Chapter 9
Enhancing Flood Early Warning System in the HKH Region

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9.1 Introduction

Flooding is a chronic natural hazard with disastrous impacts that have magnified over the last decade due to the rising trend in extreme weather events and growing societal vulnerability from global socioeconomic and environmental changes (WMO/GWP 2011). Such unprecedented change is manifest in the increased severity and frequency of climate-induced hazards that are intensifying disastrous consequences, in particular, flood disasters. While vulnerable nations grapple with the flip side, it has globally-inspired collective interest and resolves to anticipate extremes, invest in building resilient societies and economies, and make proactive interventions. Catastrophic floods impact tens of millions of people each year and cause significant infrastructure damage around the world. The situation is getting worse due to increasing population, urbanization, and economic development in hazard-prone areas (Etienne et al. 2019). Floods are among the most frequently occurring and deadly natural phenomena, affecting on an average 520 million people a year (UNESCO 2007). Almost half the people killed in the last decade (as a result of natural disasters were victims of floods, which also account for about one-third of economic losses (CRED/EM-DAT 2020). Globally, flash floods are among the world's deadliest natural disasters accounting for almost 85% of the flood incidences with the highest mortality rate among different classes of flooding and resulting in significant social, economic, and environmental impacts (Fig. 9.1). Flash floods are also difficult to forecast compared to riverine (floodplain) floods due to their rapid onset and as they occur in smaller basins due to intense and incessant rainfall. Also less frequent but more catastrophic are the flash floods

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triggered by natural and artificial dam breaches which have far more disastrous impacts on lives and properties.

Bakker (2009), analyzing flood statistics on the Emergency Events Database (EM-DAT) and the Dartmouth Flood Observatory databases for the years 1985–2005, showed that 75% of the countries affected by riverine flooding share this event with other countries, and that flooding in transnational river basins, globally, accounts for about 30% of the casualties and that it affects almost 60% of the population. A basin-wide approach linking upstream catchments with downstream riparian countries is recognized as a key consideration when dealing with transboundary floods at all phases of the flood-risk management cycle.

9.2 Flooding Trend in the HKH

The HKH region is no stranger to catastrophic floods. Seasonal, riverine, and flash floods are frequent occurrences along the rivers and tributaries in the HKH. Figure 9.2 gives an overview of the devastating flood events experienced by the HKH countries over the last 70 years, as registered in the database of the Center for Research on the Epidemiology of Disasters (CRED). Every year, destructive floods occur at one place or the other across the HKH bringing about untold suffering and often accompanied by loss of lives, livelihoods, and severe damages to property.

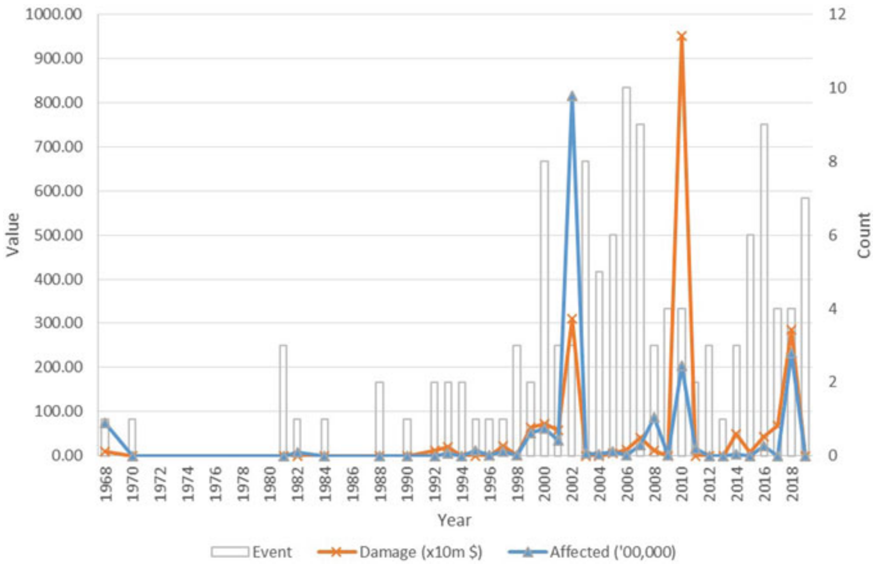


Fig. 9.1 EM-DAT historical records of flash-flood events [D. Guha-Sapir]

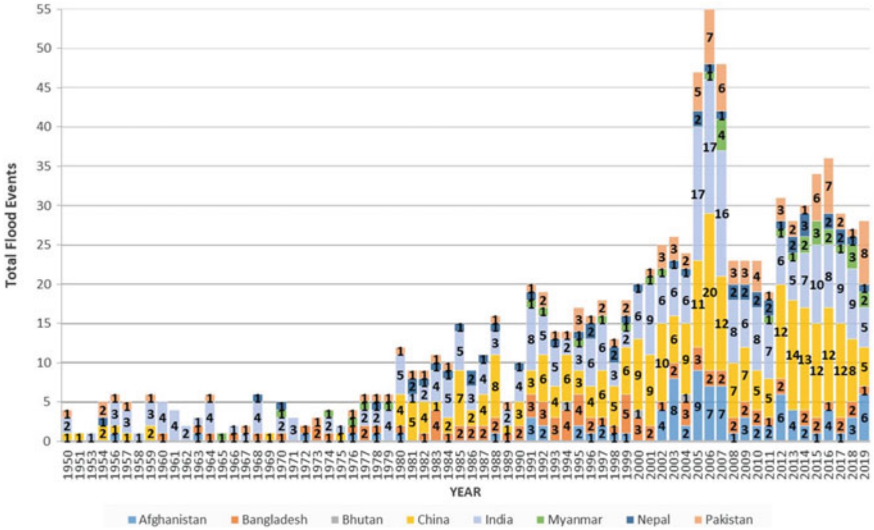


Fig. 9.2 Total number of flood events in the HKH region by member countries from 1950 to 2019. *Data source* EM-DAT: the OFDA/CRED International Disaster Database—www.emdat.be—UCLouvain—Brussels—Belgium

Bangladesh is probably the most flood-prone country in the world. Approximately, 20–25% of Bangladesh's territory gets inundated during every monsoon season, and at least 50–70% of the country's territory is exposed to intermittent extreme flooding which has far-reaching negative impacts on the national economy (Akhtar Hossain 2003). Being a lower riparian country, about 25% of the rivers in Bangladesh are of the transboundary type, with more than 93% of the drainage basins located outside its national territory. Flash floods from the surrounding uplands from April–May are followed by episodic inundation during the monsoon, with some of them persisting for months. A very recent event of consequence was the monsoonal flood of July 2019 that caused 119 human fatalities, directly affected 7.3 million people, and displaced an estimated 308,000 people in the districts of Jamalpur, Kurigram, Gaibandha, Sylhet, Sirajganj, Tangail, Sunamganj, Bogra, and Bandarban. Approximately, 584,000 houses were damaged or destroyed, including 6,641 km of road and 1,275 bridges. The same monsoonal system also wreaked havoc in Nepal and India. In Nepal, it caused several floods and landslides across 32 districts, leaving 117 dead, several injured, and many unaccounted for; close to 12,000 households were displaced, mostly in the worst-affected districts of Rautahat, Mahottari, and Siraha. Across India, 1,326 people died and over 1.8 million people were displaced (GDACS 2019).

Summarizing from the results and findings of past studies on the flooding situation in the HKH region, Shrestha et al. (2015) concluded that floods in the region cannot be totally controlled and that efforts should be directed towards reducing flood vulnerability and mitigating impacts through improved flood risk management by providing end-to-end flood forecasting and warning services. Flood events cause far more suffering and bring economic burden on the poor and the marginalized communities in the mountains since the socioeconomic situation and lack of political voice invariably condemn them to the most vulnerable sites for sustenance. The study concluded that on an average, 76 flood disasters occur annually in the region, accounting for thousands of deaths and millions of affected people. The breach of the Koshi barrage in the 2008 flood event was a textbook case during which millions were displaced across Nepal and Bihar, and hundreds of lives were lost, along with millions worth of Indian rupees' in damage and destruction.

Generally, the HKH region is vulnerable to flooding during the summer monsoon season; however, its western part does experience significant and sometimes devastating pre- and post-monsoon floods associated with mid-latitude westerly storms. Pakistan has suffered massive flood disasters in recent decades causing huge economic impact and human suffering. When normalized to the respective country's economic strength and population size, Nepal, Afghanistan, and Bangladesh show higher socioeconomic impacts of flooding (Elalem and Pal 2014).

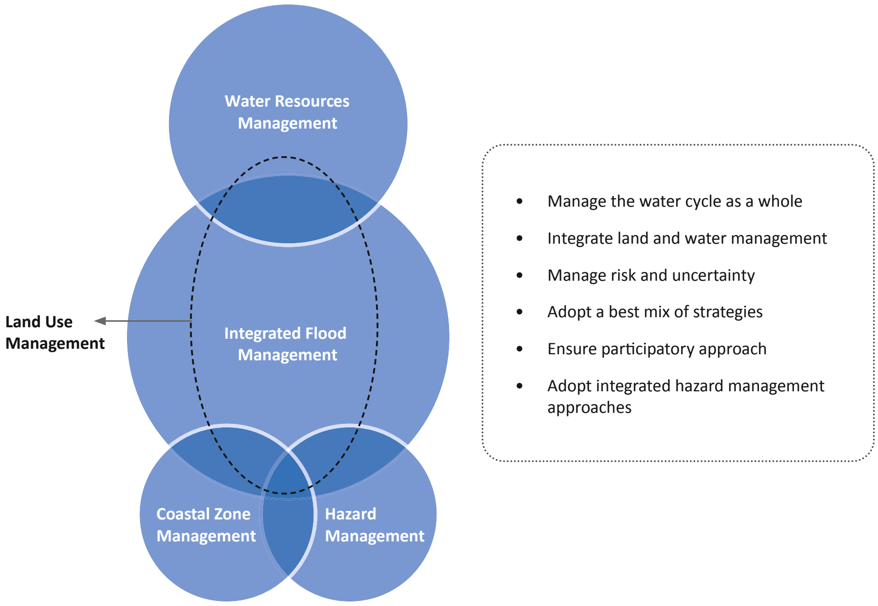
Improvements in flood forecasting and the ability to communicate actionable information to those at-risk have substantial lifesaving and monetary benefits. But the benefits will accrue only if early warnings lead to early action, which can very much depend on the credibility and available lead-time of the warning information. Communication and dissemination are consistently being identified as the weakest links in the flood management chain despite tremendous growth in information products and increasing demand from the stakeholders and affected communities. There is a real need for targeted and tailored communication of flood information to reach the local level.

The targets set under the Sendai Framework for Disaster Risk Reduction (SFDRR) and the Sustainable Development Goals (SDGs) advocate flood early warning systems (EWSs) as a flood-risk management measure (UNISDR 2006). However, despite widespread recognition (UNDRR 2004; WMO 2013; Pappenberger et al. 2015; Thielen del Pozo et al. 2015), the operational status, benefits, and costs, and the challenges and trends associated with these systems have still not been fully understood so as to garner concrete support and commitment for wider adoption and upscaling to multi-hazard capability (Perera et al. 2019).

9.2.1 Perspective on the Current State of Flood Management—Issues and Challenges

The way people deal with floods determines whether water remains a life-providing element or becomes a destructive force against human life and economic development. Traditionally, flood management has focused on reactive practices largely relying on flood control through structural and non-structural measures. Amongst many structural and non-structural measures, flood forecasting and early warning have proven to be effective in reducing flood risks through better preparedness and resilient responses. But there is an increasing urgency to address the challenges of factoring flood-hazard risks in water management, increasing multidisciplinary approaches, improving upon the information for an integrated strategy to prevent disasters, reducing vulnerabilities, and building community resilience, thereby enabling all-inclusive participation (Fig. 9.3). Adopting an integrated approach has been a paradigm shift in flood management, away from the dominantly reactive engineering interventions of flood control. While it is possible to anticipate and prepare for some floods, there are also others that take place in a totally unexpected manner. While we cannot necessarily eradicate all the threats, we can nonetheless become better aware of their likelihood and potential impacts regardless of them being perceived or real. The greatest challenge is and will continue to be, the sustainability of efforts in dealing with flood events as complacency could set in once the memory of recent occurrences subsides under a prolonged lull.

Effective flood detection is analyzed by accurate estimation of water-level thresholds that identify specific hazard levels along an entire river network. The estimation of suitable exceedance thresholds is a key task in the flood early warning system, where alerts are determined by the ratio between streamflow estimates and reference thresholds (Alfieri et al. 2019). But real-time simulation of hydrologic and hydraulic flow processes is expensive because of the computing resources and



- Manage the water cycle as a whole
- Integrate land and water management
- Manage risk and uncertainty
- Adopt a best mix of strategies
- Ensure participatory approach
- Adopt integrated hazard management approaches

Fig. 9.3 Key elements of an integrated flood management model. *Source* APFM, WMO (2009) entails a steep learning curve to build the necessary human capacity to set up and run the models. As an alternative, pre-simulated scenarios and matching processes are often employed to anticipate flood events and determine the consequences.

According to Perera et al. (2019), challenges in flood management arise from several factors related to the inadequacy in the observing and monitoring networks on the ground, poor integration of remotely sensed and satellite Earth observations, and the inability to assimilate outputs of numerical models into developing a common operating picture in flood management. The expenses involved in the acquisition of technological know-how and scientific knowledge, and other related financial issues are the primary reasons for not investing sufficiently in the critical facilities and generating actionable information in strategizing flood management systems. The appreciation for prevention and preparedness is still very low among the decision makers faced with competition for development priorities in a situation where the resources are scarce.

9.2.2 State of the Science in Flood Forecasting

The flood-forecasting process includes executing hydrological models with observed and predicted hydro-meteorological data to obtain information on river discharges and translating the predicted streamflow into simulated river-water stages. The water levels in the river channels are then assessed in the context of flood-recurrence intervals to decide on the warning levels for dissemination to areas likely to be exposed to imminent flooding hazards. Unless early warnings inspire early actions to mitigate risks, they are unlikely to deliver the anticipated socioeconomic benefits that can accrue from even the best and robust of flood prediction and early warning systems.

To start this dissection from a broader and longer perspective, it all began with relentless efforts in predicting the ENSO (El Nino-Southern Oscillation) phenomenon, which added a whole new dimension to the issue of weather and climate predictability. Since it has a dominant influence on the seasonal and annual variability of floods and droughts in South Asia, the focus was initially on precipitation forecasts as a proxy for hydrological extremes. But the relationship between extreme precipitation and extreme flooding is nonlinear and not the best of indicators. So, the improved predictability of ENSO impacts, along with recent advances in prediction science and forecasting tools, has opened up vast opportunities to provide reliable forecasts and early warnings on disastrous floods. One such approach is the dynamic seasonal river-flow outlook of the Global Flood Awareness System (GloFAS-30 Days and Seasonal: http://www.globalfloods.eu 2020). GloFAS products are now widely used by almost all the national hydromet services in the HKH region as the benchmark guidance for daily forecast routines and seasonal outlooks on flood situations.

Modeling the catchment hydrologic response to the predicted meteorological forcing in space and time defines the flow characteristics that will be evaluated as flood or not based on a set of exceedance thresholds. Flood forecasting is done to detect flood with sufficient actionable lead time to protect lives and properties through better preparedness and response measures. Modeling science has evolved to fit the circumstances in which outputs are applied and matched with the available and accessible data required to configure and run the models. A more recent approach is toward tailored, purpose-built prediction models nested within broader flood-forecasting frameworks (Fakhruddin 2010; UNDP 2018; WMO 2011). Such configurations provide flexibility in the choice of an appropriate model, chain different models with scalable and interoperable computing infrastructure, and single-window user-interface platform for dissemination.

From the operational perspective, flood forecasting is precisely about providing legitimate, credible, and reliable information to the right people at the right place, and time in a manner comprehensible and actionable (Perera et al. 2019). Observations and research findings have evidenced that natural hydroclimatic variability and imperfect understanding of the physical processes cause the issue of uncertainty in flood forecasting. This uncertainty increases as forecasts are translated into potential impacts in terms of inundation extent and early warnings. However, recent technological developments in hydrologic modeling, exponential growth in computing power, satellite earth observation, and communication advances continue to improve forecast accuracy and warning lead time. As science narrows the knowledge gap between mesoscale and convective processes, there is a real hope of developing and operationalizing a class of scale-independent forecasting and warning schemes.

9.2.3 State of Flood EWSs

Any holistic EWS should necessarily include the formulation of warning, the issuance of warning, the reception of and response to warning, and finally the feedback to those who developed and issued the warning in the first place. Formal or informal early warning systems have existed for centuries. Traditional approaches to flood early warnings have been based on the comparison of measured water stages with predetermined “threshold levels”. Current EWSs utilize water-level sensors placed at strategic locations along flood-prone drainage segments to monitor river stage and relate to predefined thresholds in order to trigger appropriate levels of warnings. Generally, different agencies are involved in the production, issuance, and response to warnings, with no single organization responsible for an end-to-end flood early warning service. More recent warnings employ scientific advances in the knowledge and understanding of hazards and the natural and human-induced processes that result in hazardous situations. Warnings are now essentially based on forecasts, projections, scenarios, and trends as a result of tracking a selected, explicitly identified set of hazard and threat indicators. These indicators must not only be reliable but also possess the ability to discriminate between levels and degrees of urgency, severity, and the certainty of the threats unleashed under every possible onset of flood events. The recent introduction of the predictive uncertainty concept enables probabilistic decision thresholds using multi-model and multi-run ensembles.

EWSs are meant to be integrated within the wider disaster risk-reduction strategy, rather than be a stand-alone solution. A flood EWS can protect livelihoods and properties and save lives only if people act on the warnings. The core purpose of any people-centric EWS is to empower individuals to act in sufficient time and in an appropriate manner to minimize as much as possible the loss and damage to people, property, and the environment. UNDRR (2006) recognizes four interrelated elements (Fig. 9.4) in a comprehensive and effective EWS; they are risk knowledge; monitoring and warning service; communication and dissemination; and response capability. But they must be grounded in good governance and supportive institutional arrangement that underscore multi-hazard readiness, community participation, and social inclusion.

EWSs do not always fit the circumstances under which they are considered as solutions to flood-risk management, nor are such systems without pitfalls in the setup and operation. Early warning dissemination and distribution rely on good telecommunication networks that may not be accessible in every flood-prone area of interest. Besides, purpose-built alternatives could turn out to be technically and economically infeasible, especially if the flood-affected sites happen to be in remote and inaccessible locations. As with everything pertaining to the future, early

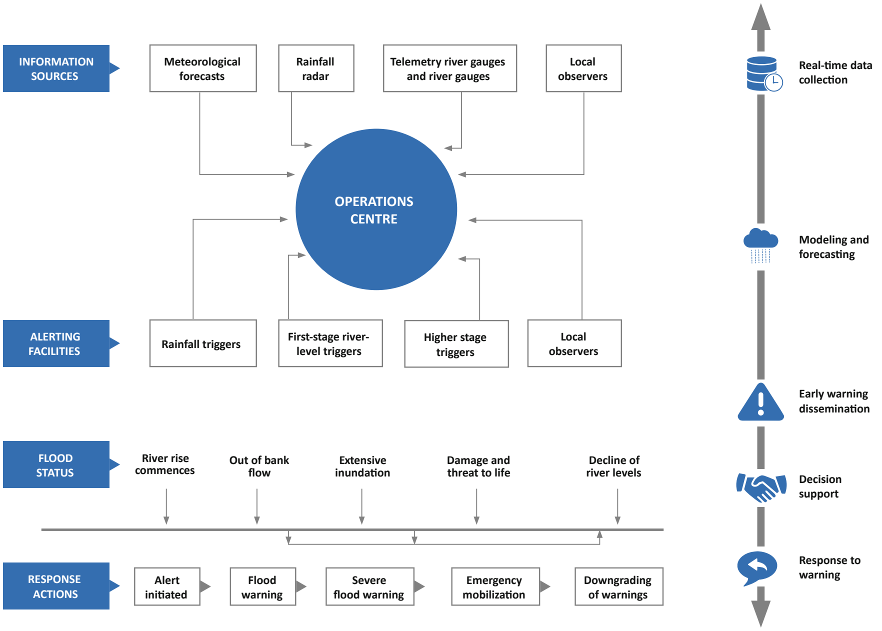


Fig. 9.4 Framework of a common approach in flood early warning (adapted from WMO 2011)

warnings inevitably involve handling uncertainties in ways that enable a risk-informed decision-making process. Similarly, floods cannot be predicted with absolute certainty because of imperfect understanding about the physical process and because of aspects of randomness that are inherent in the evolution of the process. Such limitations can sometimes result in false alarms which besides incurring unnecessary costs and inconveniences, can actually diminish trust in the system, thereby rendering it ineffective. Although a typical flood early warning system is devised around water-level sensors placed at sufficient distance from the impact zone, the warning lead time is usually extended, based on model predictions. Good quality real-time observational data are used for model calibration and the runs, but these may not be readily available or accessible. These problems continue to frustrate efforts in making EWSs more robust and credible despite significant advances in science, technology, and related approaches.

9.3 Societal Values of EWSs

9.3.1 Situational Awareness and Preparedness

The achievement of desired societal benefits is predicated on the effective communication of early warnings to those exposed to flood risk. A lingering challenge has been the integration of systems operating at different spatio-temporal scales to provide a more coordinated, comprehensive, usable, and effective early warning information. Early warnings of a flood event, combined with early warnings of underlying societal problems and processes, can lead to a strengthening of resilience and a reduction in vulnerability (Glantz 2009). EWSs are the stabilizing accessories of a nation's social, political, and economic systems; it may be tenuous at times and full of surprises, but never dispensable. It empowers governments to protect citizenries and maintain political stability. The benefits of EWSs lie in our appreciation of the knowable surprises. A case in point is the fact that while information on the flood-prone areas is known beforehand, the timing of the flood, its magnitude, and the extent of its impact may be difficult to determine accurately. Based on the historical experience of flooding vulnerability, every government must be guided by the precautionary principle to sensibly invest in operational flood EWSs in order to protect lives and properties, and reduce losses.

As noted above and to again emphasize the criticality, an effective EWS typically consists of a credible forecasting structure, a reliable communication service, and a proactive response mechanism. However, an EWS is not a static contraption but must evolve and improve with changing times and technology as we continually witness new normals due to climate, economic, and demographic changes. Almost all countries operate one form of forecast and early warning or the other, using different hydrological models, hydro-informatics, and computing infrastructure of varying strengths and capabilities. Very few actually operate basin-wide systems, limiting such services to within respective territorial boundaries and weak mechanism for information sharing. All countries follow the WMO convention of a single national voice for warning dissemination with authority delegated to single agency, but the cooperation between countries is weak and ineffective.

National and local governments and disaster-emergency managers have long identified the need for a fully functional early warning system to disseminate information well in advance of a flood situation. While it is not possible to stop natural floods from occurring, the impacts can be mitigated and the associated risks to lives and properties can be reduced through effective early warning systems. However, early flood warnings are situational and contextual in that their formulation and issuance are scale-specific and often isolated from the consequent outcomes in terms of reception and response from the intended users. Without exception, forecast-based EWSs are produced to increase the warning lead-time and the level of certainty of an event of a certain magnitude occurring at a certain time and place. Early flood information can also be verified through comparison with other forecasts that are freely available at national and regional levels. The co-benefits are numerous, ranging from stronger cooperation and better partnership networks and information exchange.

9.3.2 Loss and Damage Reduction

The costs of flood disasters from damage and loss are difficult to estimate and it is even more difficult to assess the socioeconomic and monetary benefits of EWSs in terms of the costs avoided or reduced. As a general practice, a typical cost-benefit analysis would involve knowing the index of loss and the cost of damage, as well as the cost of developing and operating an EWS, besides the cost associated with the use of an EWS service (Perera et al. 2019). An effective EWS can deliver significant benefits at all stages in the flood-risk management cycle and reduce human fatalities and injuries, loss of livelihoods, and damage to properties and infrastructure. Continuous operation of EWSs can actually lead to a better understanding of the flood situation and greater awareness about the risks that are involved. The importance of building resilience and the need to implement preparedness measures will receive greater attention as communities and authorities gain deeper insight into the urgency, severity, and the certainty of the flooding information provided by EWSs. There is also the potential to realize substantial benefits in terms of reduced costs in relief, recovery, and reconstruction if warnings are issued with sufficient lead time for preparedness action.

9.3.3 Extending the Lead Time

Warnings must be conveyed in a timely manner, particularly in vulnerable and remote locations, using clear information expressed in non-technical language; they should also identify and specifically mention the areas at risk, as well as explain the potential losses, all within certain time frames (UNDRR 2006). In most of the countries in the HKH region, warnings are formulated and issued without standard protocols in terms of the technical format, dissemination mechanism, and communication channels; so, difficulties emerge in the understanding of the message and in setting up appropriate response mechanisms. It is also crucial to emphasize that early warnings need to be followed through with early actions, but this is easier said than done because response plans are not framed to account for every warning situation. However, the situation is a lot better now, with better access to ground and satellite data, as well as due to global and continental-scale forecasting systems that predict floods over a longer lead time with a credible probabilistic scale to supplement national services. Longer lead times obviously lead to better preparedness and response measures (Smith et al. 2017). One such example is the Copernicus Emergency Management Service (CEMS), GloFAS (http://www.globalfloods.eu/), that couples state-of-the-art weather forecasts with a hydrological model to provide global flood overviews. Resolving GloFAS to local scales at finer resolution entails downscaling the global outputs through the integration of spatially granular information about the basins of interest and weather parameters. Through the SERVIR-HKH initiative, the countries in the HKH region are now equipped with customized systems to access global information through local applications. Moreover, the platforms that host and process cloud-computing and EO data are now available for running local-area models and performing complex analysis under various programs (Soille et al. 2016).

The next few sections are devoted to the efforts at ICIMOD to develop products and services aimed at bridging the knowledge and technology gaps in generating streamflow forecasts which can enhance the regional and national capacity to provide reliable and effective flood early warnings and thereby reduce risks and minimize loss and damage. The approaches leverage recent advances in scientific knowledge and cutting-edge computing technologies in flood prediction to push the limits of predictability in terms of timing, magnitude, and forecast horizons.

9.4 Flood Early Warning System (FEWS) Services and Tools in SERVIR-HKH

The SERVIR-HKH EWS service includes an operational 10-days streamflow forecast application based on the GloFAS direct runoff field routed with RAPID (Routing Application for Parallel Computation of Discharge) model (David 2019). The gridded flow predictions are downscaled to vector river network. The forecast is meant for larger rivers at designated locations agreed by the partner agencies in Bangladesh and Nepal. For Bangladesh, the forecast is implemented for 17 boundary rivers and in the case of Nepal, for all its large rivers. A customized web-based information portal has been developed to communicate warnings to the intended users. The service also includes 48–54 h of short-fused flood predictions from a quantitative precipitation forecast field generated through HIWAT (High Impact Weather Assessment Tool), an extreme weather prediction system targeted at small "flashy" rivers mainly in Nepal and north-eastern Bangladesh.

9.4.1 Flood Prediction Tools

The streamflow prediction tools (SPTs) based on HIWAT and ECMWF (European Center for Medium-Range Weather Forecasts) present an unprecedented opportunity for an integrated end-to-end flood forecasting system that can extend the currently possible lead times (Snow et al. 2016). Both the tools are based on ensemble runs using perturbed physics and the sampling probability distribution of initial and boundary conditions in order to constrain uncertainties and provide a probabilistic forecast for improved decision-making. The tools were developed through scientific collaboration between ICIMOD, the NASA Applied Science Team (AST) from Brigham Young University, the NASA Marshall Space Flight Center (MSFC), and the Jet Propulsion Laboratory (JPL).

HIWAT is a severe convection-allowing weather forecasting system that predicts extreme weather phenomena spawned by localized convective instabilities like thunderstorm, lightning, windstorm, hailstorm, and cloudbursts. The HIWAT system (Chap. 12) was implemented on a cluster at the SERVIR Global computing infrastructure and runs during the pre-monsoon and monsoon seasons from April to September every year. A visualization application runs on an open-source Tethys platform (Swain et al. 2016a, b) in ICIMOD to disseminate the forecast. HIWAT is also a severe-weather ensemble model based on the Weather Research and Forecasting (WRF) community model with a 12 km outer and 4 km nested domain positioned over South Asia. It provides daily 48 h forecasts with 1800 UTC (Universal Time Coordinate) initialization. The 12-member ensemble is created from varying planetary boundary layers and microphysics schemes that are convection-permitting. Different GEFS (Global Ensemble Forecast System) members are used to initialize each ensemble member. The model outputs are available on an hourly frequency and post-processed to generate information on severe weather products, one of which is the accumulated precipitation thresholds, the probability matched mean of which is used to force the RAPID model for flash-flood forecasting.

In the case of ECMWF-SPT, river discharge is simulated by RAPID in routing the ensemble surface run-off fields processed by HTESSEL (Hydrology Tiled ECMWF Scheme for Surface Exchange over Land) of ECMWF's (Balsamo et al. 2009) coupled land-atmosphere IFS (Integrated Forecast System). RAPID is a matrix version of the Muskingum method (David et al. 2016) that produces 51 possible evolutions of streamflow in a 15-day forecast horizon. Further, a deterministic RAPID routing is run offline using run-off fields forced by ERA-Interim near-surface variables in order to derive the seamless streamflow climatology. Then the discharge values of the daily annual maxima are extracted and submitted for extreme value analysis so as to estimate the corresponding discharge exceedance thresholds for selected return periods. These models have been extensively evaluated at several observational points across Nepal and Bangladesh. The ensemble streamflow predictions were also evaluated against the discharge-proxy simulations for the same period, which was taken from the simulated discharge climatology obtained by using ERA-Interim/Land run-off as a forcing element.

The lack of transboundary information often makes it difficult to increase the lead time on flood forecasting in downstream countries like Bangladesh. The dissemination of the warning information for timely access and use by communities is also important to get maximum return from these services. In Bangladesh, the hydrological models for an effective flood early warning system suffer from a lack of upstream data. The quality of these models can be enhanced through land-surface and hydromet data from upstream and boundary stations. In the meantime, in Nepal, given the understanding about the limitations with its in-house forecasting model, there is an interest to consume forecasts from these tools as part of the decision-support system. From a series of consultative processes, it has become apparent that there is a particular interest in the HIWAT-based RAPID model in the prediction of short-fused floodings in flashy catchments. More particularly, since the present models are not sensitive enough to predict the rapid onset of floods, extreme weather events like flash floods, triggered by intense precipitation events, are a serious threat to the local communities.

9.4.2 Hydro-Informatic Workflow

The modeled predictions are consumed using intuitive web-based interfaces so as to extract and visualize flood-forecast data for specific areas of interest via customized web applications. Further localization is enabled through the implementation of REST API (Representational State Transfer-Application Program Interface) services (Souffront Alcantara et al. 2019). The hydro-informatic workflow links the web applications with the back-end cyber infrastructure for model computation to access and display the forecast information sought by the users. A geospatial preprocessing approach (Snow et al. 2016) is used to generate information on the river network, weight tables, and RAPID parameters in order to convert the grid-based HTESSEL run-off fields and route through the vector-based river network. The HIWAT hydro-viewer and SPT are the interactive web applications that have been developed using the Tethys development and hosting platform (Swain et al. 2016a, b). The workflow resides in the cloud to compute model forecasts and host geospatial web services. The overall geospatial preprocessing and routing process of how the forecast information is delivered to the end users is illustrated in Fig. 9.5.

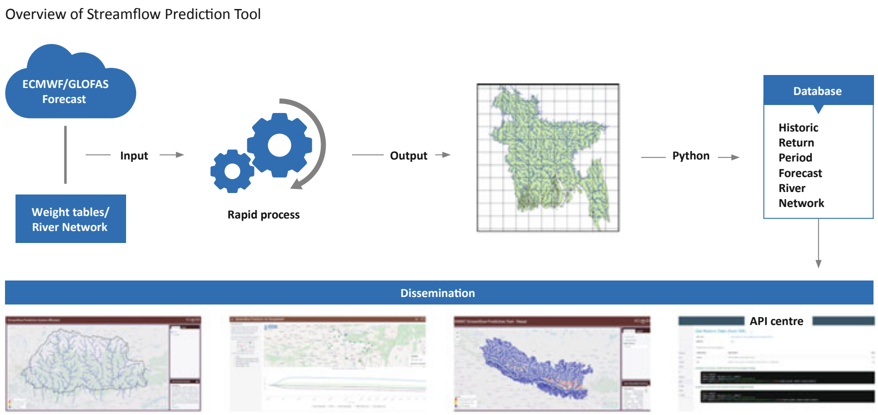


Fig. 9.5 Schema of the parallel computing framework and web-based dissemination of forecasts and warnings incorporated into the SPT web application

The web-based prediction services include an operational 15-day flood forecast based on ECMWF, and HIWAT based flash flood tool that forecast out to 48–54 h. Both tools use RAPID model to route direct runoff through drainage networks encompassing designated locations agreed by the partner agencies in Bangladesh and Nepal.

The implementation of a forecast-based EWS requires both human and computing resources to support not only the development of the system but to operate it and maintain it through time. What sets apart the SERVIR flood forecasting services from the mainstream systems is the simplification of complex processes without sacrificing the power of emerging science and technological innovations. Users can now concentrate on making informed decisions in managing flood risks without being distracted by the tedious and costly routines in collecting and processing data, setting up and running models, forecast production, and dissemination. The disconnect and seeming incoherence between the components of the service-value chain no longer constrains reliable and timely service provision.

9.4.3 Implementation of Innovative, Customizable Tools

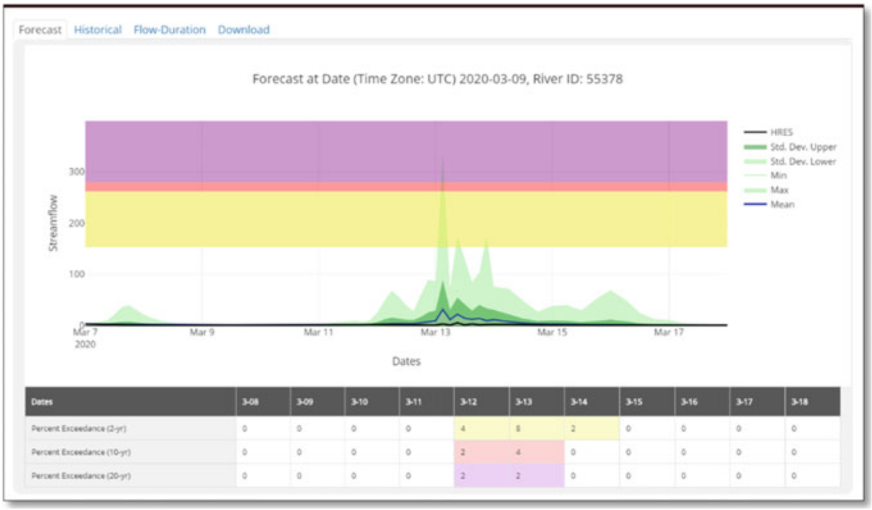
Customized web-based applications for Nepal and Bangladesh were developed and deployed in collaboration with ASTs to retrieve model outputs and visualize the information products required by the users. The HIWAT-based flash flood tool is also customized and hosted as an online application using the same Tethys platform. These tools have undergone several iterations in response to user comments and feedback on the interfaces. The SPT workflow for hydrological modeling using RAPID is also in the process of being transferred to the ICIMOD server, and once this migration is completed, the latent time from model run to ingestion and product rendering by the web application is expected to reduce significantly.

The web-based SPT system was co-developed with the help of ICIMOD's regional partners. The system is now being enhanced with inputs from the partners. It has also been customized in order to accommodate the requirements of the partners and also for them to have an easy access to the system. The system is in-built with analytical tools by which the user can interact with the system through the website. Upon clicking the desired river section, the user can view the forecast charts for that section, along with information on the rate of discharge at any particular time of the day. The SPT web application facilitates user access to forecast information in an intuitive and comprehensible format (Fig. 9.6). The major components of the chart are:

- High-resolution forecast (10 days)
- Standard deviation and mean, maximum, and minimum flow forecasts (generated through 51 ensemble forecasts, inclusive of the ensemble control run)
- Information on two-, ten-, and twenty-year return periods.

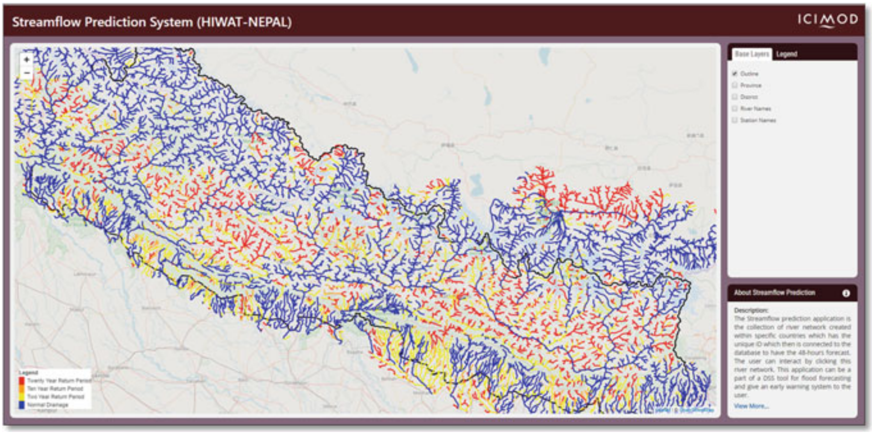
The table below the chart provides the possibilities of the return period discharge in percentage, using 51 ensemble data sets from the model. The user can also view the model historical data set starting from 1980 and also the flow-duration curve; besides, there is an option to download the data set.

The enhancement in the system is to indicate the high-risk river section with proper color codes related to the return periods. The risk-to-river section is updated daily to provide near-real-time information and show the condition of the river at



Dates	3-08	3-09	3-10	3-11	3-12	3-13	3-14	3-15	3-16	3-17	3-18
Percent Exceedance (2-yr)	0	0	0	0	4	8	2	0	0	0	0
Percent Exceedance (10-yr)	0	0	0	0	2	4	0	0	0	0	0
Percent Exceedance (20-yr)	0	0	0	0	2	2	0	0	0	0	0

Fig. 9.6 Visualization of SPT forecasts and associated statistics, along with data on exceedance thresholds showing the probability of occurrence along a 10-day forecast range



Description:
The Streamflow prediction application is the collection of river network created within specific countries which has the unique ID which then is connected to the database to have the 48-hours forecast. The user can interact by clicking this river network. This application can be a part of a DSS tool for flood forecasting and give an early warning system to the user.

Fig. 9.7 HIWAT-based flood early warning system

first glance. During the co-development process with our partner, Nepal's Department of Hydrology and Meteorology (DHM), we also incorporated the river names, administrative boundaries, and the locations of the hydro-met stations into the system. The landing page for SPT-Nepal is given in Fig. 9.7.

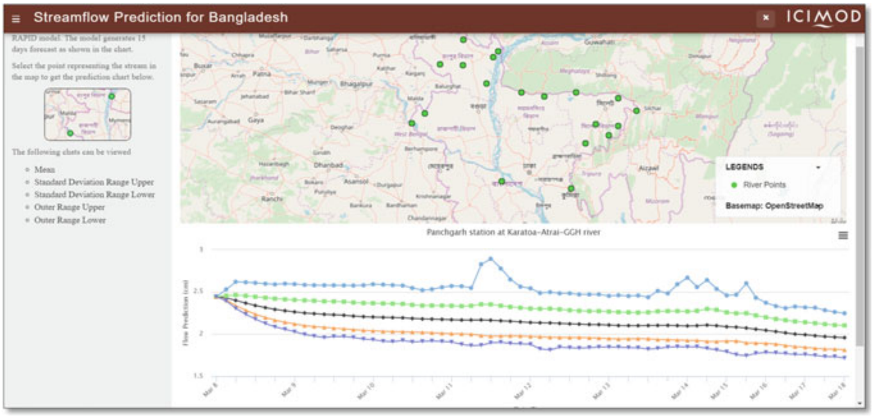
Another successful integration has been the Bangladesh transboundary prediction system. This unique system is based on the 17 transboundary stations (points) provided by the Flood Forecasting and Warning Centre (FFWC) under the Bangladesh Water Development Board (BWDB). The system provides a 10-day forecast to their internal model which increases the warning/alert lead time within the country and hence saves lives and livelihoods.

Model consistency is achieved through the use of the same hydrological model and meteorological product to derive both streamflow forecasts and the reanalysis data set used to derive the thresholds. While it is difficult to accurately represent the true-flow conditions along a river network, early warning systems developed with exceedance thresholds derived from discharge simulation based on the reanalysis data lend greater meaning and provide a consistent, historical context to the model predictions.

9.5 Current State of Service Implementation and Validation

9.5.1 Dissemination and Delivery

In Bangladesh, the FFWC monitors water levels and provides deterministic forecasts of five days at 54 stations on 21 rivers. SERVIR's collaboration with the



RAPID model. The model generates 15 days forecast as shown in the chart.

Select the point representing the stream in the map to get the prediction chart below.

The following charts can be viewed

- Mean
- Standard Deviation Range Upper
- Standard Deviation Range Lower
- Outer Range Upper
- Outer Range Lower

Fig. 9.8 Customized user interface for Bangladesh SPT web application at selected inflow stations of transboundary rivers

FFWC focused on four areas: warning on transboundary flow; flash-flood warning; flood-warning dissemination; and training and capacity development.

The FFWC forecast that is now operational was first generated using a MIKE11 Super Model, introduced in 1995–96 with a two-day lead time, and was later improved in 2012–14 to provide a five-day lead time. The model utilizes local precipitation levels and boundary flows at 17 locations across the northern boundary of Bangladesh to generate the forecast (Fig. 9.8). The data on catchment precipitation are received from the Bangladesh Meteorological Department (BMD). The boundary flows are provided through assumptions based on various regional models, including the GloFAS one.

To cite a particular instance, flash floods occurring in north-east Bangladesh, specifically in the wetlands of Haor, between April and May, pose a serious danger to crops and livelihoods. These floods are mainly caused by high-intensity rainfall in the neighboring catchment areas of India. Here, it has to be mentioned that effective forecasting of rainfall in the upper catchments is essential in capturing any potential flash-flood events which may miss the radar of the ECMWF's streamflow-prediction system. A HIWAT-based flash-flood warning system is also being developed for Bangladesh (Fig. 9.9), and it is now under the validation process. Besides, in 2018, a mobile app, integrated with the FFWC server and available for Android devices from Google Play store, was launched in Bangladesh for dissemination of flood warnings to the field-level staff and local communities. The app got a positive feedback in the monsoon periods of 2018 and 2019.

In Nepal, SERVIR-HKH is working closely with government agencies, particularly the DHM, in identifying test locations and evaluating the performance and usefulness of the service tools in adding value to the existing forecasting and early warning mechanisms. It is also partnering with service delivery and deployment organizations like Practical Action and Mercy Corps Nepal which are working

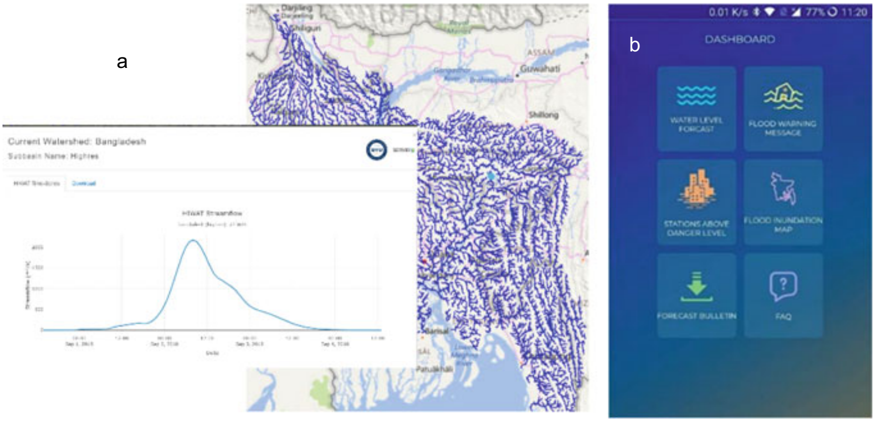


Fig. 9.9 **a** HIWAT-based flash-flood warning system for Bangladesh; and **b** mobile-app interface for early warning dissemination to the public

directly with the vulnerable communities and local administrations like the DEOC (District Emergency Operation Center) and the LEOCs (Local Emergency Operation Centers) in building capacities in flood preparedness and response. In Nepal, community-based partners are committed to augmenting new and existing community-based flood early warning schemes that have been widely adopted in flood-prone areas. The SERVIR-HKH project expects to use the information on the estimation of flood inundation to develop hazard maps in 10 watersheds spanning the Mahakali, Rapti, and Karnali basins. A network of flood warning systems has also been piloted by Mercy Corps Nepal in five watersheds of the Bagmati, Kandra, Kamala, Kankai, and Macheli using the HIWAT flash-flood prediction application. Such level of interest and engagement with a multitude of service intermediaries have led to a growth in the user base of SERVIR-HKH products and services. By increasing the lead time on warnings and by articulating forecasts in probabilistic terms, there has been a redefinition of approach in dealing with flood forecasts, and this has led to more effective preparedness and response procedures.

9.5.2 Capacity Development

Under SERVIR's capacity building program, equal attention has been paid to the professional development of the ICIMOD staff working in the SERVIR-HKH projects and to the partners in training them on the overall scientific basis, browser-based user interface, and access and interpretation of products and applications under different contexts of flood management. Following the training schedule, the group of IT personnel and programmers have acquired sufficient skills and competence to further improve on the modeling structure, implement enhanced visualization and system automation, and resolve issues that regularly come to their attention. The customized web applications on the Tethys platform continue to grow as new demands from the partners and users are being serviced. Now the streamflow-prediction model is slated to be run entirely from the in-house computing infrastructure. Besides, the control of the HIWAT run on the SCO-SOCRATES (SERVIR Coordination Office-SERVIR Operational Cluster Resource for Applications—Terabytes for Earth Science) cluster is being trialed for a phased handover. In all this, HIWAT's capabilities to enrich decision-making have been confirmed by several kinds of end-users (like the BMD and DHM).

The relevant staff of the FFWC in Bangladesh and other agencies with a stake in flood management have been trained on forecast validation to evaluate model performance and verify forecasts in order to understand the uncertainties and limitations in the forecasting models and to know about the ways in which they can be improved as reliable information for warnings. Later, a group of hydrological forecasters from Bangladesh, Bhutan, and Nepal, together with FEWS advocates and practitioners from community-based organizations, were put through a similar training program of in-depth exploration of the prediction tools and deployment in the operational mode. The participants were trained on using tools that create situational awareness and to apply products in a variety of decision-making contexts of water resources and flood management. Moreover, aspects of geoinformation technology in bringing processing and analytical focus on a specific area of interest were embedded perceptively into the practical sessions and hands-on exercises.

Skill and knowledge transfer through dedicated training runs have also been further strengthened through broadened participation in consultative workshops and knowledge fora. Hydrostats, a Tethys application, was extensively used for computing error metrics in the course of validating model forecasts and for assessing model skills in predicting an observed event. It is reasonable to state that the implementing partners and the key stakeholders have been provided with the knowledge and tools to interact, access the service products via the web interface or programmatically, and interpret and apply information to better manage water resources and reduce flood-disaster risks.

9.5.3 Validation

The forecast modeling tools have been calibrated and validated against several observed data sets collected from different locations around the world (Jackson 2018; Jackson et al. 2019; Snow et al. 2016; Swain et al. 2016a, b; Souffront-Alcantara et al. 2019; Nelson et al. 2019). Results from earlier validation efforts were optimistic that the modeled predictions were consistent with outputs from other systems using the same set of meteorological forcings and land-surface model (LSM) fields. Earlier validation works had also found out that the grid to vector adaptation did not alter the results, and showed good correspondence with the observed data from several locations around the world (Sikder et al. 2019). However, the studies were largely limited to either evaluating the ensemble mean forecasts against the simulated discharge climatology or comparing the latter with observations from selected stations.

A final round of forecast validation is being conducted focusing on predictions generated in real-time, which is archived on a daily basis to evaluate and investigate into the performance skills of the SERVIR-HKH flood-forecasting tools, i.e. HIWAT-driven flash-flood and ECMWF-IFS-based SPT tools. The approach extended the validation process to also assess the performance of ensemble forecasts in probabilistic terms using graphical measures like reliability, Talagrand, likelihood diagrams, and the Area Under the Receiver Operating Characteristics (AUROC). Brier score and skill score were used as numerical summary metrics to evaluate probabilistic forecasts in detecting flood days ahead of the actual occurrence. Besides, the forecast information primarily finds application in the development of flood early warning systems, which require an effective verification and validation method to understand the uncertainties and limitations that could be used in ways to improve the forecast and warning services. Accordingly, the forecasts were verified at each lead time with reference to observational records made available to the validation team by the partner agencies. Finally, the matching of the observed data sets were combined with modeled data sets for same time periods using a scheme of confusion tables to evaluate the tools' ability to correctly predict the dichotomous flooding events using binary scores, including, but not limited to, Probability of Detection (POD), Probability of False Detection (POFD), and Gilbert, Peirce, and Heidke skill scores. Forecasts were also evaluated against observations using a set for deterministic performance metrics using the mean of 51 ensemble members to assess temporal, bias, and spread vs skill errors. The forecast skills were demonstrated by benchmarking the forecast performance against climatology and persistence discharge upon which forecast runs were initialized on a daily basis. The validation period differed across the three countries depending on the observed time series of the discharge.

Altogether, SPT forecasts were validated against observations from 20 hydrological stations in Nepal, eight stations in Bangladesh, and 10 stations in Bhutan. Table 9.1 presents the summary scores and related statistics for a selected site from each country in order to illustrate the validation results, which are expressed as functions of prediction error and goodness of fit between modeled and observed data for the countries and stations provided with usable observational data from 1 January 2014 to the end of the observation dates. The validation exercise was performed specifically to check on the verified claims of quality, value, and reliability of the coupled ECMWF-RAPID flood-prediction model. The HIWAT-RAPID flash-flood prediction system has been evaluated and validated only at a few sites in Nepal and Bangladesh due to want of quality observations from the sites prone to flash flooding. HIWAT-based predictions present a unique challenge for validation, as the model outputs do not follow the normal hydrologic response of watersheds since the precipitation forecasts are directly translated into streamflow without adequately accounting for surface and groundwater processes.

Therefore, summary statistics and error metrics convey very limited meaningful information on the forecast performance. Graphical visuals are mainly used to validate the correspondence in timing and magnitude of flood peaks between forecasts and the observations; while qualitative verification is supplemented with categorical statistics computed from the elements of the contingency table.

The SPT-sourced predictions are an ensemble of 51 members to capture the level of uncertainty in the modeled forecasts based on the initial conditions of perturbation. The goal of validation is to assess the quality and value of SPT forecast products to accurately and reliably predict flooding events so that robust flood early warning systems are established. In order to demonstrate the full benefit of SPT, it is crucial that the service is assessed not only in the measurement space but also in the probability space to quantify uncertainties for better decision-making. Figure 9.10 shows the performance measure in probabilistic terms using reliability, talagrand, likelihood, sharpness, and ROC plots, assuming equal likelihood of each member in post-processing the ensemble timeseries to dichotomous flood events. For the purpose of this validation exercise, the 90th percentile of the observed discharge time series was selected as the threshold to distinguish between flood and non-flood situations over the period of evaluation. The exceedance probability was derived from the fraction of ensemble forecasts equaling or exceeding the threshold discharge. Brier score and Brier skill score (BSS) were computed for probabilistic forecasts as a composite score for reliability, resolution, and uncertainty. The probability forecast skill (BSS) of forecast performance is evaluated against initial state and climatology. Several other common metrics were also calculated in verifying the ensemble mean.

The average correspondence between individual forecasts and the events they predict as shown with ensemble error metrics suggests the acceptability quotient of the forecasts. Although there was generally a good linear relationship between what was observed and what was forecast (Pearson coefficient, R), the predictive ability of the model chains was consistently poor in the case of all the stations that were evaluated (in terms of NSE and KGE). While the GloFAS-RAPID system has a tendency to over-predict in mountainous areas (Bhutan), it generally under-predicts flood situations in the low-lying plain areas (Bangladesh), and the error terms and the level of bias are less than acceptable. However, overall, both the SPT and ECMWF-RAPID forecasting systems were able to capture the peaks and lows in the observed hydrographs as shown by the relatively high values of the Spectral Angle (SA) (Roberts et al. 2018) metric that compares the shape of the hydrograph time series over time. These results apparently point to the fact that the performance of the models, the ECMWF-RAPID combination in particular, could be improved further with the recalibration of the parameters of RAPID to more closely represent the local situation. Nonetheless, there was skill in the forecasting system compared to the reference persistence forecast based on using the last simulated or observed discharge, despite the fact that there was great uncertainty associated with the observed data sets shared by the collaborating national agencies. Although the coupled ECMWF-RAPID modeling system is able to predict streamflow with a

Table 9.1 Summary scores of SPT forecast performance and its evolution over a 15-day forecast horizon

Lead time															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Gandaki, *Nepal*															
BS	0.08	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.12	0.06	0.06	0.06	0.06
BSSp	0.41	0.62	0.60	0.62	0.62	0.62	0.63	0.64	0.61	0.60	0.06	0.58	0.55	0.52	0.52
KGE	0.62	0.75	0.72	0.70	0.68	0.67	0.67	0.67	0.66	0.64	0.12	0.47	0.51	0.52	0.53
NSE	0.45	0.62	0.61	0.61	0.60	0.59	0.60	0.59	0.58	0.57	−0.11	0.55	0.56	0.54	0.54
Pbias	0.33	0.07	0.02	0.03	0.03	0.03	0.05	0.04	0.02	−0.01	0.68	0.16	0.03	−0.01	−0.05
R	0.82	0.80	0.79	0.78	0.77	0.77	0.77	0.77	0.76	0.76	0.60	0.76	0.77	0.75	0.76
RMSE	82.31	68.50	69.11	69.50	70.82	70.95	70.71	70.91	72.42	72.85	117.20	74.51	73.84	75.79	75.92
Sarighat, *Bangladesh*															
BS	0.05	0.05	0.06	0.06	0.06	0.06	0.07	0.06	0.07	0.07	0.08	0.08	0.08	0.08	0.08
BSSp	0.37	0.33	0.30	0.28	0.23	0.21	0.19	0.20	0.16	0.11	0.07	0.02	0.02	0.00	−0.01
KGE	0.31	0.23	0.24	0.27	0.28	0.29	0.30	0.31	0.32	0.33	0.38	0.31	0.31	0.31	0.31
NSE	0.40	0.31	0.29	0.32	0.30	0.31	0.33	0.36	0.36	0.35	0.32	0.26	0.26	0.24	0.23
Pbias	−0.31	−0.33	−0.33	−0.33	−0.34	−0.35	−0.36	−0.37	−0.38	−0.38	−0.36	−0.39	−0.40	−0.41	−0.41
R	0.77	0.75	0.74	0.74	0.72	0.70	0.70	0.70	0.70	0.68	0.66	0.63	0.62	0.60	0.59
RMSE	147.77	159.52	161.02	157.69	159.86	159.32	156.56	153.47	153.01	154.55	157.38	164.92	165.16	167.22	168.28
Wangdi, *Bhutan*															
BS	0.06	0.05	0.06	0.07	0.07	0.07	0.07	0.07	0.07	0.08	0.08	0.08	0.08	0.08	0.08
BSSp	0.30	0.42	0.30	0.27	0.23	0.23	0.21	0.21	0.19	0.17	0.16	0.18	0.19	0.18	0.17
KGE	0.78	0.88	0.85	0.83	0.81	0.80	0.79	0.79	0.77	0.76	0.76	0.75	0.75	0.75	0.74
NSE	0.71	0.82	0.80	0.78	0.75	0.74	0.73	0.72	0.71	0.69	0.69	0.69	0.69	0.68	0.68
Pbias	0.16	−0.04	−0.09	−0.11	−0.12	−0.13	−0.13	−0.14	−0.15	−0.16	−0.16	−0.16	−0.17	−0.17	−0.17
R	0.88	0.91	0.90	0.89	0.88	0.87	0.87	0.86	0.86	0.86	0.86	0.86	0.86	0.85	0.85
RMSE	154.62	120.97	128.35	135.04	142.00	146.17	147.70	151.00	153.93	157.35	158.11	158.03	158.04	159.88	162.16

BS brier score; *BSSp* brier skill score wrt persistence; *KGE* Kling-Gupta efficiency (modified); *NSE* Nash-Sutcliffe efficiency; *Pbias* percent bias; *r* Pearson correlation coefficient; *RMSE* root mean square error

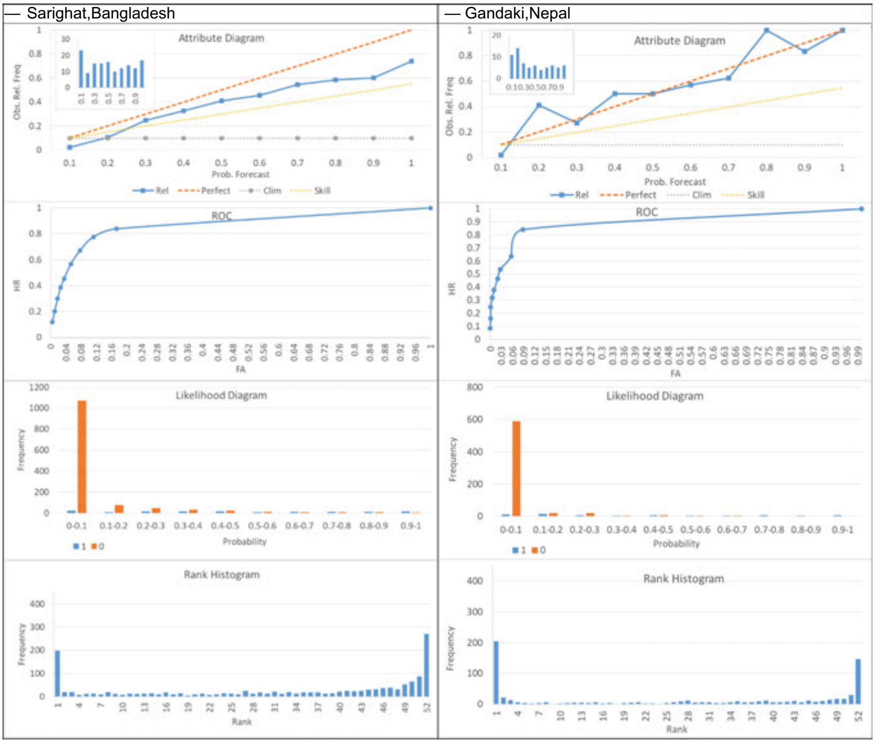


Fig. 9.10 Performance measure in probabilistic terms using reliability, Talagrand, likelihood, sharpness, and ROC plots for selected validation sites (one each from three countries as exemplar (Day-5 lead time)

15-day lead time, the forecasts are skillful only to a maximum of 10 days in the majority of the cases, after which the performance deteriorates rapidly.

Successful validation is expected to raise confidence in the forecast systems, and pave the way for the integration of the SERVIR-HKH system with the existing systems that have been operational for many years in Bangladesh and Nepal. The final integrated forecast will increase the lead time from the present two–three days to 10–15 days for river flow, and at least 40 h ahead of an extreme convection-driven flash flooding. The results from successful validation should promote the adoption of such tools as operational resource for the national hydromet services in order to improve accuracy and disseminate actionable warnings and alerts.

Small- to medium-sized basins in countries across the HKH region need such open and accessible service tools to downscale authoritative global forecast products to the level of localized ones that can create real impacts on the ground. Scaling the services up and out within the SERVIR-HKH focal countries and in the region can provide a common operating picture for countries to work and learn together in an atmosphere of shared responsibility when it comes to flood management. The prediction tools are in an advanced stage of joint evaluation under different basin scales—small, medium, and large—using river-flow observations obtained from the national partner agencies. Eventually, the service tools are pipelined for integration into respective national forecasting and warning systems so as to support decision-making and best practices in flood-risk management.

The validation process was designed around a tripartite engagement among NASA's AST, ICIMOD, and partners in Nepal and Bangladesh, and was later extended to include Bhutan. The actual validation was supported through the capacity building of partners on validation methodologies, data collection, and assemblage for target locations identified in consultation with the partners. The successful completion of the validation process will clear the products for use in operational settings.

9.5.4 Transition to Operational Service

The success in the adoption and use of flood-prediction services involves the engagement of multiple stakeholders who each have specific roles and responsibilities. A sense of ownership about the system that generates the services and adoption of the system by the local authorities responsible for disaster-emergency response operations at the district level and by the community workers at the local level are vital for sustained improvement and application. This entails continuous engagement with different levels of stakeholders.

9.5.4.1 Bangladesh

The FFWC is the mandated agency in Bangladesh to generate flood forecasts and provide early warning. The FFWC receives information on water levels from the automated stations installed by the BWDB; information on cross-border flow from the Joint River Commission (JRC); and on rainfall forecast from the BMD. These data are then used as input to a hydrodynamic model developed on a MIKE-II platform to generate water-level forecasts five days in advance. This forecast is disseminated through the FFWC website for consumption by the stakeholders, including the BWDB field operatives. With the introduction of the SERVIR streamflow prediction tool for boundary rivers, the FFWC is now initializing the model with inputs from the SPT. A mobile app has also been developed with support from SERVIR that enables wider dissemination (Fig. 9.11). And, to support the institutionalization of the process, ICIMOD and the BWDB have signed an MoU under which the FFWC officials are trained to use the system. Currently, the input from the SPT are manually ingested into the flood-forecasting model. In future, integration is planned to automatically synchronize the SPT with the flood-forecasting model to automatically ingest the boundary river flow.

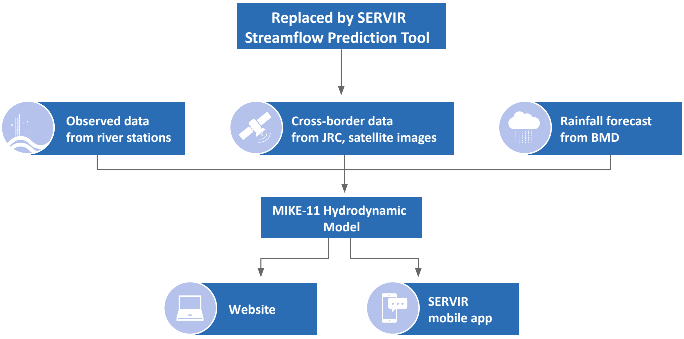


Fig. 9.11 Modified workflow in generating forecasts based on the boundary conditions derived from the SERVIR prediction models being implemented by the FFWC, Bangladesh

9.5.4.2 Nepal

In Nepal, the DHM is the primary partner in the SERVIR-HKH initiative in advancing real-time flood modeling as a service for enhancing EWS and to move the process towards formalizing the system at the national level. It is encouraging to note that from 2019 onwards, the DHM has started to include the forecasts from the SERVIR-HKH flood tools in the production and issuance of its regular flood outlook. The DHM is also currently extending all the necessary support into the joint validation of the real-time forecasts, and with renewed optimism to incorporate the products for complementary guidance, as well as to explore the prospect of future integration into its flood forecasting operations. Meanwhile, the other local partners under a similar collaborative arrangement, in particular Practical Action and Mercy Corps, working at the local level on flood-risk reduction, have reaffirmed their interest in testing the usefulness of the system at the local level. Besides, HIWAT-based flash flood prediction tools are being tested at the project sites of these local partners.

9.5.4.3 Bhutan

The National Center for Hydrology and Meteorology (NCHM) is an autonomous body of the Royal Government of Bhutan with the national mandate to establish, monitor, and inform the nation on the past, current, and future situations in weather, climate, and water-related matters of interest. However, despite Bhutan's modernization drive to improve its hydromet infrastructure, critical information on predicting the flooding conditions within relevant timescales continue to present a huge challenge in terms of the integration of decision-support tools and applications. The agency still lacks the necessary computing and trained professionals to develop and operate a modeling system to predict floods at both national and local scales. A 24-h hydrologic forecasting model-chain is being tested in one or two river basins using the meteorologic forcings from the WRF-based deterministic weather forecasts. Besides, the ECMWF-RAPID computational forecasting framework, coupled with the SPT web application on the Tethys platform, offers free access to vital flood information which can complement the local setup to provide situational awareness and outlook with quantified uncertainties. The HIWAT-RAPID modeling system is also set to be extended to predictions for smaller rivers which are naturally flashy because of severe convection-driven precipitation inputs.

Recognizing the benefits of these systems, the NCHM has decided to work closely with SERVIR-HKH in evaluating the system performance in major river basins in Bhutan. In the last one year, a group of hydromet engineers and forecasters from the NCHM participated in every capacity development event organized by ICIMOD. Recently, a combined product dissemination and model validation workshop was conducted in Bhutan to include the wider government stakeholders that are likely to benefit from the information products generated by the SERVIR-HKH tools. The event received good response from the government agencies responsible for river infrastructure, hydropower, and disaster-emergency management. Further, the NCHM has committed to strengthening collaboration in improving the systems by sharing resources, data, and experiences under a mutually agreed institutional mechanism. In the meantime, it has identified several gauging sites to validate the reliability and value of the systems in water-resource management and flood-risk reduction.

9.6 Learnings and Future Direction

9.6.1 Challenges and Opportunities

Flood frequency related thresholds that make use of recurrence intervals are found to misrepresent actual flood levels with serious implications for building trust in the system. The flow magnitudes of thresholding return periods do not always match with actual observation on the ground. The color-coded threshold envelops are misconstrued as warning levels, which, in fact, are still pending a reality check through systematic calibration with actual observations on the ground. In an ideal situation, these color bands should be associated with the magnitude of the likely impact from a flood event falling within a specific threshold band. Regardless, color-coded thresholding is unlikely to trigger response action without interpretive guidance or making sufficient efforts in raising awareness on what the colors signify.

ERA5 (Hersbach et al. 2018) is the latest climate reanalysis data set produced by ECMWF and distributed through the Copernicus Climate Change Service (C3S). ERA5 is superior to its predecessor, ERA-Interim, in that it incorporates more than 10 years of improvement in the numerical weather prediction system, higher spatial resolution, improved data assimilation, and near-real-time updates for the intermittent version, ERA5T. Using ERA5 data sets with the RAPID routing method in SPT could improve the discharge timeseries that is used in estimating flood thresholds based on frequency analysis for the return periods. In 2019, Alfeiri et al. indicated that setting discharge thresholds based on a ranged forecast horizon would be actually more informative while deploying SPT as an extension of flood early warning systems. Setting range-dependent thresholds, instead of time-invariant ones, has produced consistency along the entire forecast range, and is likely to improve the estimation of the magnitude of upcoming extreme events over longer forecast ranges.

The RAPID model, based on the traditional Muskingum formulation, routes only the surface run-off field from the ECMWF land-surface module along a vectorized river network, and does not account for the vertical water fluxes or the groundwater storage in the floodplains, or the interactions between surface and groundwater. The model can be improved further by replacing the simplistic Muskingum method with the numerical solution of the kinematic wave equation and incorporating routines for groundwater storage and transport. This enhancement to the routing process could reduce the overall model tendency to under-predict discharge in many river networks. And even if the Muskingum approach is maintained, there is ample scope to optimize its routing parameters to better represent the hydrologic characteristics of the HKH basins through a systematic calibration with the observed conditions. The other contributory features worth incorporating into a future scheme of enhancement could include simulation of transmission loss along channel reaches, and interaction with other components of river hydrology. With increasing human interference in the natural flow regime, it is also crucial that the model is capable of routing flow through channels modified by flow regulating and control structures causing backwater effects.

Flood prediction is not an end in itself; it must logically transit towards mapping the depth and extent of inundation to assess areas that are likely to be impacted to varying degrees of severity, in terms of potential costs and losses. Merely providing information on river discharge or water level will not induce appropriate response actions unless such information is translated into differential implications for lives and livelihood, asset, and infrastructure. To meet this requirement, the back-end modeling system of the prediction tools needs to be retrofitted with the capability of hydraulic simulation, or other means of implementing a flood-mapping system in an end-to-end flood early warning service chain. While the tools have inherent value in extending the lead time to actual hazard manifestation as events unfold, there are also weaknesses and limitations in any forecasting and warning services; these arise from the stochastic nature of the hydrometeorological process; for example, the non-linearity of flood hazards with no set pattern of expression. Moreover, the systems are not designed to be perceptive about societal exposures and vulnerabilities, nor do they account for the response capability in comprehending flood forecast and warning messages. Being web-based and without a localized and dedicated mobile version, the scope for widespread uptake is limited by the unequal access to the internet. Providing decision-support services online can be construed as discriminatory, favoring access by a capable few; whereas, the lower classes who are most at risk generally have no access to the internet. Thus, further customization is necessary to make the systems truly fit-for-purpose.

9.6.2 Way Forward

The scientific community in hydrological modeling is constantly developing improved methods of producing ensemble forecasts and data assimilation techniques to address the inherent uncertainty in the hydrologic modeling process. AI, machine learning, and data-mining techniques are increasingly being used for vulnerability assessment (e.g. analysis of satellite images to identify communities at risk) and also for risk calculation (Saravi et al. 2019). Through the advances and development in the last decade, these techniques have now been made available to even less developed countries through various collaborative platforms and assistance windows, thereby opening up a whole new avenue for operational FEWS.

As a result of the challenges posed by the complexity involved in inundation forecasting via predicted discharges, research efforts have expanded in recent years to seek out simplified approaches to inundation mapping, based on databases of simulated scenarios of flooding events by employing the similarity theory. However, there are major issues in recompiling the database as riverbed morphology changes over time, or significant changes occur in the land-use systems, such as the erection of artificial structures. Nonetheless, better flood-mitigation and flood-forecast planning strategies can be developed by visualizing the inundation scenarios of different magnitudes of floods and also by studying the various quantiles shown by discharge hydrographs.

As individuals are becoming more technology-bound than ever before due to smartphones, the internet, and the social media, all of these are being integrated into the warning dissemination systems by flood-forecasting centers and disaster managers worldwide. This will lead to more people acting as disseminators—communicating timely warnings widely via electronic and social media channels. Confidence and trust in FEWS are expected to increase as warnings are tailored to the needs of communities to enable them to make risk-informed decisions. Herein lies the relevance of impact-based forecasting and warning in bringing together providers and users on the same wavelength to connect the different components of early warning systems with specific focus on the sectors of interest.

9.7 Conclusion

The conventional ways of developing a hydrological modeling system for the purposes of flood forecasting and early warning present enormous challenges for countries that do not have the needed resources and technical capacity to develop, operationalize, and maintain such complex systems. The SERVIR approach of setting the modeling infrastructure in the cloud and facilitating hydro-informatics using open-source web technologies to deliver forecast results with visuals and statistical interpretation has systematically lowered those barriers in fulfilling the information needs about water in the HKH region. The approach has also addressed the communication challenges in disseminating forecast products and services that are comprehensible and usable under pressing decision contexts. The ECMWF-RAPID hydrologic modeling chain has addressed many application constraints identified in the GloFAS services used extensively by countries in the HKH region.

The streamflow-prediction system to which the web application tools serve as the intuitive and interactive user front-end has significantly enhanced the forecast capability in the HKH region by extending the forecast lead time to 15 days, and to a large extent, has quantified the uncertainties associated with deterministic forecasts. It has also reduced the processing latency in translating forecasts into early warning services by framing forecast results in the historical context of threshold exceedance in terms of the return periods. The intuitive interface and dynamic front-end processing and visualization system, with routines to access and retrieve outputs, are some of the benefits offered by the system, allowing the users to focus on the more critical and priority aspects of flood-emergency management to save lives and protect properties.

The HIWAT flash-flood prediction system is now appreciated by all national hydromet agencies within the region for its ability to forecast floods triggered by extreme precipitation events. The local convection-allowing physics configuration enables the meteorologic model to predict such events forcing the RAPID routing model. The services are especially crucial during the pre- and post-monsoon seasons when severe weather phenomena occur, and also in places dominated by conditions of poor surface infiltration and small watersheds. Flash flooding is a rare event, but the impact and consequences are far greater than those caused by seasonal riverine flooding. It is particularly important for communities settled around flashy stream beds and organizations engaged in actions of community well-being to have such reliable early warning service with sufficient lead time to plan and take action. While the system has only a 48 h forecast horizon, it provides far superior head-start than any instrument-based alternative. The outlook is promising, and SERVIR has brought cutting-edge technologies within the reach of research communities, government decision makers, emergency responders, and the general public of a region with global hydroclimatic significance.

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