Flood Forecasting and Early Warning in Transboundary River Basins: A Toolkit

Foreword

Asia and the Pacific is the most disaster prone region in the world. Building resilience to natural disasters is one of the most pressing challenges for achieving sustainable development in the region. Floods are one of the most frequent natural disasters in Asia-Pacific, with devastating impacts on the poor and vulnerable populations who live along river basins and are dependent on agriculture for their livelihoods. In 2015 alone, floods caused more than US$ 11 billion in economic damage, much of which can be attributed to large-scale transboundary floods.

Flood forecasting and early warning is one of the most effective flood risk management strategies to minimize the negative impacts of floods. Recognizing this, at the fourth session of the ESCAP Committee on Disaster Risk Reduction in October 2015, Asia-Pacific countries requested ESCAP to work towards establishing a regional cooperation mechanism for early warning of transboundary basin floods, and to galvanize experts in the field to take this priority forward, in line with the ESCAP Resolution 71/12.

Recent advances in science and technology, especially space technology applications, have enabled longer lead times of up to 5-8 days for flood forecasts along the transboundary river basins. These scientific advances, however, rarely reach the communities who live along these vast rivers. On average they get one-day notice for evacuation. It is therefore critical that the operational capacities of flood forecasting and early warning systems in the riparian countries are enhanced to effectively utilize these new tools and techniques to save lives and livelihoods.

This toolkit for flood forecasting and early warning in transboundary river-basin has been prepared in collaboration with the Regional Integrated Multi-Hazard Early Warning System (RIMES), to support the capacity building process in the region. It highlights how the tools, techniques, and other resources available from RIMES, the International Centre for Water Hazard and Risk Management (ICHARM), International Centre for Integrated Mountain Development (ICIMOD), the Mekong River Commission (MRC), the World Bank’s South Asia Water Initiative (SAWI) can be put to operational use for more effective flood forecasting. It is my hope that the toolkit would be of practical value to the flood forecasting community, technical experts, disaster risk managers, and policymakers for enhancing flood early warning systems, especially in transboundary river basins.

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Abbreviations

AIC	Akaike Information Criteria
APHRODITE	Asian Precipitation – Highly-Resolved Observational Data Integration Towards Evaluation
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
CAP	Common Alerting Protocol
CFAB-FFS	Climate Forecast Application – Bangladesh Flood Forecasting System
CRU	Climate Research Unit
CSI	Critical Success Index
DEM	Digital elevation model
DSS	Decision support system
ECMWF	European Centre for Medium-Range Weather Forecasts
EQPF	Ensemble Quantitative Precipitation Forecast
EPS	Ensemble Prediction System
ESCAP	Economic and Social Commission for Asia and the Pacific
ETS	Equitable Threat Score
EWS	Early warning system
FAO	Food and Agriculture Organization of the United Nations
FFWC	Flood Forecasting and Warning Centre, Bangladesh Water Development Board
GFS	Global Forecasting System
GIS	Geographic Information System
GS	Gerrity Score
HKH-HYCOS	Hindu Kush Himalayan Hydrological Cycle Observing System
ICHARM	International Centre for Water Hazard and Risk Management
ICIMOD	International Centre for Integrated Mountain Development
ICT	Information and communications technologies
IFAS	Integrated Flood Analysis System
IFSAR	Interferometric Synthetic Aperture Radar
IVR	Interactive Voice Response
FAR	False Alarm Ratio
HEC-DSS	Hydrologic Engineering Center Data Storage System, US Army Corps of Engineers
HEC-HMS	Hydrologic Engineering Center Hydrologic Modeling System, US Army Corps of Engineers
HEC-RAS	Hydrologic Engineering Center River Analysis System, US Army Corps of Engineers
HR	Hit Rate
HSS	Heidke Skill Score
MAE	Mean Absolute Error
ME	Mean Error
NCAR	National Center for Atmospheric Research, USA
NCEP	National Centers for Environmental Prediction, USA
NHS	National Hydrological Service
NOAA	National Oceanic and Atmospheric Administration, USA
NWP	Numerical Weather Prediction
PDF	Probability distribution function

POD	Probability of Detection
POFD	Probability of False Detection
RIMES	Regional Integrated Multi-Hazard Early Warning System
RMSE	Root Mean Square Error
SAWI	South Asia Water Initiative, The World Bank
SMA	Soil Moisture Accounting
SOTER	Soil and Terrain Database
SPAW	Soil-Plant-Air-Water model
SRTM	Shuttle Radar Topography Mission
SS	Skill Score
TRMM	Tropical Rainfall Measuring Mission
TS	Threat Score
UH	Unit Hydrograph
WMO	World Meteorological Organization
WPS	WRF Preprocessing System
WRF	Weather Research and Forecasting

1. Introduction

1.1 Context

The Asia-Pacific region is home to large river systems. Many of the largest rivers emanate from the Tibetan Plateau and the Himalayas, and are fed by glacial and snow melting as well as monsoon rainfall. A large cross-section of the region's population reside in the vast agrarian belts along the Yellow, Yangtze, Mekong, Irrawaddy, Ganges, Brahmaputra, and Indus river basins, each of which is subject to periods of widespread and seasonal flooding (Figure 1.1). These river basins are also home to large numbers of the poor and vulnerable populations dependent on subsistence agriculture. The climate variability and change often manifest themselves into monsoon variabilities, El Niño and La Niña, and other extreme weather events - resulting in large scale frequent flooding particularly in the transboundary basins.

Among all the disasters in the region, floods have been the most frequent and devastating. Floods in the transboundary river basins have had severe impacts beyond geographical boundaries. The Indus, Ganges, Brahmaputra-Meghna, and Mekong, for example, are resources to over 1 billion people, but are at high risk of transboundary flooding. The impacts of the historical floods in these river basins reveal that the adverse socioeconomic impacts are huge development concerns. Among the transboundary river-bains, Brahamputra-Meghna, Indus, and Ganges accounted for the maximum loss of lives, damages, and flood occurrences (Table 1.1). In the Indus river basin, transboundary floods in 2014 across India and Pakistan caused US$ 18 billion in economic impacts (ESCAP, 2015). In 2015, floods comprised two-fifths of all disasters in the region, and caused more than US$ 11 billion in economic damage (ESCAP, 2016b).

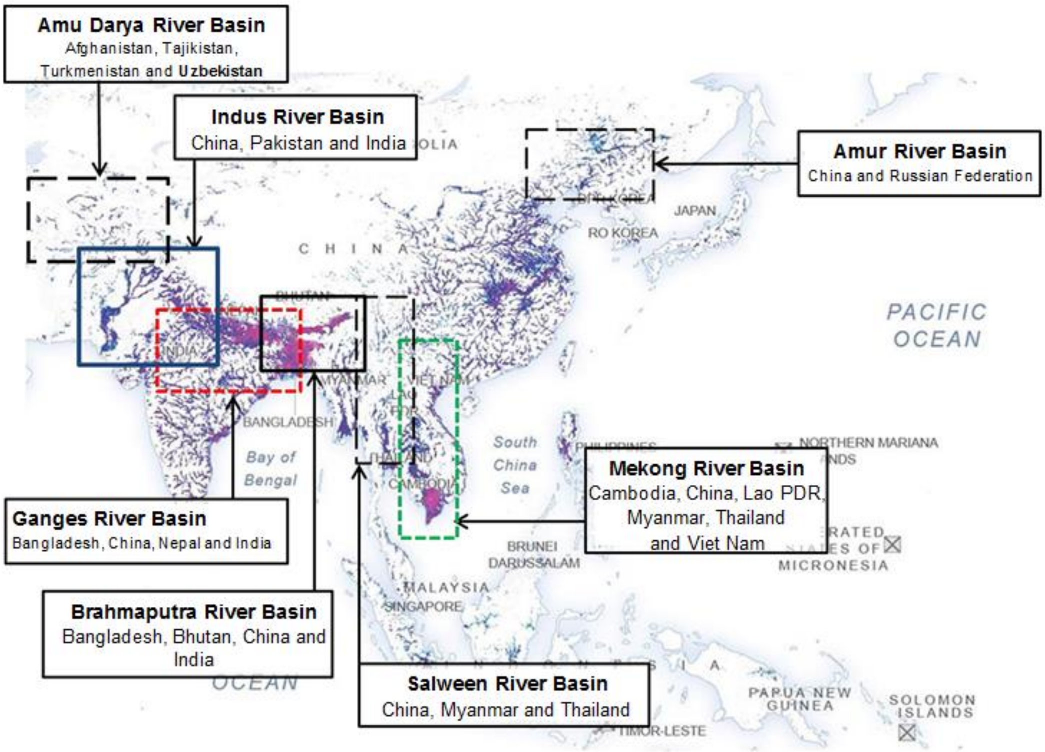


Figure 1.1 Transboundary flood risk in the Asia-Pacific region
(Source: ESCAP 2016a, based on OCHA and ICIMOD data)

Table 1.1 Summary of flood impact on river basins during past decade (2000-2010)

Name of river basin	Countries covered	No. of floods reported	Total No. of days flooded	Total No. of people dead	Total No. of people displaced (Million)	Total economic eamage (Billion US$)
Amu Darya River Basin	Afghanistan, Tajikistan, Turkmenistan, Uzbekistan	34	232	517	0.92	0.09
Indus River Basin	China, India, Pakistan	45	565	4,214	16.8	9.96
Amur River Basin	China, Russian Federation	13	247	176	0.77	0.32
Mekong River Basin	Cambodia, China, Lao PDR, Myanmar, Thailand, Viet Nam	39	1,188	2,877	10.8	2.65
Ganges River Basin	Bangladesh, China, India, Nepal	35	789	8,307	82.77	8.22
Brahmaputra-Meghna River Basin	Bangladesh, Bhutan, China, India	32	821	8,392	120.2	11.22
Salween River Basin	China, Myanmar, Thailand	6	137	223	0.3	0.04

Source: G.R.Brakenridge, "Global Active Archive of Large Flood Events", Dartmouth Flood Observatory, University of Colorado, http://floodobservatory.colorado.edu/Archives/index.html

Many of the large-scale floods during the year were transboundary in nature, and these have significant impacts, especially on the poor and vulnerable populations dependent on agriculture. Around 40% of the world's poor live on or close to the major transboundary river basins in South Asia; two-thirds of this population live in the Indus, Ganges and Brahmaputra basins (World Bank, 2015a, see Box 1.1). Annual flood impacts on national economies are highest in Bangladesh and Cambodia in the region (Figure 1.2), countries that are downstream of the Ganges-Brahmaputra-Meghna and Mekong river systems respectively. About 70% of the global population exposed to river flood risk lives in the Asia-Pacific region (ESCAP, 2016b).

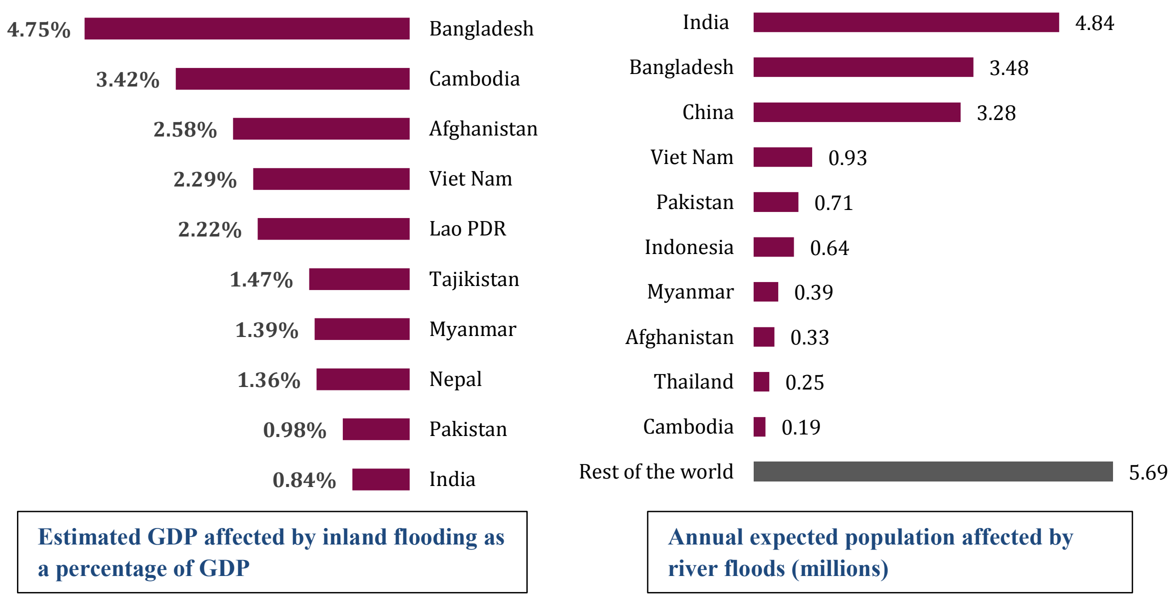


Figure 1.2 Economic impacts of (left) and exposure to (right) river floods in the Asia-Pacific region
(*Source: ESCAP, 2016b*)

Heavy rainfall, snowmelt, and glacial lake outburst are three main sources of transboundary floods in the region. Thus, flood risk management requires cooperation among countries that share the river basin. The fourth session of the ESCAP Committee on Disaster Risk Reduction in October 2015 requested ESCAP Secretariat to work towards the establishment of a regional cooperation mechanism for early warning of transboundary river basin floods, and collaborate with partners to take this priority forward, in line with Commission Resolution 71/12.

Flood forecasting has proven effective in reducing economic impacts (Box 1.2). However, capacity of countries in flood forecasting varies, and gaps remain in flood forecasting in transboundary basins, which include low capacity in flood monitoring systems, limited data exchange and technical cooperation and inadequate institutional and capacity development (Annex 1).

Recent developments in weather forecasting have enabled longer lead time for flood forecasts, and this can significantly reduce flood risks in large river basins (Figure 1.3). This toolkit has been developed jointly by ESCAP in collaboration with the Regional Integrated Multi-Hazard Early Warning System (RIMES) to provide wider access to these innovations that includes nested modeling framework for probabilistic forecast as well as conjunctive use of earth observation satellite data for monitoring precipitation and water elevation contours at different strategic locations. It's a guide book for building the capacity of flood risk management practitioners in transboundary river-basins of the Asia-Pacific region.

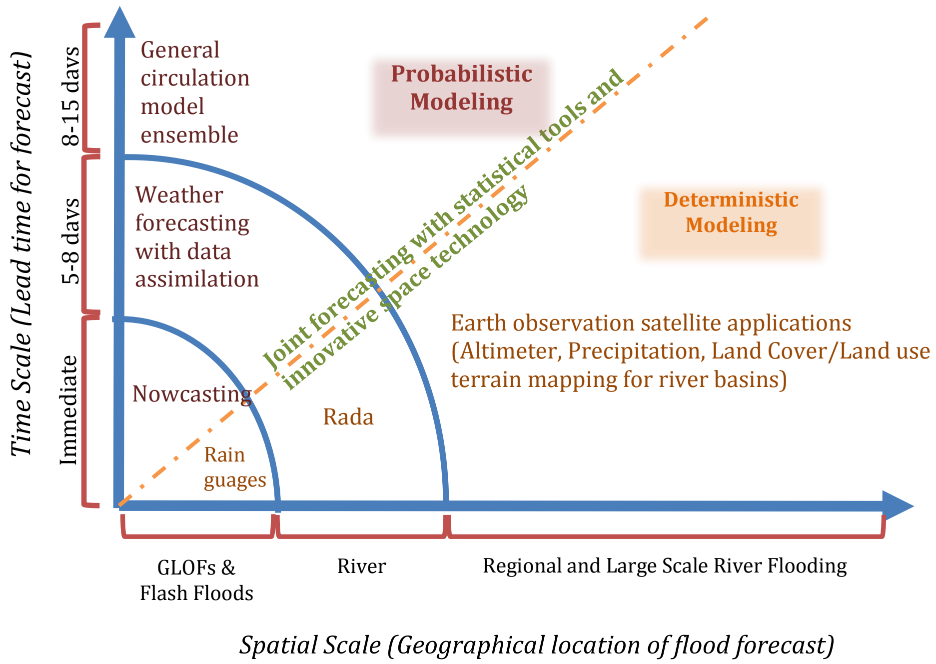
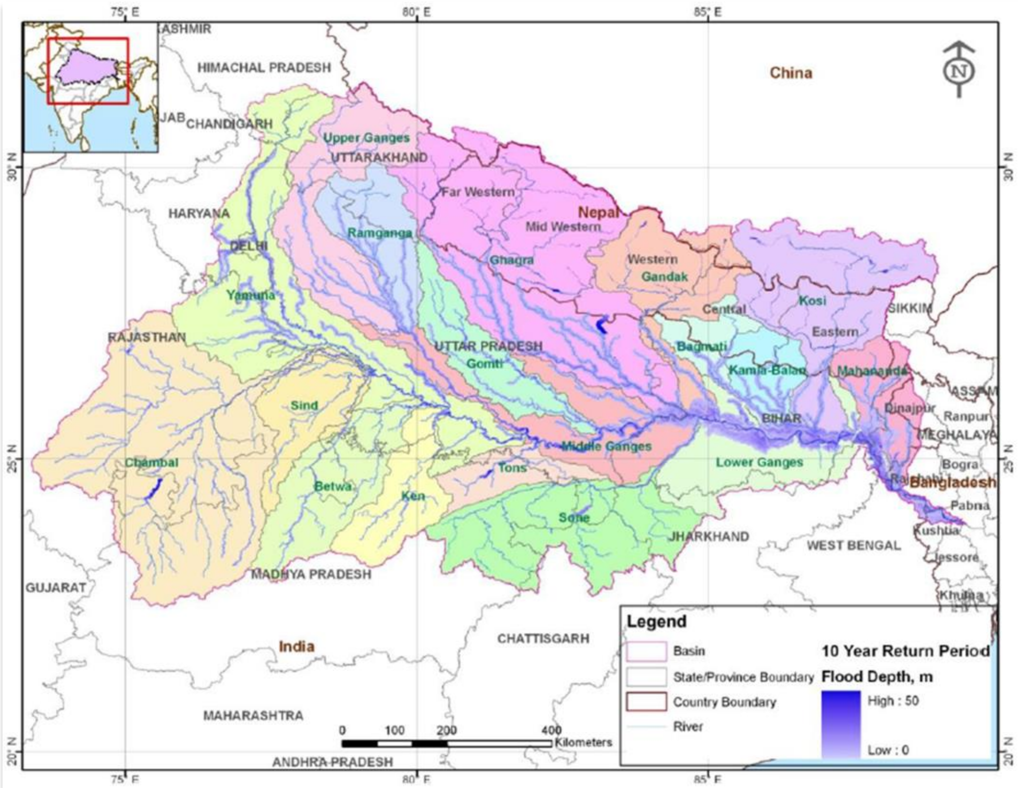


Figure 1.3 Integrating modelling and innovative space technology to enable longer lead times for floods
(*Source: ESCAP 2016b*)

Box 1.1 Flood risk in the Ganges

South Asia is home to around 40% of the world's poor. Two-thirds of them are living in the Indus, Ganges and Brahmaputra-Meghna river basins, in particular concentrating in Ganges basin shared by India, Nepal, China and Bangladesh. The Ganges basin is often affected by floods due to high discharges in the system. Widespread and heavy rainfall in the catchment areas and the inadequate capacity of the river to contain the flows cause floods in the basin. Most of the rainfall in the Ganges basin occurs during the monsoon season (June to October).

A flood hazard assessment done by the World Bank (2015b) showed high flood risk in the Ganges river basin. The study was to understand the geographical impacts of floods on various sectors through probabilistic analysis of runoff in various return periods. The figure presents flood hazard mapping for 10 year return period, and it found widespread flood risk in the Ganges basin as well as high flood risk in downstream areas (Bihar and Lower Ganges of India and Bangladesh).



Flood hazard map for 10-year return period for Ganges basin

Source: World Bank (2015b) Flood risk assessment for the Ganges basin in South Asia: Hazard report

Box 1.2 Assessing the economic value of forecasts and warnings

Quantification of the economic value of flood forecasts and warnings in planning and decision-making can facilitate user uptake and assist policymakers' decision to invest in flood forecasting and warning systems. The assessment methodology is based on potential direct losses that could be avoided if forecast is used, or warning is heeded.

For example, paddy, planted on 5 hectares of land, is at 85% maturity and shall require additional10 days to reach full maturity. The 10-day river level forecast indicates 60% probability of exceeding the threshold flood level. If the farmer decides to harvest early, the 10-day lead time gives him adequate time to organize and undertake the harvest, and safely store the paddy. Yield, however, is reduced, and the paddy would require additional time and cost for drying. His other option is to wait until the crop reaches full maturity – if the flood happens, he loses his entire crop and input investment; if the flood does not occur, he will realize 100% yield. The farmer, however, incurs cost for maintaining the crop for another 10 days.

Table Estimation of economic value for using/ not using 10-day forecast

	Harvest early	Wait; no flood
1. Additional cost for drying	5%	-
2. Additional cost/ (savings) for maintaining the crop	-5%	5%
3. Reduction in potential income due to crop quality/ loss	25%	
Economic value (100% - sum of items 1 to 3 above)	75%	95%
Probability of realizing above economic value (60% chance of flood occurring, 40% not occurring)	45%	38%

1.2 Scope and Content

This toolkit presents the tools, techniques, and capacity building experiences by RIMES, International Centre for Water Hazard and Risk Management (ICHARM), International Centre for Integrated Mountain Development (ICIMOD), and the World Bank's South Asia Water Initiative (SAWI). The toolkit also used resources from the ESCAP Expert Group Meeting on Regional Strategies towards Building Resilience to Disasters in Asia and the Pacific, held in Bangkok from 26-28 October 2015, and from the Regional Flood Early Warning System Workshop, held at the Asian Institute of Technology Campus from 23 to 27 November 2015.

This toolkit on flood forecasting and warning in transboundary river basins covers tools and practices for:

a) Assessment of user requirements for flood forecasting and warning information
b) Flood forecasting – process, requirements, models, and tools
c) Preparation of warning that is informed by risk assessment results and aided by decision support systems
d) Dissemination of warning and communication of risks/ uncertainty
e) Capacity building for appropriate warning response and flood preparedness
f) Engagement with stakeholders for feedback and support

1.3 Conceptual Framework

Flood risk information, to be useful for planning and decision-making for risk reduction, should provide information on location, onset, magnitude, extent, and duration of potential flooding and its likely impacts, and delivered with adequate lead time. This involves data from observing and monitoring systems inside the country and in neighboring countries; flood forecasting using real-time observation and weather forecast data, and integrating user requirements; warning formulation, informed by risk assessment results; and warning dissemination and risk communication. At the end of this chain is user response to flood risk information, supported by response plans and preparedness and mitigation resources. User feedback is vital to ensure that flood risk information and warning are relevant to and actionable by users. This process is illustrated in Figure 1.4.

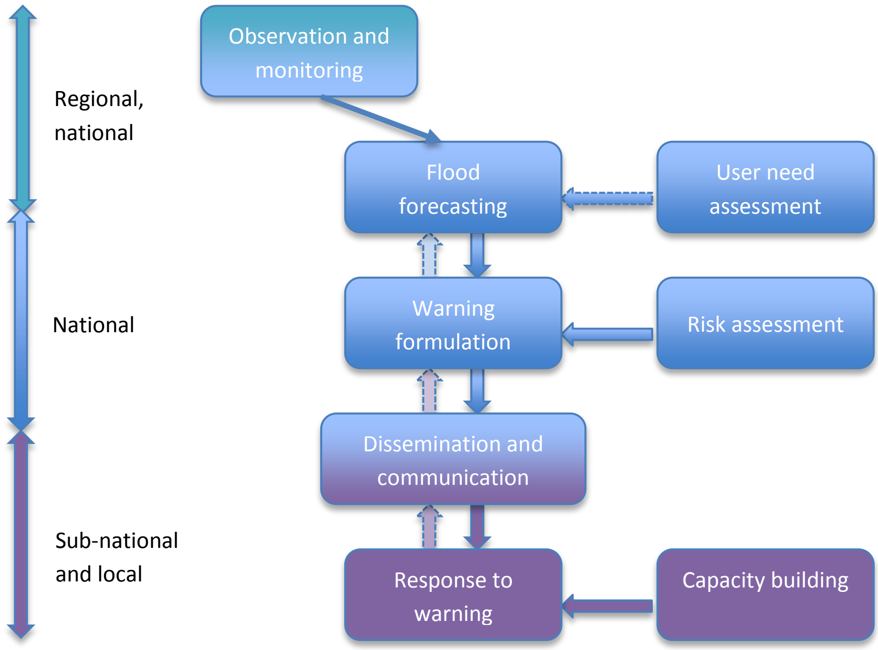


Figure 1.4 End-to-end flood forecasting and warning

2. User need assessment

2.1 Stakeholder Mapping

A people-centered flood early warning system aims to empower individuals and communities to act timely and appropriately to reduce flood risks. User participation in flood forecasting and warning system development is, thus, essential to ensure that forecast and warning information products and services are user-relevant – i.e. they are useful, applicable, and effective. Also, user participation fosters greater stake in and promotes ownership of the system. Stakeholder mapping and user need assessment can help determine who the users are, their information needs and service requirements.

Generally, there are five main user groups:

- Communities at risk, including community-based organizations and civil society action groups
- Government authorities
- Flood-sensitive economic sectors, such as agriculture, inland fisheries, transport, energy production, construction, tourism and outdoor entertainment, etc.
- Media – print, radio, television, etc.
- General public

Each group has different information requirements. Communities at risk require warnings and short- and medium-term forecasts for saving lives and protecting livelihood assets. Flood-sensitive economic sectors may require monthly to seasonal hydrological outlooks for planning, as well as short- and medium-range forecasts and warnings for daily operations. A user need assessment shall reveal what users require and by when.

2.2 Need Assessment

Secondary sources, such as reports and previous studies, could provide initial information on user needs. Primary data collection could then follow the review of secondary sources, using any of the following techniques:

a) Individual
   - Key informant interview, used with professionals or individuals of influence in an organization or community; useful for need assessments that need to be completed fast at a limited budget
   - Face-to-face interview using structured and unstructured questions; useful when there is little available information, or when dealing with less literate individuals
   - Questionnaire; can be administered by email, phone, or hand-delivered and collected after completion; information could be prone to bias if accomplished by an individual who is not the target respondent

b) Group
   - Focus group interview, which requires a questioning route and recording of the interview
   - Informal group methods, e.g. side conversations during social gatherings; requires active listening and seeking individuals to clarify information, overheard in conversations

Data collection for stakeholder mapping and need assessment shall include information on:

- Name of institution/ organization/ community/ individual
- Institutional mandate
- Planning and decision-making processes that require flood forecast and warning information
- Flood forecast and warning information requirements: what type of information, when information is required vis-à-vis planning/ decision-making process, lead time, preferred mode of access to information
- Current use of flood forecast and warning information

- Source/s of flood forecast and warning information
- Capacity to access flood forecast and warning information
- Capacity/ constraints to understand flood forecasts and warnings
- How users manage uncertainty in probabilistic flood forecast information; perception on failed forecast; how many failed forecasts could users tolerate
- View on benefits and costs associated with probabilistic forecasts
- Capacity/ constraints to use flood forecast and warning information in planning and decision-making

Analysis of data collected shall include:

- Opportunities for flood forecast information application in planning and decision-making
- Gaps in information requirements against what are available from the National Hydrological Service (NHS)
- Capacity gaps in accessing flood forecasts and warnings
- Capacity gaps in understanding flood forecasts and warnings
- Capacity gaps in using flood forecast and warning information in planning and decision-making
- Capacity of the NHS to meet user requirements

3. Flood forecasting

3.1 Data Generation and Management

3.1.1 Types and Sources of Data

Table 3.1 lists the date required for hydrological model development. Data quality is important for quality model outputs. In cases where data are not available from relevant national agencies, or from neighboring countries, data gaps could be filled by using global datasets from suggested sources listed in Table 3.1.

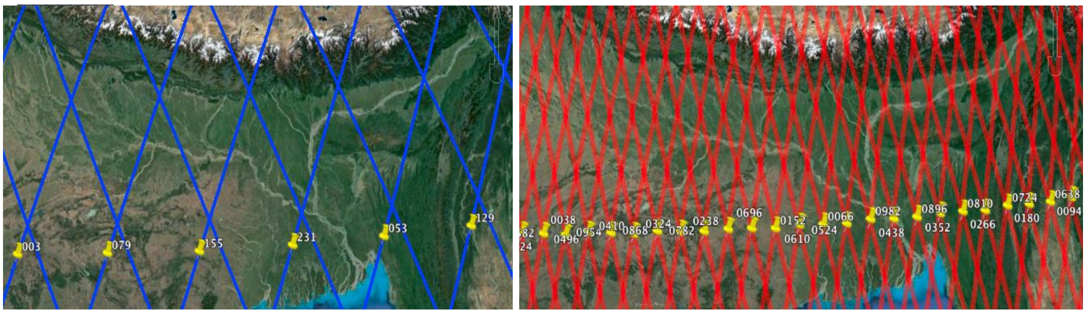
Table 3.1 Data requirements and sources

Type of data	Alternative source
1. Spatial data	
○ Digital elevation model (DEM)	○ Shuttle Radar Topography Mission (SRTM) at 90m resolution: http://srtm.csi.cgiar.org/ or http://hydrosheds.cr.usgs.gov/dataavail.php ○ Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) at 30m resolution: http://gdem.ersdac.jspacesystems.or.jp/download.jsp ○ Interferometric Synthetic Aperture Radar (IFSAR) at 5m resolution: https://lta.cr.usgs.gov/IFSAR_Alaska
○ Land use	
○ Soil types	○ FAO soils portal: http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/en/ ○ Soil and Terrain Database (SOTER): http://www.isric.org/data/data-download ○ Soil-Plant-Air-Water (SPAW) model: http://hydrolab.arsusda.gov/SPAW/SPAWDownload.html
○ Other physiographic properties	
○ Location of observation stations	
○ Location of bridges and reservoirs	
2. Meteorological observation data (at least 30-year data)	
○ Precipitation ○ Temperature	○ Tropical Rainfall Measuring Mission (TRMM) daily rainfall data at 0.25^o x 0.25^o resolution from 1998: http://disc2.nascom.nasa.gov/Giovanni/tovas/TRMM_V6.3B42.2.shtml ○ Asian Precipitation – Highly-Resolved Observational Data Integration Towards Evaluation (APHRODITE) Water Resources daily and monthly precipitation at 0.25^o x 0.25^o and 0.50^o x 0.50^o resolution from 1951-2007: http://www.chikyu.ac.jp/precip/index.html ○ Climate Research Unit (CRU) monthly precipitation and temperature data at 0.50^o x 0.50^o resolution from 1901-2009: http://badc.nerc.ac.uk/browse/badc/cru/data/cru_ts_3.10 ○ Santa Clara University daily and monthly precipitation and temperature data at 0.50^o x 0.50^o resolution from 1960-1999: http://www.engr.scu.edu/~emaurer/global_data/
○ Evapotranspiration	
3. Hydrological (at least 30-year data) and hydraulic data	
○ Discharge	
○ Water level	
○ Rating curve	
○ Channel and reservoir/ diversion hydraulic data	

Box 3.1 Surface water level monitoring using satellite radar altimetry

Satellite radar altimeters are particularly useful for large water bodies, for recording variations in surface water levels. Radar echoes, collected along the satellite's ground track, are interpreted to give surface height measurement with respect to the satellite-based reference datum.

Temporal resolution varies between 10 and 35 days. The 35-day temporal resolution provides higher density of ground track observations (see figure below). Spatial resolution of height data along each ground track is a few hundred meters. Height products could be delivered after 24 hours of receipt of altimetric data by ground processing centers.



Left: NASA/CNES Jason-2/OSTM Ku-band altimetry at 10-day resolution and 290m along-track sampling; Right: ISRO/CNES SARAL Ka-band altimetry at 35-day resolution and 175m along-track sampling (Source: Birkett, C, Regional Flood Early Warning System Workshop, Nov 2015, Bangkok)

Accuracy of altimetric measurements has been found to be 3-5cm root mean square (rms) for largest lakes and reservoirs, 10-20cm rms for smaller or more sheltered lakes, and 20-50cm rms for river channels, when compared to a time series of ground-based gauge data. Satellite radar altimeters can provide data in between gauge sites and in remote areas where gauge deployment may be difficult. They can also monitor rising or falling waters on inundated floodplains during river overbank flooding periods.

Source: Birkett, C. (2015) Regional Flood Early Warning System Workshop

Meteorological Forecast Data

Meteorological forecast data is required after hydrological model setup. Various centers provide global, regional, national, and local weather forecasts. Global forecasts are further customized for specific domains to generate high-resolution regional and local forecasts. The Weather Research and Forecasting (WRF) model is one of the most commonly used tools for this purpose.

WRF Model

The WRF model was developed collaboratively by various U.S. agencies, namely the National Center for Atmospheric Research (NCAR), National Oceanic and Atmospheric Administration (NOAA) (represented by the National Centers for Environmental Prediction (NCEP) and the Forecast Systems Laboratory), Air Force Weather Agency, Naval Research Laboratory, Oklahoma University, and Federal Aviation Administration.

The Advanced Research WRF uses fully compressible Eulerian and non-hydrostatic equations, with Arakawa C-grid staggering for horizontal grids and terrain following sigma coordinate for vertical grids. The model uses third-order Runge-Kutta scheme for time-split integration, and 2nd to 6th order schemes for spatial discretization. The model supports both idealized and real-data applications, with various lateral boundary condition options. The model also supports one-way, two-way, and moving nest options. It runs on single-processor, shared-, and distributed-memory computers.

Standard outputs from WRF Preprocessing System (WPS), real-data simulations, and WRF model are in NetCDF format (one of WRF I/O formats), and can be displayed by graphic tools, such as GrADS, RIP4 etc.

RIMES WRF Model

RIMES WRF model is set up for the domain 20˚E to 150˚E and 16˚S to 50˚N (Figure 3.1), covering RIMES Member States from Papua New Guinea in the far east, Mongolia in the north, and Madagascar and most east African countries in the west. The model uses US Geological Survey's 2-minute topographical data, and is run with NCEP Global Forecasting System (GFS) data, downloaded for 12 UTC initial condition. The model is downscaled to 9km x 9km grid resolution, with 1,470 grid points in the west-east direction, and 870 grid points in the south-north direction. Table 3.2 details the model parameters.

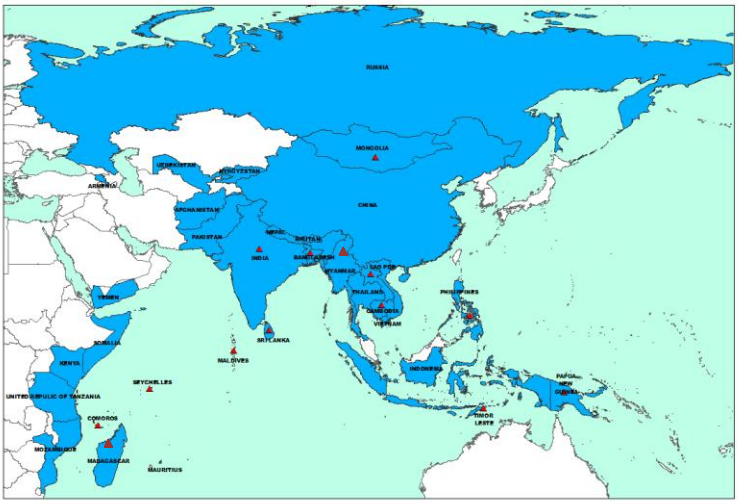


Figure 3.1 Model setup for RIMES operational domain

Table 3.2 RIMES operational WRF model parameter set

Parameter	Value
1. Model domain	20˚E to 150˚E and 16˚S to 50˚N
2. Grid resolution	9km x 9km
3. Projection	Mercator
4. Topographical data	USGS (2m)
5. No of grid points in X direction	1,470
6. No. of grid points in Y direction	870
7. Forecast interval	6 hourly
8. Time step	45s
9. No of vertical levels	27
10. Micro physics option	5 (Ferrier (new Eta))
11. Cumulus scheme	1 (Kain-Fritsch)
12. Forecast lead time	84 hours

3.1.2 Data Preprocessing

Data pre-processing comprises of data preparation, forecast verification, and bias correction.

Data Preparation

Data preparation involves data format and quality checks. For example, rainfall and temperature data need to be in the standard format required by the hydrological model. Observation data that have various outliers need to be fixed, and missing data need to be filled. A common technique in filling missing data is the normal ratio method, wherein rainfall PA at Station A is estimated as a function of the normal monthly or seasonal rainfall at Station A and those of neighboring stations, for the period the data is missing at Station A:

$$\boldsymbol{P_A} = \frac{\sum_{i=1}^{n} \frac{\boldsymbol{NR_A}}{\boldsymbol{NR_i}} \times \boldsymbol{P_i}}{\boldsymbol{n}}$$

where: P_i = rainfall at surrounding stations
NR_A = normal monthly or seasonal rainfall at Station A
NR_i = normal monthly or seasonal rainfall at Station 'i'
n = number of surrounding stations whose data are used for estimation

Forecast Verification

Verification is the process of comparing retrospectively forecast (model-based) outputs to relevant observations, to measure the quality of forecast outputs. The outcome is important for understanding model biases, and in refining the model, or choosing a better model or better model configuration.

Forecasts could be deterministic, or probabilistic (i.e. the forecast is a probability of occurrence of ranges of values of the variable in consideration). Deterministic forecasts could be:

a) Continuous (i.e. the forecast is a specific value of the variable)
b) Dichotomous (i.e. binary – yes/no; e.g. rain/ no rain)
c) Multi-Category (e.g. light/ moderate/ heavy precipitation)
d) Visual
e) Spatial

Table 3.3 lists verification measures for deterministic forecasts.

Table 3.3 Deterministic forecast verification measures

Forecast type	Measure
1. Continuous	○ Mean Error/ Bias (ME) ○ Mean Absolute Error (MAE) ○ Root Mean Square Error (RMSE) ○ Skill Score (SS)
2. Dichotomous	○ Bias Score or Frequency Bias ○ Percent Correct (Accuracy) ○ Probability of Detection (POD) or Hit Rate (HR) ○ False Alarm Ratio (FAR) ○ Probability of False Detection (POFD) or False Alarm Rate ○ Threat Score (TS) ○ Equitable Threat Score (ETS) ○ Heidke Skill Score (HSS)
3. Multi-category	○ Histograms ○ Accuracy (Percent Correct) ○ Equitable Threat Score (ETS)

Forecast type	Measure
	○ Hanssen-Kuipers Score ○ Gerrity Score (GS) ○ Heidke Skill Score (HSS)
4. Visual	○ Mapped forecasts and observations ○ Time series of forecasts and observations at selected sites ○ Scatter plots ○ Quantile-Quantile plots
5. Spatial	○ Scale decomposition methods ○ Neighborhood (fuzzy) methods

Details on some of these measures are provided below.

Quantitative (e.g. continuous) forecasts

1) Mean Error/ Bias (ME)

$$ME = (1/n) \sum(f_i - o_i)$$

where: f = forecast
o = observation
n = number of forecast/ observation data

- ME range: -∞ to +∞
- ME = 0 is perfect score
- ME > 0 means the system is over-forecasting
- ME < 0 means the system is under-forecasting
- Measures bias; does not provide magnitude of errors, hence not a measure of accuracy

2) Mean Absolute Error (MAE)

$$MAE = (1/n) \sum|f_i - o_i|$$

- MAE range: 0 to ∞
- MAE = 0 is perfect score
- MAE values closer to 0, the better
- Measures accuracy - gives average magnitude of errors in a given set of forecasts

3) Root Mean Square Error (RMSE)

$$MSE = (1/n) \sum(f_i - o_i)^2$$

$$RMSE = \sqrt{MSE}$$

- RMSE range: 0 to ∞
- RMSE = 0 is perfect score
- RMSE values closer to 0, the better
- Measures accuracy; comparison of MAE and RMSE gives error variance

Categorical (e.g. dichotomous, multi-category) forecasts

		Event Observed		
		YES	NO	Marginal Total
Event Forecast	YES	a	b	a + b
	NO	c	d	c + d
	Marginal Total	a + c	b + d	Total n = a + b + c + d

Where a =Hits, b =False Alarms, c =Misses, d =Correct Negatives

1) Bias Score or Frequency Bias

BIAS = [(Hits + False Alarms) / Hits] + Misses

- BIAS range: 0 to ∞
- BIAS = 1 is perfect score
- BIAS > 1 means the system is over-forecasting
- BIAS < 1 means the system is under-forecasting

2) Accuracy (proportion of forecast that is correct)

Accuracy = (Hits + Correct Negatives) / Total

- Accuracy range: 0 to 1
- Accuracy = 1 is perfect score
- Measure is strongly influenced by the common category

3) Probability of Detection (POD) or Hit Rate

POD = Hits/(Hits + Misses)

- POD range: 0 to 1
- POD = 1 is perfect score
- Gives the fraction of predicted YES events that occurred
- Measure is sensitive to misses

4) False Alarm Ratio (FAR)

FAR = False Alarms / (Hits+ False Alarms)

- FAR range: 0 to 1
- FAR = 0 is perfect score
- Gives the fraction of predicted YES events that did not occur
- Measure is sensitive to false alarms, not misses

5) Probability of False Detection (False Alarm Rate)

POFD = False Alarms / (Correct Negatives + False Alarms)

- POFD range: 0 to 1
- POFD = 0 is perfect score
- Gives the fraction of predicted NO events that were incorrectly forecast as YES

6) Threat Score (TS) or Critical Success Index (CSI)

TS = Hits / (Hits + Misses + False Alarms)

- TS range: 0 to 1
- TS = 1 is perfect score
- Includes hit due to random forecast
- Measures forecast performance after removing correct simple NO forecasts from consideration

7) Equitable Threat Score (ETS)

ETS = (Hits – Random Hits) / (Hits + Misses + False Alarms – Random Hits)

where: Random Hits = [(Hits + Misses) x (Hits + False Alarms)] / Total

- ETS range: 0 to 1
- ETS = 1 is perfect score
- Random Hits are hits due to random forecasts

8) Heidke Skill Score (HSS)

HSS = 2(ad – bc) / [((a+c)(c+d)) + ((a+b)(b+d))]

- HSS range: $-\infty$ to 1
- HSS = 1 is perfect score
- HSS = 0 means no skill
- Negative HSS value means negative skill, i.e. chance forecast is better, or model has poor skill
- Positive HSS value means positive (better) skill

Forecast verification using R

R is an open source, highly extensible software environment for statistical computing and graphics, providing a wide variety of statistical and graphical techniques. The package ‘verification’ of R contains utilities for verification of discrete, continuous, and probabilistic forecasts, as well as forecast expressed as parametric distributions.

Bias Correction

Bias in forecasts is due to various factors, such as errors in representation of physical processes like topographic influence. Forecast bias varies spatially and temporally. Bias needs to be corrected, before forecast data is ingested into the hydrological model. Various bias correction schemes are available; some are discussed in the following sections. The bias correction ‘qmap’ package in R could be applied in operational meteorological forecasts. This package performs empirical adjustment of the distribution of variables originating from (regional) climate model simulations, using quantile mapping.

Parametric transformation

The quantile-quantile relation of observed and modeled value is fitted, and the transformation is used to adjust the distribution of modeled data to match the distribution of observations. The following parametric transformations may be used.

Scale:

$$\hat{P}_o = b * P_m$$

Linear:

$$\hat{P}_o = a + b * P_m$$

Power:

$$\hat{P}_o = b * P^c_m$$

Exponential Asymptotic:

$$\hat{P}_o = (a + b * P_m) * (1 - e^{-(P_m - x)/\tau})$$

where: a, b, c, x and τ = constants
P_m = model precipitation
$\hat{P}_o$ = best estimate of the observed precipitation

Distribution-derived transformation

Bernoulli Gamma Transformation, which is a mix of Bernoulli and Gamma distributions. The parameters of the distributions are estimated by maximum likelihood methods for both $\hat{P}_o$ and P_m independently (Cannon, 2008).

Non-parametric transformation

Robust Empirical Quantiles, which estimates the values of the quantile-quantile relation of observed and modeled time series for regularly spaced quantile, using local linear least square regression, and performs quantile mapping by interpolating the empirical quantiles.

Empirical Quantiles, which estimates values of the empirical cumulative distribution function of observed and modeled times series for regularly spaced quantiles, and uses these estimates to perform quantile mapping.

Smoothing Spline, which fits a smoothing spline to the quantile-quantile plot of observed and modeled time series, and uses the spline function to adjust the distribution of the modeled data to match the distribution of the observations.

3.1.3 Data Archiving, Storage, and Access

Various types of data need to be efficiently stored, and retrieved at different steps of forecasting. These include time series data, spatial-oriented gridded data, curve data, and textual data. Various data storage systems are available for this purpose.

One of the common data storage and management systems is US Army Corps of Engineers' Hydrologic Engineering Center Data Storage System (HEC-DSS). HEC-DSS is a database system, designed for users and application programs to efficiently store and retrieve scientific data that is typically sequential. A modified hashing algorithm and hierarchical design provides quick access to datasets and an efficient means of adding new datasets to the database. HEC-DSS provides a flexible set of utility programs, and is easy to add to a user's application program. These features distinguish HEC-DSS from most commercial database programs and make it optimal for scientific applications.

3.1.4 Case Study: Integration of ECMWF Forecast Data into Hydrological Models

RIMES uses 15-day forecast data from the European Centre for Medium-Range Weather Forecasts' (ECMWF) Ensemble Prediction System (EPS) of 51 ensembles, which ECMWF shares daily. EPS precipitation forecasts were extracted for Ganges and Brahmaputra basins, from 70°E to 100°E longitude and 20°N to 35°N latitude. At each grid (0.5 degree) over the Ganges and Brahmaputra basins, a climatological probability distribution function (PDF) was calculated using observed daily precipitation for the period 1978-2004. The PDFs were calculated as daily rainfall, as a function of quantile at 0.5 intervals: 0, 0.5, 1, 99.5, and 100. An equivalent PDF (model-space PDF) was then calculated using ECMWF precipitation forecast data, done at each forecast lead time independently. The PDFs were then stored in accessible lookup tables.

Adjustment to each forecast ensemble followed, by determining the quantile that it corresponded to within the lookup table for that particular lead time model-space PDF. The same quantile was then extracted from the observational climatology lookup table. This extracted quantile value was used in the forecasting schemes in the hydrological model, to generate 10-day flow forecasts at the upstream boundary location of Ganges and Brahmaputra rivers at Hardinge Bridge and Bahadurabad stations, respectively (Figure 3.2). These flow forecasts provide boundary conditions for MIKE 11 hydrodynamic model, to generate water level forecasts for 36 downstream locations, as shown in Figure 3.3.

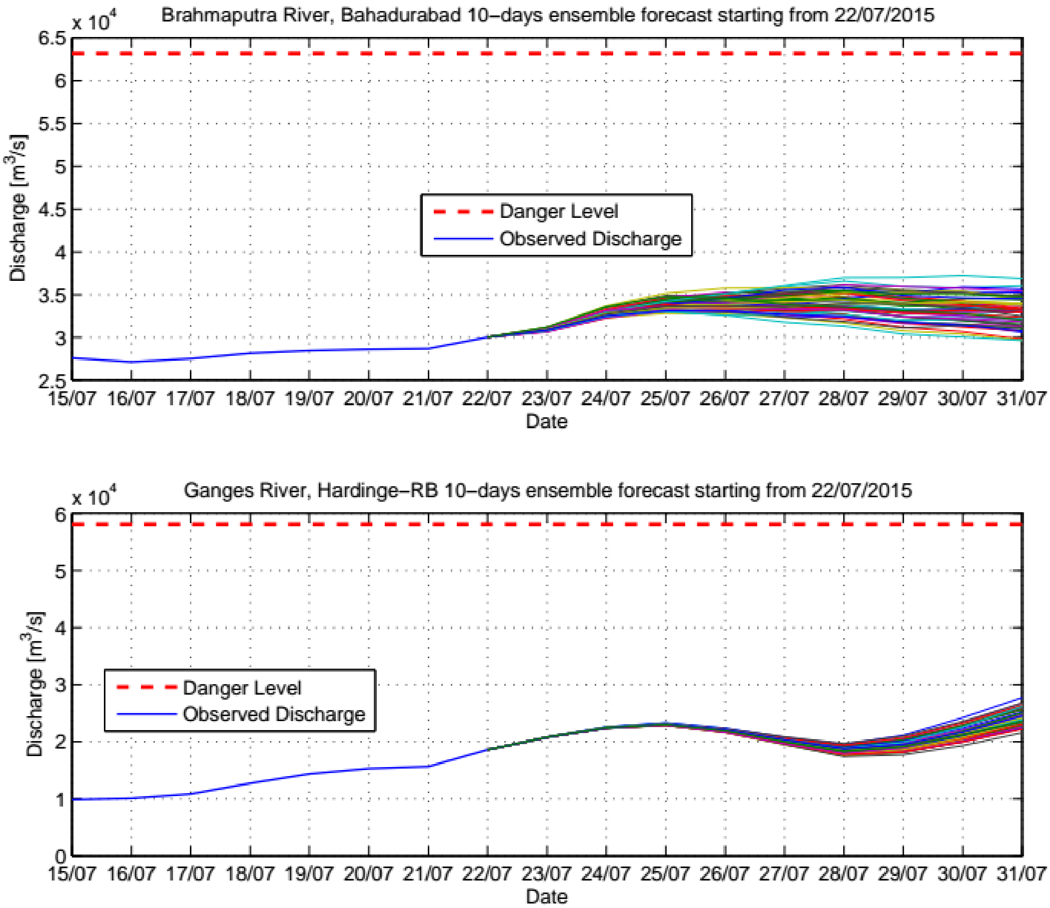


Figure 3.2 10-day discharge forecast for Brahmaputra (top) and Ganges (bottom) basin for 51 ensemble members
(Source: RIMES)

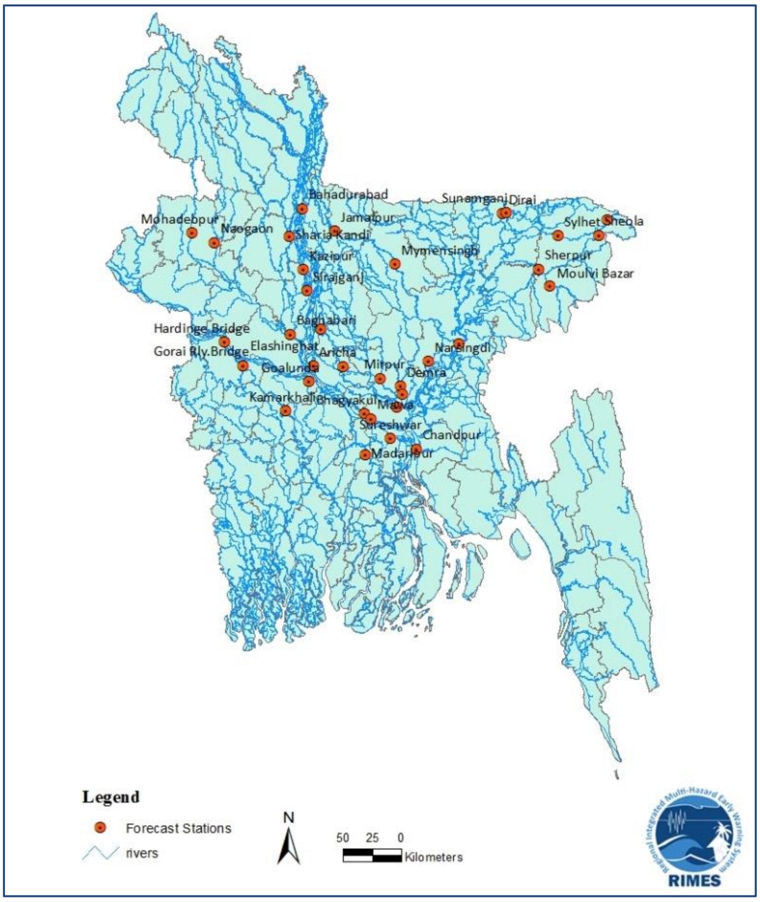


Figure 3.3 Forecast locations of the medium-range (1-10 day) flood forecast model

ECMWF EPS forecast evaluation

Performance of the ECMWF EPS forecast is continuously evaluated against rainfall observations and discharge forecast. Evaluation was undertaken for the 2013 flood season (May to October) when the country received 14.1% less rainfall than the normal value. The Brahmaputra, Meghna, and South Eastern Hill basins received 39.8%, 9.9%, and 12.4% less rainfall than normal, respectively. In contrast, the Ganges basin received 7.8% more rainfall than normal. During October, however, all basins recorded more rainfall than their respective normal values for the month.

The 2013 flood was typical in terms of magnitude and duration. The flood was not severe; duration was short in the north (along the Brahmaputra-Jamuna River), short to moderate in the northeast, and moderate in the central part (along the Padma River). Duration of flooding in the southwest (Satkhira and Khulna districts) was prolonged due to slow drainage, or very low carrying capacity of the rivers. Overall, the monsoon 2013 was a normal flood year.

Table 3.4 provides the results of the evaluation of the 3-, 5-, 7-, and 10-day forecasts. The evaluation indicated that accuracy of the probabilistic flood forecasts was more satisfactory at most stations.

Table 3.4 Results of 2013 forecast evaluation

Station Name	3 Days Forecast Evaluation Average 2013			5 Days Forecast Evaluation Average 2013			7 Days Forecast Evaluation Average 2013			10 Days Forecast Evaluation Average 2013		
	MAE	*RMSE*	R^2	*MAE*	*RMSE*	R^2	*MAE*	*RMSE*	R^2	*MAE*	*RMSE*	R^2
Aricha	0.1569	0.2027	0.9499	0.2667	0.3491	0.7907	0.3444	0.4261	0.7098	0.4248	0.5221	0.5409
Bhagyakul	0.1243	0.1559	0.9540	0.2045	0.2641	0.7472	0.2642	0.3314	0.7990	0.2930	0.3658	0.8047
Bhairab Baz.	0.1006	0.1307	0.9336	0.1523	0.1899	0.8758	0.1973	0.2393	0.7704	0.2406	0.2970	0.5980
Demra	0.1262	0.1790	0.8266	0.1958	0.2670	0.6738	0.2385	0.3227	0.5158	0.3267	0.4147	0.2260
Dhaka	0.1031	0.1348	0.9170	0.1419	0.1833	0.8575	0.1975	0.2463	0.7565	0.2271	0.2863	0.6567
Gorai RB.	0.2625	0.3792	0.9447	0.4234	0.6009	0.8727	0.5287	0.7620	0.8105	0.6139	0.9172	0.7481
Gualundo	0.1375	0.1818	0.9563	0.2681	0.3568	0.8315	0.3432	0.4355	0.8164	0.4538	0.5821	0.7059
Kamarkhali	0.2154	0.3069	0.9251	0.3633	0.5161	0.8145	0.4550	0.6491	0.7342	0.5076	0.7439	0.6949
Mirpur	0.1158	0.1488	0.9008	0.1744	0.2113	0.8158	0.2178	0.2664	0.6995	0.2480	0.3065	0.5704
Mohadevpur	0.5738	0.8531	0.5996	0.7381	1.1107	0.3190	0.7831	1.2133	0.1668	0.7992	1.2775	0.1018
Moulvi Baz.	0.4759	0.6287	0.4427	0.6278	0.8019	0.2600	0.7578	0.9407	0.1467	0.9162	1.0552	0.1387
Naogaon	0.4479	0.6877	0.4989	0.6560	0.8741	0.1799	0.7786	1.1181	0.4102	0.8777	1.1672	0.0229
Sirajganj	0.2451	0.3035	0.8846	0.3754	0.4733	0.7884	0.5228	0.6384	0.6545	0.6714	0.8375	0.4249
Sherpur	0.1140	0.1423	0.8663	0.1505	0.1838	0.7698	0.1744	0.2299	0.6803	0.2243	0.2691	0.5606
Sheola	0.4618	0.5959	0.7553	0.6260	0.7755	0.6109	0.7168	0.8431	0.5237	0.7464	0.9058	0.4539
Sunamganj	0.1853	0.2880	0.7154	0.2739	0.3678	0.5816	0.1745	0.2299	0.6602	0.4218	0.5295	0.3104
Sylhet	0.2523	0.3973	0.8150	0.3561	0.5020	0.7213	0.4134	0.5585	0.6362	0.4792	0.6072	0.6162
Tongi Khal	0.0964	0.1199	0.9259	0.1507	0.1877	0.8380	0.3982	0.2354	0.7246	0.2407	0.3038	0.5201
Baghabari	0.1747	0.2500	0.9279	0.2894	0.4210	0.8233	0.3937	0.5583	0.6885	0.5210	0.7162	0.4792
Bahadurabad	0.3203	0.4261	0.8305	0.4426	0.5638	0.7562	0.6029	0.7769	0.5692	0.7509	0.9589	0.3881
Chandpur	0.3162	0.4054	0.3518	0.4479	0.5508	0.0787	0.4717	0.5649	0.0503	0.4021	0.4971	0.1578
Dirai	0.2103	0.3125	0.6485	0.2897	0.3782	0.5036	0.3651	0.4454	0.3315	0.4366	0.5294	0.1682
Elashinghat	0.2279	0.3019	0.9050	0.3840	0.4878	0.8141	0.5145	0.6364	0.7002	0.6894	0.8538	0.4784
HardingeBR	0.3669	0.5339	0.8512	0.5507	0.8110	0.7260	0.6423	0.9628	0.6798	0.7074	1.0284	0.6447
Jagir	0.0783	0.0974	0.9392	0.1288	0.1599	0.8452	0.1993	0.2469	0.6748	0.3170	0.3955	0.3258
Jamalpur	0.2444	0.3401	0.8903	0.3663	0.5014	0.8071	0.4897	0.6345	0.6973	0.7042	0.8817	0.4348
Kanaighat	0.4688	0.6378	0.7621	0.6096	0.7975	0.6485	0.7001	0.8718	0.5594	0.6911	0.8807	0.5428
Kazipur	0.2604	0.3283	0.9013	0.3927	0.4924	0.8121	0.5388	0.6725	0.6721	0.6725	0.8508	0.4965
Madaripur	0.1319	0.1717	0.8479	0.2151	0.2828	0.6746	0.2783	0.3652	0.5606	0.3376	0.4320	0.5120
Mawa	0.1215	0.1578	0.9534	0.2102	0.2727	0.8785	0.2684	0.3408	0.8251	0.3497	0.4464	0.7137
Mymensingh	0.2527	0.3890	0.8490	0.3326	0.4700	0.8148	0.3918	0.5272	0.7565	0.5014	0.6733	0.5331
Narayanganj	0.1325	0.1712	0.8172	0.1870	0.2302	0.6762	0.2150	0.2764	0.5786	0.2327	0.3021	0.4651
Narsingdi	0.1222	0.1636	0.9465	0.1831	0.2468	0.8813	0.2275	0.3054	0.8207	0.2839	0.3658	0.7782
Rekabi Bazar	0.1181	0.1438	0.9092	0.1620	0.2022	0.8330	0.1944	0.2435	0.7634	0.2237	0.2976	0.6382
Sariakandi	0.2658	0.3283	0.9476	0.3701	0.4855	0.8964	0.5223	0.6699	0.7912	0.6369	0.8298	0.6396
Sureshwar	0.2301	0.2948	0.6268	0.3153	0.4060	0.4315	0.3342	0.4224	0.4385	0.3565	0.4420	0.4534

Discharge forecasts at Hardinge Bridge and Bahadurabad stations, the upstream boundary stations of the medium range (1-10 day) forecast model, were also evaluated by comparison with field measurements. Figure 3.4 shows the comparison plots between the discharge forecast and mean observed discharge, including the rainfall forecast for 3-, 5-, 7-, and 10-day lead times at Hardinge Bridge and Bahadurabad stations. Overall evaluation indicated that the probabilistic flood forecasts issued by the model using ECMWF forecast for monsoon 2013 at 36 stations were of satisfactory skill for all lead times.

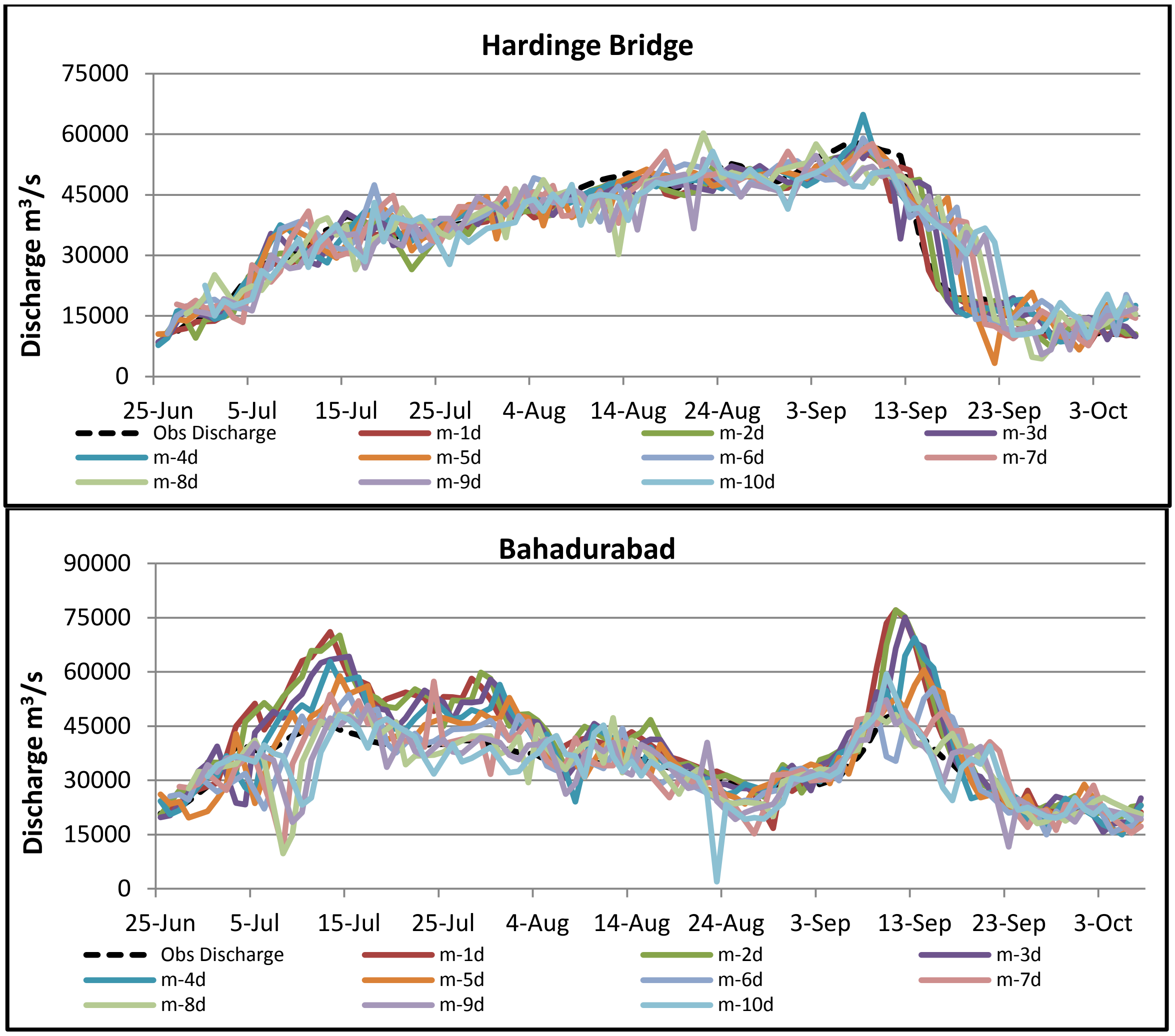


Figure 3.4 Discharge comparisons at Hardinge Bridge and Bahadurabad stations
(Source: RIMES)

3.2 Flood Forecasting

Rainfall-runoff and channel routing models are the foundation of flood forecasting systems. Floods could be forecast using rainfall-runoff models (also called hydrological models), or routing models, or combination of both. Hydrological modeling is the process of mathematically representing the response of a catchment system (runoff) to precipitation events during the time period under consideration. Hydrological modeling is a very effective tool in generating runoff forecast, based on weather forecast. Hydrological models use climatic variables (e.g. precipitation, temperature, evapotranspiration), catchment topography, and land use characteristics to simulate runoff.

Precipitation is the activating signal of a hydrological process. Runoff or streamflow is the part of precipitation that appears in a stream, and represents the total response of a basin. The total runoff consists of surface flow, subsurface flow, groundwater or base flow, and precipitation falling directly on the stream. Streamflow data is the most important data in hydrology, as it is required for planning, operation, and control of any water resource project.

Hydrological cycle is the endless circulation of water between the earth and its atmosphere. It is the most fundamental principle of hydrology. Hydrological phenomena are extremely complex, highly non-linear, and exhibit a high degree of spatial and temporal variability. It is not possible to measure everything that is required to know about hydrological systems. Therefore, modeling of hydrological variables becomes one of the important aspects in the field of hydrology. The ultimate aim of prediction, using models, is to assist in decision-making in hydrological problems, such as flood protection, water resources planning, etc.

3.2.1 Types of Models

Hydrological models are classified based on process, spatial representation, or randomness (Figure 3.5).

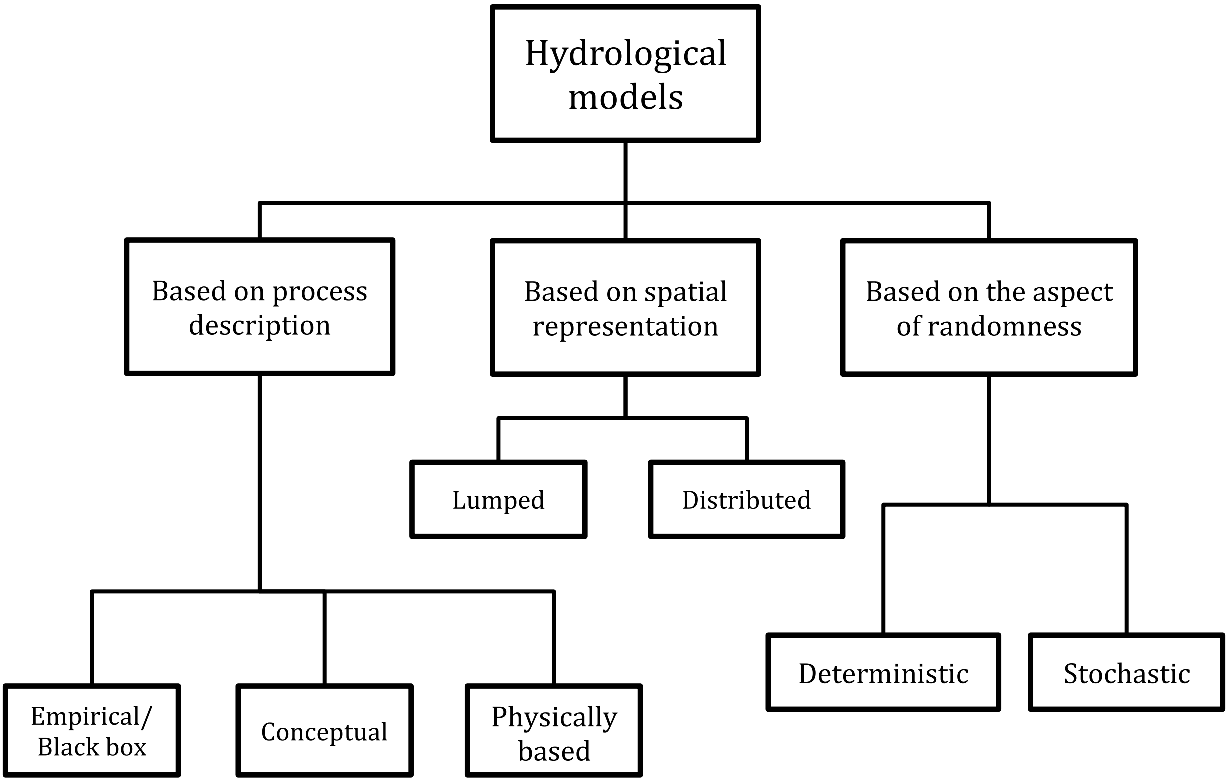


Figure 3.5 Classification of hydrological models

1) ***Process-based hydrological models***

a) *Empirical black box models (data-driven models)*

Empirical models use mathematical equations that have been assessed, not from consideration of physical processes in the catchment, but from the analysis of observed data alone. Thus, these are also called black box models.

The advantages of data-driven models are their simplicity, easy modeling approach, and rapid computation time. Use of black box models is quite simple, not demanding in terms of data due to their lumped nature. The limitations are that they cannot extrapolate, need adequate and reliable data, and cannot reflect any changes in the system.

Examples of this type of model are ARX, ARMAX, OE, Box-Jenkins, and state-space models. Along with these linear models, methods belonging to artificial intelligence, such as neural networks, fuzzy logic, and genetic algorithms, can also be included into this class (see Gautam 2000 for example).

There are three types of empirical models:

i) Empirical hydrological models

Unit hydrograph: response (direct runoff) due to unit depth of rainfall excess, linear model

$$Q_n = \sum_{m=1}^{n \le m} P_m U_{n-m+1}$$

where: n = number of runoff ordinates
m = number of periods of rainfall excess
Q_n = direct runoff
P_m = excess rainfall
U_{n-m+1} = unit hydrograph ordinate

ii) Statistical models

Linear regression:

$$Q=a.P+b$$

where: Q = runoff
P = rainfall
a, b = coefficients

Gauge to gauge correlation:

$$Q_b = Q_a \left(\frac{A_b}{A_a}\right)^k$$

where: Q_b = runoff at station B
A_a = basin area at A
Q_a = runoff at station A
A_b = basin area at B
k = coefficient

iii) Auto Regressive (AR) model: Regression in itself

$$Q_t = a.Q_{t-1} + b.Q_{t-2} + \ldots + e$$

where: Q = discharge

iv) Hydroinfomatics-based models

Neural network: non-linear model, based on the concept of working of neurons

b) Conceptual models

Conceptual models have a structure of interconnected storages. Thus, they are also called soil moisture accounting models. They are based on simplified and conceptualized representation of the physics of the system. They represent catchment as a series of storage components and fluxes with semi-empirical type of equations. Model parameters cannot usually be assessed from field data alone, but have to be obtained through the help of calibration.

Conceptual models are reliable in forecasting the most important features of the hydrograph. However, model implementation and calibration can typically present various difficulties, and they cannot provide reliable result outside the range of calibration.

Examples are AWBM, XINANJIANG, NAM, UBC, HBV, Symhyd, SSARR, TANK model (Sugawara, 1995), and SACRAMENTO model (Burnash, 1995).

c) *Physically based models*

Physically based models are based on the laws of conservation of mass and momentum/energy, such as Saint Venant equations for overland flow and channel flow, Richard's equation for unsaturated zone flow, and Boussinesq's equation for groundwater flow. These laws are expressed in the form of partial differential equations in space and time. In discrete form, these are expressed as difference equations, which are solved at each grid point in space and time using a suitable numerical operator.

These types of models give a detailed and potentially more correct description of the hydrological processes in the catchment than do the other model types. These models are very important in investigating the effects on the hydrological cycle due to climate change, change in land use patterns, and urbanization, and can be used for prediction of runoff from un-gauged catchments and for water quality and soil erosion modeling. Model parameters are, in principle, measurable in the field. These models can be applied to almost any kind of hydrological problem. They are applicable to un-gauged basins and in prediction of the effects of catchment change. However, these models require large amount of information, which is difficult to obtain, and considerable expertise and computation time.

Examples of physically based models are MIKE SHE (Abbott et al., 1986), TOPKAPI, and Vflo.

2) ***Spatial representation-based hydrological models***

a) *Lumped models*

Lumped, semi-distributed models use a lumped description of parameters and state variables, representing the average values over the entire catchment. They represent catchment as one unit. Hence, description of the hydrological processes is based on semi-empirical equations, rather than the equations that are supposed to be valid for individual soil columns. Model parameters cannot be usually assessed from field data alone, but have to be obtained through model calibration.

For example, US Army Corps of Engineers' Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) includes primarily lumped models. Such model structures are most applicable to small areas in which the physical characteristics are relatively homogeneous.

b) *Distributed models*

Distributed models use different values of parameters and state variables for each grid point over the catchment. They represent catchment as a combination of grids, sub-catchments, or hydrologically similar units.

3) Hydrological models based on the aspect of randomness

a) Deterministic model

A deterministic model does not consider randomness; a given input always produces the same output. Such model expresses the domain (physics) of system by equations. Deterministic models describe the processes in terms of mathematical relations based on physical laws, with no attempt to represent random processes. All models included in HEC-HMS are deterministic.

a) Stochastic model

A stochastic model considers randomness. Stochastic models are employed to represent irregular and unpredictable processes. This type of model reproduces hydrological time series, which is indistinguishable from historical values in terms of certain basic statistics, such as mean, variance and auto-covariance.

Flood forecasting could also be based on routing of an upstream flow to downstream forecast points. Flood routing consists of attenuation and translation of flood hydrograph from upstream to downstream. Routing models could be classified as hydrological, or hydraulic, as shown in Figure 3.6 below (WMO, 2013).

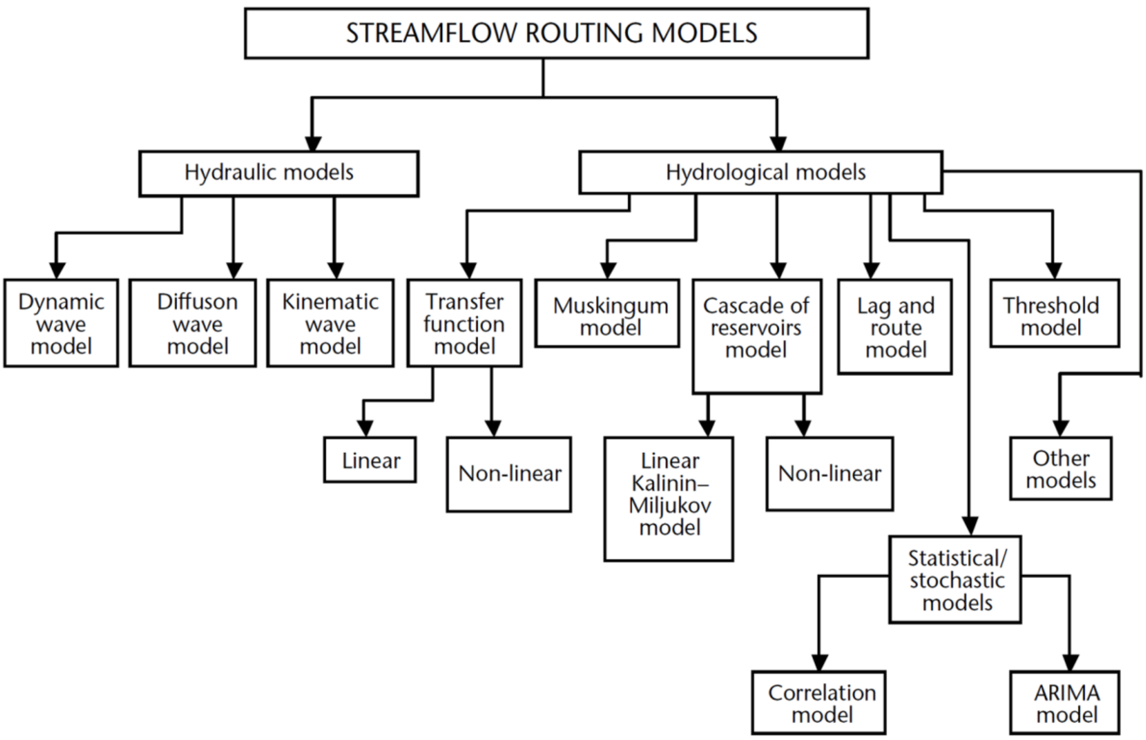


Figure 3.6 Classification of routing models

In practice, most flood forecasting centers use combination of rainfall-runoff and routing models.

HEC-HMS: An Example of Hydrological Model

HEC-HMS simulates precipitation-runoff and routing processes, both natural and controlled (USACE, 2000). Figure 3.7 shows the schematic representation of HEC-HMS.

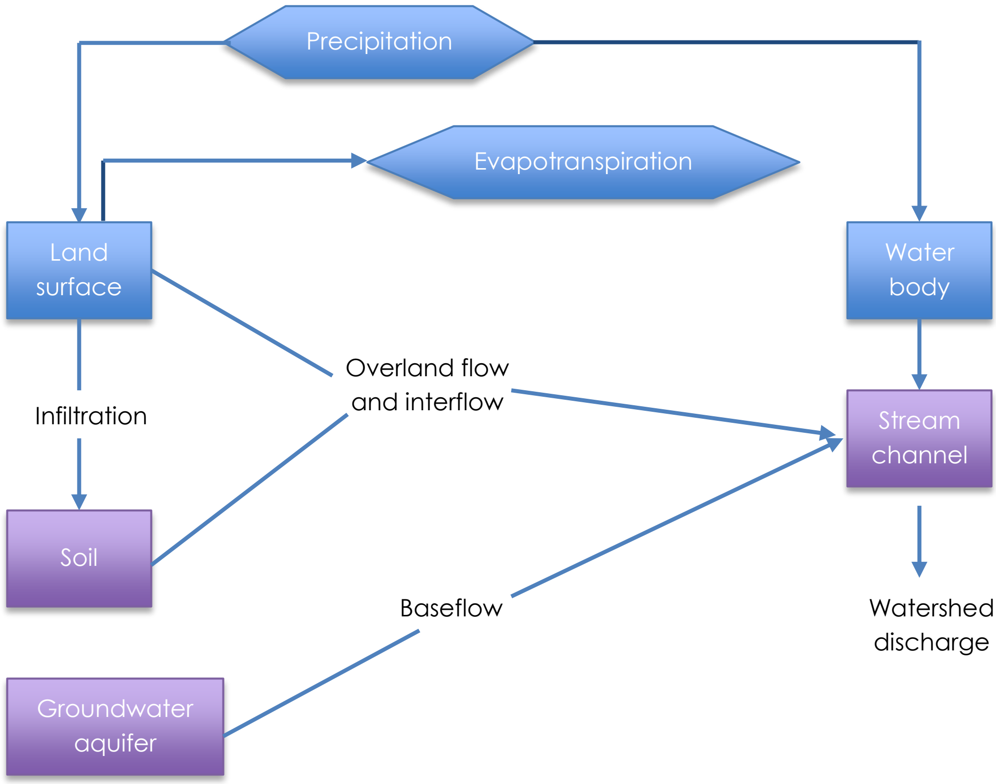


Figure 3.7 HEC-HMS representation of watershed runoff

In the natural hydrologic system, much of the water that falls as precipitation returns to the atmosphere through evaporation from vegetation, land surfaces, and water bodies, and through transpiration from vegetation. During a storm, this evaporation and transpiration is limited. Some precipitation on vegetation falls through leaves, or runs down stems, branches, and trunks to the land surface, where it joins the precipitation that fell directly onto the surface. There, water may pond, and depending on soil type, ground cover, antecedent moisture, and other watershed properties, a portion may infiltrate. This infiltrated water is stored temporarily in the upper, partially saturated layers of the soil. From there, it rises to the surface again by capillary action, moves horizontally as interflow just beneath the surface, or it percolates vertically to the groundwater aquifer beneath the watershed. The interflow eventually moves into the stream channel. Water in the aquifer moves slowly, but eventually, some returns to the channels as baseflow.

Water that does not pond or infiltrate moves by overland flow to a stream channel. The stream channel is the combination point for the overland flow, the precipitation that falls directly on water bodies in the watershed, and the interflow, and baseflow. Thus, resultant streamflow is the total watershed outflow.

HEC-HMS provides the following components for precipitation-runoff-routing simulation:

- Precipitation-specification options which can describe an observed (historical) precipitation event, a frequency-based hypothetical precipitation event, or an event that represents the upper limit of precipitation possible at a given location

- Loss models, which can estimate the volume of runoff, given the precipitation and properties of the watershed
- Direct runoff models that can account for overland flow, storage, and energy losses, as water runs off a watershed and into the stream channels
- Hydrologic routing models that account for storage and energy flux, as water moves through stream channels
- Models of naturally occurring confluences and bifurcations
- Models of water control measures, including diversions and storage facilities

In addition, HEC-HMS includes:

- A distributed runoff model for use with distributed precipitation data, such as data available from weather radar
- A continuous soil-moisture-accounting model used to simulate long-term response of a watershed to wetting and drying

HEC-HMS also includes:

- An automatic calibration package that can estimate certain model parameters and initial conditions, given observations of hydro-meteorological conditions
- Links to a database management system that permits data storage, retrieval, and connectivity with other analysis tools available from HEC and other sources

HEC-HMS uses a separate model to represent each component of the runoff process that is illustrated in Figure 3.7, including:

- Models that compute runoff volume (Table 3.5)
- Direct runoff (overland flow and interflow) models (Table 3.6)
- Baseflow models (Table 3.7)
- Channel flow models (Table 3.8)

Table 3.5 Runoff volume models

Model	Categorization
Initial and constant rate	Event, lumped, empirical, fitted parameter
SCS curve number (CN)	Event, lumped, empirical, fitted parameter
Gridded SCS CN	Event, distributed, empirical, fitted parameter
Green and Ampt	Event, distributed, empirical, fitted parameter
Deficit and constant rate	Continuous, lumped, empirical, fitted parameter
Soil moisture accounting (SMA)	Continuous, lumped, empirical, fitted parameter
Gridded SMA	Continuous, distributed, empirical, fitted parameter

Table 3.6 Direct runoff models

Model	Categorization
User-specified unit hydrograph (UH)	Event, lumped, empirical, fitted parameter
Clark’s UH	Event, lumped, empirical, fitted parameter
Snyder’s UH	Event, lumped, empirical, fitted parameter
SCS UH	Event, lumped, empirical, fitted parameter
ModClark	Event, distributed, empirical, fitted parameter
Kinematic wave	Event, lumped, conceptual, measured parameter

Table 3.7 Baseflow models

Model	Categorization
Constant monthly	Event, lumped, empirical, fitted parameter
Exponential recession	Event, lumped, empirical, fitted parameter
Linear reservoir	Event, lumped, empirical, fitted parameter

Table 3.8 Routing models

Model	Categorization
Kinematic wave	Event, lumped, conceptual, measured parameter
Lag	Event, lumped, empirical, fitted parameter
Modified Puls	Event, lumped, empirical, fitted parameter
Muskingum	Event, lumped, empirical, fitted parameter
Muskingum-Cunge Standard Section	Event, lumped, quasi-conceptual, measured parameter
Muskingum-Cunge 8-point Section	Event, lumped, quasi-conceptual, measured parameter
Confluence	Continuous, conceptual, measured parameter
Bifurcation	Continuous, conceptual, measured parameter

In addition to the models of runoff and channel processes, HEC-HMS includes models for simulating a water control structure, such as a diversion, or a reservoir/detention pond.

CFAB-FFS: Long Lead Flood Forecast Model

The Climate Forecast Application – Bangladesh Flood Forecasting System (CFAB-FFS) involves two distinct hydrological modeling approaches: i) data-based modeling, and ii) distributed modeling (Figure 3.8).

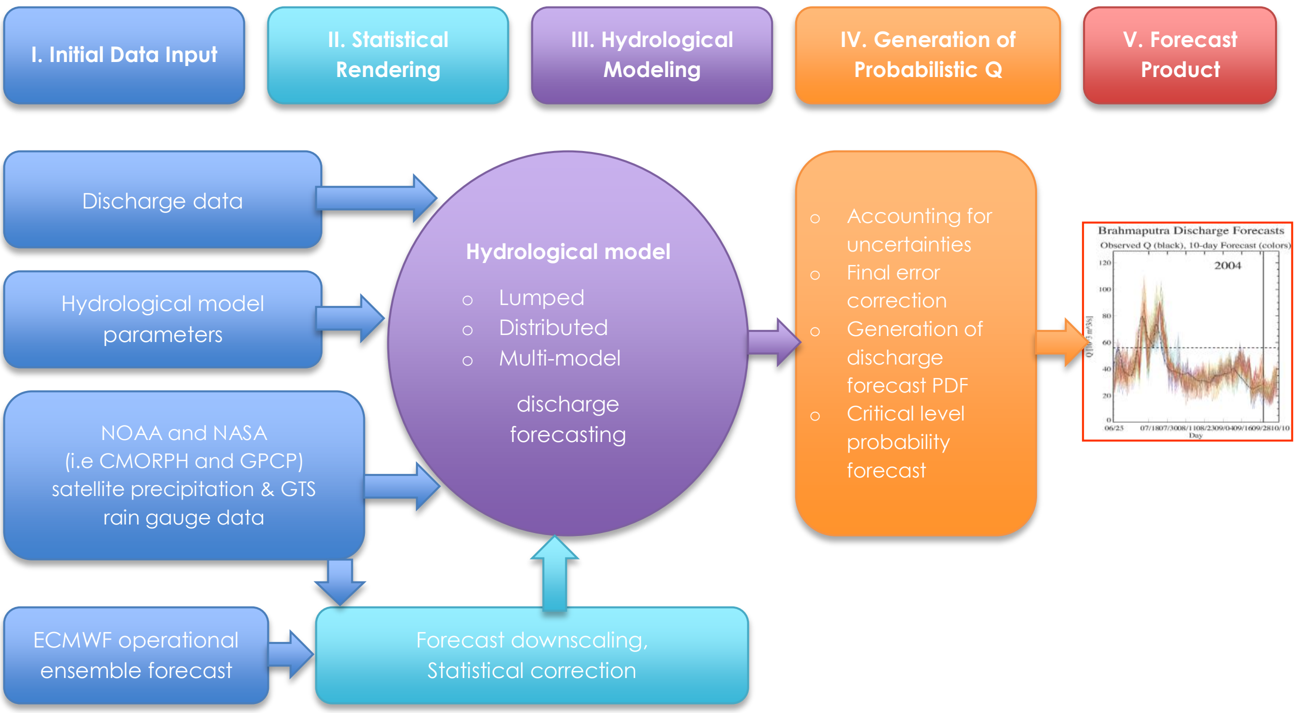


Figure 3.8 CFAB-FFS model
(Source: RIMES)

Data-based modeling employs multiple linear regression of observed discharge and observed and forecast precipitation, along with non-linear "effective rainfall" filter based on the idea that linear storage reservoirs and model structure are similar with Unit Hydrograph theory. The technique has flexible model structure, and the model can be recalibrated daily for different forecast time-horizons and for in-situ conditions. The technique tries to maximize data assimilation of near-real-time discharge measurements. The technique is implemented based on linear store and linear transfer function approach. The drawbacks of this technique are: i) catchment-averaged (lumped) model, which is more reasonable when precipitation events are of similar spatial scale as the catchment itself; and ii) limited long timescale base flow modeling.

Distributed modeling (Sacramento model derivative) was used for sub-catchment gridded 2 soil-layer model. This is similar to the one used by the U.S. National Weather Service River Forecast System. Physics of water-balance is more explicitly modeled, and the model accounts for different time delays of "distributed" precipitation events. The model, however, requires recalibration, which is costly, and data assimilation of observed discharge is limited and inflexible.

The multi-model ensemble approach is done on daily basis, and for each forecast lead time. This involves calculation of historic simulated discharges of each model (data-based and distributed models) separately, using observed weather variables (precipitation, wind speed, etc.) as inputs (i.e. not using forecast data). This is performed by simple regression of the two models' discharges against measured discharge, to minimize forecast error. It is also required to evaluate whether reduction in error residuals is significant, by using Akaike Information Criteria (AIC), which introduces a penalty function for addition of extra regression variables. If AIC is minimized (the smaller the better) by regressing the two models, then the resulting regression coefficients are used to generate multi-model ensemble. If not, then the best single model is used in the discharge forecast, which in turn assures that there is no penalty in introducing additional discharge models into the forecast scheme (see Hopson 2005).

The CFAB-FFS model provides 10-day discharge predictions at Bahadurabad on the Brahmaputra River (Figure 3.9) and Hardinge-Bridge on the Ganges River, as upstream boundary conditions for MIKE 11. Originally, CFAB-FFS generated 51 sets of ensemble forecasts for a particular day at each discharge prediction point. Use of 51 sets of data for simulation and further processing/ analyses of results is, however, not practical from operational point of view. Hence, it was decided to carry out selective simulations, and prepare forecast bulletin that would be easily understandable and usable by end users. Thus, instead of 51 ensembles, CFAB-FFS has been providing forecasts for 97.5% and 2.5% quantiles (upper and lower limits of 95% confidence limits), 16% and 84% quantiles (for -1 SD and +1 SD), and the Ensemble Mean. For ensembles that are roughly normally (Guassian) distributed, -1 SD corresponds to 16% and +1 SD corresponds to 84% quantile (i.e. roughly 68% of the time the forecasts fall within these bounds). MIKE 11 Flood Forecasting module (MIKE 11 FF) is used to forecast water level and discharge at 38 locations downstream.

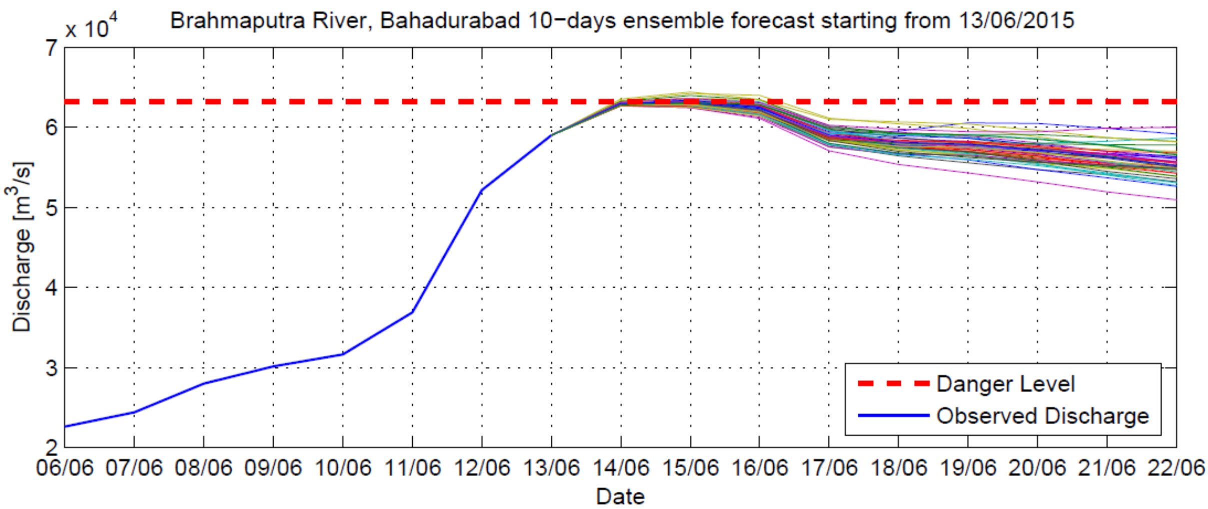


Figure 3.9 10-day ensemble forecast for Brahmaputra River at Bahadurabad
(Source: RIMES)

HEC-RAS: An Example of Hydraulic Model

The US Army Corps of Engineers' Hydrologic Engineering Center River Analysis System (HEC-RAS) was developed to perform 1D analysis of steady flow water surface profile, unsteady flow routing, movable boundary sediment transport computation, and water quality analysis (USACE 2010). Water surface profiles for steady flow are computed from one section to the next by using energy equation. The unsteady flow computation is based on the principle of conservation of mass (continuity) and momentum. Unsteady flow equations are approximated, using implicit finite difference schemes, and solved numerically using Newton-Raphson iteration procedure.

For a reach of a river, there are N computational nodes, which bound N-1 finite difference cells. From these cells 2N-2 finite difference equations can be developed, considering conservation of mass and momentum. Because there are 2N unknowns (water level and discharge at each point), 2 additional equations are required. These equations are provided by boundary conditions for each reach:

- For subcritical flow, both upstream and downstream boundary conditions are required
- For supercritical flow, only downstream boundary condition is required

Upstream boundary condition could be either flow hydrograph, or stage hydrograph. Downstream boundary condition could be one of the following:

- Flow hydrograph
- Stage hydrograph
- Single valued rating curve
- Normal depth

Interior boundary conditions are required to specify connection between reaches. Depending on type of reach junction, one of two equations, either continuity of flow or continuity of stage, is applied.

3.2.2 Model Selection

When choosing a model, it is important to bear in mind that model complexity is not synonymous with accuracy of results. Some models work well for the wrong reason, or only work well within a limited range of calibration events. The decision, in so many cases, is highly related to availability of data, i.e. a complex distributed model should not be used when available data do not support it; but when data are plentiful, physically based distributed models can perform very well. In any case, avoid a situation where the model is more complex than the data warrant.

Data-driven or conceptual models could be used where:

- Forecast location is at a gauged river section
- Relatively long data time series are available
- Required forecasting span is relatively short

Distributed models should be used when:

- Sufficient geo-morphological and hydro-meteorological data are available
- There is requirement to forecast at un-gauged locations
- Rainfall input is available in spatially distributed form
- Rainfall shows marked spatial variability over the catchment

Data requirements, model parameters, and model structure in representing hydrological processes can be considered as selecting factors. Furthermore, the models should also meet the main objective, client requirements, and be operational. The following criteria could be considered for selecting the most suitable model for flood forecasting:

- Proven reliable in terms of flood forecasting
- Operational to satisfy end user requirements
- Able to couple meteorological forecasts
- Easy/friendly to use and to implement
- Not too demanding in terms of input data
- Fast to run and produce the forecast so that adequate lead time will be available
- Economical to acquire and upgrade
- Able to generate real-time hazard maps
- Able to update the output and correct the error
- Able to generate user-friendly warning information automatically

Box 3.2 A model for an Ideal Transboundary Flood Forecasting System

A model flood forecasting and early warning systems is as follows. It is now realized that ideal river flow and flood forecasting and early warning systems should be those that have effective and efficient regional (basin wide) hydrometeorological monitoring, scientific data analysis and forecasting models at an appropriate centre producing timely warning and forecast products. The systems comprise reliable and rich data and information sources; the forecasting centre and flood areas linked with real time communication to enable operations for flood forecasting models save lives, protect property and infrastructure from destructions of floods. Essential features of comprehensive end to end flood early warning systems are given in succeeding paras.

End-to-End Flood Forecasting and Early Warning System

Flood early warning, to be effective, should provide adequate lead time for institutions and communities at-risk to undertake preparatory and mitigating actions. The chain that starts with monitoring of extreme weather and climate events, leading up to community level response can be functionally disintegrated into steps wherein developmental interventions can contribute to preparedness and reduction in disaster risks at the community level. It is end-to-end when it involves a chain of activities that connect the technical and societal aspects of warning, from understanding and mapping of the hazard and monitoring and forecasting/predicting impending/ emerging harmful disasters, to processing and disseminating understandable warnings to authorities and the population and undertaking appropriate and timely actions in response to the warnings by involvement and participation of all stakeholders. Stakeholder feedback is a key feature, allowing post-disaster assessment for learning lessons, identifying good practices, and providing recommendations for improving the early warning system. These components of an end to end flood early warning system are illustrated by the figure.

An operational end-to-end flood forecasting and warning system has the following basic elements:

- Real-time monitoring system
- Forecasting system
- Numerical Weather Prediction (NWP) system
- Data preprocessing system
- Hydrological modeling system
- Hydraulic modeling system
- Error correction system
- Warning system
- Decision Support System (DSS)
- Dissemination and communication system
- Preparedness and response system
- Feedback system

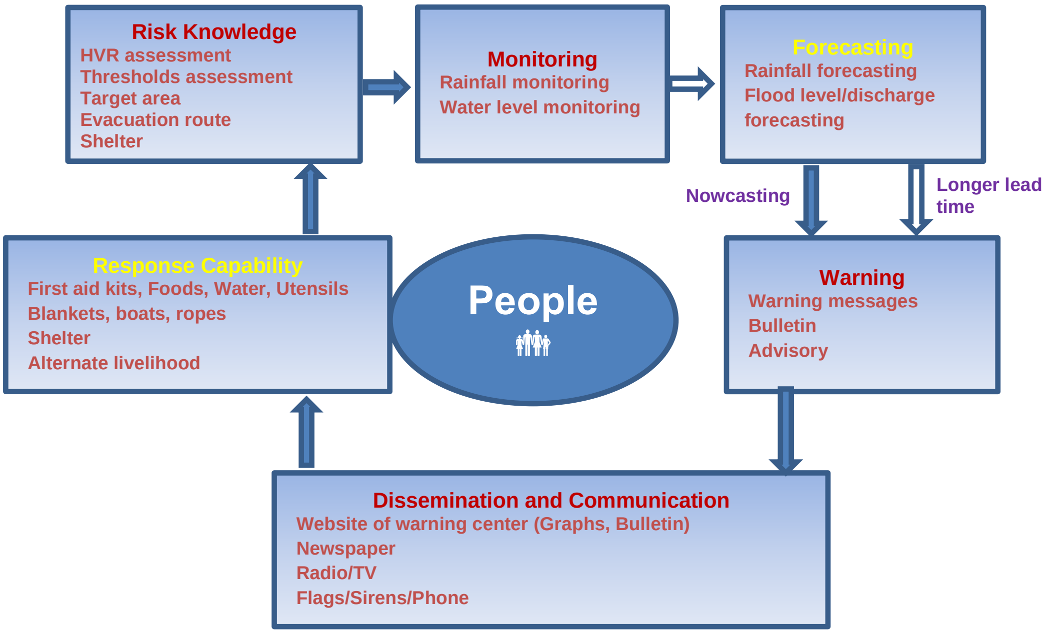


Figure End to end flood early warning system

3.2.3 Model Development

Model building is an iterative process, which consists of data acquisition and preprocessing, and model selection, calibration, and validation (Figure 3.10).

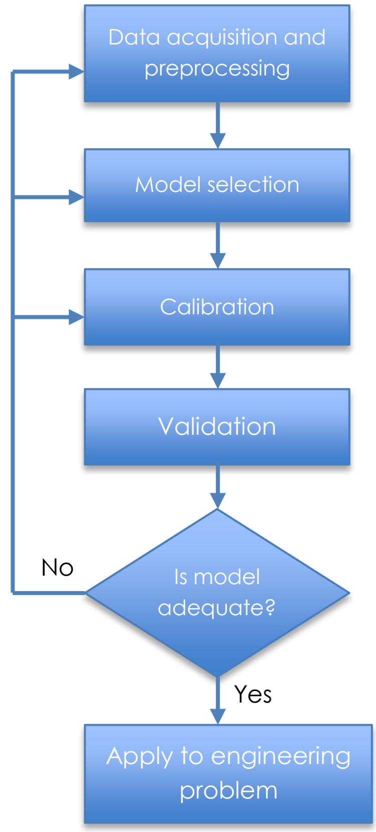


Figure 3.10 Model building procedure

Following are the major steps in hydrological modeling:

1) *Setting the purpose.* Define the purpose of the model application, e.g. rainfall-runoff simulation, prediction of changes in runoff pattern due to climate change, etc.
2) *Conceptualization.* Based on the intended application and data availability, conceptualize the model for the basin. Conceptualization comprises of perception of key hydrological processes and corresponding simplifications.
3) *Code development.* Develop the computer program for solving the mathematical model numerically.
4) *Model construction.* Design the model with regard to spatial discretization of the basin, setting boundary and initial conditions, and making a preliminary selection of parameter values from the field data.
5) *Model calibration.* Determine model parameters, such that observed values closely match the simulated value. In practice, this is most often done by trial and error adjustment of parameters, but automatic parameter estimation may also be used.
6) *Model validation.* Test the model to see whether it is capable of making sufficiently accurate predictions. This involves application of calibrated model, without changing the parameters for another period, other than the calibration period.
7) *Use of model.* Model is now ready for application for the intended purpose.

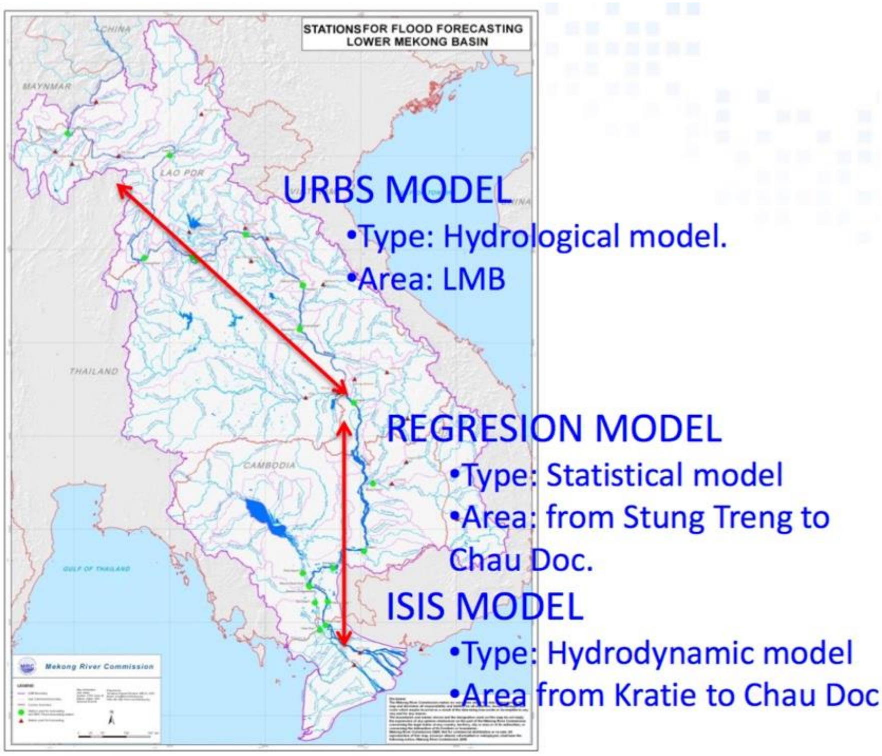
Box 3.3 Mekong River Commission – Operational Flood Forecasts

Floods in the Mekong River basin have been a significant risk factor for its local settlements. In 2013 alone, floods have cost the basin over US$2 billion and led to around 500 fatalities. This necessitated the development of a set of comprehensive flood management measures including reliable flood forecasting models.

Mekong River Commission's flood forecasting system is being administered by its Regional Flood Management and Mitigation Center (RFMMC), which serves the important role of information sharing, capacity exchange and collaboration among members. It uses two main flood warning services – the Flood Forecasting System (FFS) and the Flash Flood Guidance System (FFGS). The RFMMC uses observed river height data as well as precipitation measurements as data sources. In recent years, it has also started using satellite-based precipitation estimates to supplement ground-based data.

Data is combined using three main methods:

- ISIS, a Hydrodynamic Model used to simulate unsteady flow in channel networks;
- regression-based methods to remove statistical bias in satellite-based products; and
- the URBS event-based hydrologic model.



These techniques are combined to provide river monitoring and flood forecasting for 22 locations along the Mekong mainstream from Thailand to Viet Nam. It provides daily satellite rainfall estimates and weather predictions, and can produce 5-7 days lead time flood forecasting. Data is then recorded and processed using the HydMet platform, where information is disseminated in the form of flood warnings to government agencies and NGOs for further action.

Sources: MRC (2015) and Pagano (2015)

3.2.4 Evaluation of Model Performance

Model datasets are divided into calibration and validation datasets. Optimum values of parameters are identified for the calibration dataset by minimizing the difference between observed and computed discharges. Model performance is then tested for the validation dataset.

The following graphical plots and numerical measures can be evaluated for calibration and validation datasets:

- Joint plots of observed and computed hydrograph
- Scatterplot of observed and computed values
- Residual auto- and cross-correlation functions
- Nash-Sutcliffe coefficient, also known as determination coefficient
- Percent bias (relative bias), or mean percent error

Visual inspection of simple plots (hydrograph, scatterplot) that compare the predictions to actual measurements in calibration and validation dataset can provide significant information about how much the predictions are close to the observations, for different flow regimes. If the residuals do not contain information about past residuals, or about the dynamics of the system, it is likely that all information has been extracted from the calibration datasetset, and that the model approximates the system well. To investigate this, the residual auto- and cross-correlation functions are analyzed to check whether they are uncorrelated and, hence, converge to a Gaussian distribution with zero mean and variance 1/N.

The autocorrelation function of the residual series is obtained as follows:

$$r_{\varepsilon\varepsilon}(\tau) = \frac{\sum_{t=1}^{N-\tau}(\varepsilon_{t+\tau} - \bar{\varepsilon}).(\varepsilon_t - \bar{\varepsilon})}{\sum_{t=1}^{N}(\varepsilon_t - \bar{\varepsilon})^2} = \begin{cases} 1, & \tau = 0 \\ 0, & \tau \neq 0 \end{cases}$$

The cross-correlation function of input signal and residual series is obtained as follows:

$$r_{u\varepsilon}(\tau) = \frac{\sum_{t=1}^{N-\tau}(u_{t+\tau} - \bar{u}).(\varepsilon_t - \bar{\varepsilon})}{\sqrt{\sum_{t=1}^{N}(u_t - \bar{u})^2} \ . \ \sqrt{\sum_{t=1}^{N}(\varepsilon_t - \bar{\varepsilon})^2}} = 0, \qquad \tau \geq 0$$

$$r_{u\varepsilon}(\tau) = \frac{\sum_{t=1-\tau}^{N}(u_{t+\tau} - \bar{u}).(\varepsilon_t - \bar{\varepsilon})}{\sqrt{\sum_{t=1}^{N}(u_t - \bar{u})^2} \ . \ \sqrt{\sum_{t=1}^{N}(\varepsilon_t - \bar{\varepsilon})^2}} = 0, \qquad \tau < 0$$

where: $\bar{u} = \frac{1}{N}\sum_{t=1}^{N} u_t$

$\bar{\varepsilon} = \frac{1}{N}\sum_{t=1}^{N} \varepsilon_t$

Typically, it is checked if the functions for lags in the interval $\tau \in [-20, 20]$ are zero, or within a 95 % confidence interval, i.e., $-1.96/\sqrt{N} < r < 1.96/\sqrt{N}$.

The Nash-Sutcliffe coefficient (NS), percent bias (PBIAS), and mean percent error (MPE) can be defined respectively as follows:

$$NS = 1 - \frac{\sum_{t=1}^{N} (Q_t^{pred} - Q_t^{obs})^2}{\sum_{t=1}^{N} (Q_t^{obs} - Q^{mean})^2}$$

$$PBIAS = \frac{\sum_{t=1}^{N} (Q_t^{pred} - Q_t^{obs})}{\sum_{t=1}^{N} Q_t^{obs}} \times 100$$

$$MPE = \frac{1}{N} \sum_{t=1}^{N} \frac{Q_t^{pred} - Q_t^{obs}}{Q_t^{obs}} \times 100$$

where: Q_t^{pred} = predicted flow

Q_t^{obs} = observed flow

Q^{mean} = mean observed flow

The Nash-Sutcliffe coefficient (NS) measures the fraction of the variance of the observed flows, explained by the model in terms of the relative magnitude of the residual variance (noise) to the variance of the flows (information). The optimal value is 1.0, and values should be larger than 0.5 to indicate 'minimally acceptable' performance. It is a measure of model efficiency.

PBIAS and MPE measure the tendency of the predicted flows to be larger or smaller than their observed counterparts. Hence, they give a measure of mass conservation. The optimal value is 0.0, whereas positive value indicates a tendency of overestimation, and negative value indicates a tendency of underestimation. PBIAS value should be less than 20% to indicate ‘minimally acceptable’ performance.

3.2.5 Coupling Meteorological Forecasts to Hydrological Models

Use of meteorological forecasts as input to the flood forecasting model enhances accuracy, as well as lead time. This could be done either by coupling weather forecast model with hydrological model, or by using outputs from weather forecast model as discrete inputs into the hydrological model.

Coupling of weather forecast model with hydrological model is a complex issue, and considerable research is ongoing to develop coupled weather forecast and hydrological model. WRF-Hydro modeling system, developed by the National Center for Atmospheric Research, is an example of such model. WRF-Hydro was originally designed as a model coupling framework to facilitate easier coupling between the Weather Research and Forecasting model and components of terrestrial hydrological models. WRF-Hydro is both a stand-alone hydrological modeling architecture as well as a coupling architecture for coupling of hydrological models with atmospheric models (see https://www.ral.ucar.edu/projects/wrf_hydro). Figure 3.11 shows the schematic representation of the WRF-Hydro modeling framework.

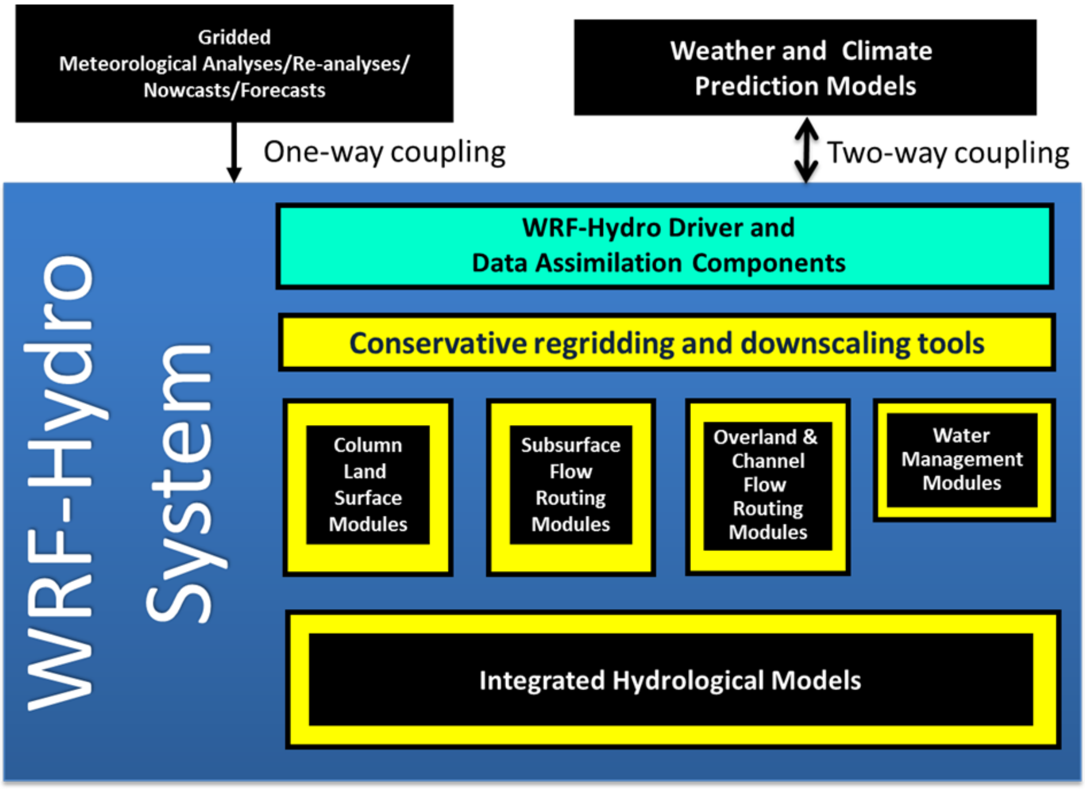


Figure 3.11 Schematic of the WRF-Hydro modeling framework
(Source: Yates et al., 2015)

Meteorological forecasts could be deterministic, probabilistic, or as Ensemble Quantitative Precipitation Forecast (EQPF). Meteorological forecasts for hydrological prediction need to be of finer spatial scale and temporal resolution. Though the hourly time-step used by numerical weather prediction (NWP) models satisfies most temporal requirements for flood forecasting, their spatial scale severely limits application. Also, NWP model forecast information tends to have uncertainty or bias (error) due to the model initialization process. Thus, it is necessary to verify model performance over a specific region, as unbiased weather forecasts are critical to the success of flood forecast models.

3.2.6 Integrating User Requirements

Lead Time

Lead time provided by flood warning has to be sufficiently long to allow response action to take place. Forecasts with short lead time are useful for saving lives, but not adequate for making decisions to reduce flood risks to livelihood systems. Community level surveys in Bangladesh (Table 3.9) revealed that at least 7 days lead time is required to save livelihood assets from flood disaster.

Table 3.9 Forecast lead time required for community-level decisions *(Source*: RIMES)

Target group	Decision	Lead time requirement
Farmers	Early harvesting of B. Aman, delayed planting of T. Aman	10 days
	Crop system selection, area of T. Aman and subsequent crops	Seasonal
	Selling cattle, goats, and poultry (extreme decision)	Seasonal
Households	Storage of dry food, safe drinking water, food grains, fire wood	10 days
	Collecting vegetables, banana	1 week

	Withdraw money from micro-financing institutions	1 week
Fishermen	Protecting fishing nets	1 week
	Harvesting fresh water fish from small ponds	10 days
Disaster Management Committees	Planning evacuation routes and boats	20 – 25 days
	Arrangements for women and children	20 – 25 days
	Distribution of water purification tablets	1 week
Char (river island) households	Storage of dry food, drinking water, deciding on temporary shelter	1 week

Delivery of lead time required by users needs to consider the time required for: data acquisition from the observation system, model run, and forecast dissemination. These activities need to be completed in the shortest time possible. Lead time, however, has an inverse relationship with forecast quality. Flood can be predicted with high accuracy only in the later stages of its development, when more information, such as observed rainfall, becomes available in real time. Warning lead time, though, becomes much shorter. Hence, for use in decision-making, it is recommended to complement longer lead forecasts with shorter-range forecasts.

Threshold

Flood threshold levels, such as warning level and danger level, are important references for the issue of flood warning. Flood warning thresholds define the meteorological, river, and coastal conditions at which decisions are taken to issue flood warnings. Flood danger thresholds are the values at which flooding occurs. Normally, a flood warning threshold is set to achieve an acceptable lead time before the flood danger threshold is reached (Figure 3.12). If proper flood warning threshold levels are identified for the areas of interest, an automatic alert system based on real-time monitoring could also be developed. Rainfall thresholds could provide additional lead time, and could be useful in mobilizing personnel to increase the frequency of monitoring.

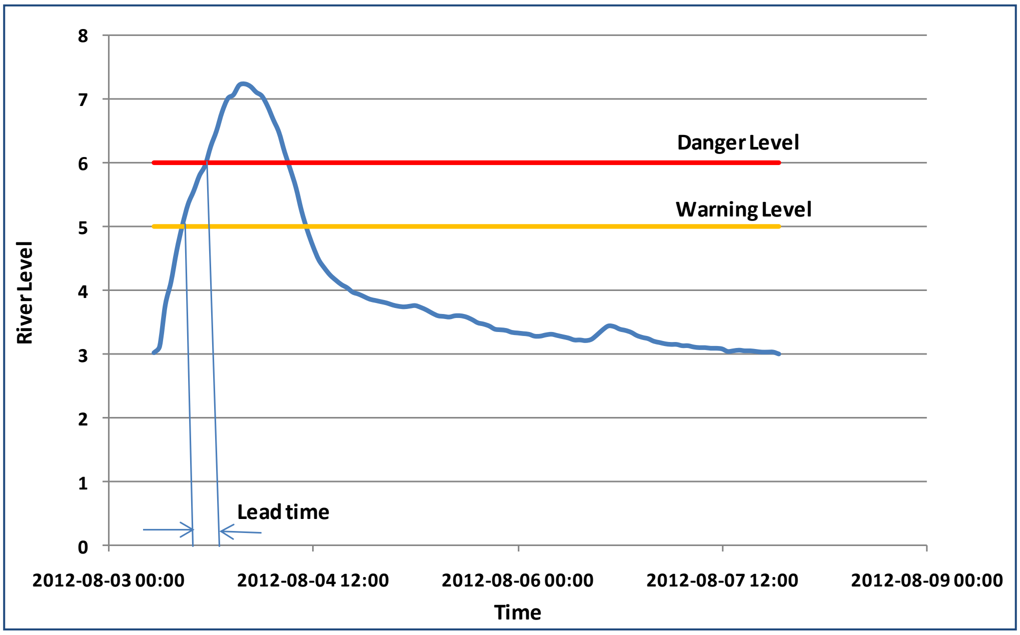


Figure 3.12 Flood thresholds and warning lead time

Threshold values may be set based on experience, analysis of historical data, or use of conceptual, data-based, or process-based modeling studies. Values are usually chosen to achieve the required lead time, without causing an unacceptable number of false alarms.

Reliability

Forecast accuracy is defined based on how well the forecast captures a disaster (e.g. rainfall), determined from retrospective comparison with observations. Forecast reliability, on the other hand, is defined based on the number of times that the forecast captures the disaster well. There is a tradeoff between forecast accuracy, reliability, and lead time. As lead time increases, forecast accuracy, as well as reliability, decreases.

Forecast accuracy and reliability are related to the uncertainty that is inherent in forecasts, more so in probabilistic forecasts. Uncertainty in flood forecasts is due to several factors that include intrinsic uncertainty in meteorological forecasts, model parameter uncertainty, as well as uncertainty in outputs, as model outputs are translated into water level forecasts. Thus, uncertainty cascades, as shown in Figure 3.13.

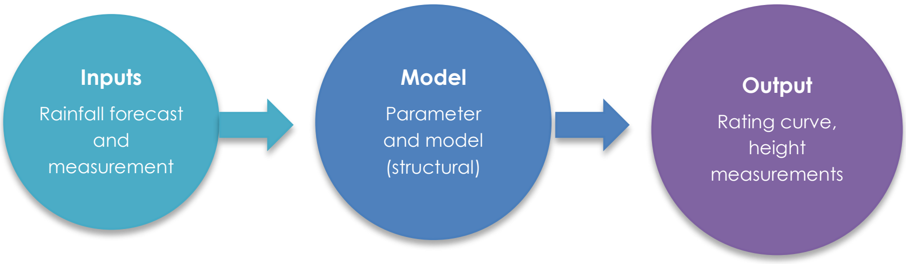


Figure 3.13 Cascading uncertainty in flood forecasts

Figure 3.14 shows that the forecast with 5 days lead time is more certain than the forecast with 10 days lead time, showing a higher probability that the flood level would be exceeded during the forecast period. Figure 3.15 illustrates the relationship between forecast lead time and uncertainty.

The user need assessment shall indicate the forecast uncertainty that is acceptable to users.

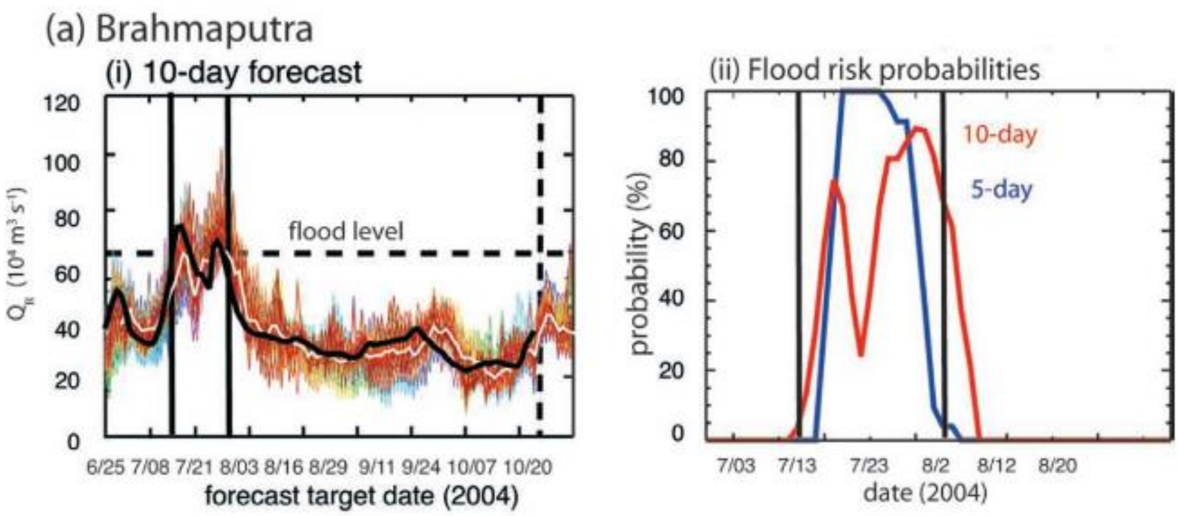


Figure 3.14 Flood risk probabilities with lead time
(Source: RIMES)

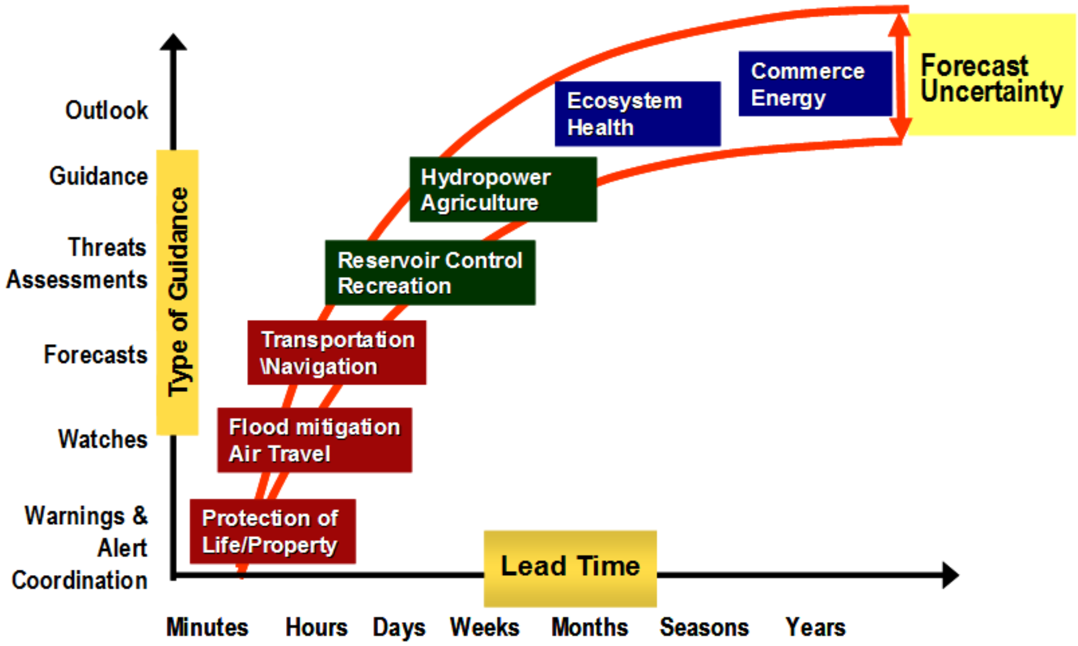


Figure 3.15 Forecast lead time and uncertainty

3.3 Resources from the Region

3.3.1 Integrated Flood Analysis System

Integrated Flood Analysis System (IFAS) is an open source rainfall-runoff analysis system (http://www.icharm.pwri.go.jp/research/ifas/), developed by the International Centre for Water Hazard and Risk Management (ICHARM) to assist flood forecasting and warning, particularly in inadequately gauged basins.

The system simulates river water accumulation and the magnitude and timing of increase in river flow, but not to the point when water volume overtops the riverbank (APAN, 2014). Since the system uses satellite-based data, which is not in real time, the system may not be applicable to small rivers that flood quickly. It is, however, useful for transboundary river basins, since the system is not dependent on ground-based observation data that may not be readily available from neighboring countries.

3.3.2 Regional Flood Outlook for the Hindu Kush Himalayan Region

The Hindu Kush Himalayan regional flood outlook (http://www.icimod.org/?q=14181) provides flow forecasts for major rivers of the Ganges-Brahmaputra basin, with 3 days lead time. The regional flood forecasting model uses rainfall-runoff and hydrodynamic (MIKE 11) models; real-time observation data from 30 hydro-meteorological stations, established under the Hindu Kush Himalayan Hydrological Cycle Observing System (HKH-HYCOS) initiative; other observation data provided by Bangladesh, Bhutan, and Nepal, as well as data shared through the World Meteorological Organization's (WMO) Global Telecommunication System; bias-corrected TRMM data to fill gaps in observation data; and quantitative precipitation and temperature forecasts from NCEP GFS model. The regional flood forecasting model covers 96 sub-catchments, with 21 nodes for calibration and validation (Shresta et al., 2015). The model was developed by the International Centre for Integrated Mountain Development (ICIMOD) and Danish Hydraulic Institute, under the HKH-HYCOS program.

The regional model was tested during 2014 monsoon for the Koshi catchment, and was found to perform well for the first 24 hours, after which forecast quality declined. Model improvement is currently being undertaken (Shresta et al., 2015).

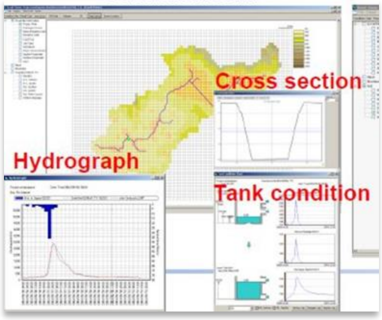
Box 3.4 Integrated Flood Analysis System (IFAS)

IFAS provides interfaces for:

a) Input of a satellite- and ground-based rainfall data, with option for correcting satellite-based rainfall data;
b) Creation of basin boundary and flow network;
c) Estimation of model parameters using global GIS data;
d) Runoff calculation using distributed hydrological models; and
e) Display of outputs.

An illustration of the adoption of IFAS can be seen with the UNESCO project on Strategically Strengthening the Flood Warning and Management Capacity of Pakistan. This project spanned two years from 2012 – 2014 and involved three main parts:

a) Strengthening flood forecasting and hazard mapping capacity through deployment of IFAS in mapping of floodplains and hazard mapping of lower Indus river basin;
b) Setting up a knowledge platform for sharing data and community flood risk information through knowledge platforms for national, provincial and district level data sharing and international networking for sharing transbounday data; and
c) Capacity development for flood forecasting and hazard mapping, which includes short-term courses and long-term academic training on flood forecasting, hazard mapping and integrated flood management.



In addition to Pakistan, implementation of flood early warning systems with satellite-based information has been implemented in various countries in South Asia and South-East Asia. This includes the flood forecasting system for the Bengawan Solo River in Indonesia, and the Research and Development Project for Reducing Geo-Hazard Damage from landslide and floods in Malaysia.

Source: Fukami, Capabilities of Data Integration and Prediction,
Available at: https://www.restec.or.jp/geoss_ap5/pdf_day2/wg1/3/7.pdf

4. Warning preparation, dissemination and communication

4.1 Risk Assessment

Recipients of warning messages respond better when warnings include the hazard's potential impacts to people's safety, livelihood systems, infrastructure, etc. Potential impacts or risk results from the interaction of vulnerability, exposure, and hazard (Figure 4.1). Vulnerability refers to predisposition to be adversely affected, while exposure is the presence of people, livelihoods, infrastructure, ecosystems, and other assets in places and settings that could be adversely affected. Hazard, in the context of this toolkit, is weather event that could trigger transboundary flood.

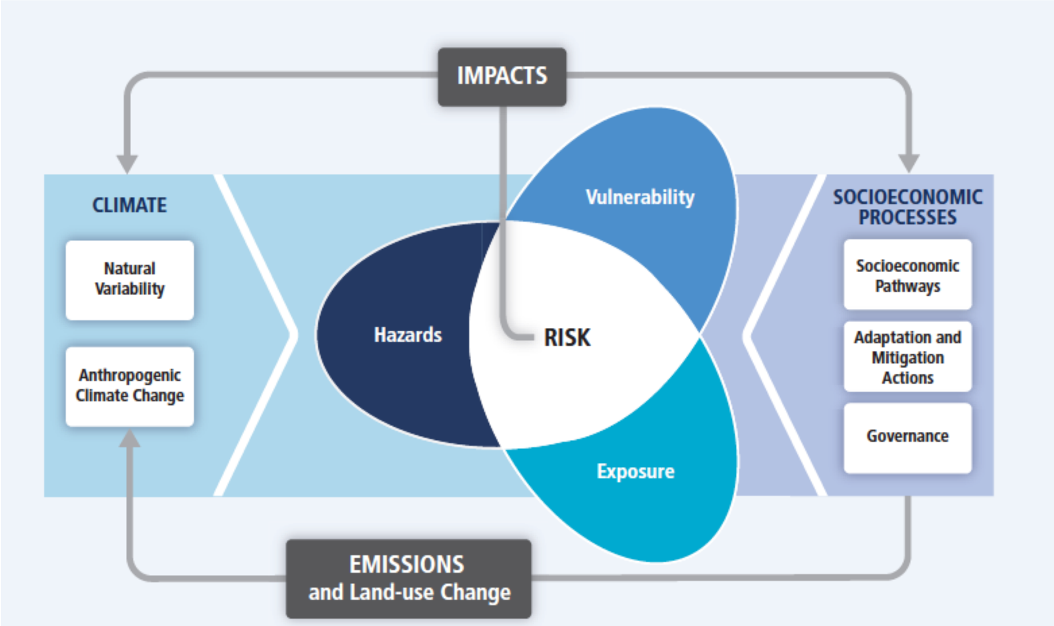


Figure 4.1 Interaction of climate-related hazards with vulnerability and exposure of human and natural systems

(Source: IPCC, 2014)

Basic risk assessment approach involves the following main steps:

1) Identification of the nature, location, intensity and probability of the hazard
2) Determination of existing level of vulnerabilities and exposure to the threat
3) Evaluation of capacities and means available to respond to such hazard
4) Establishment of risk thresholds

Figure 4.2 provides a generic framework for flood risk assessment.

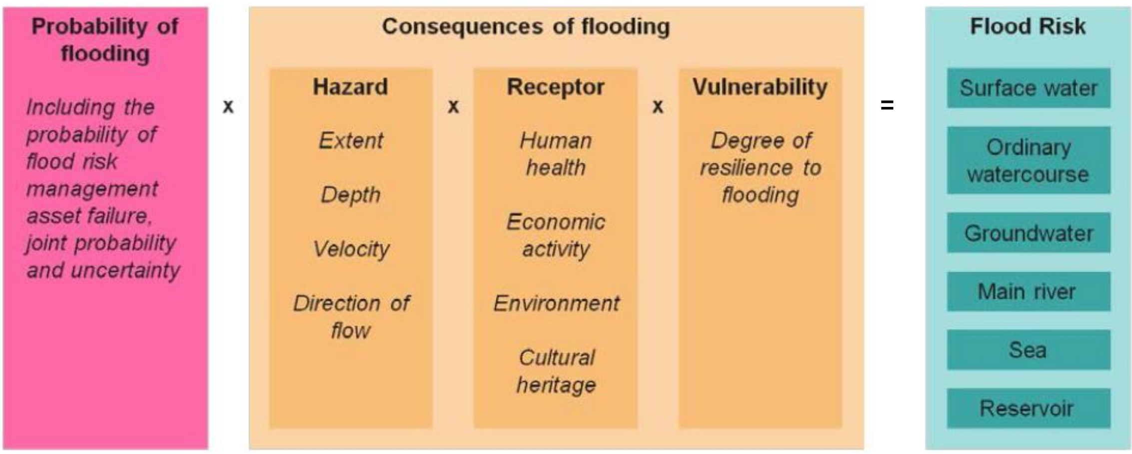


Figure 4.2 Generic flood risk assessment framework

(Source: Dale et al., 2014)

Risk assessment may be guided by key criteria listed in Table 4.1.

Table 4.1 Key criteria for assessing risks *(based on IPCC, 2014)*

Criteria	Notes
Vulnerability assessment	
1. Exposure of a society, community, or social-ecological system to climatic stressors	○ Exposure to hazardous climatic trends or events in the current and future ○ Assessed in terms of spatial and temporal dimensions
2. Importance of the vulnerable system, based on views on the importance of different aspects of societies or ecosystems; these views can vary across regions and cultures	○ Include characteristics that are crucial for survival of societies or communities, or socio-ecological systems exposed to climatic hazard ○ Context of particular societal groups or ecosystem services, taking into account the conditions that make these population groups or ecosystems highly vulnerable, such as processes of social marginalization, or degradation of ecosystems
3. Ability or limitations of societies, communities, or socio-ecological systems to cope with and to build adaptive capacities to reduce or limit the adverse consequences of climate-related hazard	○ Measure of actions taken within present constraints, and institutional setting and policy
4. Persistence of vulnerable conditions and degree of irreversibility of consequences	○ Conditions that are hard to change result to high susceptibility and very low coping and adaptive capacities
5. Presence of conditions that make societies highly susceptible to cumulative stressors in complex and multiple-interacting systems	○ Conditions that make communities or socio-ecological systems highly susceptible to imposition of additional climatic hazards, or that impinge on their ability to cope and adapt, such as violent conflict
Risk assessment	
1. Magnitude – area and intensity of impact	○ Large magnitudes of expected impacts are key, such as human mortality and morbidity, economic losses
2. Probability that significant risks will materialize and their timing	○ Frequency with high probability that hazards will occur
3. Irreversibility and persistence of conditions that determine risks	○ Persistence of root causes that cannot be reduced rapidly
4. Limited ability to reduce the magnitude and frequency or other characteristics of hazardous climatic events and trends and vulnerability of societies and socio-ecological systems exposed	○ Limited ability of communities to cope or adapt ○ Trends in climate hazards that can't be reversed

Above-listed information could be layered on a geo-referenced mapping system, for easy and flexible flood risk assessment. Flood inundation maps, flood duration maps, and maps showing change in flooding patterns could then be prepared.

Assessment of local flood risk requires collection of data for each area identified. Systematic collection and archiving of historical flood inundation information is important, as it is very useful for both risk assessment and evaluation of models.

Box 4.1 Importance of Understanding Geomorphology in Flood Risk Management

IFAS provides interfaces for:

Geomorphology includes not only the study of why landscapes look the way they do, but also mapping and modelling the earth's surface processes (Mili and Acharjee, 2014). The field has been of significant importance to disaster risk reduction and risk assessment. The majority of natural disasters are characterized by geological or hydrometeorological activities, and occurrences of natural disasters are strongly linked to geomorphological processes. To understand the effects they have on the risk of disaster occurrences such as floods and landslides, geomorphology offers a valuable toolkit for systematic assessment and analysis.

Flood is one of the main types of natural hazards in the geomorphological framework (Alcantara-Ayala, 2002). Floods are important inputs to the earth's surface dynamics and are often the result of sudden changes in the long-term processes in the landscape. To understand why they occur and how they impact human settlements, robust scientific knowledge of the physical processes is crucial.

One example of how geomorphologic study contributed to flood risk management is in the district of Assam, situated in the Dhansiri River Basin in India. This region is vulnerable to large magnitude, high frequency floods and causes significant risks to the local population settlements. As a result, a comprehensive study was carried out using primary (field survey, participation) and secondary research (topographic information, geo-reference and remote sensing data, satellite imagery) analysis. It was found that a number of factors were combined to make this region a hotspot for intense floods, including heavy rainfall, steep slopes, highly meandering and irregular rivers and unsustainable human activities in the upper catchment areas. In addition, the Dhansiri River Basin falls in a high seismic zone. Frequent earthquakes coupled with deforestation has led to soil erosion and intensified the flood risk. In response to the findings, embankment construction was made in high risk zones, and a number of anti-erosion measures were set up by the local governments. The application of geomorphologic studies can improve the quality of flood forecasting and warning.

4.2 Decision Support Systems

Assessment of a predicted flood's potential impact and subsequent generation and dissemination of warnings and advisories could be automated in a decision support system (DSS) that is linked to the flood forecasting system and dissemination system (Figure 4.3). DSS development uses Geographic Information System (GIS) tools and techniques for integrating spatial data with hazard information, and involves creation of a user interface for data and model output visualization and analysis, and warning preparation and dissemination.

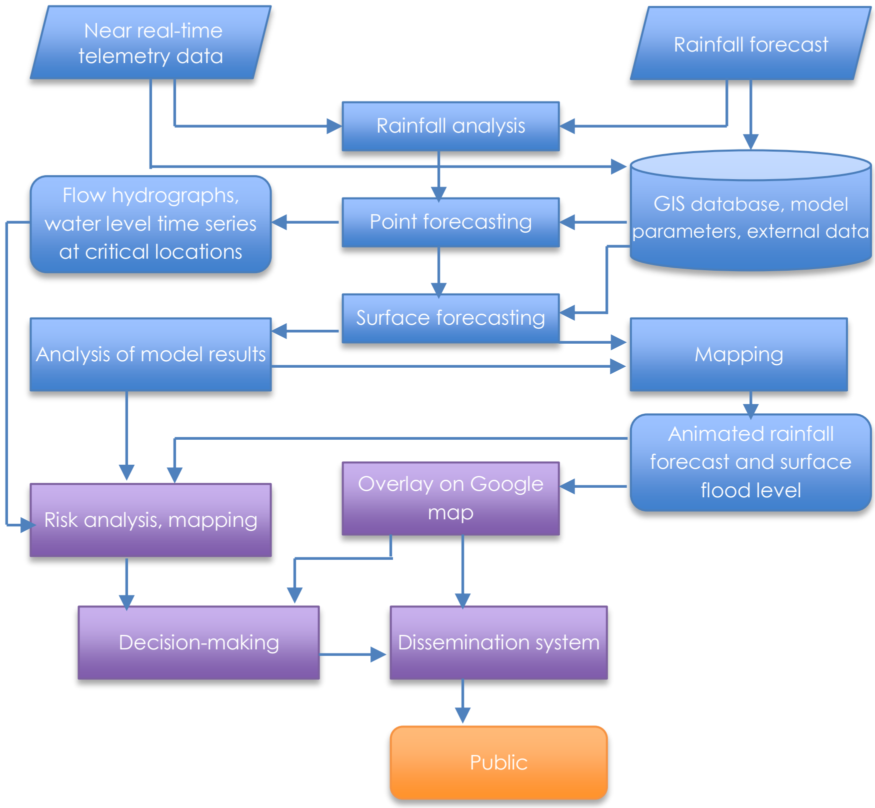


Figure 4.3 Scheme for decision support system development
(Source: RIMES)

4.2.1 Warning Preparation

The warning message should be short, concise, understandable, and actionable. It should answer the questions what (hazard), where (location), when (onset/duration/recession), how strong (magnitude), how sure (probability/ likelihood of the hazard happening), how will it affect me (potential impacts/ risks), and how do I respond (advisories).

Present the most important information first, followed by supporting information. Use simple and short sentences in plain, preferably local, language. As much as possible, avoid the use of jargon, but not at the expense of forecast/ warning integrity. If use of technical terms cannot be avoided, define/ explain the terms. Use graphics/ photos to complement the text and facilitate user understanding. Warnings may be customized for various recipients – e.g. audio format for people with reading disability, graphical format for the hearing-impaired. For flood intensity/ magnitudes on which communities do not have previous experience, the flood warning could mention inundation levels in a past flood elsewhere, and relate this to the predicted flood level.

4.3 Warning Dissemination

Dissemination is the physical delivery of flood forecast and warning information. Key considerations are:

1) Communication channels. Choice of communication channels should consider:

    - Timeliness and speed of delivery. Warnings should be delivered at the shortest time possible, to allow sufficient lead time for response.
    - Reliability. The communication channel should be stable and resistant to failure during floods.
    - Back-up. Use multiple means to deliver warnings to threatened communities so that if one fails, others could get through.
    - Accessibility. Identify communication channels that people monitor routinely and can be easily reached during emergencies.
    - Feedback. Favor communication channels that allow confirmation of warning receipt by users.
    - Effectiveness. Select communication channels that target communities at risk.

    Test communication systems routinely, involving key recipients. Automate the dissemination process to improve efficiency, reduce the time required for warning, and avoid human error. This shall include use of standard format.

2) Warning frequency. Frequency of warning updates depends on the nature, intensity, and duration of the threat; available mode of communication; and needs/ expectations of communities at risk, emergency responders, and the media. Issue of warning messages may be repeated to aid those who missed/ ignored earlier warning messages.

    Probabilistic forecasts. When longer lead forecasts indicate continuous threat, warnings may be issued despite high forecast uncertainty, as information needed to reduce uncertainty (e.g. observation data) may come much later, resulting to very short lead time for warning.

3) Follow-up. Put in place a process to follow-up on warnings to ensure that these are received and understood by target recipients. In case warning was required, but not issued, or warning was issued after the hazard has made impact, engage in a dialogue with target recipients to aid understanding of warning system limitations, and to receive recommendations for system improvement.

Partnership with the Private Sector and Mass-Based Organizations

Establish partnerships with the private sector (e.g. telecommunication companies, hotel industry, etc.) and mass-based organizations (e.g. Red Cross Societies), as they could provide complementary infrastructure and resources for dissemination. Note, though, that for those who wish to participate in warning dissemination, role may be limited to passing on the warning message from mandated government agency. In case role to downscale warning for local community is agreed on, the concerned stakeholder should be trained to ensure that scientific and best practice standards are upheld.

4.3.1 Application of Information and Communications Technology

Warning dissemination could take advantage of new information and communications technologies (ICT), which includes Internet and mobile services. Use of ICT for warning dissemination is, however, context specific, with consideration of available communication infrastructure, social culture, literacy, etc.

Websites and dashboard. These media allow sharing of observed and forecast data, hazard and risk information, and warnings in visual form, through infographic, data tables, geospatial layers, maps, etc. Figures 4.4 and 4.5 provide examples.

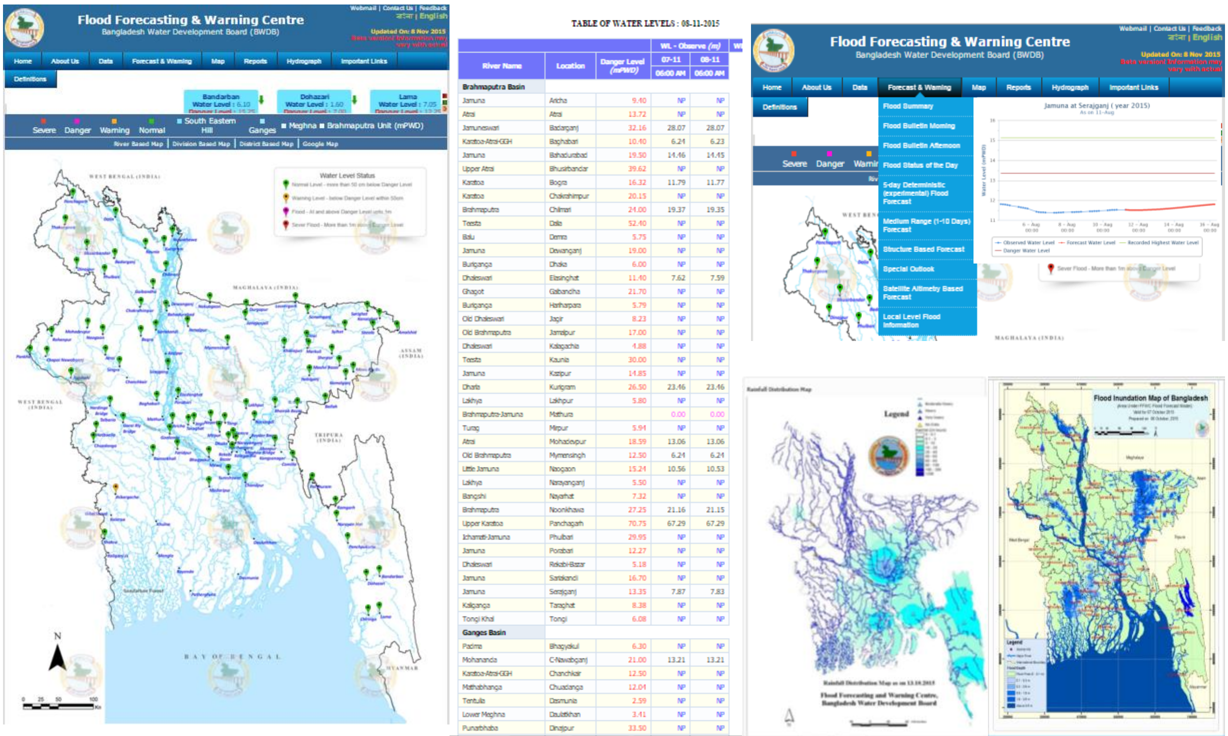


Figure 4.4 Website of the Flood Forecasting and Warning Centre, Bangladesh Water Development Board (www.ffwc.gov.bd)**, showing flood forecast locations (left) and flood risk map (right)**

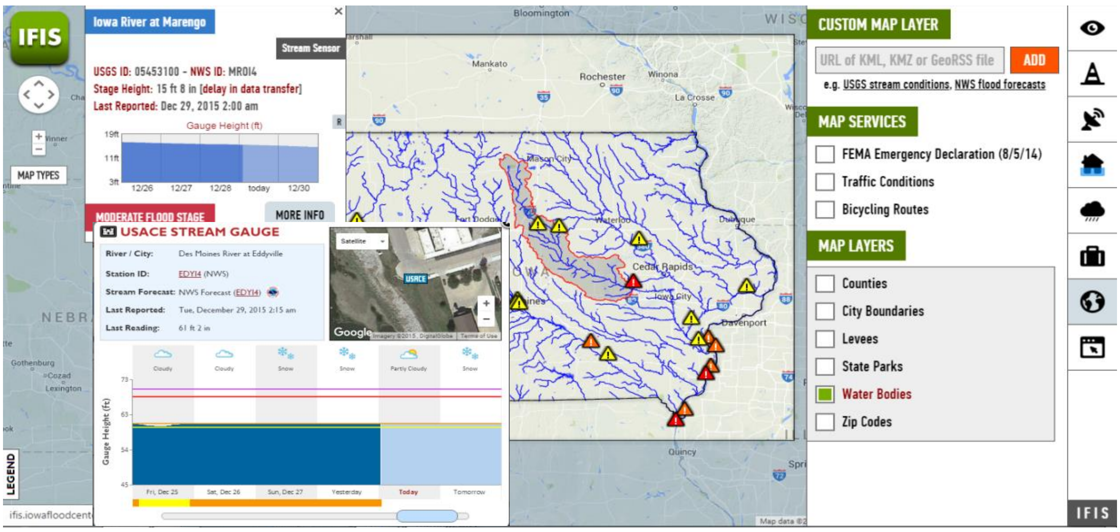


Figure 4.5 Web platform of the IOWA Flood Information Center
(https://ifis.iowafloodcenter.org/ifis/en/app/)

Emails. Emails may be customized according to information and format required by user groups. Programming tools may be used to automate email alerts for flood warning. Option for subscribing to email alerts could be added as feature of the website of the NHS or designated warning center.

SMS Alert and Cell Broadcasting. Mobile communication could provide push and pull services for warning dissemination to and fetching by users. Messages, however, may be limited by the number of characters that can be used for SMS or cell broadcasting. Also, these communication channels would require close collaboration with mobile phone operators to ensure that warnings are given priority for sending.

Interactive Voice Response (IVR). IVR is a useful dissemination tool, particularly for users with reading disability, as well as for dissemination in the local language. Messages could be recorded in various local languages, each assigned with a specific number for users to choose from and access. Voice messages can also be pushed to registered mobile phone numbers, as incoming calls. The system may be complemented by a call center, for receiving and responding to users that require more information or seek clarification.

Social Media. Social media, such as Facebook and Twitter, have become powerful communication tools, which may also be used for warning dissemination. Many national meteorological and hydrological services and warning agencies have taken advantage of social media as complementary dissemination channels.

Box 4.2 ICT for flood early warning: connecting remote communities at risk in Bangladesh

Flood is a regular occurrence in Bangladesh due to its location in the floodplains of the Ganges-Brahmaputra-Meghna basin. The Flood Forecasting and Warning Centre (FFWC) of the Bangladesh Water Development Board (BWDB) generates 5-day deterministic and 10-day probabilistic forecasts as operational flood forecast products, and 8-day satellite altimetry-based forecast and 3-day flash flood forecast products on experimental basis for pilot locations.

FFWC issues operational forecast products by fax and email to Disaster Management Committees, which translate these products into risk information and disseminate to communities at risk through display boards, community meetings, and word of mouth. With more than 100 million, of its over 156 million population, owning mobile phones, and about 45 million Internet subscribers, FFWC has adopted ICT technologies for forecast and warning dissemination.

Location-specific water level forecasts and flood warnings are sent by text and voice messages, as well as posted in FFWC Facebook page. FFWC has recently upgraded its website, making dynamic bulletins and infographic and map products available to users. Development of online interactive web portal (dashboard) at BWDB District Flood Information Centres and Union Parishad Digital Centres is ongoing, with support from Cordaid and RIMES, for data collection and analysis and dissemination of flood risks. Concurrently, a mobile phone application is also being developed to increase user access to flood forecast and risk information, facilitate user feedback, and allow user participation in water level monitoring. Another ongoing initiative is the integration of the voice message warning dissemination system into the national IVR, which currently provides flood situation updates in major rivers. These efforts are in line with the country's vision of a Digital Bangladesh by 2021.

Common Alerting Protocol (CAP). CAP (http://docs.oasis-open.org/emergency/cap/v1.2/CAP-v1.2-os.html) is an open source standardized digital message format for simultaneously disseminating alerts and warnings for various hazards and emergencies, over different communications systems, such as sirens, phone/fax, Internet-based systems, and radio/television. Its capabilities include (OASIS, 2010):

- Template for framing messages
- Support for digital images and audio

- Messaging in different languages for different receivers
- Phased/ delayed timing of message effectivity and expiration
- Message update and cancellation
- Digital signature compatibility
- Targeted geographic dissemination

CAP provides a harmonizing platform for warning sources and dissemination systems for all hazards, which are otherwise independent for each hazard (Figure 4.6).

Figure 4.6 The common alerting protocol
(Source: WMO n.d.)

4.4 Warning Communication

Warning communication, in contrast with warning dissemination, refers to users' understanding of the received message, prompting users to take appropriate actions. It, thus, depends on the presentation and dissemination of warning information, and users' awareness and understanding of risks. Communication is important because:

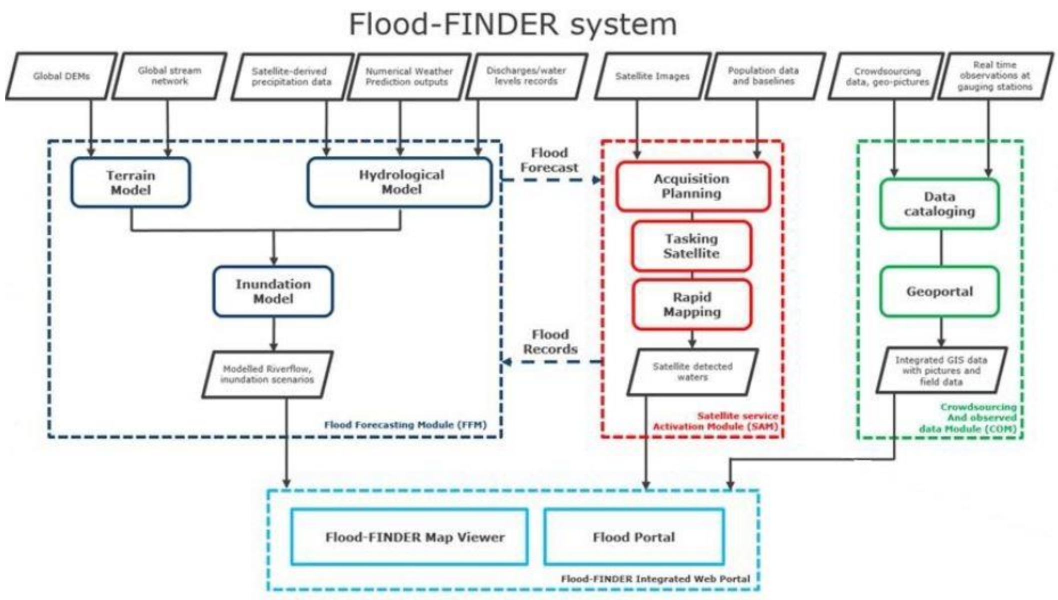
- Forecasts and warnings have value, only when users understand and use them
- Users are able to provide feedback when they understand and know how to use forecasts and warnings
- Users appreciate easy-to-understand forecasts and warnings, thus aiding credibility of the NHS

Communication skills, and education of and outreach to communities at risk are, hence, essential. Section 4.2.1 provided pointers on presenting warnings to aid user understanding of warning information; while education and outreach are included in the following chapter.

Box 4.3 Flood-FINDER system

Most flood prone areas around the world are located in developing countries, and thus making communities flood resilient is a development priority. Currently, different flood forecasting initiatives are available from the academia and research centers. However, these initiatives are limited in reducing flood impacts. What is often missing in existing forecasting initiatives is the connection between timely hazard detection and community response to warnings. In order to bridge the gap between hazard detection and response, "Flood-FINDER", the new Global Flood Early Warning System, can play an important role in disseminating information and offer capacity-building support to local governments.

The Flood-FINDER system's mission is to support decision makers throughout the disaster management cycle using flood alerts, modelled scenarios, Earth Observation-based impact assessments and direct country level participation in implementing disaster mitigation strategies. The system integrates Flood Forecasting Module (FFM), Satellite service Activation Module (SAM) and Crowdsourcing and Observed data Module (COM) to enable the production of flood warnings and forecast inundation scenarios up to three weeks in advance. Flood-FINDER aims to provide preliminary analyses without significant reliance on field data. Early identification of risks can help transform timely hazard detection into community response.



Source: Arcorace et al. (2016)

5. Warning response and preparedness

5.1 Assessment of Preparedness and Response Capacities of Communities at Risk

Preparedness of communities at risk and their capability to respond to warnings are evaluated in the context of end-to-end early warning (refer to Figure 1.3). RIMES has developed a tool to aid such assessment, using a set of criteria to determine communities':

- Level of risk knowledge
- Arrangements for local hazard monitoring, and warning receipt, customization, and dissemination
- Communication and coordination mechanism
- State of preparedness
- Response capability
- Feedback arrangement

Deficiencies noted form the basis for capacity building. Representatives of the NHS, disaster management agency, local authorities, and the community constitute the evaluation team. Annex 2 provides RIMES' generic evaluation tool, which could be customized according to national and local contexts.

It is recommended to undertake regular assessments, preferably before the flood season, to raise community awareness and promote dialogue between the NHS, disaster management agency, and communities at risk. This dialogue process shall facilitate NHS understanding of user needs, and of users' understanding of the limitations in forecast and warning products. It also facilitates user feedback, resulting in recommendations and actions for warning system improvement. Evaluation immediately after a significant flood would be helpful in identifying glaring gaps and lessons learned, as well as capturing good practices.

5.2 Capacity Building and Training

Building community capacity on end-to-end flood early warning involves education and awareness raising, investment in community-based rainfall and water level monitoring systems, preparation of standard operating procedures for local warning dissemination and emergency response, equipping and training of emergency response teams, identification of flood shelters, etc., according to gaps identified in the assessment and prioritized for capacity building by the community and local authorities.

5.2.1 Education and Awareness

Timely response to warnings depends on a person's receipt, understanding, and confidence in the warning, personalizing associated risks, and decision on appropriate action to confront/ manage risks. Public education on flood characteristics and potential impacts shall assist in understanding warning messages and how the hazard will affect them. Awareness on appropriate response actions shall aid correct and timely decisions for response.

5.3 Stakeholder Engagement

An effective and sustainable early warning system is a result of collective effort involving individuals, community groups, organizations, and institutions. These include social scientists, hydrological/ meteorological societies, academic and research institutions, the media and community radio groups, non-government organizations, government agencies at various levels, emergency responders and relief agencies, and businesses. It is therefore important to maintain effective links and close coordination with stakeholders, as each has capacity to contribute in improving warning generation, dissemination, communication and response, and public education and awareness.

Box 5.1 Importance of sustained community outreach

Engaging with users at local and community levels has not been a traditional role of National Hydrological Services. However, as presented in earlier sections of this toolkit, interaction with end users is important for ensuring that NHS products and services are useful, applicable, and effective for reducing flood risks.

In Bangladesh, the Flood Forecasting and Warning Centre (FFWC) of the Bangladesh Water Development Board (BWDB), with support from RIMES, CARE Bangladesh, and other partners conducted several activities to reach out to Union Disaster Management Committees, Union Parishads, and communities at risk, during the testing and experimental provision of the 10-day flood forecast products. This involved:

- Visit to determine receptivity for probabilistic forecasts and to understand decision systems for potential application
- Orientation workshops on the 10-day forecast and other FFWC products and services, forecast and warning delivery system, and understanding forecasts and their inherent uncertainties
- Training on using forecasts in assessing potential impacts and guiding preparedness and response actions
- Refresher training before each flood season, with practice on forecast application in decision-making through table-top exercises
- Visit at the end of each flood season to evaluate forecast receipt and application, and receive feedback
- Establishment of community-based water level monitoring system, including training of gauge readers
- Establishment of digital boards for display of forecasts and warnings

These engagements resulted to user confidence in FFWC forecasts and appreciation of the value of forecasts in saving livelihood assets.

We have very limited capacity and resources for flood management, but we consider water level forecasts as our strength in managing flood risks. Part of the Chilmari Union is char area, affected by at least some flood every year. People are eager to know about the forecast, especially during the planting and harvesting season.

- Mr. Jahangir Alam, UDMC Chairman, Chilmari

I put a bamboo stick in the river once in a while to check the water level, to validate the forecast.

- Mr. Nurunnabi, community member, Hatia

If our seedbed is inundated by floodwater, we can't save it anyway; so, we always use the forecast before preparing the seedbeds. However, if we get early warning more than ten days ahead, we could try for early planting.

- Mr. Ahsan Habib, farmer, Uria

Source: RIMES 2014

Annex 1 Current Status and Gaps in Flood Forecasting

CURRENT STATUS IN TRANSBOUNDARY FLOOD FORECAST SYSTEM

Ganges and Brahmaputra-Meghna basin

The Ganges-Brahmaputra-Meghna (GBM) river basin provides livelihood to millions of people in South Asia. During summer monsoon season, rivers and their tributaries in the basin frequently overtop the banks and create havoc due to flooding.

Riparian countries of the GBM basin – Bangladesh, Bhutan, India and Nepal – have different capacity in integrated flood forecasting and warning. Bangladesh has a fully operational flood forecasting system based on advanced hydrologic and hydrodynamic modeling. Flood forecasting in India is evolving from the use of conventional method of gauge-to-gauge correlation to advanced hydrologic, hydrodynamic and numerical weather prediction models. The integrated flood forecasting and warning system is not yet fully operational in Nepal and Bhutan.

Bangladesh

The hydrological and meteorological observation system in Bangladesh is still conventional manual type. Recently, Bangladesh has started an ambitious program of upgrading observation system with real time telemetry system.

Bangladesh has 5-days deterministic and 10-days probabilistic flood forecasting systems. RIMES has assisted Bangladesh in developing a three-tier forecast system at 10-day, monthly, and seasonal scales to demonstrate the use of these longer-lead flood forecasts for reducing losses. The forecast system was developed, with research support from Georgia Institute of Technology and in collaboration with Bangladesh Meteorological Department (BMD) and the Flood Forecasting and Warning Center (FFWC) of the Bangladesh Water Development Board (BWDB).

The 10-day flood forecast system uses the following inputs:

a) medium-range rainfall forecast from the European Centre for Medium-Range Weather Forecasts (ECMWF) ensemble prediction system;
b) satellite precipitation data from the U.S. National Oceanic and Atmospheric Administration's Climate Prediction Center Morphing Technique (NOAA/CMORPH) and U.S. National Aeronautics and Space Administration's Global Precipitation Climatology Project (NASA/GPCP);
c) rain gauge data from the World Meteorological Organization's Global Telecommunication System (WMO/GTS); and
d) local meteorological and hydrological data.

River discharges are predicted at upstream boundary locations using data-based and distributed hydrological models. Forecast errors are minimized using simple regression of model outputs against measured discharge. Discharge forecasts are made at boundary locations for 97.5% and 2.5% quintiles (upper and lower limits of 95% confidence limits), 16% and 84% quintiles (for -1 and +1 standard deviations, respectively). The ensemble mean are used in Mike 11 hydrodynamic model to generate probabilistic water level forecasts at 38 locations downstream of the Ganges, and Brahmaputra-Meghna basins (Miah et al., 2015).

This 10-day flood forecasting system is now well integrated with FFWC's flood forecasting system. It is operationally used to provide flood forecasts 10 days in advance during the monsoon season for 38 locations, with plans to expand to all other areas within the country basins (Miah et al., 2015). Disaster

Management Committees and user communities in these locations have been trained to respond to early warning messages. Actions are taken corresponding to the level of flood threat. These include: stocking of seeds, delaying of planting, early harvesting, increasing height of fish pond dykes, enclosing ponds with nets, raising livestock assets such as handlooms, increasing elevation of goods storage areas, moving of livestock to safe locations, temporary sealing of tube wells, stocking of emergency supplies (food, fuel, medicine), and securing bamboo for building temporary bridge to connect houses to high land.

In addition to the 10-days probabilistic flood forecasting systems, monthly and Seasonal Flow Outlook Systems are also being developed. They use bias-corrected monthly and seasonal (7-month) forecasts from ECMWF's ensemble prediction system, and lump conceptual rainfall-runoff model from the Rainfall-Runoff Library (RRL). The system is currently under evaluation and testing. User consultations found that these products are useful for guiding livelihoods and preparedness decisions, such as crop selection, repair of pond dykes and business shops, livestock feeds planning, increasing height/ plinth of handloom working area, elevating premises for flood protection, increasing height of tube wells, and sourcing of materials for building temporary latrines.

Moreover, RIMES, in collaboration with BMD and FFWC, also developed a flash flood warning system that uses 3-day location-specific rainfall forecast and rainfall intensity-duration threshold. The system is being pilot-tested in Sylhet and Cox's Bazar.

Bhutan

Flash floods and GLOFs cause substantial damage and loss of lives in Bhutan from time to time. Department of Hydro-Met Services (DHMS) of Bhutan maintains 20 agro-met stations, 62 climate stations, 24 automatic weather stations and 28 flood warning stations (DHMS, 2015). Some of the hydrological and meteorological stations are recently upgraded with GPRS and Iridium satellite based telemetry system. RIMES provided support for the establishment of a National Weather and Flood Forecasting and Warning Center in Bhutan, for providing reliable weather and flood forecasts for early warning of hydrometeorological hazards. Training has been provided to generate 3-days weather forecast using WRF model for Bhutan. At present, DHMS does not run any hydrologic, hydrodynamic and numerical weather prediction model for flood forecasting.

India

The "National Flood Forecasting and Warning Network" of Central Water Commission comprises of 175 flood forecasting sites including 28 inflow forecasting sites (CWC, 2015). Central Water Commission, through its twenty flood forecasting divisions, issues forecasts to various userss, including civil and engineering agencies of the States and Central Governments ministries.

The formulation of a forecast requires effective means of real time data communication network from the forecasting stations and the base stations. Wireless Communication system installed in almost 550 stations is the backbone of the communication system required for flood forecasting activities (CWC, 2015). The activity of flood forecasting comprises of Level Forecasting and Inflow Forecasting. Level Forecasting helps user agencies decide mitigation measures like evacuation of people and shifting people and their movable property to safer locations. Inflow Forecasting is used by various dam authorities in optimize operation of reservoirs for safe passage of flood downstream as well as to ensure adequate storage in the reservoirs for meeting demand during non-monsoon period.

Nepal

Nepal started modernizing hydrological and meteorological observation system with CDMA/GPRS based telemetry system since 2008. The Flood Forecasting Section of the Department of Hydrology and Meteorology (DHM) is maintaining a network of 31 hydrological stations and 36 meteorological stations equipped with telemetry system (GPRS/CDMA communication) for real-time data transmission (DHM, 2015). The hydrological and meteorological station network with telemetry system was primarily developed for flood warning in the Terai plain. The station network is sparse in hilly and mountain areas. DHM is expanding the telemetry system to about 200 stations with the support from the World Bank under Pilot Program on Climate Resilience (PPCR). RIMES is also supporting DHM to upgrade 20 stations.

DHM developed the capacity on Numerical Weather Prediction using Weather Research & Forecast (WRF) model with the assistance from RIMES. However, the NWP is not yet fully operational. At present, Nepal does not run hydrologic and hydrodynamic model for flood forecasting. Flood warning is issued to the downstream communities when water level at the upstream station exceeds predetermined threshold. DHM is currently developing flood forecasting system for three river basins using hydrologic, hydrodynamic and numerical weather prediction models.

Community based dissemination and response mechanism has been developed in collaboration with community based organizations, local governments and NGOs. Community level disaster management committees have been formed in each of the disaster prone villages. These committees have been brought into a network of District Disaster Relief Committee, local media, the Red Cross, local police, the military units and the flood monitoring and forecasting station of DHM. The disaster management committees have been equipped and trained for warning dissemination, preparedness and immediate response.

Box A-1 Regional Flood Outlook for the Himalayan Basins

Floods are annual features on Himalayan Basins. Flood early warning systems are an essential element of flood management. The International Centre for Integrated Mountain Development (ICIMOD) has been cooperating with national hydrometeorological organizations in Nepal, Bhutan, Pakistan and China and disaster management authorities in Bihar, India to develop flood outlook systems for the Ganges-Brahmaputra and Koshi basins to support national flood forecasting efforts. The pilot flood outlook, which was tested and showed promising results during the 2014 monsoon, is an integrated hydrological and hydrodynamic model of the basins. The outputs of this real-time forecasting system include a flood stance for the next three days by way of flows and water levels at key locations in the river system, for use by member countries in their own forecasting activities.

Currently the system is upgraded to include more tributaries, major water structures, and more forecast locations to improve the predictive capacity of the system in selected basins. Drawing from the experience of flood outlook systems for Ganges-Brahmaputra and Koshi basins, this session shall describe flood outlook development phases, including data sources, model setup, user interface design, dissemination methods, and challenges.

ICIMOD is a regional knowledge development and learning centre that serves its eight regional member countries of the Hindu Kush Himalayas – Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan.

Indus river basin

The Indus river basin has a catchment area of 1.12 million km^2 that stretches over Afghanistan, China, India and Pakistan. The majority areas of the river basin are in Pakistan and India (Ali, 2013).

Pakistan

The Permanent Indus Commission has been created after the Indus Waters Treaty (1960), between Pakistan and India. This Commission has two commissioners, one from Pakistan and another from India. The commission's main functions are (i) to establish and maintain cooperative arrangements for the implementation of the treaty; (ii) to promote cooperation between the two countries in developing the waters of the rivers; (iii) to settle disputes between the two countries over water; and (iv) to inspect the rivers, with a view to coordinate flow data.

The Pakistan commissioner receives flood data on almost a daily basis, and passes the data on to the Flood Forecast Division (FFD), where they are used in flood forecasting for the Chenab, Jhelum, Ravi, and Sutlej rivers. During severe flood situations, the frequency of data reception is increased to every six hours, or even to every hour (Tariq and Van De Giesen, 2012).

The Pakistan Meteorology Department (PMD) has a key role in managing and forecasting the river basin. For the flood forecasting and early warnings, PMD has the following technical and instrumental capacities:

(i) the quantitative precipitation-measuring Doppler radar facilities (10-centimeter, S-band) in Lahore and at Mangla Dam over the catchments of the Beas, Chenab, Ravi, and Sutlej rivers. They have meteor burst communications for the transmission of the hydrometric data;

(ii) 5-centimeter weather surveillance radar facilities are used for measuring weather parameters in the cities of Dera Ismail Khan, Islamabad, Karachi, Rahim Yar Khan, and Sialkot; and

(iii) the existing mathematical model at PMD computes stream hydraulics (stage and discharge hydrographs along the rivers) to estimate the inundation areas for issuing flood warning.

The PMD's flood fighting and post-flood operations include monitoring the movement of flood waves closely along the rivers to take actions for regulating the water flow at critical and vulnerable locations. However, it does not currently cover the entire basin, and as a result, the system's predictive capacity over the basin is limited. There is an urgent need to extend the system's coverage to the upper Indus reach, to the Swat and Kabul rivers, and to the major hill torrents. The required organizational setup is already in place, so procurement and implementation could be immediately carried out.

Amu Daryar basin

Most water resources in Uzbekistan come from Kyrgyzstan. Most floods are originated from Kyrgyzstan and Tajikistan in April and May. Sometimes floods originate from high-altitude lakes causing serious impacts as in the year 1988 that registered three glacial lake outburst flows causing about 100 fatalities.

Flood forecasting is not sufficient due to the lack of measurement points. Especially in the upper reaches – the source areas – instrumentation is lacking and expensive to maintain. A hydrological model has been developed, but it is difficult to use due to the lack of data from upstream countries. Lack of data and hydrometric networks is a serious problem in Central Asia, where 70% of the hydrometric stations have disappeared since the break-up of former Soviet Union (UNRCCA, 2011). Communication between countries in the region is seen as a major challenge. The most urgent needs include:

- Collecting and exchanging information between countries in the sub region;
- Sharing the same data by introducing regional databases;
- Increasing the efficiency of meteorological equipment; and
- Developing early warning systems for dangerous hydrometeorological phenomena.

Mekong river basin

The Mekong river basin, the largest river basin in South East Asia, originates from the Tibetan plateau, with length more than 4,900 km, flowing across 6 countries Cambodia, China, Lao PDR, Myanmar, Thailand, and Viet Nam. It mainly supports lives and livelihoods of lower Mekong countries, Cambodia, Lao PDR, Thailand and Viet Nam, especially through aquatic lives and irrigation for agriculture lands.

The institutional arrangements in the Mekong river basin are summarized below:

- The agreement between the lower Mekong countries, Cambodia, Lao PDR, Thailand and Viet Nam led to the establishment of Mekong River Commission (MRC), an intergovernmental body started in 1995. MRC focuses on transboundary effects of river basin, and its main role is to "cooperate *in all fields of sustainable development, utilization, management and conservation of the water and related resources of the Mekong River Basin*." (UNRCCA 2011). MRC develops rules and regulation regarding water sharing, monitors the water quality, flood mitigation and many other requirements related to the Mekong river basin.

- The cooperation of data sharing at the Regional Flood Management and Mitigation Centre began in 1950s, since then the data is collected at the center including the upstream data from China. The staffs from the member states are seconded to the regional center to participate in flood forecasting and early warning services, so that they are exposed to how countries affected can take mitigation measures on time in order to reduce flood impacts.

- The MRC's Flood Management and Mitigation Programme (FMMP) monitors river levels throughout the flood season and generates early warning forecasts at different time scales based on the upstream data proven its effectiveness in supporting governmental agencies for flood management.

- The *MekongInfo*, hosted by MRC, is an interactive web portal for sharing information and experiences in natural resources management in the Mekong River Basin, including flood reports from the FMMP. The system provides flood warning information up to 10 days in advance. This supplements the national operational flood forecasting information and is also conveyed to the EFAS partner network twice a day in a secured way.

Amur-Heilong river basin

The Amur-Heilong, the largest river basin in North East Asia, has almost 4,444 km length flows eastwards through China, Mongolia, the Russian Federation and covers a part of the Democratic People's Republic of Korea. Majority of the river flows over China and the Russian Federation.

There are bi-lateral agreements between China, Mongolia, and the Russian Federation exist for aquatic resources, but they are not for the flood risk management in the basin. The Russian Federation proposed for the Sino-Russian agreement in 1997, but the priority was given to water pollution issues and it was not related regulation and management of water flows in the river basin.

The "Sino-Russian Strategy for Transboundary System of Protected Areas in Amur River Basin" that includes cooperation during flood emergencies has been finally signed in 2014 between China and the Russian Federation. During a flood emergency, they exchange the flood water level forecast within both sides. The agreement emphasizes measures of protecting ecosystem that is directly relevant to flood retention aspects. The joint expert committee of China and the Russian Federation was organized in 2014 to investigate about the extreme floods in 2013. This case by case cooperation may not be very effective for transboundary flood risk management, and the initiatives between the two countries should be strengthened in terms of data sharing and extensive cooperation for flood risk management. All the existing initiatives seem like in nascent stage, and they are not extensively focused on flood risk management (Berglund et al. 2015).

Salween river basin

The Salween River, known as the Nu in China and the Thanlwin in Myanmar, stretches over 2,800 kilometers from its source to the Andaman Sea. Myanmar and Thailand face frequent floods in Salween river basin. 2013 floods revealed the vulnerabilities ethnic minorities of Myanmar Karen State and Thailand's Mot Municipality to floods. Its catchment can be classified as ungauged basin with lack of rainfall data and no any stream gauging station was reported. The functional flood warning system is not in place, and no formal institutional structure has been set up for the three Salween Basin countries to share data.

GAPS IN THE EXISTING TRANSBOUNDARY FLOOD FORECAST SYSTEM

The gaps in flood forecasting in transboundary river basins include low capacity in flood monitoring systems, limited data exchange and technical cooperation and inadequate institutional and capacity development.

Deficiencies in Flood Monitoring Systems

There are several challenges in improving flood monitoring systems as follows.

- While the hydrometric and meteorological monitoring networks in MRC appear adequate and work effectively in collecting data, there are deficiencies in other river basins. Real time or near real time monitoring systems in these countries need improvement. This will enable the collection and transmission of data and information needed for flood forecasting.

- Upstream countries do not have incentives to establish and maintain in remote locations and most of upstream catchments remain with no observation systems. Data from these locations are not available flood forecast models.

- Capacities of using satellite rainfall estimation techniques are emerging but challenges exist, particularly ground level measurements, with the actual rainfall using estimates from radar measurements or observation gauges.

- While each country has its own teams for collection, processing and analysis of hydrological data used in flood forecasting, different standards and guidelines are used. Thus, challenges exist in synthesizing the data and information from all the countries and use it for flood forecasting.

- The development and operation of a unified basin wide flood forecasting modelling framework requires adequate historical and current short duration as well as daily data. The challenge is how such models will be developed and implemented with limited availability of the data.

- Deteriorating hydrological services, particularly in carrying discharge measurements, maintenance and servicing of the gauging stations is also a challenge. This creates further limitations to data quality assurance in using data and information from all four countries.

Limited Data Exchange

The gauging stations data and information is only readily accessible and available to National Hydrological Services of the country of origin. The limited data exchange mechanisms only serve as flood alerts and hence not serving for flood forecasting purpose with required lead time

Uncoordinated and incomplete forecasting and warning systems

Countries have some kind of river flood forecasting and early warning systems individually developed and operated. However, these are generally uncoordinated, and these flood forecast facilities do not adequately integrate with user system with DSS. MRC operations are well coordinated and serve as a model for other river basins.

Capacity concerns

Most of the National flood forecasting centers including those in Afghanistan, Cambodia, Kyrgyzstan, Lao PDR, Mongolia, Myanmar, and Tajikistan have limited human and institutional capacity such as data processing and communication capabilities. Even advanced centers such as MRC do not fully integrate weather forecast data into hydrological modeling systems. An exception is Bangladesh, which has experienced significant technical advancements.

Building Capacity for Flood Forecasting

Countries are in the different stages of institutional development capacities. ESCAP can support the capacity building for transboundary flood forecast and early warning system.

In Asia and the Pacific, the following areas need significant improvement to build meteorological and hydrological real-time monitoring capacities in support of flood forecasting.

- Development of integrated flood forecast models for selected basins, using inputs from numerical weather prediction system
- Development of decision support system for potential impact assessment and communication of advisories
- Integration of flood early warning systems into community based flood preparedness and response systems

An entry point in each participating country could be chosen depending on receptivity of each participating country. National flood forecast and warning centers should be building blocks of a regional transboundary river basin flood early warning systems.

Annex 2 A generic evaluation tool for preparedness and response capacities of communities at risk

Community Level Early Warning System Audit

Basic Information

Name of Community: District/ Province:

Population:

Natural hazards affecting the community:

- ☐ Cyclone/ Storms
- ☐ Flood
- ☐ Landslide
- ☐ Surge
- ☐ Earthquake
- ☐ Tsunami
- ☐ Others (________________________)

1. Warning Focal Point

Primary Warning Focal Person(s)
(Please tick appropriate box/boxes)

- ☐ Person on Duty at Operation Center
- ☐ Atoll Council Chief
- ☐ Island Council Chief
- ☐ Police Chief/ MNDF Commander
- ☐ Others *(Please specify. Use extra sheet if necessary)*

Focal area for warning communication and coordination
(Please tick appropriate box/boxes)

- ☐ 24/7 Operation Center
- ☐ Community Center(s)
- ☐ Others (____________________________)

Secondary/Back up Focal Person(s)

- ☐ Yes
- ☐ No

If yes, identify back-up focal person(s):

1) ________________________________
2) ________________________________
3) ________________________________

Evaluation Team's Comments/Notes
(Please highlight strengths and weaknesses)

Recommendation(s):

2. Warning Reception

Through what channel/s is the community receiving warning information:
(Functionality of at least 3. Please tick appropriate boxes.)

- ☐ Telephone / Fax
- ☐ Mobile Phone (Call and SMS)
- ☐ AM / FM radio
- ☐ VHF/HF Radio Transceivers
- ☐ Television
- ☐ Internet
- ☐ Others *(Please specify. If necessary, use additional sheet.)*

From where are the warning information coming from?

- ☐ MMS
- ☐ NDMC
- ☐ Adjacent Islands
- ☐ Others *(Please specify)*

Are warning information properly logged in Communication Log Book?

☐ Yes ☐ No

If no, give reason: ______________________________

Evaluation Team's Comments/Notes
(Please highlight strengths and weaknesses)

Recommendation(s):

3. Local Hazard Monitoring

How does the Island monitor hazards?

Tsunami

- ☐ Monitoring for "natural signs"
- ☐ Others *(Please specify)*
- ☐ No monitoring

Swells/ Tidal Waves

- ☐ Visual and other sensory observations
- ☐ Others *(Please specify)*

Rain-induced Floods

- ☐ Rain Gauge
- ☐ Others *(Please specify)*

How does the Island monitor hazards?

Hydro-meteorological hazards

- ☐ Rain Gauge
- ☐ Calibrated and well maintained improvised rain-catching equipment
- ☐ Water level gauge(s) *(Please specify location[s]. If necessary, use additional sheet.)*
- ☐ Others *(Please specify. If necessary, use additional sheet.)*

Island monitoring equipment / tools have designated observer(s)?

☐ Yes ☐ No

Designated observer(s) properly trained?

☐ Yes ☐ No

Evaluation Team’s Comments/Notes
(Please highlight strengths and weaknesses)

Recommendation(s):

4. Local Warning Dissemination

Through what channels does the Island disseminate warning information?
(Functionality of at least 3. Please tick appropriate boxes.)

- ☐ Telephone
- ☐ Mobile Phone (Call and SMS)
- ☐ VHF/HF Radio
- ☐ Flag Warning Signals
- ☐ Person to Person
- ☐ Alarm /siren
- ☐ Bell
- ☐ Public Address System / megaphone
- ☐ Indigenous device (Please specify)
- ☐ Others (________________________________)

Directory of message recipients available at the operation center? ☐ Yes ☐ No How often is the directory updated? ______________	Communication flowchart posted at the operation center? ☐ Yes ☐ No If no, give reason: ______________________________

Evaluation Team’s Comments/Notes
(Please highlight strengths and weaknesses)

Recommendation(s):

5. Community Preparedness

Compliance with the following:

- ☐ Functional Island Disaster Committees
- ☐ Island Response Teams
- ☐ Updated directories e.g. Local Officials/ Gov't Executives; Island Committee Chair(s), Emergency Hotlines (Police, Fire Departments, Hospitals, Emergency Clinics, Religious groups, etc.)
- ☐ Inventory of families/ persons that will mostly be affected, including their evacuation center assignment(s)
- ☐ Awareness Programs/Education, Information, and Communication (IEC) Materials: EW Posters, streamers, signboards, etc…
- ☐ Hazard Map/ Vulnerability Maps/ Resource Maps
- ☐ EW/DRM Trainings
- ☐ Evacuation Center
- ☐ Evacuation Routes
- ☐ Access to transportation system for evacuation etc., during emergencies
- ☐ Access to food and water
- ☐ First Aid/ Medical Kit
- ☐ Simulation Drill (at least annually)
- ☐ Others (Please specify. Use extra sheet if necessary)

Evaluation Team's Comments/Notes
(Please highlight strengths and weaknesses)

Recommendation(s):

6. Administrative Requirements

Compliance with the following:

- ☐ Island Disaster Risk Reduction and Management Plan or equivalent document duly approved by the Island Council.
- ☐ Guidelines and protocols for the established warning thresholds.
- ☐ Standard Operating Procedures for Emergency Response, Evacuation, etc.
- ☐ Standard Operating Procedures/Guidelines/Protocols for warning communication and coordination
- ☐ Approved communication/information dissemination flowchart
- ☐ Others *(Please specify. Use additional sheet if necessary.)*

Evaluation Team's Comments/Notes
(Please highlight strengths and weaknesses)

Recommendation(s):

Summary				
Components	Score/ Criteria			Score
	1	2	3	
1. Warning focal point	Identified& available 24/7	Identified, with back-up arrangement, & available 24/7	Identified, with back-up arrangement and focal area for communication and coordination, and available 24/7	
2. Warning reception	NMHS as warning source; uses 1 functional channel for receiving warning, information received not recorded	NMHS and NDMO as sources; primary and secondary channels available; information received recorded, but not consistently	NMHS, NDMO & adjacent communities as sources; more than 2 functional channels available; information received recorded properly and consistently	
3. Local hazard monitoring	Observes "natural signs" using visual and other sensory means	Uses monitoring sensors/ equipment for most hazards, with designated observers	Uses monitoring sensors/ equipment for all hazards, with designated trained observers; data transmitted to MMS headquarters; maintenance program in place	
4. Local warning dissemination	Directory of message recipients available; uses 1 functional channel for dissemination	Protocols available; primary and secondary functional channels available	Communication flowchart visible; updated directory available; compliance with SOP; more than 2 functional channels available	
5. Community preparedness	No institutional arrangement to coordinate response; DP plan drafted, but not approved; no awareness program in place; response teams not available; evacuation centers and routes identified; have access to food and water	Institutional arrangement to coordinate response available but not functional; DP Plan approved; sporadic event-based awareness program; trained response teams; evacuation centers and routes identified; inventory of resources available; access to food, water and first aid	Institutional arrangement to coordinate response available and functional with equipped response teams; DP Plan approved, resourced, and practiced; continuous awareness program using a variety of media; trained response teams; evacuation drill at least once a year; evacuation centers and routes identified; inventory of resources available; compliance with SOP	

			for response; access to food, water, first aid, and sanitation facilities	
6. Administrative requirements	Systems have been recently developed	Systems are in place, supported by DRRM Plan, communication protocols, SOPs for response, etc.	Systems are in place; practices are in compliance with approved DRRM Plan, communication protocols, SOPs for response, etc.	
Overall Evaluation Result (score out of 18)				
Overall recommendations:				
Signatures of Evaluation Team Members:				
Date Evaluated:				

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