Development of Flood Forecasting System for the Wangchhu River Basin in Bhutan

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Abstract

In mountainous countries like Bhutan, floods are potentially serious dangers for communities since they trigger subsequent hazards such as landslides. The countries lying in the Himalayan Mountain are exposed to floods owing to the heavy rainfall and glacial lake outburst floods. The forecasting of catastrophic flood hazards is crucial for the sustainability of these mountainous countries. At the same time, the hydro-met observation system is inadequate to set up a robust flood-forecasting model in Bhutan. This paper focuses on developing a flood forecasting model for the Wangchhu river basin in Bhutan, by assimilating the hydrological gauge data and satellite rainfall, and by providing stream flow frequency, rating curve and stream characteristics of the Wangchhu basin. The study depicts the poor efficiency without upstream rainfall gauges. Using satellite database with proxy stations in the upper catchments increase the accuracy of the model. The Weather Research Forecast (WRF) model generated 3-day rainfall forecasts, which were used to generate flow forecasting. The WRF result for Bhutan is poor; thus, other sources of rainfall prediction need to be incorporated in the model. The model has been calibrated for 2003-2004 and validated for 2005, 2009 and 2010 data.

Keywords: floods, flood forecasting, hydro-met

1. Introduction

The Kingdom of Bhutan is a small mountainous country approximately 300 km long and 150 km wide with an area of 47,000 sq. km (Bawa and Kadur, 2012). The altitude ranges from 160 m in the southern foothills to 7541 m high in the northern high mountains. Bhutan is prone to flooding and landslides. A combination of steep topography and the projected increase in rainfall in the coming decades poses major natural hazards, particularly during the monsoon season. The currently abundant water resources of Bhutan will need careful management as demand grows from the expanding hydropower sector and an urban population (Baillie and Norbu, 2004). Flood forecasting plays an important role in Bhutan for saving people's lives and reducing property damages.

The main water resources in Bhutan are primarily in the form of rivers. There are quite a few lakes, but they are mostly small and located in the remote high-altitude alpine areas, and thus are of not much economic utility. The rainy and dry seasons result in large seasonal variations in river flows (IPCC, 2013). Some of Bhutan's lakes are glacial lakes, and occasional outbursts from them have resulted in enormous flash floods, leading to significant damage to lives and property (Clague and O'Connor, 2015)

1.1 River Basins in Bhutan

According to the National Environment Commission (NEC, 2014), Bhutan's water resources are drawn from four major river basins: Amochhu, Wangchhu, Puna-Tsangchhu and Manas River (Figure 1). There appear to be different interpretations of what should be considered the main river basins. Some reports speak of three basins, NEC (2014) refers to four basins, and the Watershed Management Department (WMD) refers to five main basins and two minor ones (ADB, 2014). They all originate from the high-altitude alpine area and the perpetual snow cover in the north, and then flow into the Brahmaputra River in the Indian plains. Due to the topographic nature of the country, the major rivers flow north to south, right down to the tropical zone on the border with India. While most of them originate in Bhutan itself, a few of them have their origin in China. These rivers have steep longitudinal gradients and narrow precipitous gorges, which occasionally open up and provide broader valleys

with small areas of flat land for cultivation. Some of the main rivers have cut 1,000 m deep valleys through the mountains (WMD, 2011). The biggest river basin is the Manas River, which drains almost all of the catchments of Central and Eastern Bhutan. The total length of all rivers, with their tributaries, in Bhutan is about 7,200 km (Liu et al., 2012).
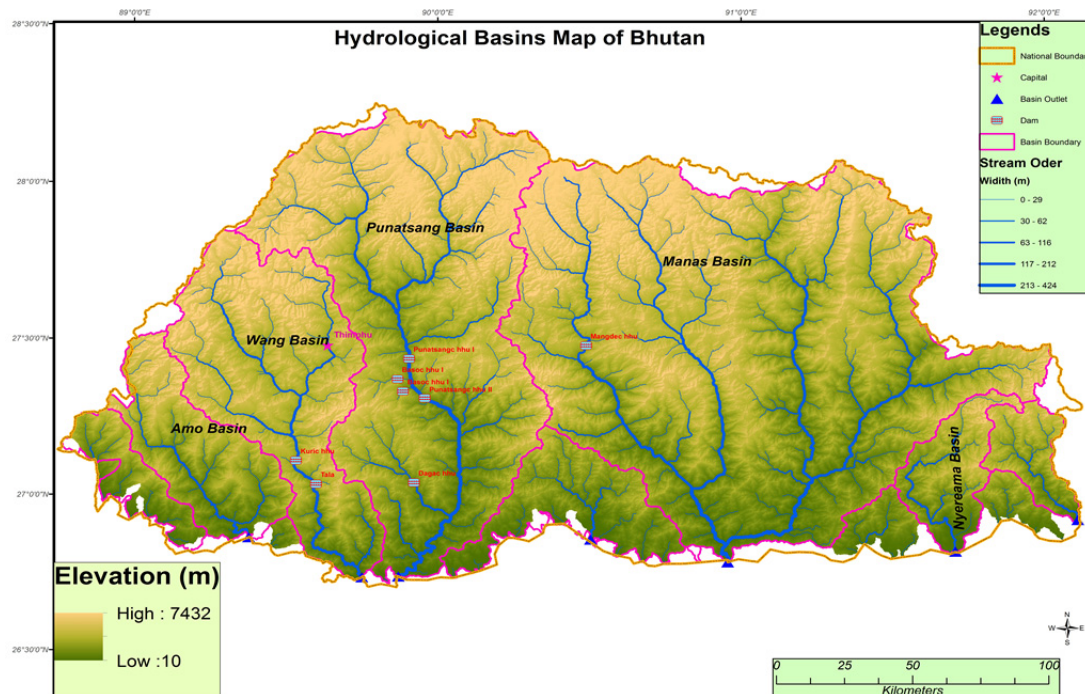

Figure 1. River Network System in Bhutan

The flow regime in Bhutan is relatively stable in that the year-to-year variations in minimum, average and maximum flow are relatively small compared to what is experienced in many other parts of the world (SAF, nd). Unlike other countries with very high population density, there are few people who settle along riverbanks in areas subject to regular flooding (Elalem and Pal, nd). Nevertheless, flash floods carrying large amounts of boulders and debris, and other types of flooding, cause substantial damage and loss of lives in Bhutan (Westoby, Glasser et al., 2014). The most severe floods reported in the past include a glacial lake outburst flood (GLOFs) in 1994 and a flood due to Cyclone Aila in 2009. However, only three GLOFs have been reported; all of them took place on the Puna-Tsang Chhu and were due to outbursts of glacial lakes in the Lunana area. There are 2,647 glacial lakes in Bhutan, and 24 of them pose a high risk for a GLOF. There have been various flood incidents in Bhutan. For example, the 1994 flood in Punakha was triggered due to the Lugge lake outburst in the Lunana region (Dey, 2002). That flood contained 18 million cubic metres of water, killed 22 people, and damaged 1,700 acres of agriculture, pastureland, and public infrastructure.

In the year 2000, flash floods triggered by monsoon rains, particularly in southern Bhutan along the border with India, severe floods were observed at Barsachhu, Dutikhola (small catchments) and Amo chhu sub-basins, which has caused severe damage to lives and properties. In general, the regions that are most affected by floods in Bhutan are the Phochu, Mochu in the northern part of the country, and the Amo chhu basins in the western part. In 2009, Cyclone Aila originated in the Bay of Bengal and brought unprecedented rainfall and consequent flooding and landslides. Major roads and a number of bridges were damaged, along with other vital public infrastructure. In 2010, landslides and flash floods damaged or washed away more than 2,000 acres of agricultural lands affecting more than 4,000 households in 20 districts (SDMC, 2010).

1.2 Flood Forecasting and Warning System in Bhutan

The Flood Warning Section which is under the Hydro-met Services Division of the Department of Energy is responsible for providing flood warning services. There are flood warning stations on all north-south flowing rivers, which are equipped with HF wireless sets and as back up some stations have telephone lines. Water level information is transmitted to Central Water Commission stations in India and downstream stations in Bhutan. The Thanza Warning Station for GLOF is equipped with a wireless set and a Thuraya satellite phone. The water

level at the junction is measured every hour and transmitted to stations in India and Bhutan. Two stations in Bhutan are on round-the-clock watch. It is not economically viable to protect against all effects of the maximum possible flood for any given river basin. The flood forecasting and warning system needs to be upgraded, along with improved public awareness and information.

2. Study Area, Data and Methodology

2.1Study Area

The Wangchu basin, with a total drainage area of approximately 3,550 sq. km consists of three major tributaries from the three valleys of Thimphu, Paro and Ha (Figure 2). The Wangchu basin is the most populous part of the country with about 3/5 of the total population living in 1/5 of the basin area (Xue et al., 2013). The basin is equipped with one stream flow gauge at the outlet Chhukha Dam Hydrological station and five rain gauge stations.

The northern periphery of the Wangchu basin in the Himalayas has elevations over 6,000 m and maintains an annual snowpack. Lower portions of the basin are drastically different and are subject to a summer monsoon from May to October (Bookhagen and Burbank, 2010). The Wangchhu itself flows south-easterly through west-central Bhutan, drains the Ha, Paro, and Thimphu valleys, and continues into the Duars, where it enters West Bengal as the Raigye Chhu.

The main soil types of the basin includes sandy clay loam constituting around 75%, and the remaining 25% is loam according to the Harmonized World Soil Database (FAO, 2009). The vegetation in the basin consists of evergreen needleleaf forest, which is almost 48% of the total vegetation, other types includes woodland, open shrubland, wooded grassland, and grassland (Hansen et al., 2000). The basin experiences the summer monsoon during the months of May to October and high precipitation during July and August (Bookhagen and Burbank, 2010).
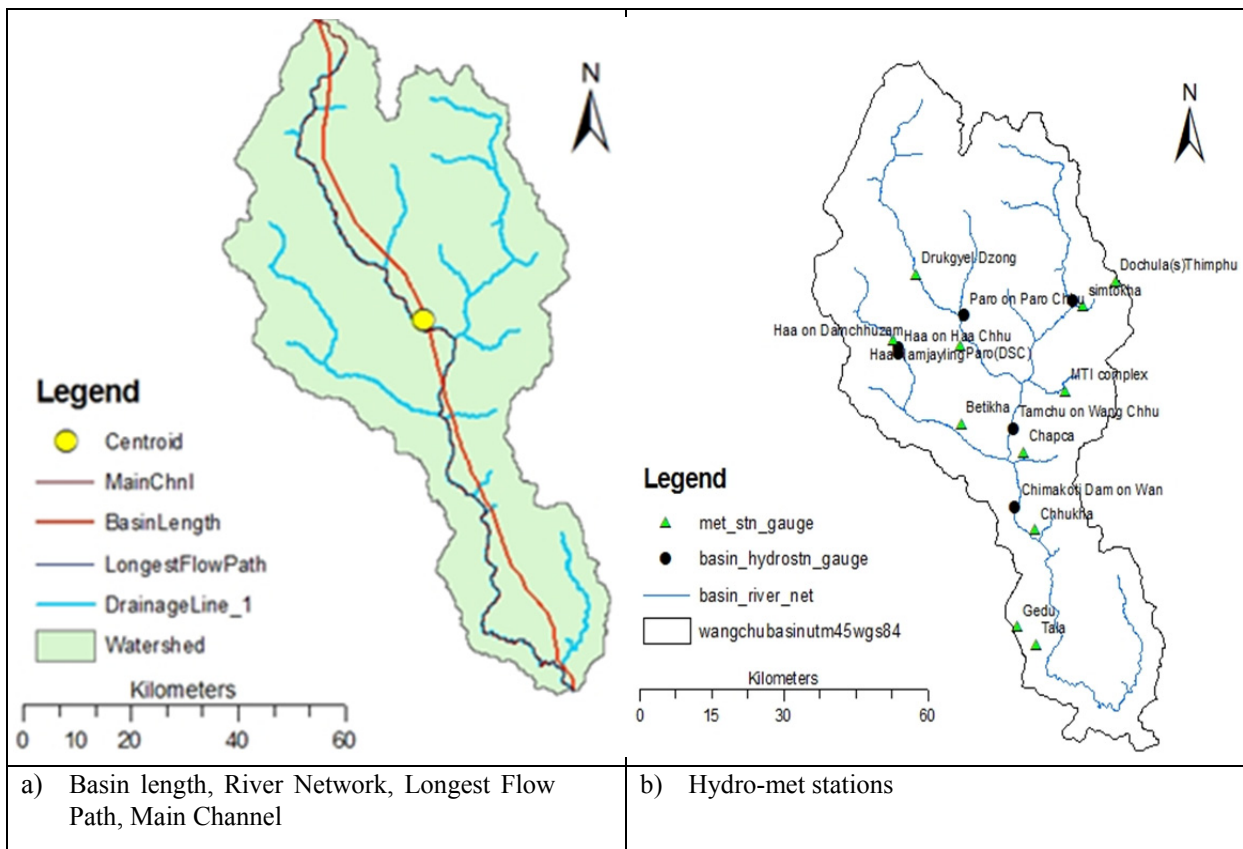

a) Basin length, River Network, Longest Flow Path, Main Channel	b) Hydro-met stations

Figure 2. Wangchhu River Basin and its stations

2.2 Hydro-Meteorological Data

Data used for the study is provided by the Hydro-Met Service Division (HMSD). Daily data (1990-2009) for different stations has been collected from 11 stations in the basin (Table 1). Only the years 1998 to 2008 included data that was common for all stations and used for the model.

Table 1. List of rainfall stations

ID	Station name	Lat	Long	Elevation, m	Remark
12580046	Drukyel Dzong	27.50	89.33	2467	Daily
2740044	Dochula	27.48	89.57	3273	Daily
12700046	Simtokha	27.44	89.68	2504	Daily
12470046	Namjeyling (Haa)	27.39	89.28	2726	Daily
12510046	Paro (DSC)	27.38	89.42	2402	Daily
12820046	MTI Complex	27.30	89.64	3199	Daily
12410046	Betikha	27.25	89.42	2919	Daily
12390046	Chapca	27.20	89.55	2620	Daily
12320048	Chhukha	27.07	89.57	2110	Daily
12220046	Gedu	26.91	89.53	1976	Daily
12210046	Tala	26.88	89.57	1337	Daily

TRMM rain data and daily TRMM 3B42 V6 derived for the period 1998 to 2008 was downloaded (Source: http://disc2.nascom.nasa.gov/Giovanni/tovas/TRMM_V6.3B42_daily.shtml) for the basin. Stream flow and water level data was not regular and has been collected for six stations shown in Tables 2 and 3.

Table 2. List of streamflow measuring stations

Station Name	ID	Period	Lat	Long	Remark
Tamchu on Wang Chhu	12490045	Jul. 2002-2009	27.24	89.53	Daily
Paro on Paro Chuu	12530045	1988-2009	27.43	89.43	Daily
Lungtenphung on Thimp	12800045	1992-2009	27.45	89.66	Daily
Chimakoti Dam on Wan	12350073	1976-2007	27.11	89.53	Daily
Haa on Damchhu	12440045	1991-1999	27.38	89.29	Daily
Haa on Haa Chhu	12460045	2000-2007	27.37	89.29	Daily

Table 3. List water level measuring stations

Station Name	ID	Period	Remark	Lat	Long
Tamchu on Wang Chhu	12490045	1 Jul'02-31 Mar'10	9:00, 15:00 hr	27.24	89.53
Lungtenphung on Thimp	12800045	23 Apr'91- 23 Jan'10	3:00, 9:00, 15:00, 21:00 hr	27.45	89.66
Haa on Haa Chhu	12460045	1 Jan'09-31 Dec'09	Daily	27.37	89.29

Land use data was downloaded from the European Commission Joint Research Center (http://bioval.jrc.ec.europa.eu/products/glc2000/products.php). Soil data was sourced from the Food and Agriculture Organization (FAO). The base material is the FAO/UNESCO Soil Map of the World at an original scale of 1:5 million. (http://www.fao.org/ag/agl/lwdms.stm).

2.3 Methodology

Many indices have been used to analyse flood risk (Bloch et al., 2008; Wang et al., 2008), and focused flood forecasting should undertaken as a major mitigating mechanism. Flood forecasting was carried out using the U.S. Army Corp. of Engineers' (USACE) Hydrologic Engineering Center – the Hydrologic Modeling Software (HEC-HMS). The Geospatial Hydrologic Modeling Extension (HEC-GeoHMS), a software package for use with Environmental Systems Research Institute's (ESRI) ArcMap, was used to create sub-basins (basin merge, locating outlet points, creating basins according to the outlet point, basin divide. etc.) and the hydrologic schematic of the watershed and stream network. Dividing the watersheds into sub-basins was an important step in modeling. HEC-HMS requires the selection of specific processes for losses, including the hydrograph transform method, baseflow type, and routing.

The outlet point was selected since stream flow measuring stations were available downstream. The basin was divided into five sub-basins as shown in Figures 3 representing the main river and tributaries in the Wangchhu River Basin.
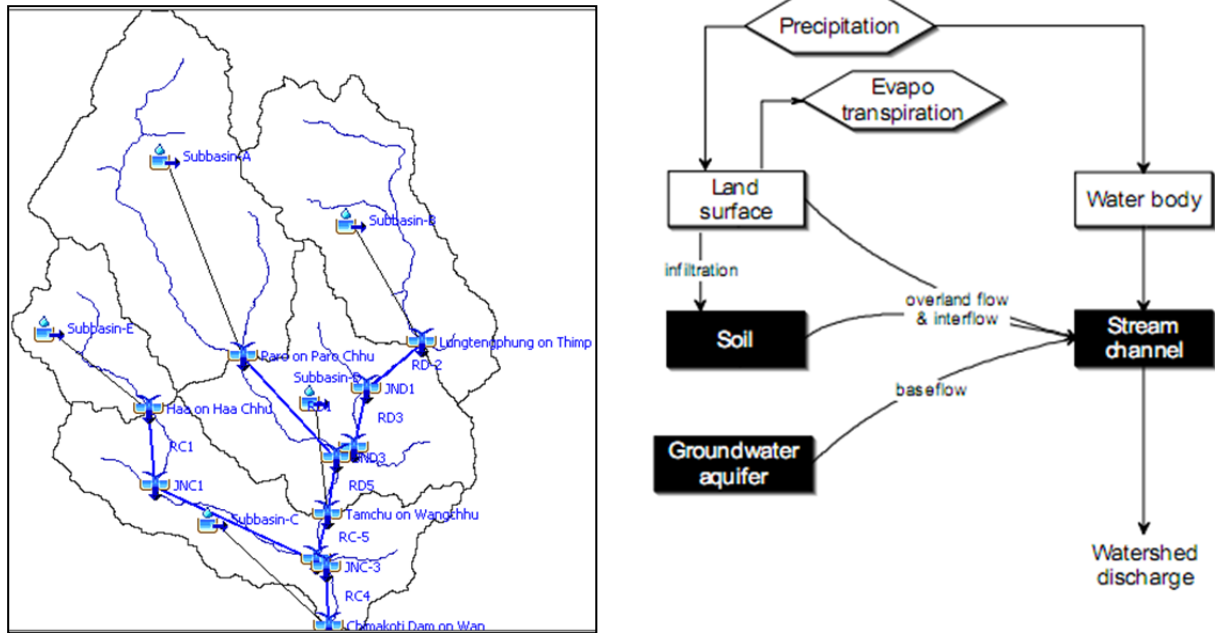

Figure 3. HEC-HMS schematic representation of Wangchhu basin (left), and the typical representation of the HEC-HMS process (right)

Table 4. Basin model, method, and parameters

Model	Method	Parameters
Runoff Volume Model	SCS CN	CN and Ia
Direct Runoff Model	Clark UH	Tc and Sc
Baseflow Model	Constant Monthly	Constant Monthly
Channel Flow Model	Muskingum Routing	Muskingum K and X

HEC-GeoHMS was used to calculate the longest flow path and average slope determination, then the time of concentration was calculated using various methods (e.g. the Kirpich, Kerby, Bransby Williams, and Federal Aviation Agency formulas) and several simulation runs were performed in HEC-HMS using obtained tc values. Finally the values from Kirpich's formula were used.

$$Tc = \frac{0.0078L^{0.77}}{S^{0.385}} \; ; L = \text{longest flow path, ft and S} = \text{slope Tc in min}$$

After identification of soil class and land use of each sub basin Curve Number (CN) was estimated (Table 5). Land use type over selected basin, was used for identification of CN values. Weighted CN value was calculated as per following formula,

$CN weighted = \sum Ai. CNi / \sum Ai$

Ai = Drainage area of the sub-division; CNi= CN value for sub-division

Table 5. Sub-basin derived physical properties

Sub-Basin	HEC-HMS	Area	HSG's	CN	Longest Length	Slope	Kirpich's Method
Name	symbol	Sq. km			m	m/m	Tc, hr
Paro on	A	1019.31	C	73.34	68011.71	0.06	4.90

Paro Chhu Lungtengphung on Thimpu	B	698.20	C	71.24	59021.62	0.05	4.74
Tamchhu on Wangchhu	D	714.85	C	72.19	46514.33	0.05	3.93
Haa on Haa chhu	E	286.41	C	71.84	35268.90	0.07	2.89
Chimakoti Dam on Wan	C	695.04	C	70.95	57633.42	0.04	5.10

Baseflow model is an important parameter for the flood studies. Neglecting the baseflow may result in an underestimate of the outflow. The monthly constant baseflow was used in the model; it was computed from the minimum flow from each river in each month. Muskingum's K and X are estimated via calibration, K is the time of travel (hr) ranging from 0.1 to 150 hr, and X ranges from 0.0 to 0.5.

HEC-HMS meteorological model

Precipitation gauge weights are used in the meteorological model. The Thiessen polygon weight method is used for weighting gauges in this study. The Thiessen polygon was created over the basin using HEC-GeoHMS. After completion of the Thiessen polygon, the upstream area was found to be ungauged. Therefore the first case was to extend the Thiessen polygon towards the ungauged area, and the second case was to add three new points of data from TRMM (Figure 4).
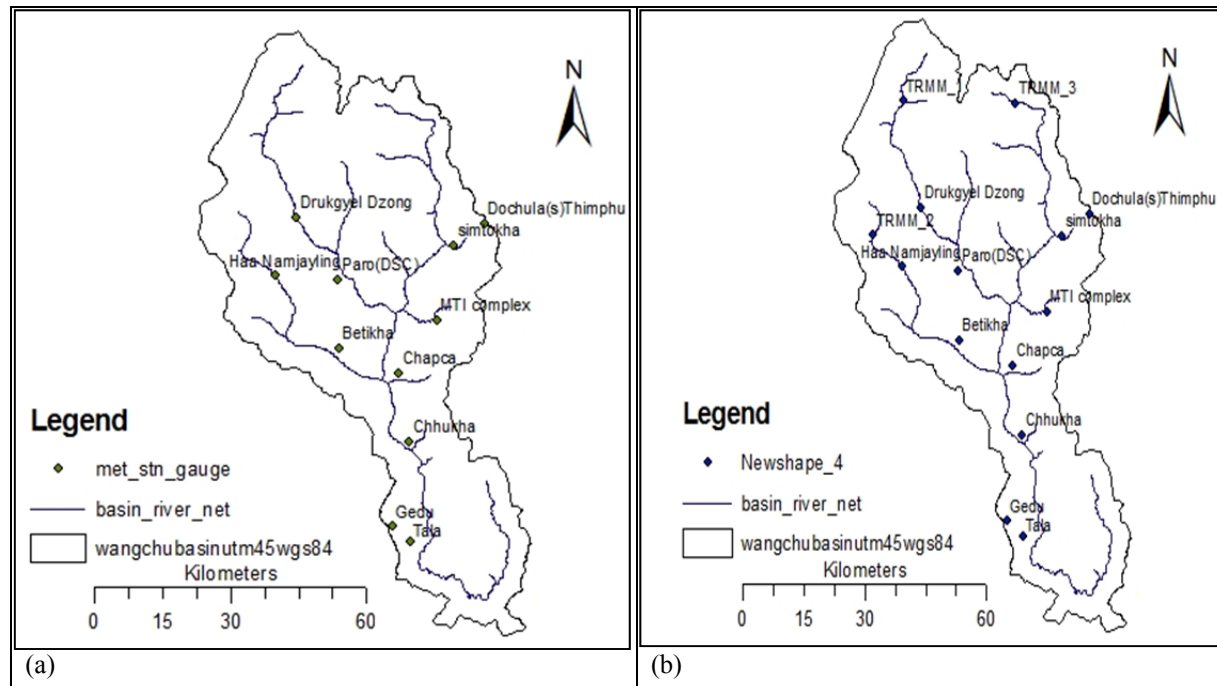

Figure 4. (a) Available meteorological stations, (b) After adding TRMM location

Table 6. TRMM 3B42 V6 derived data locations

Station Name	Lat	Long	Period	Remark
TRMM_1	27.70	89.29	1998-2008	Daily
TRMM_2	27.45	89.21	1998-2009	Daily
TRMM_3	27.69	89.57	1998-2010	Daily

Table 7. Precipitation gauge weights

		Case 1: Extending Thiessen polygon		Case 2: After TRMM data	
Sub basin	Station Name	Gauge Weight		Station Name	Gauge Weight
Sub basin A	Paro	0.062		TRMM_1	0.482
	DD	0.920		Drukyel Dzong	0.399
	Haa	0.017		Namjeyling Haa	0.019

			TRMM_2	0.011
			TRMM_3	0.020
			Paro	0.068
Sub Basin B	Sim	0.427	Dochula	0.116
	Dochula	0.301	Simatokha	0.294
	DD	0.272	TRMM_3	0.586
			TRMM1	0.003
Sub Basin D	Chapca	0.043	TRMM_3	0.016
	Betikha	0.065	Betikha	0.065
	MTI	0.322	Namjeyling Haa	0.006
	Paro	0.366	Drukyel Dzong	0.010
	Haa	0.006	MTI	0.322
	Sim	0.178	Simatokha	0.173
	DD	0.021	Chapcha	0.043
			Paro	0.366
Sub Basin E	Haa	0.661	Namjeyling Haa	0.279
	DD	0.339	TRMM_2	0.687
			Drukyel Dzong	0.034
Sub Basin C	Haa	0.261	Haa	0.260
	Paro	0.019	Betikha	0.351
	Betikha	0.351	Chapcha	0.276
	MTI	0.062	MTI	0.062
	Chapca	0.307	Chukha	0.031
			Paro	0.019
			TRMM_2	0.001

The simulation run is controlled by using control specifications. In both of the cases (case 1 and case 2 as per precipitation gauge weight mentioned in the meteorological model), the simulation run was carried out for the same time span. (Calibration time span; Date: 01Jan2003 to 31Dec2004). Validation is carried out for one year of data due a lack of availability of time series data for rainfall. The validation run time span is from 1Jan2005 to 31Dec2005.

Model performance

The Nash–Sutcliffe model efficiency coefficient (NC) is used to assess the predictive power of hydrological models. It is defined as:

$$NC = 1 - \frac{\sum_0^t (Q_o - Q_c)}{\sum_0^t (Q_o - \overline{Q_o})}$$

Where Qo is observed discharge and Qc is calibrated discharge

Coefficient of Determination (R2): it is the square of the correlation coefficient R. The quantity R, called the linear correlation coefficient, measures the strength and the direction of a linear relationship between two variables.

$$R = \frac{n \sum xy - (\sum x)(\sum y)}{\sqrt{n(\sum x^2) - (\sum x)^2} \sqrt{n(\sum y^2) - (\sum y)^2}}$$

x is observed value and y is calibrated value.

Percent Volume Error (PVE) it is the ratio of the difference between the calibrated volume and observed volume to the observed volume.

$$PVE = \frac{V_c - V_o}{V_o}$$

Where Vc is calibrated volume and Vo is observed volume.

3. Data Analysis

3.1 Rainfall Data Statistical Analysis

TRMM Rain Data and Observed Annual Rain Data for the 11 stations have been compared to select the stations. Based on that statistical analysis of maximum one day rainfall (during the period 1998-2008) has been analyzed.

The annual maximum rainfall data from all stations (except Dochula) was tested for five probability distribution functions, and out of five distribution functions the goodness of fit test of distributions has been ensured by the Chi Square Test and the Kolmogorov-Smirnovo Test at significance level 5 percent. In addition, the least squares were also tested using Standard Error (SE) of Sum of Square Error. The distribution analysis is to be carried out for the method of moments (MOM). The result of goodness of fit of all distribution functions is presented in Table 8. The GAMMA distribution is the best fit; hence the GAMMA distribution of return period rain values can be used for further calculations.

Table 8. Goodness of fit test to annual maximum rainfall

Station Name	Test	N	LN	LP	EV	Gamma	Remark
Betikha	CHI-SQUARE	R	R	R	R	R	
	KOLMOGOROV-SMIRNOV	A	A	A	A	A	GAMMA
	LEAST-SQUARE	30.771	28.402	32.379	27.482	26.603	
Chapcha	CHI-SQUARE	R	R	R	R	R	
	KOLMOGOROV-SMIRNOV	A	A	A	A	A	GAMMA
	LEAST-SQUARE	80.306	66.969	82.980	65.631	59.613	
Chhukha	CHI-SQUARE	R	R	R	R	R	
	KOLMOGOROV-SMIRNOV	A	A	A	A	A	GAMMA
	LEAST-SQUARE	27.755	21.659	22.423	20.850	20.306	
Drukyel Dzongrain	CHI-SQUARE	R	R	R	R	R	
	KOLMOGOROV-SMIRNOV	A	A	A	A	A	GAMMA
	LEAST-SQUARE	14.644	12.204	11.997	11.602	11.298	
MoEA	CHI-SQUARE	R	R	R	R	R	
	KOLMOGOROV-SMIRNOV	A	A	A	A	A	EV
	LEAST-SQUARE	3.084	2.802	2.671	2.628	2.789	
Paro	CHI-SQUARE	R	R	R	R	R	
	KOLMOGOROV-SMIRNOV	A	A	A	A	A	GAMMA
	LEAST-SQUARE	9.373	7.750	7.189	7.314	7.186	
Tala	CHI-SQUARE	R	R	R	R	R	
	KOLMOGOROV-SMIRNOV	A	A	A	A	A	GAMMA
	LEAST-SQUARE	34.707	30.036	28.269	28.581	27.885	
Gedu	CHI-SQUARE	R	R	R	R	R	
	KOLMOGOROV-SMIRNOV	A	A	A	A	A	GAMMA
	LEAST-SQUARE	44.853	37.383	35.842	35.577	34.670	
Namjeyling Haa	CHI-SQUARE	R		R	R	R	
	KOLMOGOROV-SMIRNOV	A		A	A	A	GAMMA
	LEAST-SQUARE	5.599	4.732	4.573	4.496	4.533	
Simtokha	CHI-SQUARE	R	R	R	R	R	
	KOLMOGOROV-SMIRNOV	A	A	A	A	A	GAMMA
	LEAST-SQUARE	5.520	4.234	4.887	4.184	4.601	

N – Normal Distribution, LN – Three Parameter Log Normal Distribution, LP – Log Pearson Type 3 Distribution, EV- Extreme Value Type 1 Distribution, GAMMA- Gamma Distribution.

3.2 Streamflow Statistical Analysis

Streamflow frequency curves have been developed for daily maximum flow events for the period 1992-2007. The annual maximum streamflow data from the Paro, Thimpu, and Wangchhu rivers, which was tested with five probability distribution functions and the Chi Square Test and Kolmogorov-Smirnov (K-S) Test at 5 percent level of significance, ensured the goodness of fit test of the distributions. In addition, the Least Squares were also tested using Standard Error of Sum of Square Errors. The result of all distribution functions is tabulated in Table 9 for each river.

Table 9. Goodness of fit to annual maximum streamflow

Station Name	Test	N	LN	LP	EV	Gamma	Remark
Paro on	CHI-SQUARE	A	-	A	A	A	
Paro Chuu	KOLMOGOROV-SMIRNOV	A	-	A	A	A	LP
	LEAST-SQUARE	12.59	-	10.26	17.75	15.05	

Lungtenphung on Thimp	CHI-SQUARE	A	A	A		A	A	
	KOLMOGOROV-SMIRNOV	A	A	A		A	A	LN, LP
	LEAST-SQUARE	4.82	4.79		4.82	6.34	4.85	
Chimakoti Dam on Wan	CHI-SQUARE	A	A	R		A	A	
	KOLMOGOROV-SMIRNOV	A	A	A		A	A	GAMMA
	LEAST-SQUARE	29.39	27.35	26.90		28.37	26.10	

A= Accepted and R= Rejected at significance level of 5%.

For the Paro River, Log Pearson Type 3 estimates of parameters using the method of moments give the best fit. For Thimpu River, it was the three parameter Log Normal Distribution, and for Wangchhu River, the Gamma Distrbution. Table 9 shows that Log Pearson Type III fit for all three rivers.

3.3 Annual Maximum Streamflow Analysis

An annual maximum streamflow analysis has been carried out using the Bulletin 17B method using the HEC-SSP tool. Bulletin 17B recommends using the method of moments (MOM) to fit a Log Pearson type 3 distribution to the logarithms of the flood series, thereby yielding a log-Pearson type 3 (LP3) distribution to model observed streamflow data. Estimates of the mean, standard deviation, and skew coefficient of the logarithms of the sample data are computed using traditional moment estimators. However, because the data available at a site are generally limited to less than 100 years, and are often less than 30 years, the skewness estimator can be particularly unstable. To address that concern, Bulletin 17B wisely suggests the at-site skew be weighted with a regional skewness estimator, where the recommended weights are inversely proportional to the precision of each estimator. A flood frequency analysis method was developed to address the use of regional skew information, the use of historical flood information, the identification of low outliers, and the adjustment of the flood frequency curve when low outliers were identified. Griffis and Stedinger (2007) show that the LP3 distribution is a very reasonable and flexible model of flood risk within the range of parameter values consistent with U.S. flood series. In addition, Bulletin 17B's use of low outlier detection and censoring algorithm allows the fitting procedure to focus on the distribution of the events of interest large floods with protection that a long lower tail will not distort the description of the distribution of the larger events (Griffis et al., 2004) (Figure 5).
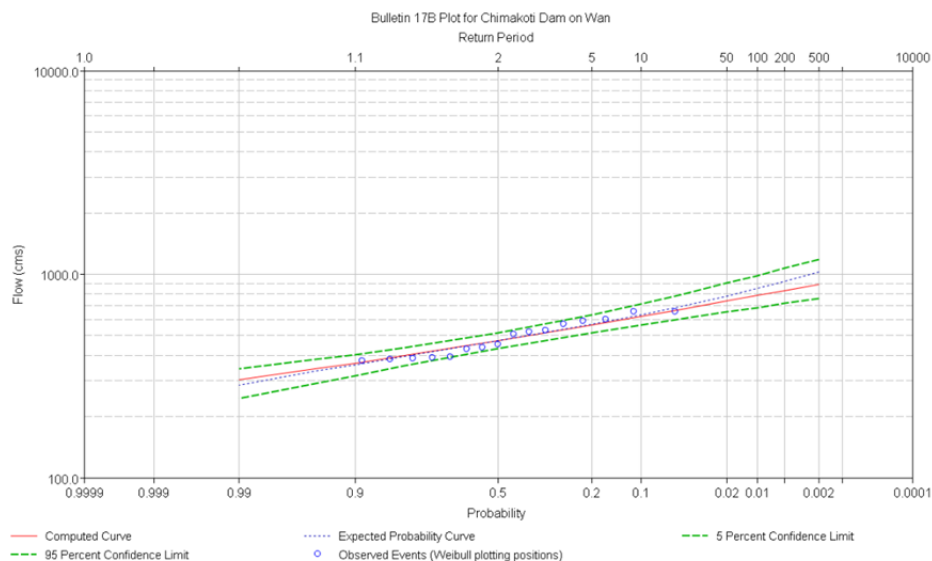

Figure 5. Annual maximum streamflow frequency plot (HEC-SSP) for Wangchhu river

3.4 Rating Curve

Based on the available water level and streamflow data rating curve for the three rivers – Lungtengphung on Thimpu, Tamchhu on Wangchhu, and Haa on Haa Chu River were established (Figure 6).
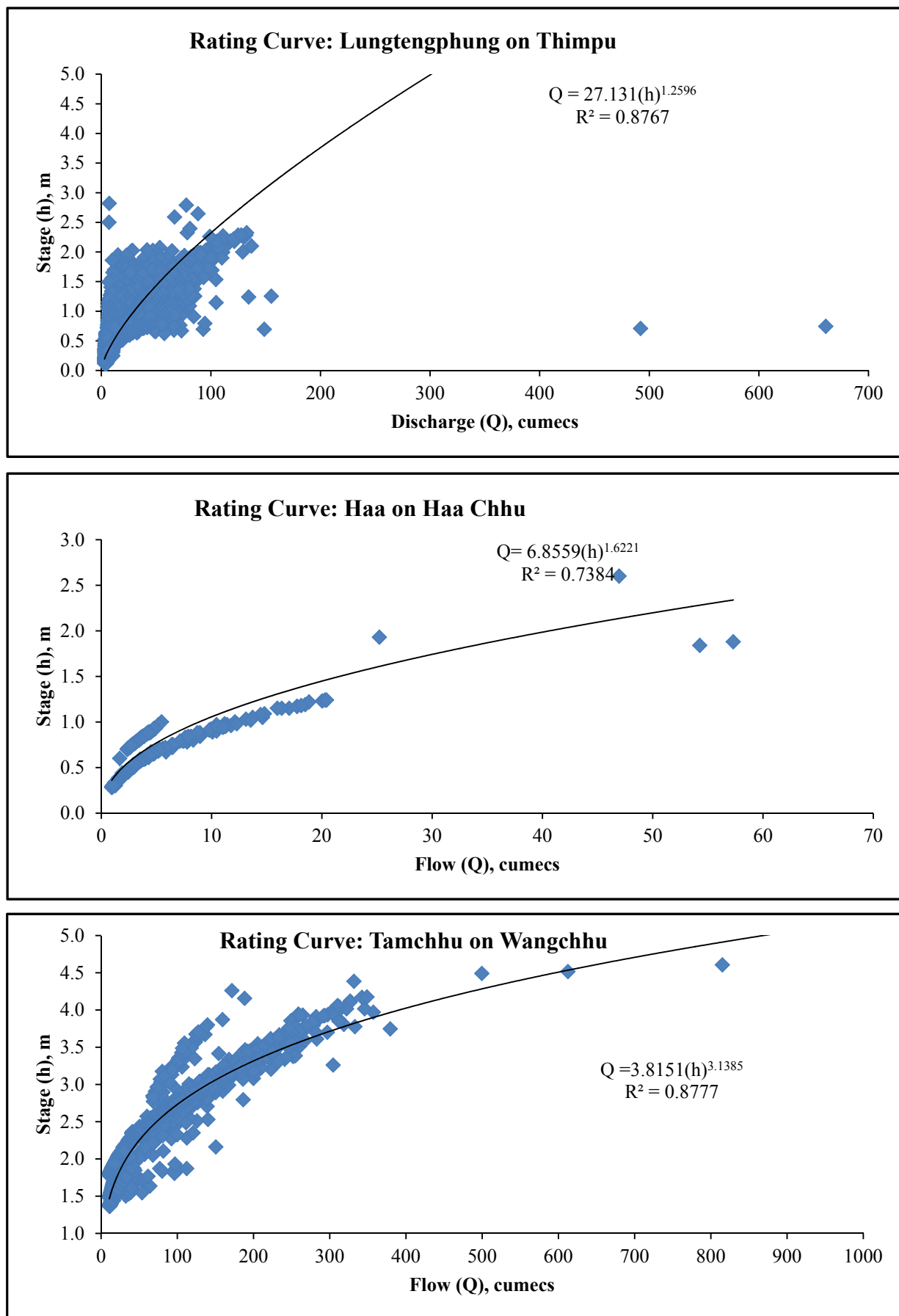
Figure 6. Rating curve at Lungtengphung on Thimpu, Haa on Haa Chu and Tamchhu on Wangchhu

4. Results and Discussion

The result of streamflow frequency analysis (Peak Q, m3/s) (Log Pearson Type 3) for annual maximum streamflow from 1992-2007 were calculated. Model calibration and validation are two important steps in flood forecasting model application. The calibration results (01Jan2003 to 31Dec2004) are presented in Table 10, for case 1 and case 2.

Table 10. Calibration result comparison

		Calibration 2003 – 2004					
		Case 1: Observed Data			Case2: After TRMM and Observed Data		
Location	Sub basin	NC	R2	PVE	NC	R2	PVE
U/S	A	0.55	0.68	6.68	0.67	0.69	-7.60
	B	0.67	0.84	12.32	0.82	0.84	-13.05
	D	0.48	0.77	26.13	0.73	0.80	10.45
	E	0.05	0.73	17.00	0.54	0.73	-3.10
D/S	C	0.57	0.79	19.18	0.71	0.79	9.20

Case 2 shows the good calibration; hence further validation is carried out for the case 2 model. A graphical presentation of the calibrated model, a hydrograph for each sub-basin, is presented in Figure 7.
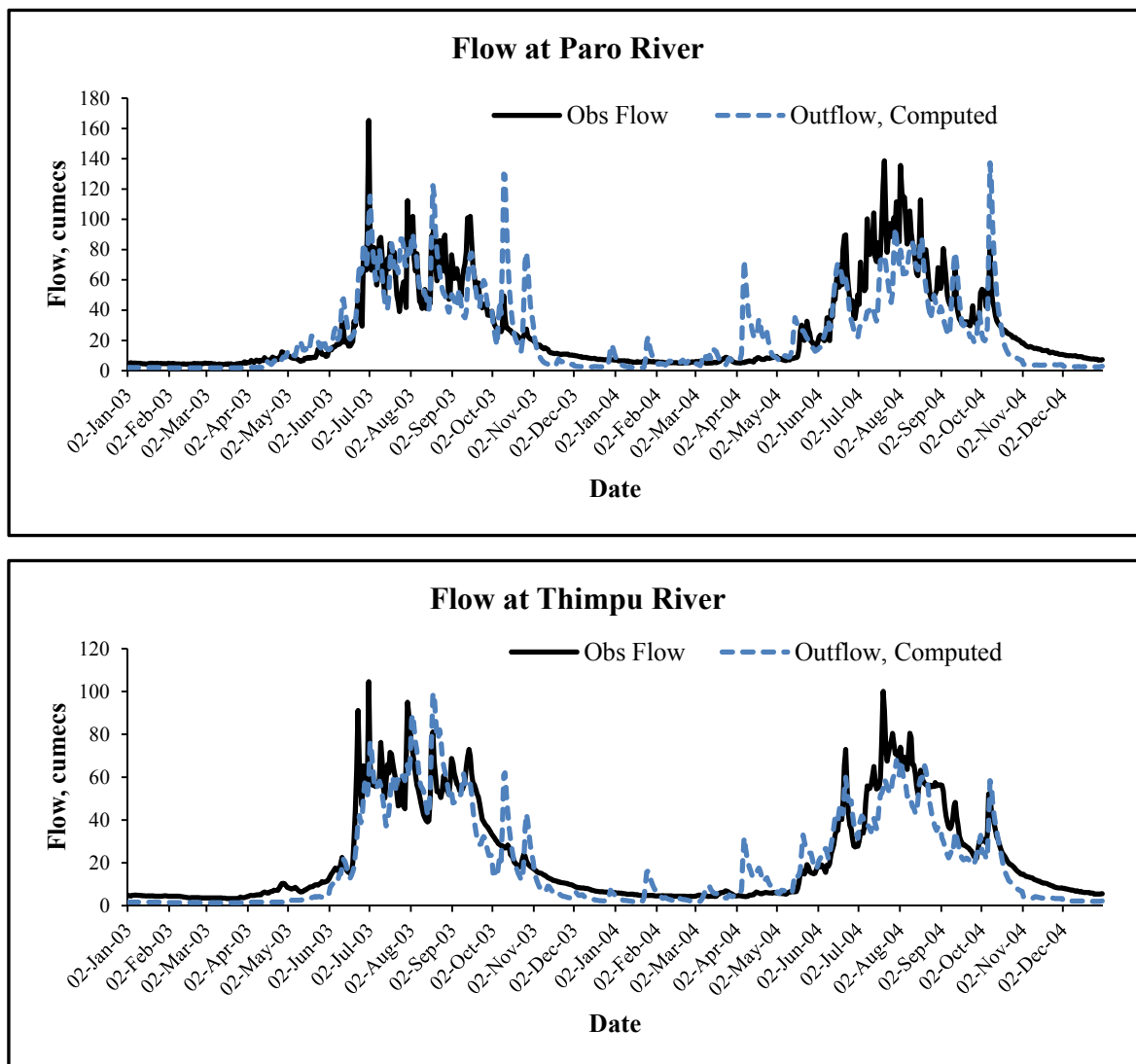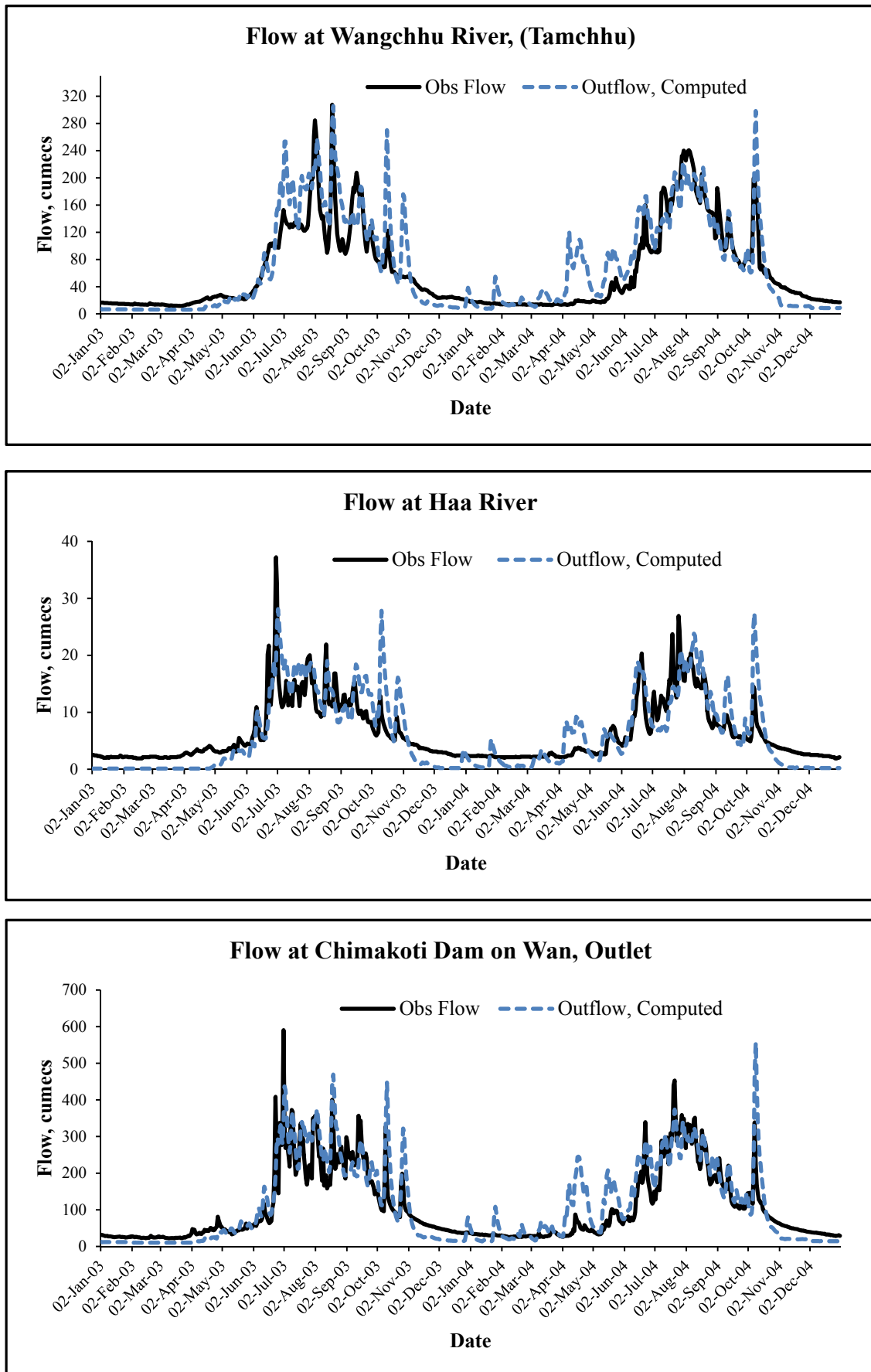
Figure 7. Observed and calibrated hydrograph for all stations

Model Validation

The model was validated using a time series rain and flow data from 01Jan2005 to 31Dec2005. The validated results are tabulated in Table 11.

Table 11. Validation result

Location	Sub basin	Validation 2005		
		NC	R2	PVE
U/S	A	0.52	0.67	-16.98
	B	0.83	0.90	-21.04
	D	0.53	0.80	13.75
	E	0.12	0.77	-2.08
D/S	C	0.58	0.86	15.75

From the validated result it can be seen that NC is 83% at sub-basin B, while at sub-basin E it is 12%. Low NC at sub-basin E shows poor performance of the model, and the reasons may be: i) ungauged area, lack of data availability, or ii) validation time span. But the coefficient of determination noted at sub-basin E is 0.77. The downstream sub-basin NC is 0.58 and R2 0.86, hence the calibrated model can be used for flood forecasting application as well a warning system.
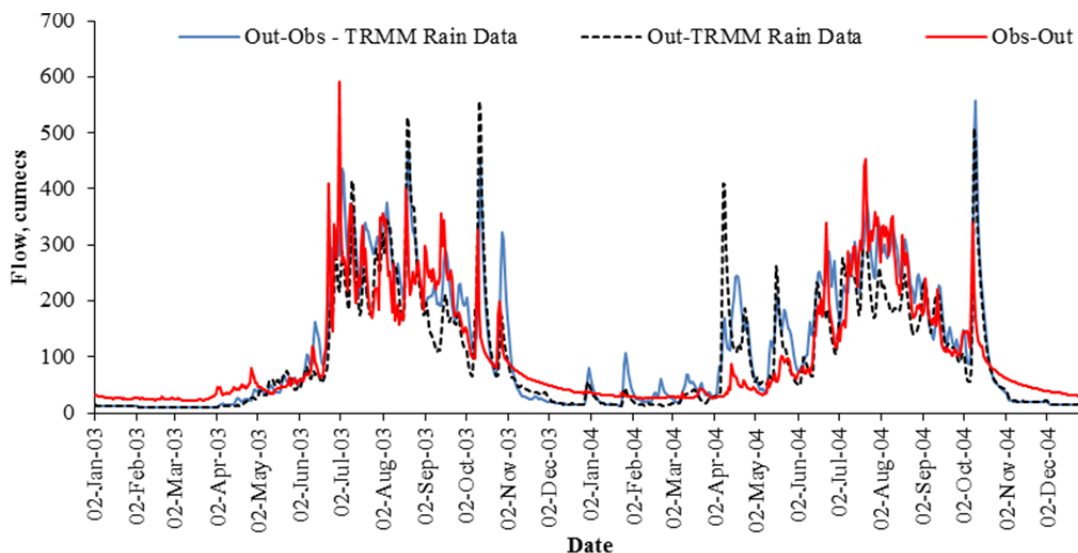

Figure 8. Comparison of flow at outlet Chimakoti Dam on Wan

4.1 Discussion

The model shows poor efficiency without upstream rainfall gauges. The model run using calibrated parameters and TRMM rain data (Figure 8) showed that in case the observed data is not available, the TRMM rain data may be used to forecast floods. The percent volume error is lower than that of the actual calibrated model. The percent volume error downstream is -7.03%. There is only a major difference in the Paro and Haa Rivers at sub-basin A and E respectively in terms of the Nash–Sutcliffe model efficiency coefficient (NC), which is less than 0.50. At the outlet/downstream part of the basin, R2, NC > 0.50.

The model did not incorporate the snowmelt condition due to lack of data. The sediment transport is also not incorporated in the model. Some rain gauge data is missing for 2009-2010 (Dochula) and other stations, which may create a problem in real time forecasting and accuracy. The model has been calibrated for 2003-2004 and validated for 2005, 2009 and 2010 data. A new station Begana has been added in the model. This model can be replicated for other basins. The WRF result for Bhutan is poor, thus other sources of rainfall prediction need to be incorporated in the model. An accurate rainfall forecast is essential to produce flood forecasts for mountainous river basins in Bhutan. The model did not consider snowmelt and sediment transport due to lack of data. The observed hydro-met data, gathered on an hourly basis, is crucial for Bhutan so that the model can run

in 3- to 6-hour intervals. For example, Dochula station should be replaced immediately to improve accuracy.

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