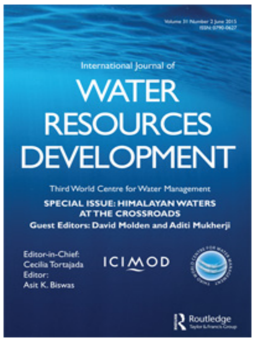

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Establishment of a regional flood information system in the Hindu Kush Himalayas: challenges and opportunities

Mandira Singh Shrestha[a]*, Wolfgang E. Grabs[b] and Vijay R. Khadgi[a]

[a]*International Centre for Integrated Mountain Development, Kathmandu, Nepal;* [b]*Federal Institute of Hydrology, Koblenz, Germany*

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Rapid advances in communication technology are making access to information faster, more reliable, and cheaper. At the same time, hydrological and meteorological monitoring technologies continue to improve significantly. These technological advances can be exploited to promote regional cooperation for flood risk reduction in the Hindu Kush Himalayas by providing an end-to-end flood information system. The system will function as a decision support tool for decision makers to alert vulnerable communities in a timely and accurate manner. This article provides an example of how regional cooperation has been achieved and is being promoted in the Hindu Kush Himalayas through the development of a regional flood information system.

Keywords: floods; regional cooperation; information system; technology; Hindu Kush Himalayas

Introduction

Recurring floods of large magnitude and frequency compounded by anthropogenic factors cause immense damage to lives and property in the Hindu Kush Himalayas (HKH). Floods account for more than a third of the total natural disasters in the region and affect millions of people. The peak flow in the rivers of the HKH region during the monsoon season can be 10 to 20 times the flow during the winter season (Alford, 1992; Molden, Vaidya, Shrestha, Rasul, & Shrestha, 2014; Rasul, 2014). The abundant water during the monsoon results in frequent flooding across national boundaries, resulting in lives lost and huge economic damage. The losses are likely to increase in the coming years, both because climate-related extreme events like floods are likely to become more frequent (IPCC, 2012) and because increases in population are putting more people at risk and increasing settlement in flood-vulnerable areas.

It is widely recognized that floods in the HKH region cannot be totally controlled. The question is: What can be done to reduce the severity of and better manage flood disasters in the future? Efforts should be directed towards reducing flood vulnerability and mitigating flood impacts through improved flood risk management. One of the most important approaches to flood management is the provision of end-to-end flood forecasting and warning services.

The need for an institutionalized system for the exchange of real-time hydrological and meteorological data and information to support flood forecasting in the HKH region was recognized more than a decade ago (Ahmad & Ahmed, 2003; Chalise & Shrestha, 2002; ICIMOD, 2003). Several high-level consultations resulted in awareness of the need for

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*Corresponding author. Email: mandira.shrestha@icimod.org

regional collaborative efforts aimed at improving flood information systems complementary to national flood forecasting systems, thus enabling better management of floods and flood impacts.

At the level of an international river basin, effective flood risk management calls for meaningful cooperation amongst all the riparian countries. Improved flood management and mitigation of adverse impacts calls for a regional basin-wide approach with efforts in timely data sharing and modelling (Ahmad & Ahmed, 2003; Kattelmann, 1990; Sadoff et al., 2013). In the international river basins of the HKH region, this approach has the greatest potential for regional co-operation. There are a number of bilateral cooperation agreements between India and the riparian countries of Bangladesh, Bhutan, China, Pakistan and Nepal, but as yet there is no formal multilateral arrangement. Sadoff et al. (2013) emphasize the need for regional cooperation in water, weather and climate information and recommend investments in regional information, forecasts and warning systems.

This article provides an example of how regional cooperation has been achieved and is being promoted in the HKH region through the development of a regional flood information system (RFIS). It looks at the different capacities of the countries and the current institutional set-up for flood forecasting, and describes the rationale of an RFIS, its key components and its use to minimize the loss of lives, livelihoods, property and infrastructure.

Flood disasters in the Hindu Kush Himalayas

About 40% of the world's poor live in the Ganges and Brahmaputra River basins (Ahmad, Biswas, Rangachari, & Sainji, 2001; Shah, 2001). With the increase in population and lack of other options, these economically disadvantaged people are increasingly populating high-flood-risk areas. Adaptive capacity to minimize risk and respond to imminent flood hazards is critically low in these communities. Because of the frequency of devastating floods, the floodplain poor lack the financial and organizational resources to recover from flood disasters.

Statistics show that the number of people killed and affected per flood event is significantly higher in Asia than elsewhere in the world (Jonkman, 2005). According to the OFDA/CRED Emergency Disaster Database (http://www.emdat.be/disaster_profiles/index.html), in 1990–2014 an average of 84 people lost their lives per flood event in Asia, which is significantly higher than the second-worst figures, for the Americas, where an average of 65 people lost their lives per flood event. Floods have a greater effect on the poor and marginalized communities in the mountains of the HKH region. Studies indicate that the incidence of heavy monsoon rains over India has doubled in the last 50 years, while the incidence of moderate and weak monsoons has decreased (Goswami, Venugopal, Sengupta, Madhusoodanan, & Xavier, 2006; Krishnamurthy, 2012). Economic flood damage has risen over the past decades, in part because of population increases and human encroachment onto the floodplains.

Floods impose severe constraints on socio-economic development, investment in agriculture, physical infrastructure and industrial production in the poorer areas, where these are most needed. Annual flooding exacerbates poverty in the region and damages infrastructure and the environment (Paudyal, 2001). It has been shown around the world that reducing the damage caused by annual floods can increase social and economic prosperity (Ahmad et al., 2001). Flood mitigation in the Ganges-Brahmaputra-Meghna (GBM) and Indus basins is more than a regional hydrological priority; it is a socio-economic priority.

Recent floods and impacts

Devastating floods are an annual phenomenon in the HKH region and downstream in the GBM and Indus Basins. On average, there are some 76 disasters each year in the HKH countries, with 36,000 people killed and over a million affected. It is estimated that about 55% of the total flood damage in India occurs in the Ganges and Brahmaputra Basins (Shah, 2001). Of the total estimated flood-prone area in India, about 68% lies in the GBM states, mostly in Assam, West Bengal, Bihar and Uttar Pradesh (Ahmad et al., 2001). About 80% of the area of Bangladesh is prone to floods, and every year at least one-third of the country's territory is affected (Shah, 2001).

The four largest floods in the region between 2000 and 2013 took more than 10,000 lives, displaced more than 50 million people, and caused an estimated USD 20 billion in damage. A breach of the Koshi embankment in Nepal in 2008 displaced more than 70,000 people in the country and over 4 million in Bihar, in neighbouring India. Every year, millions of people in India and Bangladesh are displaced, with total damage estimated at billions of dollars. In 2007, according to the EM-DAT database, 13.7 million people were affected by floods and around 1100 people were killed in Bangladesh. Pakistan experienced extreme floods in 1950, 1957, 1976, 1992, 1998 and recently in 2010. Each of these flood events impacted at least 10,000 villages with more than 100 deaths (Mustafa & Wrathall, 2011; Sheikh, 2001). The flood in 2010 resulted in more than 2000 deaths, 20 million persons affected, and an estimated USD 10 billion in damage (Akhtar, 2013; FFC, 2010). In 2011, monsoon floods in the eastern region of Pakistan affected 9.6 million people, killing 520 and injuring more than 1180 (World Bank, 2014). Table 1 shows the worst floods that occurred in 1990–2013 in the HKH countries. The frequency and intensity of water-related hazards and disasters are expected to increase in the Himalayan region as a result of climate change, and without adequate flood forecasting and management practices, the disastrous impacts of these floods will rise as the population in the floodplains grows and the value of infrastructure increases. Thus, the risks and vulnerabilities of the population and the capacities of institutions need to be better understood and addressed.

Flood forecasting capacity in the HKH region

Understanding the present capabilities of hydrometeorological services in the participating countries and disaster management authorities and utilizing the expertise available is necessary for the development of an RFIS.

Adequacy of hydrometeorological observation networks and quality control of observations

Hydrometric information is fundamental to the planning, operation and management of water resources and flood defence (Walker, 2000). Hydrometeorological observation networks include stage and discharge measurements as well as meteorological observations such as rainfall, temperature, humidity, pressure and wind speed. According to the World Meteorological Organization (WMO, 2008), the hydrometeorological network does not necessarily have to be full-scale but it should be such as to maximize information content. In a study conducted by Perks et al. (1991) on the adequacy of hydrometeorological observations in Canada, WMO noted that the minimum required density was not reached in the mountainous and inland regions, where densities were only one-fifth to one-third of those recommended by WMO. The density of hydrometeor-

Table 1. Worst floods during 1990–2013 in the Hindu Kush Himalayan countries.

Country	Year	Month	People killed	People affected	Location
India	2013	June	6,453	3,419,473	Himachal Pradesh, Haryana, Delhi and Uttar Pradesh
India	1997	September	2,357	30,259,020	Bihar, Telengana region
India	1998	July	2,131	29,652,200	Assam, Arunachal Pradesh, Jammu and Kashmir, Himachal Pradesh, Uttar Pradesh, Goa, Kerala
Bangladesh	2007	September	1,230	13,851,440	Dhaka
Bangladesh	1998	September	1,050	15,000,050	Dhaka
Nepal	1993	July	1,048	553,268	Rauthat, Siraha, Chitwan, Dhanusha, Sarlahi, Kathmandu, Lalitpur, Bhaktapur, Dhading, Makwanpur, Sindhuli, Ramechhap, Okhanldunga, Palpa
Pakistan	2010	July	2,113	20,363,496	Khyber Pakhtunkhwa, Sindh, Punjab and Balochistan
Pakistan	1992	September	1,446	12,839,868	North Western Frontier Province and Punjab
Afghanistan	1991	May	1,193	139,400	Northern Province of Jawzian

Source: OFDA/CRED Emergency Disaster Database (EM-DAT).

ological stations in the central Himalayan region of Nepal is low, with most located in valley bottoms and in areas that are easily accessible and populated (Barros, Joshi, Putkonen, & Burbank, 2000). A similar situation prevails across the HKH region.

The manually observed data, including in remote mountainous areas, vary to a significant degree in their accuracy and are now being replaced by automatic sensors. Reliable, continuous 24-hour observations are now possible, with data transmission in real time. In many of the countries in the HKH region the manual hydrometeorological stations are being upgraded to real-time stations for improved flood forecasts. Table 2 shows the country-wise availability of real-time hydrometeorological stations. In an overall assessment, besides the limited availability of suitable data for flood forecasting purposes, quality management of data in many institutions is still in its infancy. This situation negatively affects the utility of hydrological information for flood forecasting purposes.

Flood forecasting skills and extension of lead time for early warning

The hydrometeorological services in the HKH region have a varying capability to deliver timely and accurate flood forecasting services, as presented in Table 2. Flood forecasting capacity in Bhutan and Nepal is still in its infancy, because flood forecasting systems have yet to be made operational. This is primarily due to the lack of skilled technical human resources and adequate allocation of financial resources. The existing facilities are not sufficient to run numerical weather prediction models. In Bangladesh, China, India and Pakistan there are various hydrological and meteorological models in operation that provide weather forecasts and operational flood forecasts to support community preparedness. Thus, there is considerable potential for scientific, professional and technical cooperation between the countries of the region and between flood forecasting services at different stages of development.

Table 2. Flood forecasting capacity in the Hindu Kush Himalayan region.

Country	Institution for flood forecasting[a]	Observation network (no. of real-time stations)[b]	Flood forecasting model	Numerical weather prediction	Operational flood forecasting in place?
Bangladesh	FFWC (BWDB)	84 water level 59 rainfall	Mike 11	NOAA Global Forecast system, WRF	Yes
Bhutan	DHMS	21 hydrological 22 meteorological (AWS)	IFAS, HEC-RAS, HBV	WRF	No
China	MWR	NA	Xinanjiang	T639	Yes
India	CWC	NA	Mike 11	WRF	Yes
Nepal	DHM	32 hydrological 46 meteorological (AWS)	Mike 11	WRF	No
Pakistan	PMD	24 hydromet 24 hydrological	FEWS, Indus-IFAS, CLS	NOAA GFS, WRF	Yes

[a] FFWC = Flood Forecasting and Warning Centre; BWDB = Bangladesh Water Development Board; CWC = Central Water Commission; DHM = Department of Hydrology and Meteorology; DHMS = Department of Hydromet Services; MWR = Ministry of Water Resources; PMD = Pakistan Meteorological Department.

[b] NA = not available.

There are a number of critical factors needed to ensure reliable delivery of a service meeting the needs of a diverse user community (WMO, 2011). Models must be carefully selected to ensure that they are applicable under the specific circumstances of data availability, overall hydrometeorological regime, and skill requirements for model operation and interpretation of model results, in particular for the purpose of flood forecasting, including required minimum lead times for warnings. Greater lead times can only be accomplished through model-based forecasting systems; longer-range predictions require advanced forecasting environments such as using numerical weather prediction methods or flood predictions on the basis of seasonal climate predictions. These could be especially useful in large river basins such as in Bangladesh.

Development of a regional flood information system

Efforts in disaster risk reduction are likely to provide a useful framework for collaboration. The occurrence or threat of natural disasters creates opportunities to facilitate cooperation among countries by fostering linkages which otherwise might not have existed (Kelman & Koukis, 2000). Given the geopolitical sensitivity in the HKH region, there are few regional initiatives for cooperation and management of hazards and water resources. But the increasing problems of floods that are common to all countries have brought them together to work collectively in looking at ways to minimize the adverse impacts.

One such example is the HKH Hydrological Cycle Observing System (HYCOS), a regional initiative to establish an RFIS in the Ganga-Brahmaputra-Meghna and Indus Basins. ICIMOD initiated this project in partnership with WMO and the regional member countries Bangladesh, Bhutan, China, India, Nepal and Pakistan (Molden et al., 2014). Based on the WMO World Hydrological Cycle Observing System (WHYCOS) concept, the initiative covers all the important steps of the provision of hydrological information: monitoring, data transmission, data analysis, data quality checking, data processing, data delivery and development of products for users. The regional flood information provided to all participating agencies on the basis of equal access is compatible with national flood information systems and is the backbone for the development and operation of model-based regional flood outlooks that complement national flood forecasting services.

In setting up an RFIS, several challenges were faced, which included the varying institutional capabilities of the countries in terms of know-how and technology, differing perceptions of the problem and its solutions, and mechanisms of sharing data and information. To set up monitoring networks, data acquisition and transmission in the four countries, Bangladesh, Bhutan, Nepal and Pakistan, it was essential to understand the existing capacities of the agencies and build upon them to ensure sustainable solutions.

Real-time monitoring network

Early flood warning for better preparedness is largely dependent on the timely availability and quality of hydrometeorological data. Collection of hydrometeorological data in real time requires a range of sophisticated sensors together with professional competence in management and operation. The first priority was to update and automate existing hydrometeorological stations to make them capable of observing parameters and transmitting the data at regular and specific intervals. A wide range of options are available for automatic *in situ* water-level observations, including stilling wells, pressure sensors, bubbler sensors and radar sensors.

The first challenge was to prioritize station locations, because funding was available for only 38 stations. Partners were therefore asked to prioritize stations for updating based on the significance of the stations in contributing to regional and national flood forecasting objectives. The locations of these stations then required choices with respect to adequate technologies for the technological upgrade of the selected stations. This was undertaken through detailed field studies considering river morphology, environmental conditions surrounding the site, and the capacity of the national hydrometeorological agencies to manage and maintain the sensors. The recommendations were based on WMO-specific standards. The final configuration of the stations is presented in Table 3.

Recognizing the overall inadequacy of the precipitation network to serve an RFIS, use is also made of the regional network of synoptic weather stations that report in the context of WMO's Global Telecommunication System (GTS). The locations of the upgraded hydrometeorological stations and the GTS stations are shown in Figure 1.

Data acquisition and transmission

Data for flood forecasting should be transmitted in real time. For flood forecasting purposes, hydrometeorological data is most valuable if it reaches the forecaster almost instantly. Mountainous basins with flashy rivers need more frequent data acquisition than basins in flat lands. Meeting the needs of the agencies, data from the HYCOS stations is transmitted at 15-minute intervals over the Internet using general packet radio service (GPRS) cellular communication technology. This mode of communication is both cheap and reliable for data transmission, but problems such as system downtime and service disruption of the mobile service provider regularly challenge the effectiveness of the system in the region. To counter such problems, the data collection platform is equipped with a backup mobile communications system GSM/GPRS SIM card from alternate service providers. The system switches automatically to transmit data from the backup SIM if the first SIM fails. During extreme events, GSM/GPRS networks can also be overloaded, causing transmission failures, and during extreme climatic or natural events such as cloudburst precipitation or earthquakes that can result in floods, transmission lines are vulnerable to failure. Therefore, the system has a further fall-back option, using INMARSAT satellite communication facilities as the method of last resort. Across the world, similar GSM/GPRS telecommunication technologies have been successfully integrated with hydrometeorological stations to transmit data in real time at an affordable cost (Doong et al., 2012).

Table 3. Hydrometric monitoring network in the regional flood information system.

Station type	Quantity	Observations	Function
Radar	13 (7 Bangladesh, 1 Nepal, 5 Pakistan)	Water level	Monitoring water level in real time
Bubbler	12 (6 Bhutan, 5 Nepal)	Water level	Monitoring water level in real time
Stilling well	1 (Nepal)	Water Level	Monitoring water level in real time
Tipping bucket rain gauge	38 (9 Bangladesh, 9 Bhutan, 12 Nepal, 8 Pakistan)	Rainfall	Monitoring volume of rainfall in real time
Automated weather station	11 (2 Bangladesh, 3 Bhutan, 3 Nepal, 3 Pakistan)	Rainfall, temperature, wind speed, wind direction, humidity and pressure	Monitoring meteorological parameters in real time

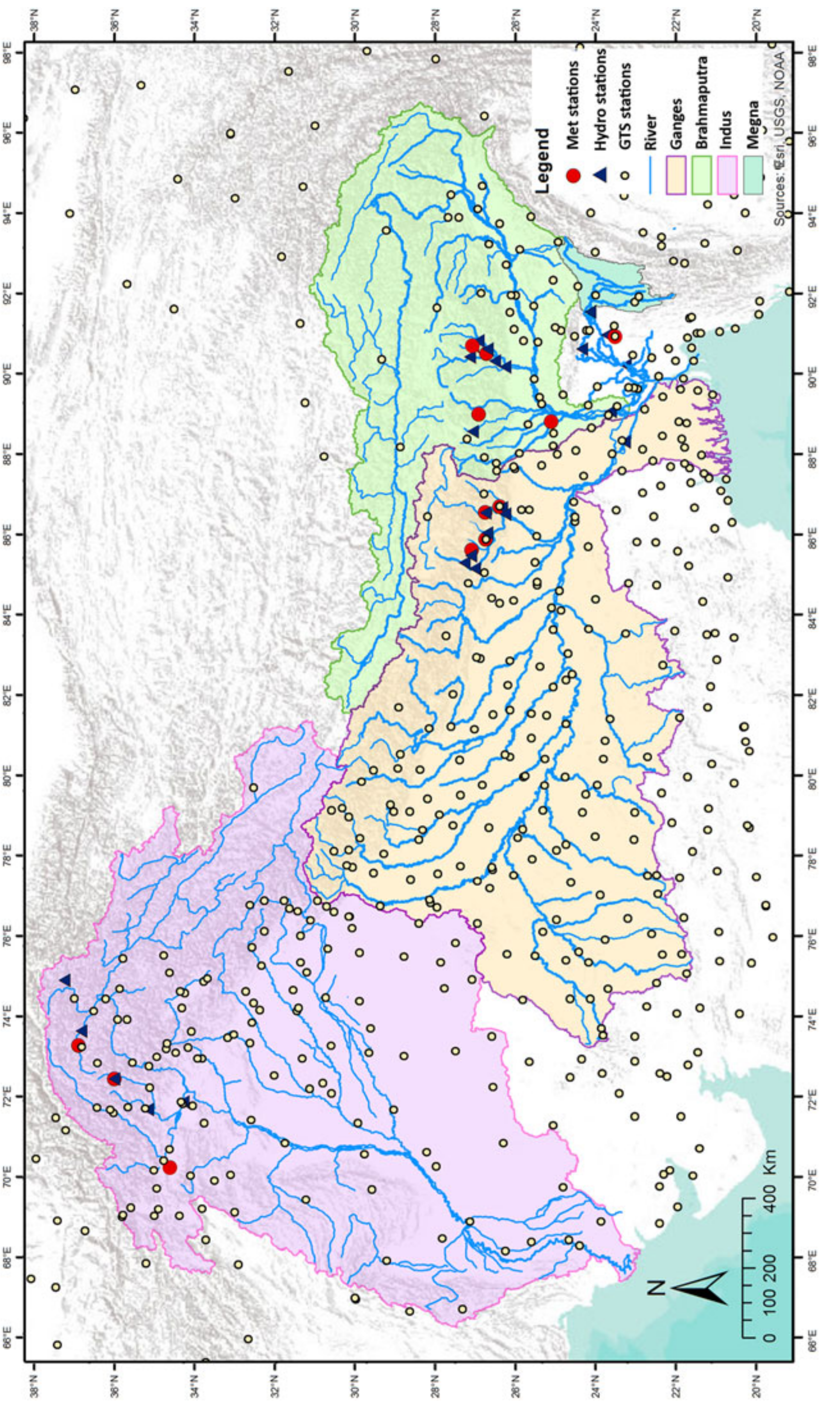

Figure 1. Locations of upgraded hydrometeorological stations and WMO Global Telecommunication System stations.

Data storage, quality control and management

Although real-time data possess the greatest value at the time of their generation, the value is not lost with age; rather, the nature of the value changes from being relevant for immediate flood forecasting to being relevant for historical analysis and model development. Thus, data should be archived and stored in a format that is easily accessible, searchable, and backed up regularly.

For the HYCOS initiative, data storage is provided in three different places. At the site level, site-specific data are stored in a cyclic memory that can hold data for 2–10 years. Real-time data is transmitted simultaneously to the national servers and a regional server; the two servers are synchronized periodically to ensure that the same set of data is available on both. In addition, an automated plausibility analysis of incoming data is performed as a first-order quality check.

Good-quality data from hydrometeorological stations is a prerequisite for reliable services of flood and weather forecasting. A real-time quality control tool has been built into the flood information systems to detect data of suspicious quality and false alarms that include applying limit checks (to detect if parameters have crossed predetermined maximum or minimum limits), step checks (to detect cases where a parameter rises or falls abnormally in a one-step time interval), and constant checks (to detect cases where a parameter reading is constant for a long period). Previously, almost all stations in the region were observing data only three times a day, and only during daytime, with a 3-hour time step. The new system polls data every 15 minutes, and hence it is difficult to determine the appropriate thresholds for step check and constant check. At the moment, most of the quality control is based on educated guesses; the experiment lays a foundation for continuously improving the quality control. Quality control is a never-ending process, and a lot of effort is needed to sustain it.

Utility of data for generating flood outlooks

The regional flood outlook generated in the project provides early notice of the potential for flooding based on weather forecasts and real-time data. As an equivalent example, in the USA the river forecast centres of the National Oceanic and Atmospheric Administration (NOAA) provide a flood outlook based on hydrometeorological conditions that indicate whether significant flooding can be expected during the outlook period (http://www.cnrfc.noaa.gov/flood_outlook.php).

The HKH-HYCOS regional flood outlook provides real-time flood information products pertaining to the threat of potential large-scale flooding to provide adequate products to the national hydrometeorological agencies to support and enhance national flood forecasting and warning services.

Detailed rainfall-runoff and river hydrodynamic models using MIKE 11 (DHI, 2002) have been configured for the Ganges and Brahmaputra Basins to compute flood propagation along the major rivers using input data from various sources. The system is linked to the real-time precipitation and hydrological data from the 38 stations in the HYCOS initiative as well as data made available from various other sources. Bias-corrected Tropical Rainfall Measuring Mission (TRMM) 3B42 data are used for locations where no stations are available, and quantitative precipitation and temperature forecasts are obtained from the NOAA Global Forecast System model. The model includes 96 sub-catchments with 21 nodes for calibration and validation. The modelling system is based on historical data for calibration and validation such that extreme events that have occurred in the past are simulated correctly. The developed model forms the basis of the real-time flood forecasting

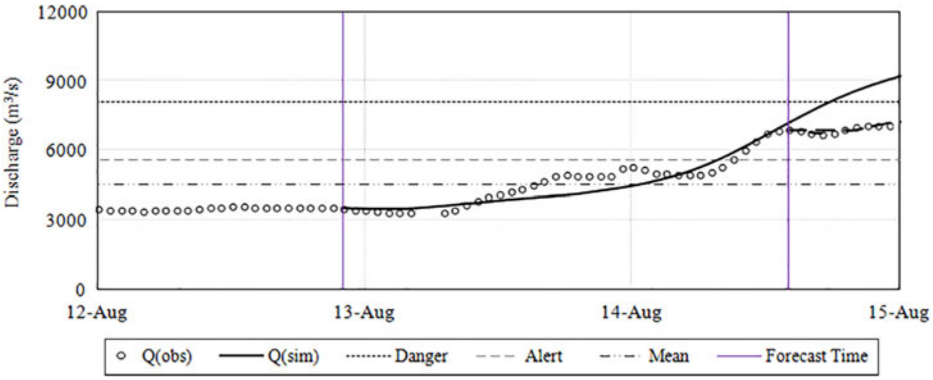

Figure 2. Performance of flood outlook at Chatara on the Koshi Rriver.

system, which will require real-time data from the various sub-basins within the participating countries. The computed forecasts are based on data assimilation using the actually observed real-time data, which has been found to significantly improve forecasts (Madsen, Rosbjerg, Damgard, & Hansen, 2003). The real-time information allows comparison of observed and forecast data for evaluation of the performance of the developed system.

The model was applied to simulate the flows during the 2014 monsoon. During 14–16 August, many parts of Nepal experienced continuous rainfall, resulting in widespread flooding. The model was used to prepare forecasts with a lead time of 72 hours every 12 hours. Observed discharge data were assimilated at several gauging stations up to the time of forecast. The flood outlook was found to perform well in generating flow forecasts up to 24 hours in advance. The model results for 12–15 August are shown in Figure 2. The initial conditions at the time of forecast are updated; the forecasts improved significantly for the first 24 hours, after which they deteriorated. These results are based on a crude development of the model and are now being updated with cross-sections and additional ground information, which is expected to significantly improve model performance. With further improvement, the regional flood outlook is expected to support national hydrometeorological services in providing better forecasts, preparing timely flood bulletins, and increasing the forecast lead time for timely action by decision makers.

Challenges and opportunities for cooperation

Throughout the planning and implementation phases of the project, a number of challenges were faced that needed adequate response for their solving. This in turn provided opportunities for further cooperation between countries and their hydrometeorological agencies that provide flood-forecasting services.

The most prominent challenges were related to:

(1) Acceptance of the overall rationale and objectives by all project partners
(2) Technical issues related to the establishment, operation and maintenance of the stations and related infrastructure
(3) Preferred ways of communication, including telecommunication
(4) The development and operation of the core regional flood information system
(5) Institutional issues at the level of ICIMOD and the participating hydrometeorological agencies in the partner countries

Acceptance of the overall rationale and objectives of the project was achieved through intense bilateral and multilateral consultations on the basis that an RFIS is complementary to national flood forecasting systems and provides additional basin-wide flood information that typically cannot be obtained from national systems. This also included the acceptance of the principle of equal access to data generated through the project by all partners.

Technical challenges were addressed through a two-pronged approach: (a) the selection of the most appropriate technology in the selection of the instruments chosen for the observations, including on the basis of lessons learnt from a similar project, the Mekong-HYCOS project. With regard to data management, harmonization of data collection, acquisition and transmission for sharing of data and information was achieved to ensure interoperability and compatibility of data management for flood forecasting in the region; and (b) A strong capacity-building and training component aimed mainly at technical staff and station observers on the basis of established standing operating procedures for all technical installations.

Communication and telecommunication had been a central challenge to ensure 24/7 operation of the stations and immediate response to data transmission failures. This was achieved through the identification of focal points in all participating institutions, the development of software to monitor and provide automated plausibility checks of the data transmissions, and the selection of an Internet-based data transmission protocol, backed by a satellite transmission facility through INMARSAT, resulting in a largely strengthened and resilient communication system.

From the beginning, the establishment of the station network was seen in support of the flood information system itself. As it was clear that the number of stations that could be established through the project was minimal, the focus of development of the RFIS was on the ingestion of multiple-platform additional information sources, including information from several hundred meteorological stations through the WMO GTS, stations that countries voluntarily contributed to the HKH-HYCOS project on the same level of quality of data provision, and satellite-based precipitation information. The development of a prototype regional flood forecasting model, ingesting data from all sources mentioned in addition to the network established by the project, forms the core operation part of the RFIS. Training courses were provided in the use of the RFIS at national and regional levels.

Institutional issues at the national level focused on the ‘ownership’ of the project and its activities. This was approached by ensuring that all project activities were fully embedded in the national flood forecasting activities from its inception through the full operation of forecasting services, to avoid a separation between ‘project’ and ‘routine activities’ of the hydrometeorological services. In addition, a procedure was established in the implementation plan of the project to facilitate gradual taking-over of the added operational and financial responsibilities of the services as part of the full ingestion of the project network stations and associated activities in the routine service delivery capability of the hydrometeorological services.

The wide diversity of know-how and abilities of the hydrometeorological services in the countries of the HKH region with regard to flood forecasting and management offers an opportunity for bilateral and regional technical cooperation. In addition to existing bilateral agreements between countries, the concept of regional cooperation, as already implemented in many other regions of the world, offers a much wider scope for the exchange of know-how, knowledge, technology, data and information.

Lessons learnt

The planning and implementation of the project have shown that huge data gaps still persist across the region as a result of sparse observation networks. With respect to flood forecasting services, existing networks need to be reviewed in terms of their adequacy for the objectives. From the viewpoint of end-to-end flood forecasting services, the institutional mechanisms for the provision of flood warnings to communities need to be further strengthened.

To be more effective, flood forecasting and warning services need to be integrated with overall disaster management activities, both nationally and internationally, and efforts made towards risk communication, awareness raising and better preparedness. Transboundary cooperation is required to effectively address flood risks. Riparian states need to exchange relevant hydrological data on a real-time basis. Especially for large river basins, satellite-based observations using radar altimetry have shown their potential to complement *in situ* gauge observations.

From a hydrological perspective, improvement is needed in the regional flood outlook from the genesis of floods to the propagation of flood waves along river stretches, including major tributaries. This could be supported by using data from the stations established in the course of the project, and expanding the network by adding national network stations to the system. Taken together, the availability of such analyses, using numerical weather prediction and including water-balance models for large rivers, has the potential to greatly improve long-range prediction of riverine flood events. Water-balance modelling of the catchment to include the status of soil moisture is another requirement to improve hydrological modelling and understand and predict the genesis and generation of floods.

A number of specific activities linked to the development of the RFIS have made a marked contribution to the promotion of regional cooperation. These include study visits to the Mekong River basin, which has a similar system in place for flood management, with participants from different countries; and capacity-building activities in the form of training events at regional and national levels, which encourage participants from different countries to share each other's technologies and know-how, and learn from each other's experience. The project also promotes and supports the development of partnerships at a higher level among different agencies and countries. Sharing of data and mutual commitment to address the challenges of flooding, as well as recognizing the essentially transboundary nature of the problem, help engender a feeling of regional solidarity, an opportunity for continued dialogue, and a strong spirit of cooperation.

Research needs

A comprehensive research package is needed to underpin the establishment of an RFIS that aims to support sustainable flood risk management based on a more scientific understanding of floods. The major research requirements can be summarized as follows.

Given the diversity of data sources at the level of participating hydrometeorological services, there is a need for systematic examination and verification of basic data resources, including hydrological, meteorological and socio-economic data. It would be extremely valuable to compile a register of historically recorded and reported floods, with the aim of analyzing historic flood events, the genesis of floods, and documented impacts. The genesis of floods needs to be analyzed using meteorological inputs in particular and including numerical weather prediction model results, to detect changes or variability in weather patterns, cyclone tracks and related precipitation extremes.

Further improvement of the regional flood outlook to increase the scientific understanding of the genesis and propagation of floods has the potential to serve as a major input in developing scenario-based support for decision-making tools to support policy development and adaptation planning and implementation, including the effect of changes such as demographic change, land use, infrastructure and climate.

In order to transfer flood forecasting into flood risk management practice, it is also necessary to conduct research on the subject of risk itself. As risk assessment is a political process, related research needs to address the perception of risk of the affected population. Such research would provide valuable inputs in the development of policies to improve flood risk management and minimize flood disasters.

As a practical step forward, ICIMOD, as a regional knowledge hub, is invited to increase its efforts to create a collaborative platform for regional centres of excellence to form a research network to address the scientific challenges described above and to initiate the development of concept documents describing the research requirements in more detail, together with suggested methodologies and supporting infrastructure to conduct the research.

Conclusion

A large part of the population in the HKH region is at risk from recurring floods that often have a disastrous impact. The transboundary nature of the large rivers in the region calls for a broader river basin approach to flood forecasting, flood warning and flood risk management. Climate change and the perceived increase in the frequency and magnitude of floods in the region have amplified the need for an RFIS for sharing real-time data and information across borders. In addition, demographic changes are increasing the number of people living in the flood plains and the amount of valuable infrastructure, intensive agriculture and production facilities in these areas.

Recognizing this challenge, governments, through their hydrometeorological agencies, have started collaborating under the HKH HYCOS project to establish an RFIS to improve flood risk management practices at national, transboundary and regional levels with three major components:

- Improvement of the observation infrastructure
- Development of a regional flood information system
- Capacity building

The conceptual framework of HKH HYCOS creates a favourable environment and working conditions for sharing the required hydrometeorological data and information and for joint consultations at the technical, professional and institutional levels. By helping with the exchange of real-time data, it will promote awareness and understanding of water resources issues regionally, within each country, and within entire transboundary river basins. The project ensures that the system operates on the basis of high-quality observations, regional communication, provision of flood information services, and development of flood information services at national and regional levels.

A key element of the RFIS is its multi-observation-platform approach, integrating terrestrial and satellite-based observations, and its access to the WMO Information System (WIS) for real-time transmission of hydrological data, as well as the WMO Integrated Global Observing System (WIGOS).

A comprehensive research approach is needed to improve flood forecasting capacities in support of enhanced regional cooperation in flood risk management practices in the HKH region. The initiative has helped increase the capacity of national hydrological and meteorological services for flood forecasting and has had a positive effect on flood risk management through the improvement in observation infrastructure, capacity building and institutionalized cooperation; it has also created an environment of trust and confidence amongst institutions and helped promote transboundary and regional cooperation. Much has been achieved in the past years, but to secure and consolidate the achievements, more needs to be done in the near future.

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