, however, considerably uncertain, given the distances involved and difficulty of precipitation estimation with radar in mountainous areas.

Hydrological and Hydraulic modelling

The Indus Flood Forecasting System uses the Sacramento conceptual rainfall runoff model to describe response to rainfall and snowmelt in the 970,000 km^2 catchment of the Indus basin. The hydrological model has been divided into numerous sub-catchments. To reduce the errors in the rainfall-runoff prediction, ARMA error correction is applied at the gauging stations that form the upper boundaries of the hydrodynamic models. With the long lead times and warnings issued largely on the basis of observed flows in the main rivers, emphasis has been placed in the Indus flood forecasting system on the hydrodynamic modelling of these main rivers. This is achieved using the SOBEK hydrodynamic model, with a total modelled river length of 3073 km. To improve the reliability of flood predictions, an extended Kalman Filter is applied in the SOBEK model, using observations where available from the various gauges. Despite this, modelling flood flows, with peak flows in the individual tributaries sometimes reaching 20,000 m^3/s or more is no mean feat. The interaction of the floodplains, often with widths of 10-20 km, has a significant impact on the propagation of the flood wave, as does breaching of levees along the river (sometimes man-made breaches to reduce damage to the barrages). Both these effects have been incorporated in the hydrodynamic model, and when data on occurrence of breaches is available, this can be input through the DELFT-FEWS front end.

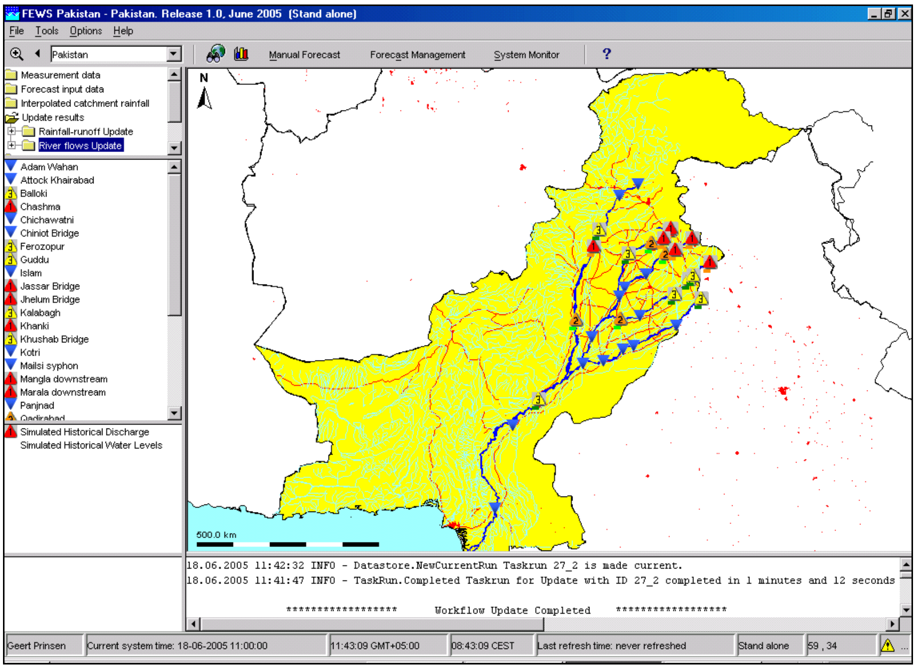

Figure 6 Main user interface for FEWS-Pakistan, the Indus Flood Forecasting System.

CONCLUSIONS

The brief description of four operational flood forecasting systems given is an example of the variability of data, methods and approaches used in flood forecasting. Integrating these approaches to form an operational system is a significant challenge. With the traditional strategy of model centred flood forecasting systems, the consequence was often that once developed the system would not adapt to advances in data availability and modelling techniques, due to the significance of such change in terms of development work and perhaps more importantly, organisational change.

The DELFT-FEWS flood forecasting system provides an open architecture framework, allowing a more flexible strategy to be chosen. Through its modular structure, and support of open, published interfaces, the system can be easily extended to include additional data formats and models. Numerous models have been included in the four systems described previously, and additional applications of DELFT-FEWS not described here include many more lumped and distributed hydrological as well as 1D and 2D hydraulic models (e.g. Vflo PRMS, LISFLOOD). With this open approach, changes to the models and data used need not have an impact on how the system is used operationally, thus reducing the organisational impact of adaptation, and allowing easy integration of advances in data provision and modelling. This seems a logical strategy in developing operational flood forecasting systems, and the flexibility in changing underlying models reflects a growing realisation that no single model concept is suitable in all cases.

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