3

Integrated Flood Forecasting, Warning and Response System

3.1 Defining an Integrated System

Establishing a viable flood forecasting and warning system for communities at risk requires the combination of data, forecast tools, and trained forecasters. A flood-forecast system must provide sufficient lead time for communities to respond. Increasing lead time increases the potential to lower the level of damages and loss of life. Forecasts must be sufficiently accurate to promote confidence so that communities will respond when warned. If forecasts are inaccurate, then credibility of the programme will be questioned and no response actions will occur.

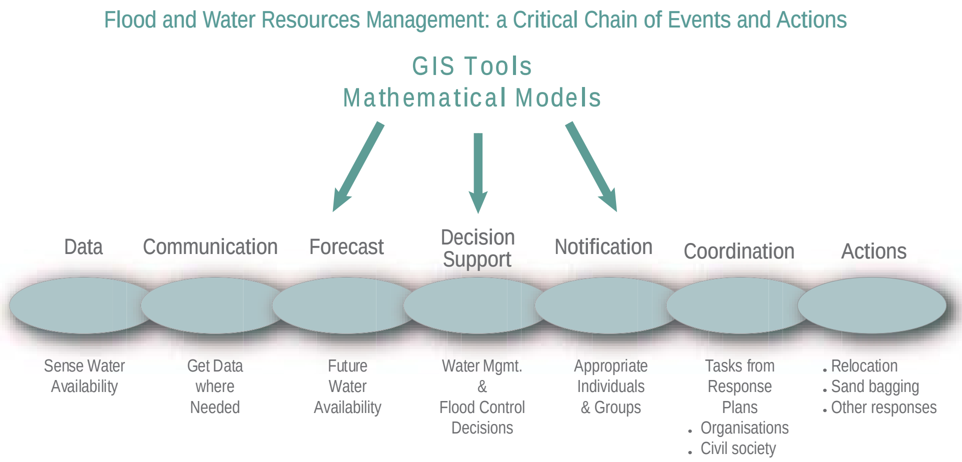
Flood-warning systems must be reliable and designed to operate during the most severe floods. The greatest benefits for an effective flood-warning programme occur when flooding is severe, widespread, and/or sudden, and when communities and organizations are prepared to mitigate impacts.

The implementation of an end-to-end flood forecast, warning and response system consists of many components. These components must be linked for successful operation. The interaction of components of the integrated flood forecast system or programme could be represented as a chain composed of many links. Each link must be present and functional if benefits are to be achieved. Figure 12 shows a schematic representation of the system as links in a chain.

The essential links or components of the integrated flood forecasting, warning and response system consist of a Data Source, Communications, Forecasts, Decision Support, Notification (often referred to as dissemination), Coordination, and Actions (or responses). A flood forecast and warning programme should be designed to mitigate floods, and, as such, it is an asset to overall water management. To achieve this, it is important that all of the components of the system be functional. If any component is dysfunctional, then this weak link could break the chain, resulting in an ineffective warning and response process. For example, if critical rainfall or streamflow data are unavailable or if the data are not relayed to a forecast centre for use in forecasting, then the critical lead time required to make decisions, coordinate activities, warn citizens, and take actions is not possible. If a perfect flood forecast is generated but does not reach the population at risk, then the warning system is useless. Equally, should the population at risk receive the warning

Figure 12

Integrated flood forecasting, warning and response system within IWRM



but not know what actions should be taken, then the system again would not have accomplished its purpose.

In the overall design of the integrated system, there are many factors that should be considered. The remainder of this chapter reviews some of these factors.

Basin characteristics

The physical characteristics of the basin, such as surface area, topography, geology, and land surface cover, will help to determine the nature of potential flooding and the basin's susceptibility to related hazards such as landslides and mudflows.

The hydrological response of the basin can be impacted upon by changes in land use associated with urbanization, forestry, agriculture, drainage, or channel modifications. A record of such changes over time is useful in establishing the dynamic relationship between rainfall and runoff. The following also contribute to an understanding of flood hazards: records of climate norms and trends for parameters, such as precipitation and evapotranspiration; and information on the usual effects of ENSO events and extreme events, from synoptic to mesoscale.

Population centres often are adjacent to rivers, and flood plains can be rich agricultural resources. Identification of populations and economic activities at risk should be carried out early in the process, as this will shape the eventual forecast output.

Flood history

Flood history, also known as paleohydrology, can be inferred from study of sediment deposits, tree ring analysis, and examination of a number of other biological indicators. Such analyses will not lead to a determination of flood volumes, but may help put a recent flood into context. Often, such records are of value in defining the flood history in a river basin, particularly when combined with stream gauge records that exist for contemporary periods. Other more recent historical information can be drawn from newspapers, journals and oral histories. Usually there is a perception level associated with flooding at a given location; large events are noted, smaller events are not.

The flood history will identify the portions of a basin subject to flooding, whether flooding is urban or rural or both, seasonal characteristics of flooding, and the feasible warning time. The type of flooding and associated hazards may be significantly different on tributaries compared to the main stem of the river. Knowledge of the factors contributing to or causing the flooding such as meteorological and antecedent conditions should be established for each flood event.

Lake flooding as well as flooding from ocean surge and tsunamis may pose problems quite different from river flooding. These guidelines are oriented to river flooding, but many principles contained herein are also applicable to varying degrees to other water-related disasters.

Environmental factors

Floods can induce major changes in river morphology, mobilize nutrients and contaminants in the soil, release other contaminants from storage depots, and discharge effluents to the river. Deforestation, fires and erosion of materials combined with saturated soils can lead to landslides, mudflows and other threats to human settlements. Sometimes floods are accompanied by strong winds that also can pose threats to human life and property. An analysis of potential environmental risks will help determine flood forecasting and warning needs. This can help to shape future approaches to flood plain management and regulation, and can assist in the design and establishment of response actions.

Economic factors

A flood forecasting, warning and response system comprises an important element of integrated water resources management. The benefits of river forecasts for power generation, navigation or irrigated agriculture make implementation of such a system more cost effective and sustainable. Even then, maintaining a system in a state of readiness between floods may be difficult.

An examination of past damages and the potential for future damages will help determine priority areas for flood forecasting, warning and response. Rigorous analysis would call for statistical analysis of flood peaks and the calculation of the present value of costs and benefits of flood forecasting and warning. In most cases, however, the benefits of flood forecasting, warning and response are virtually self-evident. The real questions are the affordability of various options and the desire of society to invoke a more pro-active stance to reducing flood losses.

Communities at risk

While flood losses in rural districts can be devastating to those areas, the most significant losses are usually in urban communities because of the concentration of people and related socio-economic investments. The basin characteristics and flood history of individual communities, combined with damage estimates from previous floods, will give some indication of the type of flood forecasting and warning system that may be most suitable for effective warnings. Once the system is defined, consideration should be given as to how it could benefit rural areas as well.

System identification

Depending on the nature of the basin and the type of event causing the flooding, potential warning times could vary from hours to several days to weeks. Communities subject to flash flooding require warnings of meteorological conditions that, when combined with antecedent basin conditions, could lead to flooding. This represents a special case of flood forecasting and warning. The challenge in such cases is rapid depiction of critical flood thresholds and their subsequent communication and emergency response. An analysis of historical rainfall records, including storm transposition and the resulting streamflow would help to identify areas of concern.

Photo: J. Laurie, Las Vegas Review Journal

Las Vegas, July 1999, flash flood meets desert

When warning times are longer than a few hours, full-fledged forecast systems should be contemplated. The degree of desired automation and sophistication must be considered in light of current needs and capabilities. Automation needs can be considered in sub-systems: data acquisition and transmission; data processing; forecast preparation; and forecast distribution. Different levels of automation may be required as the overall system develops and expands, and as financial resources become available. Systems may vary from those using largely manual observations, graphs and tables to highly automated multi-model systems running on computer workstations.

Benefit-Cost analysis

An analysis of the cost of floods and the potential benefits may help determine the type of forecast and warning system and response mechanisms that would be most cost effective. Costs resulting from flooding can be estimated for various magnitudes of events for various centres. Damage statistics from previous floods are also valuable in establishing the costs associated with such events. Judgement is needed to estimate the benefit of flood forecasting and warning in reducing damages and loss of life. Governments and financial institutions require such information on costs and benefits to help understand where expenditures will reap the largest rewards. Studies and analyses have shown that damage reduction due to forecast improvements can range from a few percentage points to as much as 35% of average annual flood damages.

A standard set of flood damage categories relevant to the basin should be developed. When loss of life is a threat, this too should be identified, even though it is difficult or impossible to quantify in economic terms. Other damage categories could include residential buildings; commercial, institutional and industrial buildings; agricultural lands; and infrastructure. Additional costs include temporary relocation and flood-fighting costs. Floods can have an effect on the population and economy of an entire country, and business losses should also be included in the analysis. Developing standard damage categories allows damages to be more accurately estimated for various levels of flooding.

A rigorous cost-benefit analysis would require determining a flood frequency distribution so that the present value of future benefits can be determined. In the absence of sufficient data or analysis, a more rudimentary presentation of costs and benefits may be sufficient to determine the size of the investment that is justified for flood forecasting, warning and response.

Evaluating existing capabilities

Most countries have basic networks of meteorological and hydrometric stations that are necessary for flood forecasting and warning. It is likely that the operators of the existing networks may be in many different agencies. In many cases, the networks may not have been designed to acquire data during extreme events, or they may not provide data in real-time or to common standards. Also, networks may not provide data for key urban centres where forecasts are required or for areas where the major inputs to the flooding are occurring. Identifying the existing network, its operators, and the existing approaches and capabilities are necessary steps in the evolution of a flood forecast system.

Another important element is an examination of existing communications capability. Given that important data are available at a remote site, how can these data be reliably transmitted to a flood-forecasting centre? Will telephone or radio links - manual or automated - function during a flood emergency?

Some agencies may have developed hydrological mathematical rainfall-runoff models and flow routing models for their own purposes. These models may be useful as flood forecasting models. An inventory of existing models will also help define current capability within individual agencies.

Identification of key users and collaborators

Establishment of a successful flood forecasting, warning and response system depends on a thorough analysis of existing capabilities, identification of key users for the system, and a good understanding of the interagency arrangements needed in an effective system. Considering these factors will lead to forecasts that meet user needs and that are more likely to be acted upon during an emergency. The ultimate goal of such a system is to ensure the safety and security of the public and to protect property and the environment. To achieve this result, however, means that the public must receive and understand forecasts, and the myriad of agencies having responsibility for emergency action and response also must receive the forecasts, have response strategies in place, and act upon the forecasts accordingly.

Key users typically include: civil agencies at the national, provincial/state, and local level; military organizations; corporations, especially those which operate structures; volunteer emergency response organizations; and the media. A user analysis, and close ties and interaction with these groups should be considered to help establish overall flood forecast needs and response measures. The role of the media in informing the public cannot be underestimated. It is critical that the media receive timely and authoritative forecasts and warnings. Media communications should encourage the appropriate public response and should not lead to counterproductive speculation.

Photo: V. Thanh, IFRC

Vietnam Mekong Delta floods, 2000
Roads and infrastructures were badly damaged by the floods in An Giang province, making relief distributions a challenge.

Many of the world's river basins have a transboundary component. In some cases transboundary basins are covered by treaty, international agreements, or other institutional arrangements. Such arrangements may or may not include river or flood forecasting. Shared basins imply a shared responsibility; an analysis of user needs should include users in other countries.

Often the mandate and capabilities of governmental organizations are not entirely clear. An institutional analysis of each agency's mandate, needs, capabilities and legal responsibility during a flood emergency will help shape an emergency preparedness and response plan. Overall, one agency should be assigned the lead responsibility (and accountability) for an end-to-end system, with the system itself potentially being operated by a number of organizations.

In the evaluation of the existing system, agencies that operate data collection networks or models, or that can contribute to a forecast system in other ways, will have been identified. In some cases the potential role of a specific agency in a flood forecast system may be relatively clear, while in other cases that role may have to be identified and negotiated.

A fundamental question is that of hydrological and meteorological coordination. In many countries one or more agencies operate meteorological forecast and climate networks, while hydrological networks may be the responsibility of entirely different agencies or departments. Coordination among these bodies is essential because development of a flood forecasting system may require the addition of new sensors or telemetry equipment funded by one agency being installed at a site operated by another one. A successful forecast system will depend upon cooperation among meteorological and hydrological agencies and could involve financial transactions among them.

Similarly there may be a number of agencies with responsibility for operation of structures for water management and flood control. These could include hydroelectric generation facilities, irrigation headworks, water supply reservoirs, and so forth. Individual structures may have an established operating plan, but an integrated plan for operations during extreme events is needed to provide optimal flood control benefits and to avoid structural failure. Interagency co-ordination and cooperation is required to ensure the integrity of the entire water management system during extreme events. A flood forecasting and warning system provides the information necessary to improve decision support for the operation of structures.

Some agencies may have arrangements for technical support or financial assistance with international organizations or with other countries. These may prove beneficial in developing or improving a forecast system through training and in general strengthening of much needed organizational infrastructure.

A logical agency to lead a country's flood forecasting and warning effort may emerge from this analysis. The identified agency will require technical support and leadership from several agencies. More importantly, there is a need for long-term political support for the endeavour. Flood forecasting and warning will have to compete with other national priorities, and resources and financial support can atrophy, particularly in the absence of flooding.

There is a need to establish a flood-forecasting centre having a legal mandate to issue authoritative forecasts and warnings on the river basin or at the provincial/state or national level. These forecasts must be understood by agencies having the responsibility for emergency response and by the general public. Such agencies, civil organizations and the general public must be aware of their roles, have response mechanisms in place, and know what actions to take under various circumstances.

Determination of specific forecast system requirements

Analysis of the basin characteristics, flood history, flood damages, and the existing databases will give some indication of the type of forecast system that is achievable and affordable. It is likely that the system will be based on enhancing existing networks and agency capabilities. Establishing a new system implies phased development from the existing system to the new one. Establishing a long-term plan with specific milestones is critical to future success.

3.2 The Hydrometeorological Network for Forecasting

The hydrometeorological network is the key requirement for most flood forecasting. In particular, precipitation and streamflow data are needed. If snowmelt is a factor in flooding, then measurements of snow water equivalent, extent of snow cover, and air temperature are also important. In many cases agencies other than the forecast agency have useful data. Rather than duplicate networks, it is preferable to develop cooperative arrangements. In some respects, it is preferable that the network serves many purposes as this may result in its broader financial support.

In most cases data network operational performance is the weakest link within the integrated system. Operational data networks must be examined. Are the rainfall and stream gauge (hydrometric) data networks satisfactory in sampling rainfall (intensity and spatial distribution) and streamflow response for the river basin? Are stream gauges operating properly, and are they providing accurate conditions of water level and streamflow? Are data communicated reliably between the gauge sites and the forecast centre? How often are observations taken, and how long does it take for observations to be transmitted to the forecast centre? Are data available to users who need the information for decision making? Are the data archived for future use? Are the data collected to known standards, is the equipment properly maintained and calibrated, and are the data quality controlled?

Network design

It is not possible to manage water or forecast floods without data. Various types and sources of data are needed to monitor the environment, conduct a water balance or provide input to hydrological models that estimate streamflow from rainfall. Operating a real-time hydrometeorological network is essential, as data provide the foundation for establishing the potential for flooding. In-situ observations of meteorological and hydrological parameters are required as inputs to the hydrological prediction system.

An analysis of the existing network should be undertaken. Tables and maps should be available providing details on monitoring locations, parameters, sensors, recorders, telemetry equipment and other related data. In addition, monitoring sites in adjacent basins should be inventoried. In low relief basins, data from those sites could be very useful. Analysis should be performed to identify sub-basins that are hydrologically or meteorologically similar.

Based on forecast needs, the adequacy of networks can be determined and required modifications can be noted. These could include new stream gauges, rain gauges and possibly other sensors in the headwaters, or additional telemetry equipment. In some cases, network sites may not be well suited for obtaining flow measurements or other data under extreme conditions. Costly structural alterations may be needed. Interagency agreements may be needed for maintenance and operation of the network.

A key variable to be established is the time step needed to adequately forecast a flood for a given location. If the time step is, say, six hours then data must be collected every three hours or even more frequently. In many cases, supplementing a manual observer network with some automated gauges may provide an adequate operational network.

Data acquisition

Generally the design and operation of data networks have a large influence on forecast system accuracy and in the ability of the system to provide the necessary lead-time to issue warnings so that response actions can be taken. It should be underscored that the design of reliable real-time operational observing networks is critical to the success of a forecast, warning and response programme. In order to be effective during extreme conditions, sensor installations may have to be "hardened" to withstand extremes in wind, rain or flood stage.

The advent of remotely sensed data has significantly improved the ability of operational hydrology to infer watershed conditions in data-sparse regions. The application of radar-derived precipitation estimates serves as the principle tool in forecasting floods and flash floods in many countries. The use of geostationary and polar orbiting satellites to derive large volumes of meteorological and hydrological products is rapidly advancing. Remotely sensed data can now be used to provide estimates of precipitation, snowpack extent, vegetation type, land use, evapotranspiration, soil moisture and flood inundation. This information is becoming increasingly useful in data-sparse regions of the world where water availability and flood forecasts are needed.

Many countries use the Global Telecommunications System (GTS) of the World Meteorological Organization (WMO) for the transfer of real-time meteorological data. More recently, some hydrological data from a number of projects were added to the system. Even with these advances in remotely sensed data and their use, inadequacy of data remains the biggest weakness in establishing a viable flood forecast programme for a river basin or for a country.

Data communications

For data to be useful to the forecast centre, point data observed at remote locations must be converted to digital formats. This may require changing the sensor itself or simply adding another component to an existing system. The format for the digital data must be specified. Remotely sensed images used in forecasts are usually already in a specified digital format. If the sensor output is film, arrangements must be made to make the conversion to a specified digital format within the required time.

Once data have been observed or collected at sites throughout the river basin or country, the data must be transmitted to locations where they can be stored, accessed, and used. The value of data increases with the speed of transmission and processing, from their initial observation to where they are used. Meteorological and hydrological data are needed almost instantaneously so that the hydrological forecast system can produce up-to-date and reliable forecasts. More importantly, this allows the system to provide the critical warning times needed for users to take actions. This is especially true for issuing warnings of flash flood events and of potentially hazardous mudslide conditions.

There are many types of communication technologies that can be applied to transmit data from sites in remote locations to the forecast centres. The most common form of data communication is by telephone. However, telephone lines frequently fail during severe flood events. More reliable but potentially more expensive forms of data communications are satellite, line of site radio, cellular radio and meteor bursts. These also have their strengths and weaknesses. An evaluation should be performed to establish the most suitable, reliable and cost-effective form of communication for the local situation.

Data may be transmitted by dedicated satellite links, radio links, by commercial telephone links or other shared services. In some cases the data link could simply be a voice telephone communication. The forecast centre may be required to poll sites individually, interrogate a third-party system, or use the Internet to obtain data. Data transmission links must be identified, and their reliability and speed should be determined. If image products are to play a role in the real time forecasts, bandwidth of the transmission system and speed of the processing system should be examined.

In many cases, national, provincial/state, local governments and the private sector operate real-time data networks to support their individual needs. In most cases, these data are not shared, and each organization is limited to its own data. Coordination and data sharing can significantly increase the amount of data available for all organizations. These additional data, possibly complemented with new sites, will help increase forecast accuracy at the least cost.

Network operation

Often times the current operator of a site will not have had a need for, or experience with, real time data acquisition. Intensive staff training may be required to ensure that data are available when needed and are of a suitable quality.

Long-term maintenance is a major requirement in operational forecasting. The forecast network may be in operation only seasonally or less frequently. Keeping the network in a state of readiness though necessitates major changes in operating philosophy. The development of water management operational forecasts by the forecast centre, as well as flood forecasts, enhances the usefulness of the data network and communications systems, as well as maintaining a state of readiness.

Funding of alterations to existing networks and for future maintenance presents a major challenge. Negotiations among operating or funding agencies may require abandoning entrenched positions if success is to be achieved.

3.3 Meteorological Support

Given the importance of meteorological data and forecasts to the production of flood forecasts, it is very important that there be close collaboration between national meteorological and hydrological services. This collaboration could take several forms and should focus on increasing the accuracy and utility of knowledge of existing conditions and forecasted states. Two important products are optimal quantitative precipitation estimates - where, when and how much precipitation has actually fallen - and quantitative precipitation forecasts - where, when, and how much precipitation will actually fall. Other parameters of interest include wind speed and direction, surface temperature, and relative humidity.

Quantitative Precipitation Estimation (QPE)

Optimal estimates of existing precipitation conditions provide the hydrologist with the most accurate estimates of what are termed "antecedent conditions". These are extremely important for hydrological process modelling. Much work has been done to increase the accuracy of the estimates through increasing the density of in-situ stations, implementing ground-based surface radar, in processing of satellite based data, and in merging various sources of data.

Quantitative Precipitation Forecasting (QPF)

The ultimate goal of flood forecasting is to provide accurate forecasts of hydrological conditions. Currently, deterministic quantitative precipitation forecasts and other forecasted meteorological parameters can be applied as input to hydrological models in order to derive hydrological forecasts using numerical modelling methods.

It is typical that the hydrological forecaster receives single "best effort" meteorological products such as QPF, wind speeds and direction, temperature, and pressure. These products are based on numerical weather prediction model output and are modified using expert forecaster judgement. Forecast models are typically run once or twice daily depending on the operational practices of the national meteorological service. The useful forecast horizon of such products is typically about five days, with accuracy decreasing rapidly towards that of long-term climatology. The usefulness of QPF products derived from such modelling is usually constrained to one to two days due to poor performance beyond these limits.

When very short forecast horizons on the order of six hours or less could prove beneficial, extrapolative and trend-based meteorological techniques are used. The use of these techniques is referred to as "nowcasting", resulting in short-range QPF. These shorter time horizons associated with nowcasting are particularly useful for flash-flood forecasting. Beyond this horizon, numerical weather prediction models combined with expert judgement provide more accurate estimates of future meteorological conditions such as QPF.

Work is currently proceeding on the coupling of mesoscale numerical weather prediction models with high-resolution hydrological process models. Questions still exist on how to best incorporate expert judgement into this process in order to provide a single "best effort" estimate of future hydrological conditions.

One forecast methodology that can be applied to both meteorological and hydrological forecasting is the "Ensemble Technique", wherein multiple forecast scenarios are generated by the execution of several model runs, each with slightly varied initial states. The magnitude and degree of the uncertainty associated with the forecast ensemble provide a probabilistic view of the potential future meteorological and hydrological states. Although more study and further development are needed before this becomes more broadly used in operational practice, the technique holds much promise.

Once a flood forecasting centre has been in operation for a period of time and close collaboration exists with meteorological counterparts, weaknesses in both meteorological and hydrological forecast products may become evident. Sometimes the weaknesses can be overcome by improving the database used for the forecast. In other cases, there will be a need to improve understanding of the underlying hydrological processes involved in the production of hydrological forecasts.

Other parameters of interest

Estimation of other parameters is important for flood forecasting and for assessing antecedent basin conditions. These include antecedent temperature, humidity, and evapotranspiration, all of which are very important in assessing soil moisture conditions and water deficits prior to the onset of precipitation.

3.4 The Forecast Centre

The flood forecast centre must be identifiable to agencies and to the public as the authoritative source of flood forecasts and warnings. The forecasts produced by the centre must be to the highest achievable technical standard and be released to the public unfiltered by agency or political interests. The long-term stability of the centre is dependent on the credibility and utility of its forecasts.

Administratively the centre can be part of one agency or it could be a new entity supported by several agencies. The forecast centre could be self-contained or, more likely, will depend on other agencies for support.

Establishment of the centre

Analysis of existing conditions and needs will determine whether a forecast centre will be established by strengthening an existing facility or by creating a completely new enterprise. The decision should be based on political, administrative and technical leadership of candidate agencies, as well as the ability of the selected agency to work with others.

A project initiation team drawn from several national agencies or consultants, with support from international organizations and working to agreed-upon terms of reference, could examine the issues identified in these Guidelines and make recommendations concerning the development of a Forecast Centre. Their report should identify technical issues, personnel needed, administrative issues, costs, and timelines.

Interagency agreements will be needed for provision of data, operation of structures, weather forecasts, technical and administrative support, and other tasks. Depending on the basin, it is possible that such agreements might already exist. They may include clearly articulated roles and responsibilities, clear specifications of work, performance measures, and provisions for financial arrangements. International agreements for provision of data, use of satellite technology, and other support activities may also be required.

The Centre needs financing over both the short and longer term. Short-term financing will be capital intensive as funding may be necessary for network improvements, construction, the acquisition of computers and software, and many other items. These could best be funded by special national appropriations or international support. There may also be a local market for specialized forecast products, which could be paid for by users.

Long-term financing will be needed to operate the Centre, pay staff, upgrade computer systems, and make improvements in the forecast methodologies. This operation will require on-going national support even where specific improvements are funded internationally. If the mandate of the Centre were expanded to include river forecasts for operational water management purposes, financial support could be made available from agencies using the river forecasts. The possibilities include revenue from sale of water licenses, other water use charges, or fees assessed to discourage development within the flood plain.

To operate effectively the Centre will need key personnel. Aside from technical skills, the Centre will need people capable of working collaboratively with other agencies and who can communicate effectively. A significant training programme will be needed at the onset of the Centre, and the costs of on-going training should be built into the budget. In the early stages, forecast procedures may have to be tailored to the ability of existing staff, and a training and development plan should be established to upgrade skills and techniques to improve the accuracy and utility of the forecast.

There will be an early need to gather basic data, calibrate and verify models, and establish working arrangements with other agencies. Visiting experts, or placing key staff in other Forecast Centres for training, could aid this process.

One approach in the early stages of development would be to concentrate efforts on a key basin or one of its sub-basins. Such a pilot project could help verify the suitability of models selected and the capabilities of staff. This would give funding agencies a level of comfort. In the very earliest stages of development, the Centre could simply analyze weather forecasts and provide warnings of potential high flow conditions.

Data processing

Although data may have been pre-processed elsewhere, the Forecast Centre will require in-house data processing capability. Although some work could be done manually, computer systems should have uninterruptible power supplies. At the very least, emergency power systems should be available.

If Geographic Information Systems and image products are expected to be used for real-time forecasts, computer memory and speed must be taken into account. Overall computing system architecture and design should be planned for as part of the future development of the Centre.

Data processing needs will also depend upon the selected forecast models and their data processing requirements. In the absence of other requirements, data should be digitally available and easily converted to formats used by commercially-available spreadsheet programmes.

Arrangements must also be made to electronically archive data so that they are available for use in subsequent years. Some data will have to be brought forward frequently for use, while other data will only be used on occasion.

Forecast Centre operation

It is necessary to establish basic operating procedures and assign staff responsibilities early in the operation of the Centre. Part of this is the assignment of responsibilities for on-going maintenance of systems.

Capable staff are the key to producing good forecasts and maintaining the Centre's credibility. Capable staff will also be attracted to positions elsewhere so some staff turnover can be expected. A systematic plan for staff training and development and the assignment of challenging work will help reduce turnover rates. Some contingency planning will be needed to ensure that the Centre will continue to operate when key staff members leave. Efforts should be made to develop an operations manual in order to reduce the Centre's vulnerability to loss of staff or other unanticipated events. The manual should cover all aspects of the Centre's operation and maintenance, and it should include lists of key contacts beyond the Centre.

Once the Centre has completed its first significant flood forecast season, an end-to-end review of all aspects of the forecast should be conducted to identify what went well and where improvement might be necessary. The review should include interviews with persons from other agencies and forecast users. The results of such a review should be used to modify procedures. Periodic audits of forecast procedures and Centre operations should be carried out, perhaps involving staff from other Forecast Centres.

Forecast models

There are a large number of public domain and proprietary models available for use in flood forecasting. Sometimes the model can be simply a statistical rainfall-runoff relation with a routing equation, while other models can be much more complex. Hydrological models can be classified as lumped, semi-distributed or distributed, and as being single event or continuous. Probabilistic models that take data uncertainties into account are also available. Model selection will depend on available data, basin characteristics, and the needs of the local user community.

A lumped model treats the watershed as a single unit for inputting data and calculating runoff. The calculations are statistically based and relate to the underlying hydrological processes as a spatially averaged process. Models based on scaling unit hydrographs would fall into this category. Some lumped models allow the watershed to be subdivided or for some parameters to be physically estimated and modelled. When subdivisions of a basin are combined to produce a forecast, this modelling approach is termed semi-distributed. Depending on forecast needs and the characteristics of the watershed, a lumped model may be all that is required.

A distributed model simulates the key hydrological processes that occur in a watershed using distributed data inputs and processes. For forecasting purposes these commonly include precipitation, interception, infiltration, interflow, and baseflow. Overland flow and channel routing may be incorporated into the model or calculated in a hydraulic model. Distributed models require much more data and knowledge of watershed processes than lumped models. When the model is first established, precipitation and land cover characteristics may be the only distributed features.

Hydraulic models used in channel routing calculate the travel time of the flood wave and its attenuation. These models use the standard equations of unsteady, non-uniform flow with various simplifications depending on the channel characteristics, available data and accuracy requirements. Storage-flow relations are often incorporated into hydrological models. One-dimensional unsteady flow hydraulic models can be used to route flows through multiple channels or in situations where overland flow is a serious concern.

Probabilistic forecasts are typically derived using hydrological process models wherein statistical distributions are used to describe the uncertainty of input data and basin conditions such as precipitation data, soil moisture and snow pack conditions. A large number of model projections are produced that can be statistically analyzed to allow for a better understanding of the uncertainty of the forecasted future water conditions. This approach is rapidly gaining popularity, as it provides the decision-maker with the probability of an extreme event to occur, not just that it might occur.

Simplified probabilistic methodologies that provide a range of possible forecasts have existed for some time. This is achieved by the forecaster making assumptions concerning future precipitation to determine runoff under normal, lower, or upper decile conditions. More modern approaches, which tend to be in the pilot testing stage, attempt to better quantify the uncertainty associated with the forecasted meteorological conditions and to directly link this uncertainty to the uncertainty of the flood estimate.

Sophistication of hydrological forecasting

Essentially, the prevailing geomorphological conditions of the river basin and the interaction of communities at risk with the river system dictate the level of sophistication of the modelling solution. The performance of existing models or forecast procedures should be evaluated. Whether the forecast process involves use of simple graphs or tables or a robust integrated modelling system, evaluation of forecast accuracy versus lead-time should be determined. Does the system perform well when adequate data are available? Are model parameters up-to-date? Do model parameters reflect land use changes that have occurred within the basin? Can the model or its parameters be easily modified to reflect pending land-use changes within the basin? Does the modelling system reflect flood control structures and their operations within the basin? Are there important hydrological processes occurring in the basin that are not reflected in the existing forecast model? Does the forecast system perform well for flooding but is inadequate to meet routine or low flow forecast requirements? Is there a need to convert hydrological forecasts to water level (stage) using a hydraulic model? In general, is the existing modelling system appropriate and sufficient to meet user requirements?

Hydrological forecasting knowledge

Highly trained hydrologists produce reliable hydrological forecasts. Forecasters use real-time data, knowledge of hydrology, knowledge of the hydrological modelling system and experience in producing forecasts and warnings. In determining the operational readiness or hydrological forecast capability of a forecast centre, the education, knowledge and skills of the forecasters are as important as the tools they use. Is the number of forecasters available sufficient to handle the flooding situation? Do the forecasters have sufficient education in hydrology and meteorology to appropriately apply the tools? Are they properly trained, and do they understand the limitations of the modelling system being used? Do the forecasters know the users, how to contact them, and what information they require for flood response actions? An assessment of the adequacy of the operational forecaster capability is important in determining how to improve flood forecast operations.

Forecasts

In order to produce a flood forecast for the communities and locations at risk, there must be a hydrological modelling capability that uses meteorological and hydrological data. Hydrological models use real-time precipitation and streamflow data. The models translate observed conditions into future stream conditions. Hydrological models or procedures vary in complexity, accuracy and ease of use. Simple hydrological models consist of tables, graphs or empirically derived relationships. More sophisticated hydrological modelling systems use in-situ data, remotely sensed data, and multiple hydrological models that are integrated to produce very accurate hydrological forecasts. Due to advances in Geographic Information Systems and the availability of geo-referenced data, parameters of some hydrological models can now be estimated without having to rely exclusively on historical hydrological data for model calibration. The evolution of personal computer technology has paved the way for quite complex modelling systems to be run on them. These systems are easier to use, are easier to maintain, and are more affordable.

Current hydrological forecast systems are quite affordable and powerful. The degree of success associated with these systems is dependent on the amount of training received by the hydrologists using them. These systems are capable of producing a broad range of forecasts of stream conditions that will occur in a few hours to seasonal probabilistic outlooks targeted to months in advance for larger rivers. Model system selection depends on the amount of data available, complexity of hydrological processes to be modelled, accuracy and reliability required, lead-time required, type and frequency of floods that occur, and user requirements.

Hydraulic models are often used to translate hydrological model-derived streamflow to water-level conditions. Hydraulic models are also valuable in forecasting the streamflow conditions of large rivers where sufficient lead-time is accorded through translation of upstream water levels to downstream communities at risk. Such models can be interfaced with geographical information systems to provide dynamic water level conditions on maps of communities. These types of forecast products can be invaluable to communities and emergency organizations, as they provide very precise information about areas that will be inundated and when.

Decision support

Hydrometeorological data and accurate forecasts are of no value if the forecasts do not reach users and if decisions are not made as to the appropriate actions required. Hydrological forecasts and hydraulic conditions must be disseminated so that decisions can be made and actions taken to reduce the impact of the pending event. Decision support refers to everything from forecasts reaching decision makers such as a mayor of a flood-prone community to the operator of a flood-control structure. For decision support to be effective, advanced planning must define prescribed actions linked to forecasted values.

Decision support systems vary from rules or procedures that must be followed under prescribed conditions to mathematical optimization programmes. Such approaches define actions to be taken based on tradeoffs among various options for water allocation.

Forecast output

Typically, calculations used in preparing a forecast are based on units of discharge, although some simplified systems correlate upstream with downstream water levels. However, decision makers and the public are most often concerned with water levels and velocities at specific points, usually urban centres. Forecasted flows can be converted to water levels and velocities using stage-discharge and stage-velocity relations, hydraulic models, or other techniques. Decision makers and emergency workers should be consulted on their specific forecast requirements.

In many cases, forecast water levels are given according to a local vertical datum. This may be convenient for some purposes but may introduce potential for confusion. With the advent of global positioning systems, it is possible to provide a geodetic datum at any location and this should be done.

The forecast water levels released to the public could be in several formats: tabular, hydrographs, or inundation maps. It is very useful to provide comparisons with the previous year or with previous major floods. Inundation maps linked to databases can provide information on individual properties and can be most useful for public awareness and emergency services.

The forecast should be formally released and made available to key agencies as well as the media. The forecast should also be placed on Internet websites for easy access.

The points for which the forecast applies should be communicated very clearly. For example, the name of a city in the basin should be identified, or in the case of very large cities, well-known points within the city should be specified.

Uncertainty in the forecast should be represented accurately, but in non-technical language. Phrases such as "if present conditions continue…" are useful as are those that require simple statistical knowledge such as "there is an 80% chance that…"

Dissemination of forecasts and warnings

Forecast and warning dissemination is extremely important. Frequently, the lack of ability to disseminate warnings to the population at risk is the weakest link in the integrated system. Forecasts and warnings must reach users without delay and with sufficient lead-time to permit response actions to take place. Dissemination of forecasts and warnings can be achieved through a variety of communication methods. An inventory of the various communications media used by the forecast system will reveal the competency of the dissemination process. How are warnings transmitted to the public, to the flood control agencies, to the emergency services and civil protection organizations? Are communication systems reliable? What types of communication modes are used (such as satellite, radio, meteor bursts, telephone or internet)? How are communications lines maintained? Are there backup modes of communication? In what format are warnings transmitted? Do users understand the content of the warnings? These are a few of the questions that need to be answered in assessing the performance of dissemination systems.

Users

Who are the users? Understanding the needs of users is fundamental to achieving a successful flood forecast, warning and response programme. What kinds of data and information do they need? Where are they? How do you reach them during the day or late at night or during a national holiday? How do they make decisions?

Establishing a user group association or an inventory of users is important for a well functioning and effective forecasting system. The sophistication and needs of users can vary considerably. For example, the hydropower industry needs high-resolution data, detailed hydrological forecasts for short-term as well as for longer time horizons. Emergency services groups and media organizations need clearly stated warning information that defines the hazard and spells out what steps the public must take to minimize their risk.

Notification and action

The entire process of establishing a flood forecast is of no value unless data and forecasts reach users. An effective fail-safe forecast dissemination system must be established to allow forecasts and warnings to reach users, wherever they are. Notifying users is often problematic because many countries do not have communication systems that reach rural villages and other communities at risk. Internet is an effective worldwide communication system, but the user must have access and be vigilant in order to receive the warning. There are many examples of effective dissemination systems based on high-speed telecommunications that use satellite, microwave, radio, or meteor burst technology.

An effective flood-warning programme must also be linked to the media to reach populations inhabiting the areas at risk. In many cases, the media can provide an effective means of re-broadcasting warnings and assist in response-oriented communications.

The payoff from a successful end-to-end flood forecast and response programme is when actions are taken to reduce the impact of the impending flood. Actions can be as simple as moving contents from the first floor of a person's house to the second floor, evacuating the flood plain, blocking roads that will be flooded, or closing floodgates of a levee system that protects a city. If no mitigation actions result from flood forecasts and warnings, society is simply paying money for ineffective results.