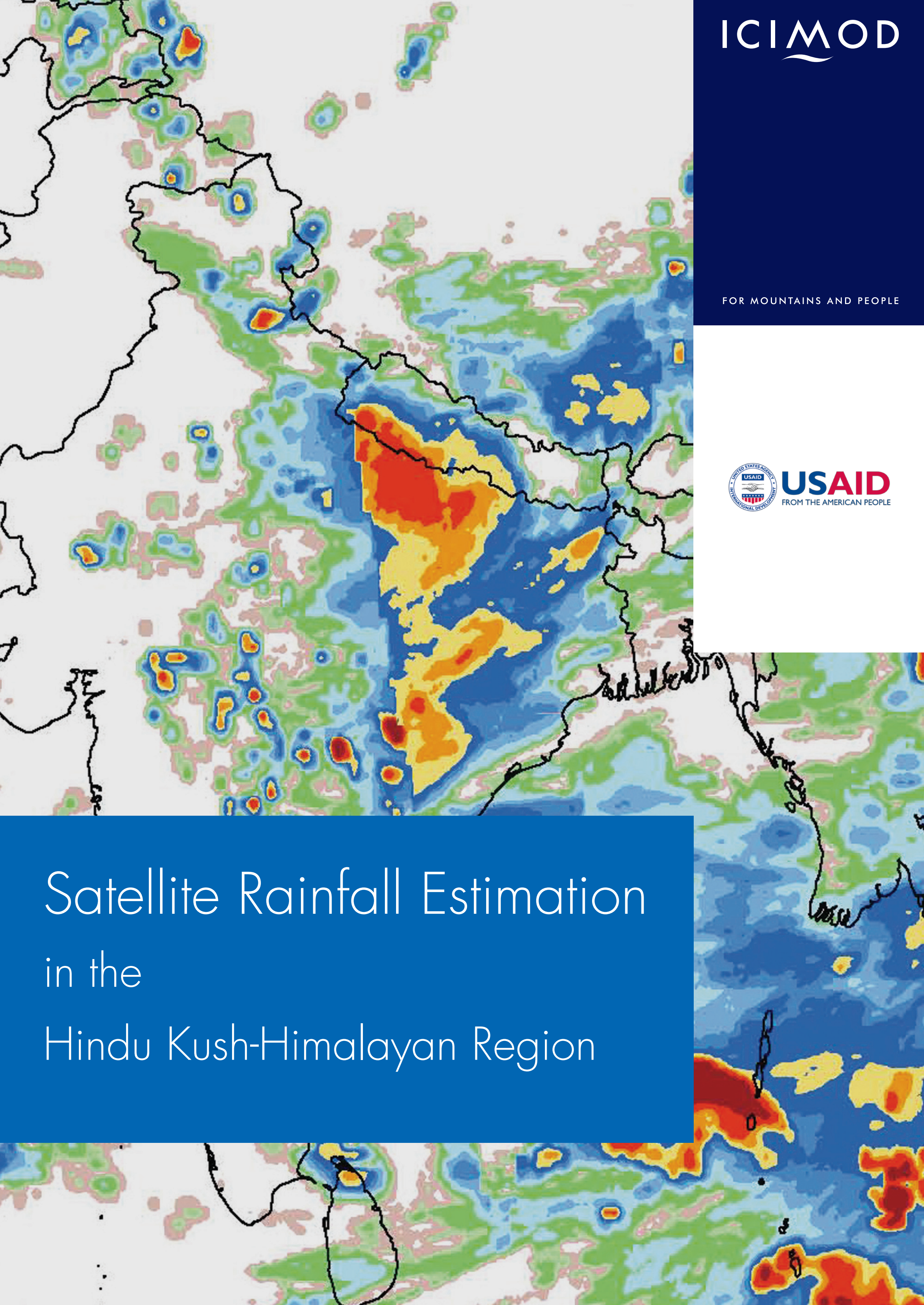

ICIMOD

FOR MOUNTAINS AND PEOPLE

USAID
FROM THE AMERICAN PEOPLE

Satellite Rainfall Estimation in the Hindu Kush-Himalayan Region

About ICIMOD

The International Centre for Integrated Mountain Development, ICIMOD, is a regional knowledge development and learning centre serving the eight regional member countries of the Hindu Kush-Himalayas – Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan – and based in Kathmandu, Nepal. Globalisation and climate change have an increasing influence on the stability of fragile mountain ecosystems and the livelihoods of mountain people. ICIMOD aims to assist mountain people to understand these changes, adapt to them, and make the most of new opportunities, while addressing upstream-downstream issues. We support regional transboundary programmes through partnership with regional partner institutions, facilitate the exchange of experience, and serve as a regional knowledge hub. We strengthen networking among regional and global centres of excellence. Overall, we are working to develop an economically and environmentally sound mountain ecosystem to improve the living standards of mountain populations and to sustain vital ecosystem services for the billions of people living downstream – now, and for the future.

Satellite Rainfall Estimation

in the Hindu Kush-Himalayan Region

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Contents

About the booklet and CD

This booklet provides a short summary of the 'Application of Satellite Rainfall Estimation in the Hindu Kush-Himalayan Region' project implemented by ICIMOD together with partners from Bangladesh, Bhutan, China, India, Nepal, and Pakistan from June 2006 to 2008, supported by USAID/OFDA and by experts from NOAA and USGS. The CD included in the back pocket provides the detailed project report, which includes the project overview, a summary of flood management issues in the HKH region, and the validation methodology, analysis, and detailed results. It also includes the article, "Satellite-based Rainfall Estimates for Streamflow Modelling: Bagmati", published in the Journal of Flood Risk Management in 2008.

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ICIMOD is grateful to USAID/OFDA for funding this project. Our special thanks go to A. Sezin Tokar, hydrometeorological hazard advisor, USAID/OFDA for her help and valuable suggestions. We would also like to express gratitude to the resource people from NOAA and USGS for their technical support, in particular Eric Wolvovsky, Guleid Artan, Jim Verdin, Richard Paulson, and Tim Love. The work would not have been possible without the active support and participation of the partner countries. Therefore we would like to thank all the partners from Bangladesh, Bhutan, China, India, Nepal, and Pakistan for providing data and for their valuable contributions. Finally, the author would like to than all those in ICIMOD who contribute to the success of the project and to preparation of the publication itself.

Acronyms and Abbreviations

CPC	Climate Prediction Centre
HKH	Hindu Kush-Himalayas/n
GBM	Ganges-Brahmaputra-Meghna
GeoSFM	Geospatial Stream Flow Model
ICIMOD	International Centre for Integrated Mountain Development
IR	infrared
NOAA	National Oceanic and Atmospheric Administration
NSCE	Nash-Sutcliffe coefficient of efficiency
RFE	rainfall estimation
RMSE	root mean square error
SRE	satellite rainfall estimation
USAID/OFDA	United States Agency for International Development/ Office of U.S. Foreign Disaster Assistance
USGS	United States Geological Survey

Foreword

The Hindu Kush-Himalayan region, whose mass of glacier and snow resources have given it the name of the 'third pole', is the world's largest storehouse of freshwater. The region itself directly sustains about 210 million people; but the downstream water basins serve some 1.3 billion inhabitants, and up to 3 billion people benefit from the food and energy produced by rivers that have their source in these mountains. At the same time, there is a huge spatial and temporal variability of precipitation, with too much water at some times and acute shortages at others. Now, as a result of global warming and climate change, the region is faced with more intense floods and droughts, which affect people's lives and livelihoods, and the water resources themselves are threatened by the warming trend observed over the past century.

Floods and droughts cannot easily be avoided, but their effects can be minimised through preparation and sufficient warning. However, accurate estimates of rainfall are needed for warning to be given, and even to develop and understanding of the basic mechanisms on which the warnings are based. Until recently, the main method used to estimate rainfall has been interpolation of measurements from a network of hydrometeorological stations. The closer the spacing between stations, the more accurate the total rainfall estimate. However, in the sparsely populated, poorly inaccessible region of the Himalayan mountains, hydrometeorological stations are sparse and their network weak. Moreover, these mountains are shared among eight countries, but data and information sharing at a regional scale on climate, hydrology, and meteorology are still inadequate, and this also hinders proper planning and decision making.

Recently, it has become possible to make more accurate estimates of rainfall using observations from satellites to enhance the ground-based data – 'satellite-enhanced rainfall estimation'. This approach is especially appropriate for areas like the Hindu Kush-Himalayas, with sparse rain gauges and difficult terrain. Improved satellite-based rainfall estimates have the potential to facilitate both timely flood forecasting and drought monitoring in the region.

Since 2001, ICIMOD has worked with its member countries to establish a regional flood information system to minimise the adverse impact of floods. A project on 'Application of Satellite Rainfall Estimation in the Hindu Kush-Himalayan Region' was implemented jointly by ICIMOD and its partner countries, with technical support from the United States Geological Survey (USGS) and the National Oceanic and Atmospheric Administration (NOAA), and funded by the United States Agency for International Development Office for US Foreign Disaster Assistance (USAID/OFDA). Representatives of the hydrometeorological services of six countries were trained in satellite rainfall estimation (SRE). Together with ICIMOD, they carried out quantitative validation of the satellite rainfall estimates (CPC-RFE2.0) obtained from NOAA climate prediction centres at the national and regional levels, and tested a rainfall-runoff model (GeoSFM) to predict discharge. This publication presents the project's findings, results, and recommendations. The results provide an important first step in the use of this new methodology in the region to reduce the impact of water-related disasters.

We would like to thank USAID/OFDA, which supported the project and introduced the state-of-the-art technology to the region. We would also like to thank the experts from NOAA and USGS for providing technical expertise and enhancing the capacity of ICIMOD and its partners in rainfall estimation and its application. ICIMOD and its partners are committed to working together on disaster risk reduction and flood forecasting to minimise the adverse impact of floods in the region. Technical advances in flood forecasting and management like that described here, offer further opportunities for mutually beneficial regional cooperation in disaster risk reduction.

Andreas Schild
Director General, ICIMOD

Satellite Rainfall Estimation in the Hindu Kush-Himalayan Region

Introduction

The need for rainfall data in the Himalayan region

The Hindu Kush-Himalayan (HKH) region extends 3,500 km from Afghanistan through Pakistan, China, Nepal, India, Bangladesh, Bhutan, and Myanmar and is the water tower of South Asia. The Indus, Ganges, and Brahmaputra rivers originate from the Tibetan Plateau to the north of the region and flow through several countries before reaching the ocean. These river basins are home to more than 600 million people and the rivers meet their needs for drinking water, irrigation, hydropower, fisheries, inland navigation, and the sustenance of wetlands and biodiversity. However, these rivers also pose a threat of riverine and flash floods, especially during the monsoon period when they overflow their banks and cause recurrent extensive loss of life and property. Flooding poses severe constraints on socioeconomic development and investment in agriculture, infrastructure, and industrial production; high rates of poverty and population growth force people to live on floodplains increasing their vulnerability to flood disaster. Management of floods is vital; reducing the adverse impacts of floods will help to reduce poverty and save lives.

Floods of different extent occur every year in the Ganges-Brahmaputra-Meghna (GBM) and Indus basins. About 55% of all flood damage in India occurs in the Ganges and Brahmaputra basins (Hoque 1995). Of the total estimated flood-prone area in India, about 68% lies in GBM states, mostly in Assam, West Bengal, Bihar, and Uttar Pradesh. Among India's states, 8.1% of Uttar Pradesh is flood prone, 8.2% of Bihar, 9.4% of West Bengal, and 13.1% if Assam (Hofer 1998). About 80% of Bangladesh is prone to floods and every year at least one-third of the country's territory is affected (Hoque 1995). Over the last 30 years South Asia has experienced more than 65,000 deaths and about a billion people have been affected by floods and landslides. This accounts for around 33% of all flood events in Asia. The India and Bangladesh floods of 1998 caused over 2,600 deaths, displaced 25 million people, and caused an estimated US$ 3.4 billion of damage. In 2007, floods in India, Nepal, and Bangladesh caused more than 3,400 deaths, affected 30 million people, and caused an estimated US$ 5 billion in economic damage. The impact of floods can only rise as the population in floodplains grows and the value of infrastructure increases. Reliable and timely flood forecasting and warning are some of the most effective non-structural measures to minimise the loss of life and adverse socioeconomic impacts of floods.

Precipitation is an important component of the hydrological cycle, and accurate rainfall estimates are necessary not only to improve weather forecasts and climate prediction, but also for timely flood forecasting and warning. However, estimating rainfall accurately in the HKH is a challenging task due to the intense seasonal rainfall, the scarcity and uneven distribution of real-time rain-gauge data, the large areas of unpopulated, rugged terrain with limited distribution and numbers of hydrometeorological observation stations, and complex transboundary issues. In mountainous areas, the rain-gauge network is sparse and the information unreliable. The distribution of rain gauges is insufficient in most cases to provide the detailed perspective on spatial distribution of rainfall which is needed to apply modelling techniques. The existing network of stations is inadequate to capture accurately the highly varied nature of rainfall in the region. Accurate quantitative documentation of regional rainfall analysis (gridded data) remains a challenging task because of the large spatial and temporal variability of rainfall and the lack of a comprehensive observation system.

Satellite rainfall estimation

Recently, methods have become available for making accurate estimates of rainfall using supplementary information from satellite observations – 'satellite-enhanced rainfall estimates'. Data derived from an array of space-based meteorological sensors is used to enhance rainfall measurements from conventional surface-based rain gauges. Conventional gauge data are first used to calibrate the satellite-based information, which increases accuracy. Once calibrated, satellite observations become one of the easiest ways to estimate total rainfall over a large region or watershed. Satellite rainfall estimation (SRE) provides information on rainfall occurrence, amount, and spatial distribution over the region. Advanced remote-sensing tools and techniques like SRE can provide reliable and timely data to supplement conventional gauge data and fill in data gaps, allowing floods to be forecast with greater accuracy. With sufficient lead time, people can evacuate to safer places, thereby reducing the loss of life and property. The use of satellite-derived quantitative rainfall estimate technology can be crucial for obtaining rainfall patterns to use in hydrological models to forecast discharge, study hydrological cycles, plan water management, identify flash floods, and monitor drought in the HKH region.

The last two decades have produced a great deal of research on methods for estimating rainfall from infrared (IR) and microwave satellite observations, and now there are several operational and semi-operational satellite algorithms available from national centres and universities to produce rainfall estimates for time periods ranging from half-hourly to monthly. The great advantage of space-based precipitation estimates is their global coverage, providing information on rainfall frequency and intensity in regions that are inaccessible to other observing systems such as rain gauges and radar. The disadvantage is that they are indirect estimates. It is therefore important to establish their accuracy and expected error characteristics by validating the satellite precipitation estimates against ground measurements from rain gauges or radar observations. A thorough verification of satellite-based precipitation products will make it possible to quantify their accuracy in a wide range of weather and climate regimes, give users information on expected errors in the estimates and in which applications a given model should be used, help developers understand the strengths and weaknesses of the algorithms and monitor their performance, and assist with evaluating algorithm upgrades.

Until now, it has been difficult to use traditional flood forecasting systems across the HKH region because of the paucity of ground-based hydrometeorological data collection networks, significant delays in data availability in some countries, and limited sharing of hydrometeorological data across international borders. Satellite-enhanced rainfall estimation appears to offer an effective and viable alternative means for estimating precipitation. Satellite-improved rainfall estimates for the HKH region delivered in a timely fashion will facilitate the use of regional flood-information systems. These estimates, enhanced by gauge data, will improve rainfall analyses that are currently interpolated solely from sparse rain-gauge data, and will lead to value-added agricultural and hydrological applications such as crop monitoring and flood forecasting. Mitigation measures for weather-related disasters will thus be able to use more accurate and timely information in the decision-making process.

The NOAA satellite rainfall estimation system

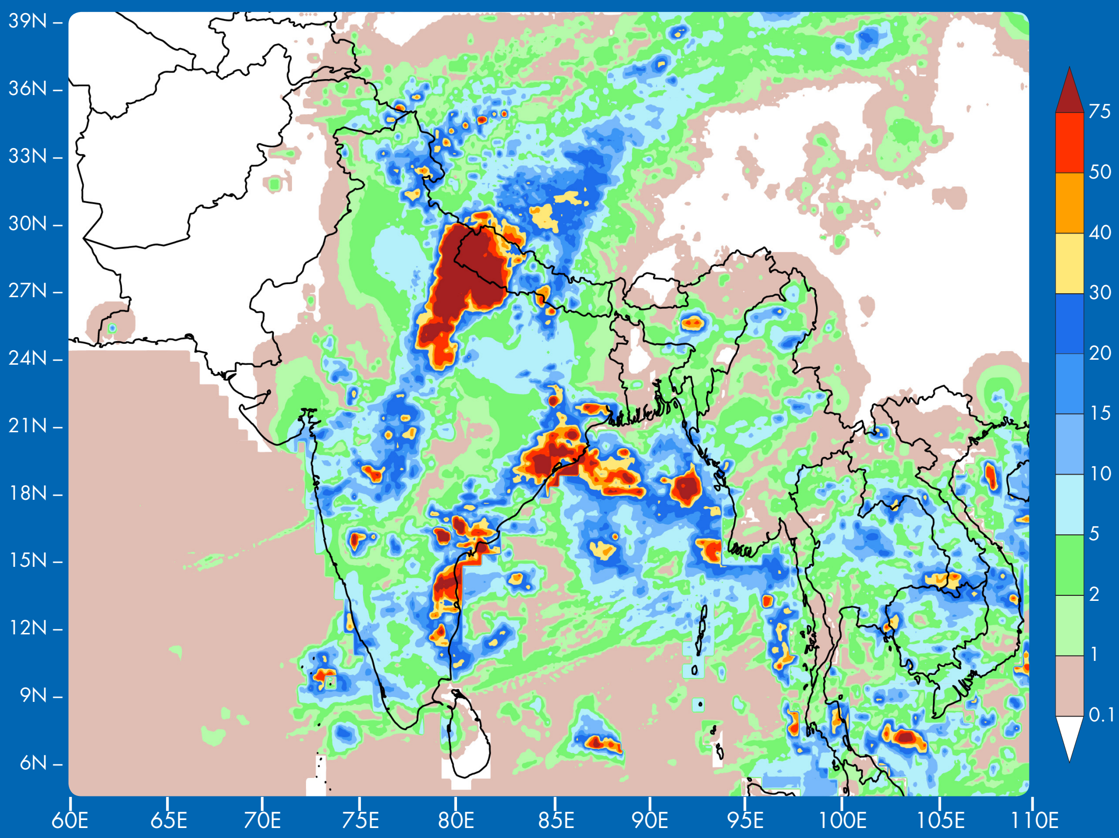
The Climate Prediction Center (CPC) of the National Oceanic and Atmospheric Administration (NOAA) has developed a system known as CPC-RFE2.0 to estimate rainfall for the entire globe, including the Hindu Kush-Himalayan region, at a spatial resolution of 0.1° by 0.1°. The CPC-RFE2.0 uses a merging technique for satellite-based rainfall data and ground gauge data from the Global Telecommuinication System of the World Meteorological Organization that increases the accuracy of rainfall estimates by reducing significant bias and random error compared to individual data sources. Before these estimates can actually be used in modelling, however, they must be tested and optimised to ensure that they really reflect the situation on the ground. This system has produced an automatic rainfall analysis in South Asia since May 2001, but without validation. The system has been validated successfully for regions in Africa, and is now being validated in South Asia.

The ICIMOD Satellite Rainfall Estimation Project

ICIMOD has collaborated with regional partner countries since 2001 on a long-term project 'Regional Cooperation in Flood Forecasting and Information Exchange in the HKH Region' funded by the United States Agency for International Development Office for Foreign Disaster Assistance (USAID/OFDA). As a part of the project, ICIMOD shared 24-hr, 48-hr, and 72-hr rainfall forecasts over the HKH region, made available by OFDA, with all its partners during the monsoon of 2004. Partners' requests for training on satellite rainfall estimation led to workshops in 2005 and 2006 that transferred the NOAA and US Geological Survey (USGS) technology in SRE to the partners. During the 2005 training workshop, participants prepared national implementation plans. The 'Application of Satellite Rainfall Estimation in the Hindu Kush-Himalayan Region' project was developed to support implementation of these plans. This is a regional project implemented jointly by ICIMOD and its partner countries Bangladesh, Bhutan, China, India, Nepal, and Pakistan; Phase I commenced in June 2006. Technical support is provided by experts from NOAA and USGS; ICIMOD provides overall coordination, guidance, regional analysis, and administration; financial support is provided by USAID/OFDA. The overall objective is to strengthen regional cooperation in data and information exchange and to build the capacity of partner institutions in satellite rainfall estimation and its use. The end goal is to minimise the loss of lives and property by reducing the natural vulnerability in the HKH region (riverine floods, flash floods, drought, climate change), in particular in the Indus, Ganges, and Brahmaputra basins.

The specific aim of the satellite rainfall estimation project is to validate a model developed for the Himalayan region by refining NOAA's CPC-RFE2.0 system, and to test a streamflow model (GeoSFM) developed by the United States Geological Survey (USGS) for flood hazard monitoring. The CPC-RFE2.0 produces an automatic daily rainfall analysis for southern and eastern Asia using satellite data and ground-based information (Xie et al. 2002). The results are updated three

Figure 1: **CPC-RFE2.0 satellite rainfall estimate for South Asia (NOAA/CPC precipitation estimate (MM): based on GPI, SSM/I, AMSUB & GTS 09/20/2008)**



CPC RFE Version 2.0 - Expanded ASIA

times daily and cover a cumulative 24-hour period of rainfall. The domain of the model has been expanded over the HKH region, but needs to be validated against ground measurements from rain gauges to determine its operational viability and to improve its accuracy and applicability. Figure 1 shows an example of the daily satellite rainfall estimates provided by CPC-RFE2.0.

The GeoSFM is a spatially distributed, physically based hydrological model developed by the USGS and used for wide-area flood risk monitoring; it employs remote sensing data together with widely available global datasets related to topography, soils, and land cover (Artan et al. 2007a; Asante et al. 2007). The rainfall estimates are used in the GeoSFM model to find out whether they can be applied in flood forecasting.

The methodology of the SRE validation was developed based on a review of the literature on validation conducted for similar projects in other regions. The independent rain-gauge data were screened and subjected to rigorous quality control prior to using them for analysis. The validation was done at both national and regional levels. Most of the national level validations considered the whole of a country as a single homogeneous unit. At a regional level, the HKH region was divided into summer and winter monsoon dominated areas, and analysis was performed at a 0.1° x 0.1° spatial resolution and temporal accumulation of 24 hrs. The krigging interpolation technique was used to convert point rainfall to aerial. Observed and estimated rainfalls were compared using both visual and statistical analysis (Ebert 2007).

Summary of Results

The project engaged government representatives of national hydrological and meteorological services, and organisations involved in flood-disaster management in each participating country. It fostered discussions and dialogue among the participating countries and contributed towards strengthening the capacities of partner institutions in applying satellite rainfall estimates to flood forecasting. The major achievements of the project are summarised in the following.

Sharing of data and information

The project enabled the collection of meteorological and hydrological data from all six member countries and encouraged data sharing among the countries. A meta-database was prepared with details of 422 measuring stations in the HKH areas of Bangladesh, Bhutan, China, India, Nepal, and Pakistan.

Strengthening of national and regional capacity

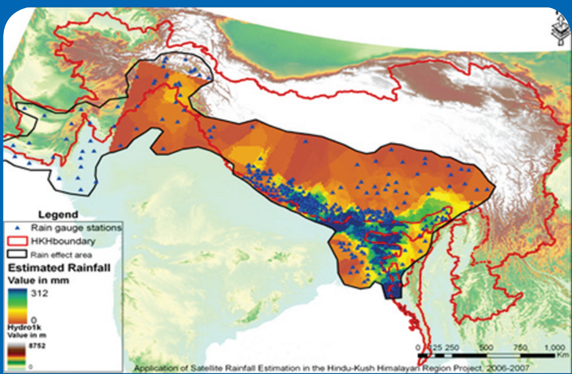
The project introduced and trained the national partners in satellite rainfall estimation, an area new to most of them. It succeeded in transferring state-of-the-art technology to the partner countries. The countries also agreed to work together and exchange expertise, which is an important step towards improving regional networking.

Satellite rainfall validation

The project used archived rain-gauge data to validate selected satellite rainfall estimates made at the same time as the gauge measurements were taken. At a regional level, the analysis considered the HKH as one homogenous region, as shown in Figure 2, and also partitioned the region into summer-monsoon dominated and winter-monsoon dominated areas using data from 422 stations for the validation. The quality of the estimates was assessed using visual analysis as well as continuous verification statistics and categorical verification statistics. Visual verification was subjective and compared maps of satellite estimates with observations. The continuous verification statistics included correlation coefficient, root mean square error (RMSE), bias, and percentage error, to provide a quantitative assessment for each set of validation data (Ebert 2007). The categorical verification statistics were qualitative and included probability of detection (i.e., events diagnosed correctly) and false-alarm ratio (which detects non-events). The correlation was best on high rainfall days and lowest on minimum rainfall days with an underestimation on high rainfall

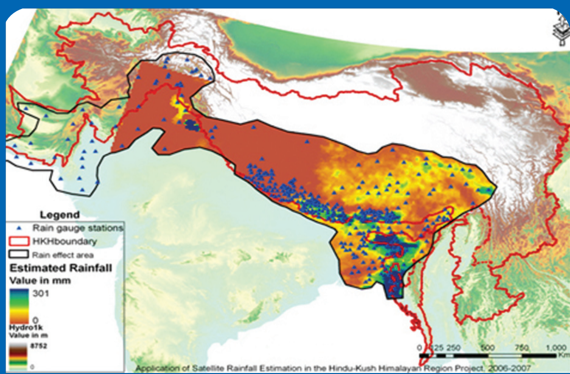
Figure 2: **Regional validation analysis maps for the Hindu Kush-Himalayan region**

Observed rainfall from raingause stations,2002204, Regional

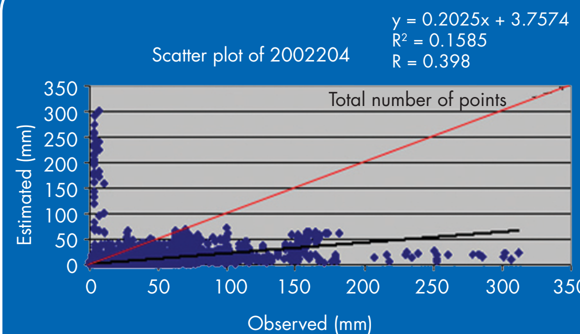


Rainfall 0mm 312mm

Estimated rainfall from NOAA, 2002204, Regional



Rainfall 0mm 301mm



Contingency Table

		Estimated	
		No Rain	Rain
Observed	No Rain	516	14
	Rain	4234	7337

Bias = -11.4
RMSE = 28.44
Skill = 0.7487
CORR = 0.398

Probability of detection (POD) = 0.716
False alarm ratio (FAR) = 0.02

	Observed	Estimated
Number of points:	12101	12101
Raining points:	11571	7351
Mean rain total:	19	8

days and an overestimation on low rainfall days. The root mean square error was higher on high rainfall days and lower on low rainfall days. Rainfall was underestimated by about half in monsoon during heavy rainfall and more than half in monsoon during moderate rainfall. The algorithm captures active monsoon and break in monsoon, but does not accurately detect the process related to mountains (orography). Some statistics showed that the RFE estimates improved when the region was divided into winter and summer monsoon dominated areas. In the summer monsoon dominated areas the RFE estimates were low compared to observed data, while in the winter monsoon dominated areas rainfall was overestimated. Investigating gaps and shortfalls, particularly related to mountain orographic processes, will increase the technique's application and usefulness in the region

At a country level, the partner countries themselves conducted preliminary validation considering each country as a single, homogeneous unit. The preliminary results show underestimation of rainfall in intense rainfall periods and wet regions and overestimation of rainfall in rainshadow and arid areas. In general the rainfall events matched qualitatively when spotting extreme rainfall, but quantitatively there were some differences. This finding was true in the cases of Nepal, Bhutan, and the Tibet Autonomous Region of China.

The results indicate that the CPC-RFE2.0 provides reasonable rainfall estimates over the HKH region but needs to be improved before it can be implemented for operational flood forecasting.

GeoSFM modelling

The GeoSFM model was tested in Phase I of the project. The NOAA/CPC-RFE2.0 rainfall estimates and globally available soil and land cover datasets (the Digital Soil Map of the world from FAO and the USGS Land Cover dataset) were used as an input to the GeoSFM model. This approach is mainly useful in countries where the density of hydrological stations is sparse and the data sets available to support flood forecasting and flood hazard monitoring are limited. The GeoSFM simulates the dynamics of numerous rainfall-runoff models and blends remotely sensed and in-situ data of basin physical parameters and dynamic forcing variables (Artan et al. 2007b). Further work on the application is required before the model can be used for flood forecasting purposes.

The Bagmati and Narayani river basins in Nepal were tested for the national level, and the Brahmaputra basin (shared among Bangladesh, Bhutan, China, and India) for the regional level. Uncalibrated runs were made for the Brahmaputra basin, and the variation of the flow along the river from the Tibet Autonomous Region of China to Bangladesh was studied. The flows at the highest gauging station, Nuxia, and the downstream stations of Nughesa, Pasighat, and Panda were 15%, 36%, 46%, and 81% respectively, of the flow at the lowest station, Bahadurabad. There was a good correlation between the simulated and observed discharge at Bahadurabad, Bangladesh, for the period 2002-2004 (Figure 3), with correlation values of 0.84 for 2002, 0.79 for 2003, 0.85 for 2004, and an overall value of 0.82. In general the simulated discharges followed the trend of the observed values quite well, although there was some difference in the magnitude of the flows as demonstrated by the Brahmaputra and Bagmati Basin simulations (Shrestha et al. 2008).

Results of the model with estimates from 2002, 2003, and 2004 in the Bagmati basin at Pandhera Dovan

As three years of daily discharge data were available, 2002 to 2003 were used as the calibration period and 2004 for validation. The comparison of observed and simulated hydrographs from the model is summarised in Figure 4. The years 2002 and 2003 show reasonably good agreement between the observed and simulated flows. The Nash-Sutcliffe coefficient of efficiency (NSCE) was 0.23 with a correlation of 0.59. The RFE time series was too short (available only from 2002) to fully calibrate a continuous hydrological model.

Using the same parameters from the calibration period, the GeoSFM was run using the 2004 RFE values. The peak flows predicted in 2004 were extremely low compared to the observed flows, as shown in Figure 5; in other words the performance of the validation period was not satisfactory. There are several possible reasons: the calibration period 2002 to 2003 may not have been appropriate or long enough; the data may not have been of high enough quality; and the 2004 RFE might have significantly underestimated rainfall, amplifying any error.

Figure 3: **Observed and simulated flows of the Brahmaputra River at Bahadurabad station in Bangladesh**

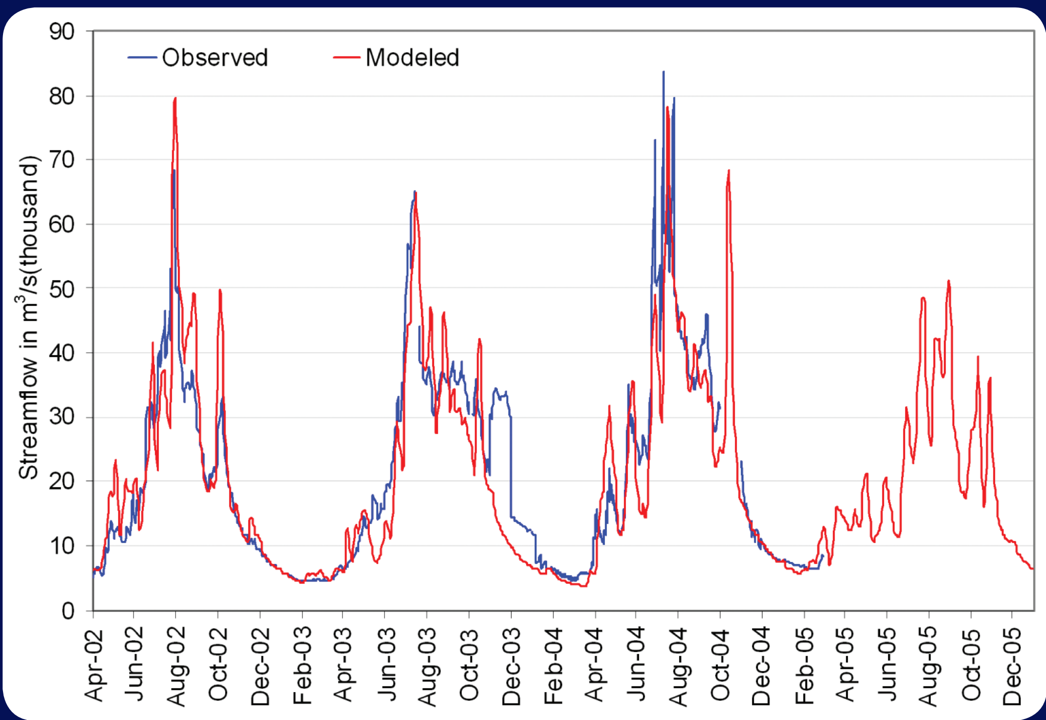


Figure 4: **Observed and simulated flows of the Bagmati river at Pandhera Dovan using RFE from 2002 to 2003 (calibration)**

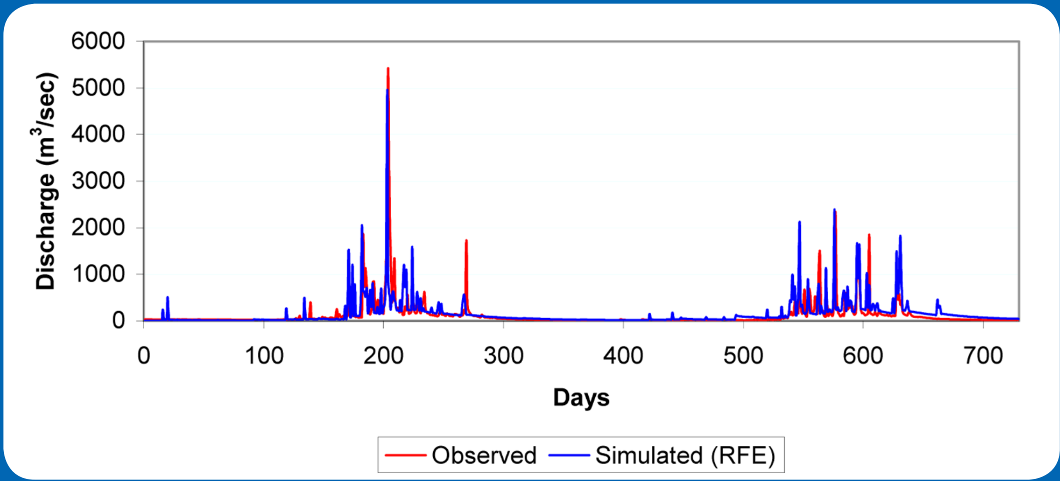
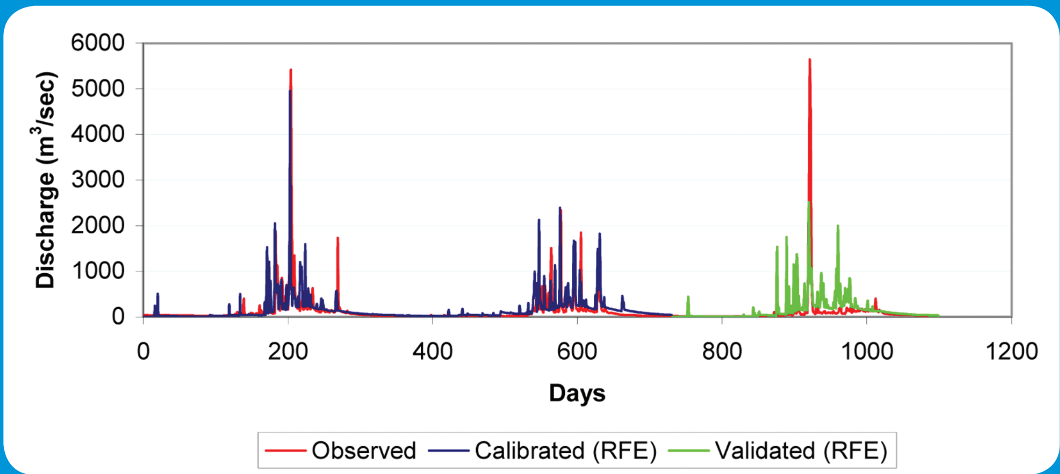


Figure 5: **Observed and simulated flows of the Bagmati river at Pandhera Dovan using RFE for 2004 (validation)**



The Road Ahead

Given the regional geo-political constraints to collaboration on water issues and the sensitivity of hydrometeorological data, the degree of cooperation achieved through the project was very encouraging and suggests the usefulness of a follow-up project (Phase 2). The preliminary results suggest that it will be useful to proceed with improving the model parameters and calibrating and validating SRE for application to flood forecasting. Most country-level validations considered the country as a single, homogeneous unit. Phase II should include further rigorous validation at country level, as well as validation for different rainfall regimes and for sub-national domains. The improved rainfall estimates can then be used in modelling and flood forecasting processes. Investigations related to orographic processes will also be conducted to evaluate further applications and usefulness in the region.

CD-ROM

The full report is provided on the CD-ROM included with this publication.

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