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Climate Change Impact on Hydropower Projects in Marsyangdi Basin, Nepal: A Comparative Study using GCM-led Top-down and Bottom-Up Approaches

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Abstract - *Nepal's power (electricity) system is hydropower-dominated. The high climate and hydrological variability are a major challenge for hydropower generation in Nepal. Climate change is expected to further exacerbate the hydrological variability and impact hydropower generation in the future. Major climate change impacts on the hydropower projects are related to increased risks due to changes in water availability, extreme events like flood, droughts and sediment transport and subsequently on energy generation. This study adopts the combined form of General Circulation Model (GCM)-led top-down and bottom-up climate change impact assessment approaches to assess the impacts of climate change on hydropower projects in the Marsyangdi River Basin of Nepal. The combination of the two approaches is adopted because of the high uncertainty of the future climate among the available models (GCMs). The projected changes in climate data with other hydrological parameters were input into the Hydrologic Engineering Centre-Hydrologic Modelling System (HEC-HMS) to simulate the response of the hydrological system. Four representative s GCMs under the Representative Concentration Pathways (RCP 4.5 and RCP 8.5) climate scenario selected using an Envelope Method were used for the top-down method. Future climate scenarios simulated using a Stochastic Weather Generator for a range of future changes in climate conditions were used for the bottom-up approach. The impacts of future climate scenarios of the two methods were then compared to assess the climate risks to hydropower projects in term of water availability, extreme floods and energy generation.*

***Key Words*: Climate Change; Climate Risk Assessment, HEC-HMS, GCM, Bottom-up Approach, Hydropower, Marsyangdi River Basin**

1. INTRODUCTION

Climate change has become a major global issue at national and international levels. Nepal has not remained indifferent from climate change risk due to the result of complex characteristics like extreme topography, quick responding catchments with intense seasonal and climatic variability [1]. Nepal has an estimated economic hydropower potential of 43,000 MW and has plans to increase its current installed capacity of about 1600 MW by 10,000 – 15,000 MW of additional capacity in the next decade [2]. Assessment of the risks of climate change to hydropower projects is critical for countries like Nepal, as hydropower project are directly influenced by hydrological, meteorological, geotechnical, glacial and geological processes, which are affected by the climate change [3, 4]. The analysis of the past recorded rainfall time series data in many regions shows increasing trend of the intensity of extreme rainfall events [4, 5]. This directly impacts on alteration of the intensity, frequency, amount and type of precipitation. Considering the impact of climate change on water availability and extreme events in Nepal, a clear understanding of climatic variability and change is very important for the development and management of the hydropower sector in the long run [6].

There are basically two approaches used in climate change impact studies of water and hydropower projects, namely, the General Circulation Models (GCM)-led top-down approach and the stakeholder driven bottom-up approach [7]. Top–down (or 'scenario-centered') method involves downscaling climate projections from GCMs under a range of emissions scenarios, providing inputs for hydrologic and management models to estimate potential impacts and, finally, to analyze adaptation measures. In the top-down approach information is cascaded from one step to the next with uncertainty increasing at each step of this process. It provides results highly uncertain for decision making [8]. The bottom–up approach analyzes vulnerability and adaptive capacity to climate variations to make adaptation decisions (decision-centered approaches) [7]. The high uncertainty associated with the effect of global change on water resource systems calls for a better combination of conventional top–down and bottom–up approaches, in order to design robust adaptation plans at the local scale. The two approaches meet and feed each other through the development of an integrated water resources management model to support the definition of a climate adaptation strategy for global change. The results derived from the integration of the bottom–up and top–down approaches illustrate the sensitivity of the adaptation strategies to the climate projections [9]. The International Hydropower Association (IHA) Hydropower Sector Climate Resilience Guide recommends a six-phase approach to climate resilience for the hydropower sector. The climate stress test (Phase 3) of the approach is based on the bottom-up approach to assess project performance under possible future climate change scenario [10].

In the top-down approach, one or a few GCMs are selected and bias corrected before using as input to hydrological models [11, 12, 3]. However, due to major differences in climate projections with large differences across future scenarios and between climate models, using one or several climate models arbitrarily can be misleading. Instead, an envelope-based selection [13, 14, 15] of representative climate models is proposed for impact studies. Alternatively, Climate Risk Assessment (CRA) methodology based on a "bottom up" decision-scaling approach has been used to test the vulnerability of the hydroelectricity projects [16] and the sector in Nepal [17]. The climate risk assessment of the hydropower sector [17] highlighted that assessing the future impacts of climate change on the hydro-electricity sector in Nepal is challenging due to the complex climate and hydrology, as well as the very large changes in elevation that occur across the country.

Impact of climate change on hydropower generation is basically manifested through the changes on hydrology, specifically in terms of the impacts on water available and extreme floods and low flows. Hydrological modelling is used to analyze the catchment response (impact on hydrology) to future climate change. The selection of a hydrological model mainly depends upon the complexity, available resources and modelling objectives [18]. Hydrological Engineering Center-Hydrological Modelling System (HEC-HMS) is extensively used in flood frequency analysis, reservoir and hydraulic structure design, river training planning and impact of climate change on water resources and hydropower [19, 20, 21, 22, 23, 24, 12, 25, 26].

Nepal's hydropower portfolio consists of mainly two types of projects, the run of river (ROR) and seasonal storage type projects. The ROR projects are also of two types, some with pondage for daily peaking capacity and others without any pondage. The ROR projects are generally designed based on the dry season flows. These ROR power plants, without substantial storage, have been already facing the problem due to high seasonal variation of flows generating only about 30% of the total installed capacity in the dry months. Storage project are less affected by the seasonal variation flow if there is adequate reservoir storage capacity to regulate flow [17]. Therefore, the assessment of the climate change impact on water resources and hydropower project is crucial to assess the vulnerability and risk of existing and planned projects [27].

This research focuses on the assessment of climate change impacts on four existing ROR hydropower plants in the Marsyangdi River Basin in Nepal (Figure **2.1**). Considering the high uncertainty of future climate projections, a comparative assessment of future climate scenarios for a GCM based top-down approach using representative GCMs selected using an envelope method and a bottom-up approach is carried out. The former is based in the impact assessment using four GCMs selected to cover the four extreme corners (envelop) of the precipitation and temperature changes [13, 28]. The latter uses future climate scenario generated using stochastic weather generators [29].

2. MATERIALS and METHOD

2.1 Study Area

The Marsyangdi River Basin lies in Gandaki province of Nepal (Figure **2.1)**. It is located between 27°50'42" N to 28°54'11" N latitudes and 83°47'24" E to 84°48'04" E longitudes. The basin has a total area of 4,789 sq. km. Marsyangdi River Basin at the (Lower) Marsyangdi hydropower project has a wide range of altitude ranging from 7938m to 287m. The mean slope of this basin is 29.38°, which reflects the high potential relief energy of the catchment. The climate in the study area is predominately governed by the summer monsoon, which extends from June to September [3].

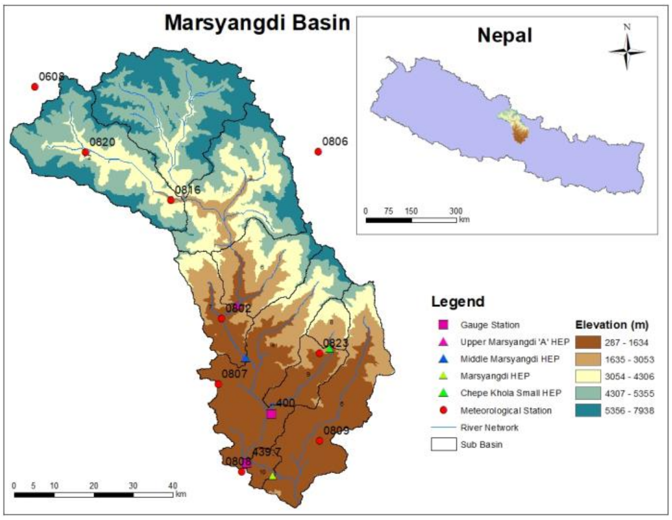


Fig - 2.1 Study Area Map

Two peaking run of the river (P-RoR) functional hydropower plants under Nepal Electricity Authority (NEA) are located in the Marsyangdi river basin. They are Middle Marsyangdi Hydropower Station (70MW) and Marsyangdi Hydropower Station (69MW). The existing RoR-type Upper Marsyangdi 'A' Hydropower Station (50MW) and the under-construction Chepe Khola Small Hydropower Station (8.836MW) are other two projects are under the private sector (Table **2.1**).

Table 2.1 Features of Hydropower Projects

S. N	Name of Project	Design Discharge (m^3/s)	Net Head (m)	Installed Capacity (MW)	Catchment Area (km^2)	Catchment Area below 3000m (km^2)	Catchment Area below 5000m (km^2)
1	Upper Marsyangdi 'A'	48	113	50	3008	276	1626
2	Middle Marsyangdi	80	98	70	3406	492	1885
3	(Lower) Marsyangdi	91.5	90.5	69	4110	1389	2939
4	Chepe Khola Small	4.82	217.8	8.63	99	54	99

2.2 INPUT DATA

2.2.1 Baseline Climate Data

The meteorological stations used to estimate the average basin precipitation are: Station No. 608, 802, 806, 807, 808, 809, 816, 820, and 823. Similarly, the stations used to estimate the average basin and sub-basin temperature are 816, 802, and 808. The precipitation and temperature records of these stations from 1990-2014 were acquired from Department of Hydrology and Meteorology (DHM). The long-term annual average precipitation and temperature in the basin are 1690 mm and 18°C. The list of meteorological stations used in this study is shown in Table **2.2**.

S.N	Station ID	Station Name	Latitude (N)	Longitude (E)	Period	Data Available
1	608	Ranipauwa	28° 29' 24"	83° 31' 48"	1990-2014	Precipitation
2	802	Khudi	28° 10' 12"	84° 13' 12"	1990-2014	Precipitation, Temperature
3	806	Larke Samdo	28° 24' 0"	84° 22' 12"	1990-2014	Precipitation
4	807	Kunchha	28° 4' 48"	84° 12' 36"	1990-2014	Precipitation
5	808	Bandipur	27° 33' 36"	84° 15' 0"	1990-2014	Precipitation, Temperature
6	809	Gorkha	28° 0' 0"	84° 22' 12"	1990-2014	Precipitation
7	816	Chame	28° 19' 48"	84° 8' 24"	1990-2014	Precipitation, Temperature
8	820	Manang Bhot	28° 24' 0"	84° 0' 36"	1990-2014	Precipitation
9	823	Gharedhunge	28° 7' 12"	84° 22' 12"	1990-2014	Precipitation

Table 2.2 List of meteorological station used in study

2.2.2 Climate Change Scenarios

A wide range of general circulation models (GCMs) has been developed to explore the expected climatic consequences of increasing greenhouse gas emission. GCM outputs for specific climate change scenarios provide climate information are larger than hydrologic modelling scale of watershed or sub-watersheds. The IPCC's Fifth Assessment Report (AR5) identified four scenarios, or Representative Concentration Pathways (RCPs) – RCP2.6, RCP4.5, RCP6, and RCP8.5. Each of them represents different volumes of greenhouse gas emissions, and hence varied levels of their concentrations in the atmosphere in the year 2100 [30]. Regional climate models (RCMs) and downscaling are developed over a smaller scale to generate information for hydrologic studies of watershed. GCM and RCM model results often show significant biases from systematic model errors or spatial resolution [31].

The representative GCMs for two RCPs, 4.5 (stabilization scenario) and 8.5 (high emission scenario) were selected using the envelop-based climate selection method [15] and Ministry of Forests and Environment, Nepal [13]. The method selects the GCMs for each scenario based on three factors: (i) change in projected mean for four conditions (Wet-warm, wet-cold, dry-warm, dry-cold), (ii) change in projected climate extremes, and (iii) based on performance with past condition. One model each for four conditions (corners of the spread of changes) are selected for each RCP. The selected models are then bias corrected using Quantile Mapping before being used as inputs to the hydrological model. The selected, boas corrected GCMs were obtained from the Nepal Development Research Institute (NDRI).

The biased corrected precipitation and temperature data of warm-wet (w-w), warm-dry (w-d), cold-wet (c-w) and cold-dry (c-d) model under representative concentration pathway RCP4.5 and RCP8.5 scenarios were obtained from Nepal Development Research Institute (NDRI) for the period between 2016 to 2050. The selected GCMs, and the variation of precipitation and temperature with base period for different climatic condition are given in Table **2.3**.

Table 2.3 Percentage change in precipitation and temperature under RCP 4.5 and 8.5 with base case

	RCP 4.5			
Condition	CanESM2	CCSM4	HadGEM-CC	MPI-ESM-LR
Model	warm-wet (w-w)	cold-wet (c-w)	cold-dry (c-d)	warm-dry (w-d)
% P Change	24	9	1	14
T Change in (°C)	0.95	0.63	0.72	0.99
	RCP 8.5			
Condition	CanESM2	CISRO-MK3-6-0	HadGEM-CC	MIROC-ESM-CHEM
Model	warm-wet (w-w)	cold-wet (c-w)	cold-dry (c-d)	warm-dry (w-d)
% P Change	13	40	4	7
T Change in (°C)	1.04	0.89	1.19	1.29

Note: P = Annual Average Precipitation

T = Annual Average Temperature

For the impact analysis, future projection data from 2025-2050 were used. The projected trendline (Figure **2.2**, **2.3**, **2.4** and **2.5**) between the baseline (1990 – 2014) and the period from 2025-2050 (near future) under RCP 4.5 and RCP 8.5 shows an increasing and a more variable trend. The temperature projection rate is higher in all projection by the RCP 8.5 than RCP 4.5 as expected.

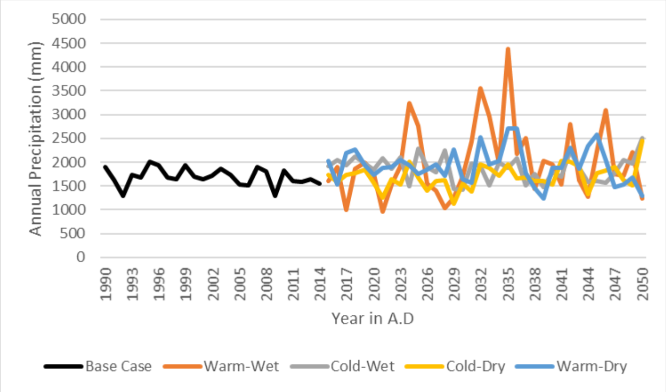


Fig -2.2 Observed and bias corrected precipitation under RCP 4.5

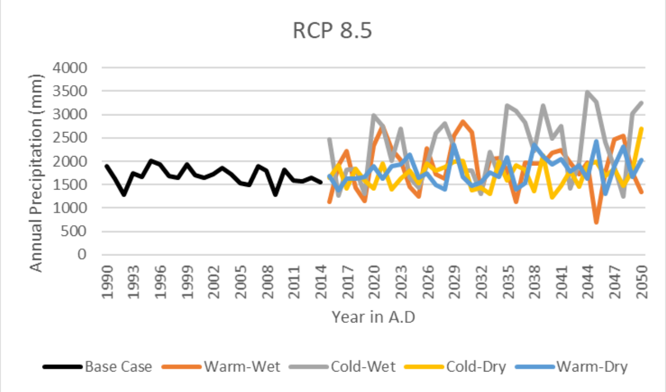


Fig- 2.3 Observed and bias corrected precipitation under RCP 8.5

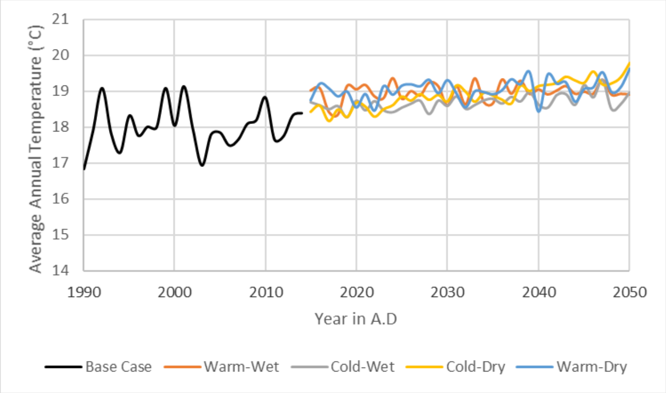


Fig – 2.4 Observed and bias corrected temperature under RCP 4.5

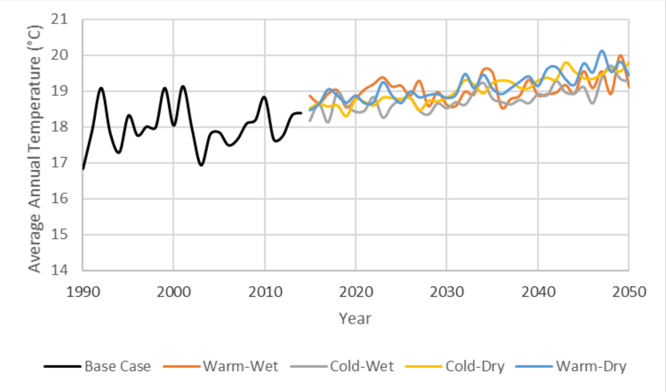


Fig -2.5 Observed and bias corrected temperature under RCP 8.5

2.2.3 Climate Scenarios using Stochastic Weather Generator

The 'Weather Generator and Climate Scenario Generator (version 0.1.0 Beta)'developed by NDRI [29] was used to generate the future temperature and precipitation data for the bottom-up approach. This tool is mainly based on the research papers of Apipattanavis et al. [32] and Steinschneider and Brown [33]. The tool generates inputs for "climate stress test" by enforcing changes in climatic means to produce climate change scenarios. The shifts or changes in distributional properties of weather variables are applied using quantile mapping approach for precipitation and simple shifting approach for temperature. The precipitation (P) changes from -40% to +40% and temperature (T) changes from 0°C to 5°C from the base case scenario were used to generate P and T simulated data for the climate change scenarios. A total of 54 scenarios (simulated time series) for the combination of P and T changes were generated. These climate data are then used as input to the hydrological model.

2.3 Discharge Data

The daily flow data from 1990-2014 were acquired from the Department of Hydrology and Meteorology (DHM). These data are used for calibration and validation of the rainfall-runoff simulation model (HEC-HMS). The data range from 1st Jan 1992 to 31st Dec 2004 is used for calibration, and the data range from 1st Jan 2005 to 31st Dec 2014 is used for validation. The details of gauging stations are shown in Table **2.4**.

Table 2.4 Hydrological Stations of Marsyangdi River Basin

Index No	Station Name	District	Latitude	Longitude
440	Garam Besi	Lamjung	28˚03’41”	84˚29’23”
439	Bimal Nagar	Tanahu	27˚57’00”	84˚25’48”

2.4 Potential Evapotranspiration Data

Thornthwaite method is widely used for estimating potential evapotranspiration for hydrological analysis based on monthly average temperature [34]. Thornthwaite methods is used for each sub-basin to calculate the potential evapotranspiration in the HEC-HMS model. The Potential evapotranspiration of each sub-basin is given in Figure **2.6.**

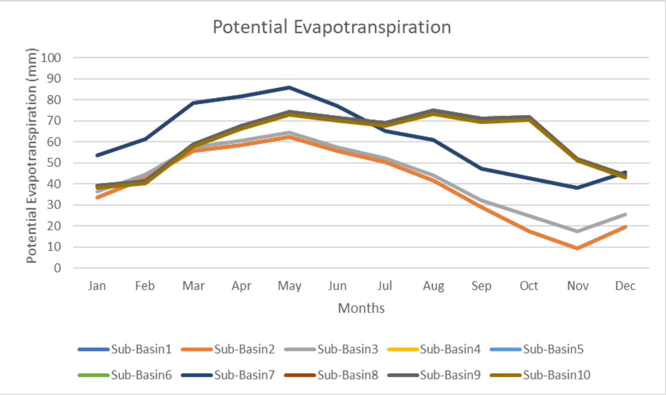


Fig -2.6 Monthly averaged potential evapotranspiration in each sub-basin of Marsyangdi River Basin

2.5 Methodology

An overview of the framework adopted to combine top-down (‘scenario-centered’) and bottom-up approaches is presented in figure **2.7**. The top-down approach starts by choosing the bias corrected future climate scenario of different global climate models (GCMs) for 26 years (2025-2050) by considering two stabilization scenario RCPs 4.5 and high emission scenario RCPs 8.5. The bias corrected data of the four selected GCMs were provided by Nepal Development Research Institute (NDRI) as mentioned earlier.

For the bottom-up approach, the future climate data were simulated using the Stochastic Weather Generator [29] described earlier for the climate scenarios ranging from -40% to +40% changes in annual precipitation and +1 to + 5° rise in temperature. The top-down and bottom-up approaches’ results are then assessed and compared to assess the range of impacts on hydrology and hydropower energy generation for future climate change scenarios. Such an assessment provides a sound basis for designing climate adaptation strategy for the range of future climate in the context of high uncertainty of climate change projections.

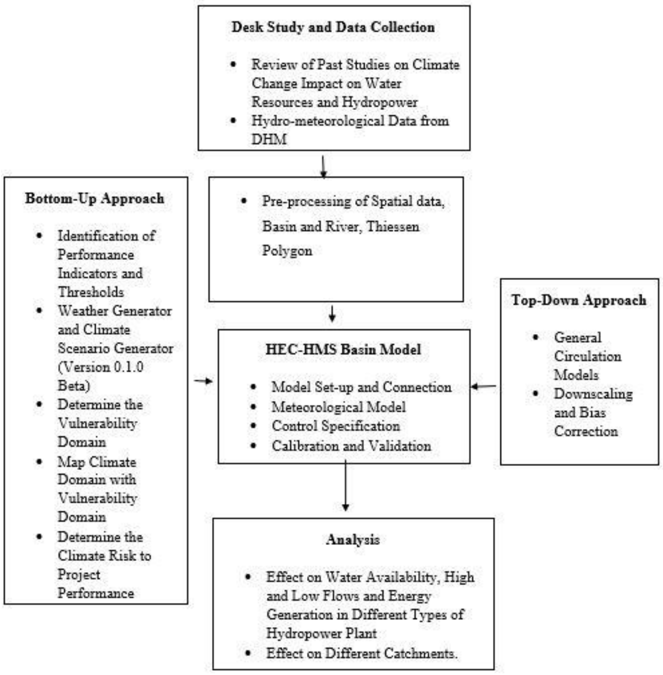


Fig -2.7 Overall methodological frameworks

3.0 HEC-HMS MODEL

The HEC-HMS model is developed by the United States Army Corps of Engineers, which is designed to simulate the rainfall-runoff process of a dendritic watershed system. HEC-HMS model setup consists of basin model, meteorological model, data manager and control specification. The DEM (Digital Elevation Model) data of 30m resolution was obtained from Department of Survey, Nepal. DEM along with GIS (Geographical Information System) was used in HEC-HMS to interlink each sub-basin and river network.

The Table **3.1** shows the selected processes of HEC-HMS in this catchment, to change the meteorological parameters into the discharge at desired locations. The HEC-HMS is set up as a semi-distributed model by sub-dividing the catchment into 10 sub-basins. Junctions are created at the desired locations in the basin for calibration and validation as well as to select locations of concern, such as the location of the hydropower projects.

The Soil Moisture Accounting (SMA) is used for loss method. It accounts for watershed soil moisture balance over a long-term period and suitable for simulating daily stream flow

[35]. Linear reservoir method is selected for base flow analysis due to relationship between SMA and linear reservoir [36]. The HEC-HMS has two snowmelt modelling methods namely: temperature index method and gridded temperature index method. Temperature index method is computed easily with only air temperature and precipitation input. It is also simpler than numerical snow model [37]. The antecedent temperature index (ATI) melt-rate and cold-rate function are specified separately along with one elevation band for each sub-basin. The schematic model of Marsyangdi basin is shown in Figure **3.1**.

Table -3.1 Selected processes in HEC-HMS for both catchment

Process	Selected methods for Bimal Nagar	Selected methods for Garam Besi
Canopy Storage	Simple Canopy	Simple Canopy
Surface	Simple Surface	Simple Surface
Loss	Soil Moisture Accounting (SMA)	Soil Moisture Accounting (SMA)
Transform	SCS Unit Hydrograph	SCS Unit Hydrograph
Base Flow	Linear Reservoir	Linear Reservoir
River Routing	Muskingum	Muskingum
Precipitation	Specified Hyetograph	Specified Hyetograph
Evapotranspiration	Monthly Average	Monthly Average
Snowmelt	Temperature Index	Temperature Index

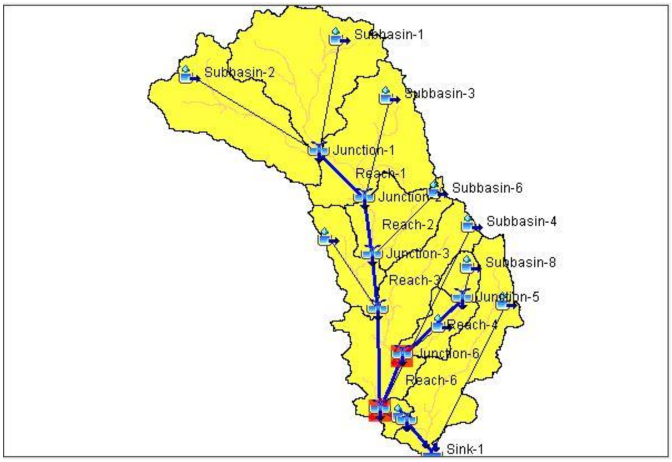


Fig -3.1 Schematic model of Marsyangdi River Basin

3.1 Model Evaluation

The values of different parameters are set within the range and calibrated using manual and inbuilt systematic (automatic) calibration methods. For this, simulated and observed daily discharge data are needed at the point of calibration and validation. Calibration process is an iterative method to find the agreement between simulated and observed flow data. To check the efficiency of hydrological model during calibration and validation. different criteria have been developed. For this study, Nash-Sutcliffe Efficiency (NSE), Percentage error bias, coefficient of determination (R^2) and deviation of runoff volume (D_o) were used to measure the goodness of fit between the simulated and the observed discharge time series data [38, 39].

4.0 RESULTS and DISCUSSION

4.1 Calibration and Validation of Model

Model calibration consists of the modification of model parameters value within the range and comparison of predicted output to measured data based on a predefined objective function. Before calibration process, a warmup period was provided from 1 Jan 1990 to 1 Jan 1992 for better performance of the model. Both manual and automatic calibration technique were implemented for the calibration and validation of model. Firstly, the model is calibrated from 1 Jan 1992 to 31 Dec 2004 and validation process was performed from 1 Jan 2005 to 31 Dec 2014 using the same calibration input parameters. For the better model performance, calibration and validation were done at Garam Besi and Bimal Nagar gauge station. The model evaluation parameters: Nash-Sutcliffe coefficient of efficiency (Ns), deviation of volume change (Do), coefficient of determination (R2) and percentage of error bias (PBAIS) are given in Table **4.1** for Garam Besi and Bimal Nagar station during calibration and validation periods. Observed versus simulated hydrograph for calibration and validation periods for both catchments are shown in Figure **4.1**, **4.2**, **4.3** and **4.4**. Thus, it is observed that this model is capable of simulating discharge for future periods.

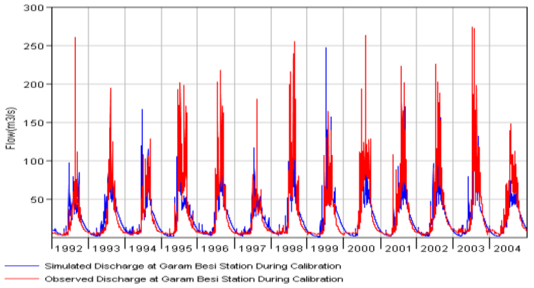


Fig -4.1 Observed vs. simulated flow hydrograph at Garam Besi station during calibration period

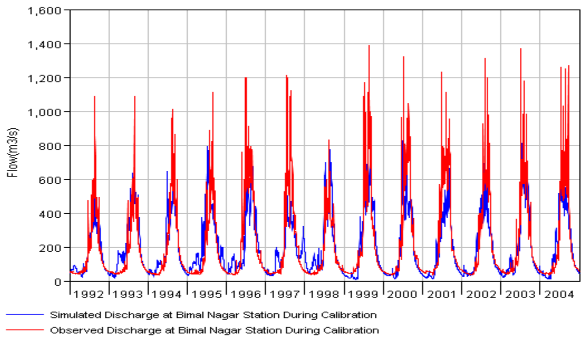


Fig -4.2 Observed vs. simulated flow hydrograph at Bimal Nagar station during calibration period

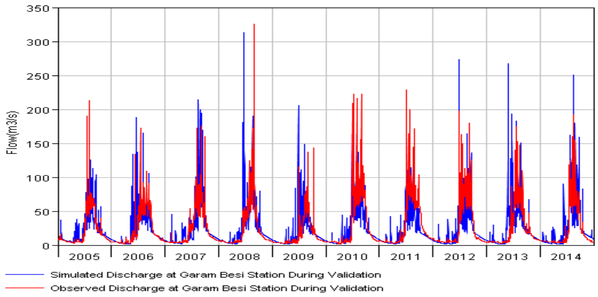


Fig -4.3 Observed vs. simulated flow hydrograph at Garam Besi station during validation period

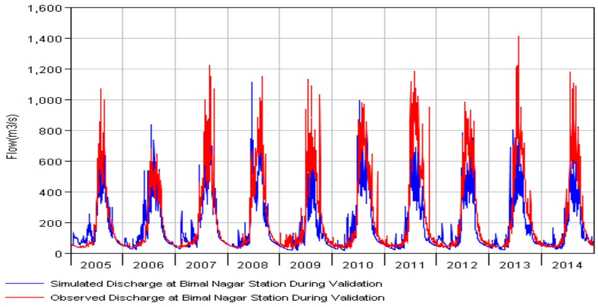


Fig -4.4 Observed vs. simulated flow hydrograph at Bimal Nagar station during validation period

Table -4.1 Model evaluation parameters during calibration and validation

S.N	Gauging Name	Type	NSE	R^2	PBAIS (%)	Volume Change (%)
1	Garam Besi	Calibration	0.637	0.55	6.51	-6.58
		Validation	0.56	0.51	3.43	3.88
2	Bimal Nagar	Calibration	0.783	0.84	-8.8	-6.75
		Validation	0.72	0.79	-12.5	-12.12

4.2 Climate Change Impact on Water Availability

4.2.1 Seasonal Flows

The year is divided in two broad seasons, the dry season is considered from December - May and the wet season is from June - November. Table **4.2** provides the change in the two seasons from the base case to the near future (2025-2050) for the four representative GCMs. The dry season (since dry season flow is critical for power generation) flow changes from -4.3% to 45.57%, from -6.16% to 42.33%, from -2.92% to 49.62% and from -11.35% to 38.3% for Upper Marsyangdi 'A', Middle Marsyangdi, Marsyangdi and Chepe Khola Small hydropower project respectively. The dry season flow under bottom-up approach for four hydropower projects shown in Table **4.3**, **4.4**, **4.5** and **4.6.** As per Table **2.3,** P changes are from 1%-24% and T changes are from 0.72°C–0.92°C for RCP 4.5. Similarly, P changes from 4%-40% and T changes from 0.89°C-1.29°C for RCP 8.5. Comparing the changes in the bottom-up approach for the same P and T changes. It can be seen that the changes in dry season flow is higher than that using the GCMs in the top-down approach for all hydropower projects. **Fig 4.5** presents the monthly variation of flow for the all climate scenario under RCP 4.5 and 8.5.

Table -4.2 Impact of climate change in dry and wet season flow in different hydropower project

Name of Plant	Condition	Time Window	RCP 4.5				RCP 8.5			
			Dry Flow (m^3/s)	% Change	Wet Flow (m^3/s)	% Change	Dry Flow (m^3/s)	% Change	Wet Flow (m^3/s)	% Change
Upper Marsyangdi Hydropower	Base Line		29.54		119.30		29.54		119.30	
	Warm-Wet (CanESM2)	Near Future	36.67	24.14	173.30	45.26	33.00	11.71	151.00	26.57
	Cold-Wet (CCSM4)	Near Future	40.12	35.82	142.30	19.28	43.00	45.57	184.80	54.90
	Cold-Dry (HadGEM2-CC)	Near Future	32.11	8.70	113.80	-4.61	30.10	1.90	131.10	9.89
	Warm-Dry (MPI-ESM-LR)	Near Future	28.27	-4.30	156.00	30.76	30.60	3.59	146.20	22.55
Middle Marsyangdi Hydropower	Base Line		40.94		137.63		40.94		137.63	
	Warm-Wet (CanESM2)	Near Future	46.53	13.65	228.05	65.70	44.44	8.55	197.00	43.14
	Cold-Wet (CCSM4)	Near Future	54.48	33.07	196.75	42.96	58.27	42.33	240.00	74.38
	Cold-Dry (HadGEM2-CC)	Near Future	40.42	-1.27	149.75	8.81	38.42	-6.16	172.36	25.23
	Warm-Dry (MPI-ESM-LR)	Near Future	39.33	-3.93	202.34	47.02	41.10	0.39	192.10	39.58
Marsyangdi Hydropower	Base Line		63.80		275.30		63.80		275.30	
	Warm-Wet (CanESM2)	Near Future	69.57	9.04	412.23	49.74	71.70	12.38	362.80	31.78
	Cold-Wet (CCSM4)	Near Future	76.68	20.19	348.37	26.54	95.46	49.62	445.14	61.69
	Cold-Dry (HadGEM2-CC)	Near Future	61.94	-2.92	279.04	1.36	62.50	-2.04	311.00	12.97
	Warm-Dry (MPI-ESM-LR)	Near Future	62.21	-2.49	376.00	36.58	64.44	1.00	346.60	25.90
Chepe Khola Small Hydropower	Base Line		2.82		9.87		2.82		9.87	
	Warm-Wet (CanESM2)	Near Future	2.91	3.19	18.71	89.56	2.84	0.71	16.70	69.20
	Cold-Wet (CCSM4)	Near Future	3.68	30.50	15.60	58.05	3.90	38.30	20.15	104.15
	Cold-Dry (HadGEM2-CC)	Near Future	2.95	4.61	12.29	24.52	2.50	-11.35	14.20	43.87
	Warm-Dry (MPI-ESM-LR)	Near Future	2.60	-7.80	17.63	78.62	2.70	-4.26	16.00	62.11

Table -4.3 Dry season flow variation for Upper Marsyangdi 'A' project

Change in Temperature (°C)		% Dry Flow Change								
	5	-37%	-23%	-13%	-10%	7%	17%	33%	40%	57%
	4	-33%	-17%	-10%	-10%	7%	20%	37%	47%	60%
	3	-27%	-10%	-10%	-7%	10%	23%	40%	53%	70%
	2	-37%	-17%	-13%	-10%	7%	20%	33%	50%	73%
	1	-40%	-20%	-17%	-10%	3%	17%	30%	47%	60%
	0	-43%	-27%	-20%	-13%	0%	13%	27%	43%	57%
		-40	-30	-20	-10	0	10	20	30	40
		% Change in Precipitation								

Table -4.4 Dry season flow variation for Middle Marsyangdi Project

Change in Temperature (°C)		% Dry Flow Change								
	5	-43%	-30%	-15%	-10%	5%	13%	33%	35%	53%
	4	-40%	-28%	-13%	-8%	5%	15%	35%	40%	55%
	3	-35%	-25%	-10%	-5%	8%	18%	38%	45%	58%
	2	-40%	-25%	-13%	-8%	5%	18%	35%	48%	60%
	1	-43%	-28%	-15%	-10%	3%	15%	30%	45%	55%
	0	-48%	-33%	-18%	-13%	0%	13%	25%	40%	50%
		-40	-30	-20	-10	0	10	20	30	40
		% Change in Precipitation								

Table -4.5 Dry season flow variation for Marsyangd Project

Change in Temperature (°C)		% Dry Flow Change								
	5	-39%	-25%	-13%	-4%	3%	13%	33%	39%	45%
	4	-37%	-24%	-12%	-3%	4%	15%	36%	40%	48%
	3	-36%	-22%	-12%	-3%	6%	16%	33%	37%	46%
	2	-37%	-24%	-13%	-4%	4%	15%	30%	34%	45%
	1	-39%	-25%	-15%	-6%	3%	13%	28%	33%	43%
	0	-40%	-28%	-18%	-7%	0%	10%	24%	28%	39%
		-40	-30	-20	-10	0	10	20	30	40
		% Change in Precipitation								

Table -4.6 Dry season flow variation for Chepe Khola Small project

		% Dry Flow Change								
Change in Temperature (°C)	5	-38%	-24%	-11%	-6%	1%	21%	56%	66%	78%
	4	-37%	-23%	-10%	-5%	2%	22%	58%	67%	80%
	3	-37%	-22%	-9%	-5%	2%	22%	58%	67%	81%
	2	-37%	-23%	-10%	-5%	1%	21%	57%	66%	79%
	1	-38%	-24%	-11%	-6%	1%	21%	56%	65%	78%
	0	-38%	-25%	-12%	-7%	0%	19%	54%	63%	76%
		-40	-30	-20	-10	0	10	20	30	40
		% Change in Precipitation								

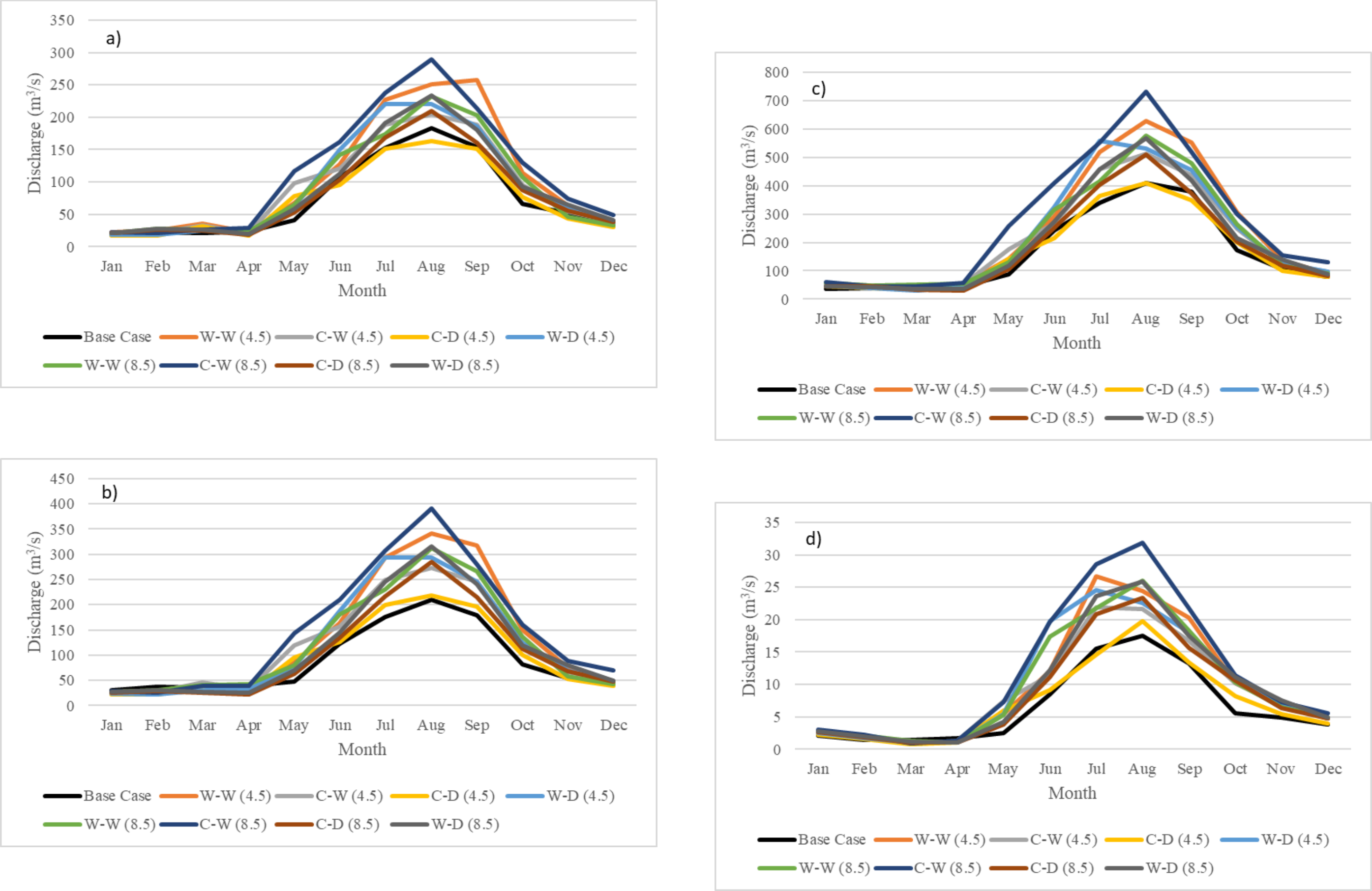


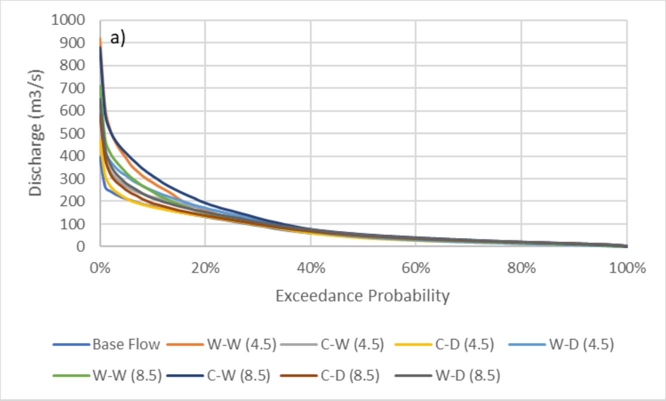
Fig -4.5 Comparison of monthly flow hydrograph between base case and climate change; (a: Upper Marsyangdi 'A', b: Middle Marsyangdi, c: Marsyangdi and d: Chepe Khola Small) hydropower project

4.2.2 Flow Duration Curves (FDCs), High and Low Flows

The 10th percentile (Q10, high flow) and 90th percentile (Q90, low flow) values were determined from the corresponding baseline and flow duration curves predicted by all GCMs for each hydropower project. The 10th percentile of baseline flow are 178.39 m^3/s, 203.64 m^3/s, 400.2 m^3/s and 12.9 m^3/s and the 90th percentile of baseline flow are 14.34 m^3/s, 23.72m^3/s, 32.2 m^3/s and 0.933 m^3/s for Upper Marsyangdi 'A', Middle Marsyangdi, Marsyangdi and Chepe Khola Small Hydropower projects, respectively. This means that the ratio of Q10 and Q90 of the baseline flow is found to be 13, 11, 12 and 15 for Upper Marsyangdi 'A', Middle Marsyangdi, Marsyangdi and Chepe Khola Small hydropower project, respectively.

For RCP 4.5, the fractional differences of the ensembled flow are found to be 20, 19, 18 and 28, and for RCP 8.5 they are 21, 19, 19 and 25 for Upper Marsyangdi 'A', Middle Marsyangdi, Marsyangdi and Chepe Khola Small hydropower projects, respectively. Also, the 40th percentile and 60th percentile flow is prime concern for power production in ROR projects. The variation in 40th and 60th percentile flow under different climatic conditions are shown in Table **4.7.** The flow duration curve under RCP 4.5 and 8.5 are given in Fig **4.6.** This result indicates a higher probability for high flows to increase and low flows to in the future.

While from the bottom-up approach, the dependable flow Q90, Q60, Q40 and Q10 values were determined from the corresponding baseline period. The 90th percentile flow will change from-50% to 72%, from -44% to 81%, from -50% to 54% and from -61% to 70% for Upper Marsyangdi 'A', Middle Marsyangdi, Marsyangdi and Chepe Khola Small hydropower projects, respectively. The 10th percentile flow will vary from -40% to 59%, from -41% to 61%, from -43% to 59% and from -52% to 58% for Upper Marsyangdi 'A', Middle Marsyangdi, Marsyangdi and Chepe Khola Small hydropower projects, respectively. From bottom-up approach the variation of Q60 and Q40 shown in Table **4.8** and **4.9** for Upper Marsyangdi 'A' project. Similar changes of Q60 and Q40 occur for other projects.



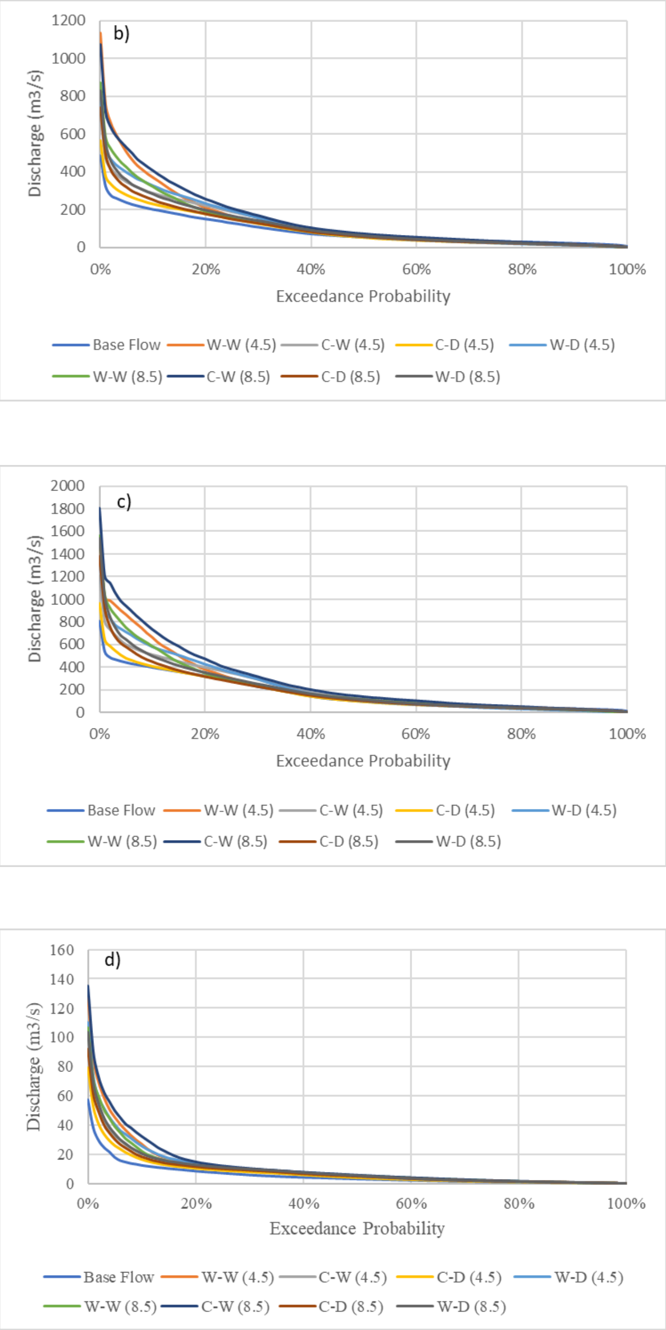


Fig -4.6 Flow duration curve between base case and climate change; (a: Upper Marsyangdi 'A', b: Middle Marsyangdi, c: Marsyangdi and d: Chepe Khola Small) hydropower project

Table -4.7 CC impact on different dependable flow for each project

Project	Condition	RCP 4.5		RCP 8.5	
		% Change Q40	% Change Q60	% Change Q40	% Change Q60
Upper Marsyangdi 'A'	Base Case	0	0	0	0
	Warm-Wet	21	12	12	6
	Cold-Wet	35	7	31	22
	Cold-Dry	8	-15	12	0
	Warm-Dry	21	-9	23	10
Middle Marsyangdi	Base Case	0	0	0	0
	Warm-Wet	20	6	24	7
	Cold-Wet	34	4	39	22
	Cold-Dry	7	-17	12	-7
	Warm-Dry	22	-13	23	1
Marsyangdi	Base Case	0	0	0	0
	Warm-Wet	16	9	16	15
	Cold-Wet	24	12	42	28
	Cold-Dry	-1	-11	5	-5
	Warm-Dry	18	-3	15	4
Chepe Khola Small	Base Case	0	0	0	0
	Warm-Wet	31	20	31	24
	Cold-Wet	35	27	40	35
	Cold-Dry	-1	-17	4	-15
	Warm-Dry	19	6	20	-9

Table -4.8 Q60 variation surface for Upper Marsyangdi 'A' project

		Q60 Variation								
Change in Temperature (°C)	5	-45%	-36%	-23%	-17%	2%	19%	28%	42%	43%
	4	-45%	-36%	-21%	-13%	4%	21%	32%	45%	47%
	3	-40%	-34%	-17%	-11%	8%	23%	28%	47%	51%
	2	-43%	-28%	-19%	-4%	6%	19%	28%	43%	49%
	1	-42%	-26%	-21%	-2%	2%	15%	26%	42%	42%
	0	-47%	-30%	-21%	-15%	0%	12%	25%	38%	42%
		-40	-30	-20	-10	0	10	20	30	40
	% Change in Precipitation									

Table -4.9 Q40 variation surface for Upper Marsyangdi 'A' project

		Q40 Variation								
Change in Temperature (°C)	5	-44%	-35%	-20%	-8%	2%	25%	26%	43%	46%
	4	-43%	-28%	-18%	-12%	6%	28%	34%	42%	53%
	3	-38%	-31%	-22%	-13%	5%	30%	33%	43%	57%
	2	-42%	-31%	-20%	-7%	6%	27%	31%	43%	57%
	1	-42%	-30%	-21%	-3%	2%	24%	31%	42%	55%
	0	-45%	-31%	-22%	-14%	0%	20%	29%	40%	54%
		-40	-30	-20	-10	0	10	20	30	40
	% Change in Precipitation									

4.3 CC Impact on Energy Generation

Dry season energy is the main concern for the hydropower projects. From the GCMs, the dry energy changes from -14.75% to 9.84%, from -15.79% to 9.21%, from -4.44% to 20% and from -14.29% to 21.43% for Upper Marsyangdi 'A', Middle Marsyangdi, Marsyangdi and Chepe Khola Small projects, respectively. In the wet season, there is not considerable change in energy production as the flow changes will not affect the availability of the design discharge. The total energy change under GCMs are given in Table **4.10**.

From the bottom-up approach, the dry energy varies from -30% to 18%, from -30% to 22%, from -30% to 15% and from -22% to 85% for Upper Marsyangdi 'A', Middle Marsyangdi, Marsyangdi and Chepe Khola Small projects. The impact on dry season energy is more than wet season for all projects in all climate scenarios. The total energy surface for each project is given in Table **4.11**, **4.12**, **4.13** and **4.14.** The bottom-up analysis shows the higher variation in total energy change than the representatives GCMs.

Table -4.10 Total energy change under RCP 4.5 and 8.5 for all project

Name of Plant	Condition	Time Window	RCP 4.5		RCP 8.5	
			Total Energy (GWh)	% Change	Total Energy (GWh)	% Change
Upper Marsyangdi Hydropower	Base Line		0.88		0.88	
	Warm-Wet (CanESM2)	Near Future	0.91	3.41	0.91	3.41
	Cold-Wet (CCSM4)	Near Future	0.89	1.14	0.91	3.41
	Cold-Dry (HadGEM2-CC)	Near Future	0.85	-3.41	0.84	-4.55
	Warm-Dry (MPI-ESM-LR)	Near Future	0.88	0.00	0.85	-3.41
Middle Marsyangdi Hydropower	Base Line		1.14		1.14	
	Warm-Wet (CanESM2)	Near Future	1.20	5.26	1.20	5.26
	Cold-Wet (CCSM4)	Near Future	1.20	5.26	1.18	3.51
	Cold-Dry (HadGEM2-CC)	Near Future	1.08	-5.26	1.08	-5.26
	Warm-Dry (MPI-ESM-LR)	Near Future	1.09	-4.39	1.09	-4.39
Marsyangdi Hydropower	Base Line		1.27		1.27	
	Warm-Wet (CanESM2)	Near Future	1.31	3.15	1.30	2.36
	Cold-Wet (CCSM4)	Near Future	1.31	3.15	1.36	7.09
	Cold-Dry (HadGEM2-CC)	Near Future	1.28	0.79	1.24	-2.36
	Warm-Dry (MPI-ESM-LR)	Near Future	1.28	0.79	1.27	0.00
Chepe Khola Small Hydropower	Base Line		0.13		0.13	
	Warm-Wet (CanESM2)	Near Future	0.15	15.38	0.14	7.69
	Cold-Wet (CCSM4)	Near Future	0.15	15.38	0.15	15.38
	Cold-Dry (HadGEM2-CC)	Near Future	0.14	7.69	0.13	0.00
	Warm-Dry (MPI-ESM-LR)	Near Future	0.14	7.69	0.14	7.69

Table -4.11 Total energy change surface for Upper Marsyangdi 'A' project

		Total Energy (GWh)								
Change in Temperature (°C)	5	-19%	-13%	-8%	-3%	1%	5%	7%	10%	11%
	4	-20%	-10%	-5%	-3%	2%	6%	8%	10%	10%
	3	-16%	-13%	-6%	-3%	5%	7%	6%	10%	12%
	2	-19%	-11%	-6%	0%	3%	6%	5%	7%	10%
	1	-17%	-13%	-6%	0%	2%	7%	8%	7%	10%
	0	-22%	-11%	-6%	-5%	0%	4%	8%	8%	11%
		-40	-30	-20	-10	0	10	20	30	40
		% Change in Precipitation								

Table -4.12 Total energy change surface for Middle Marsyangdi project

		Total Energy (GWh)								
Change in Temperature (°C)	5	-19%	-17%	-10%	-4%	3%	6%	8%	13%	13%
	4	-19%	-14%	-7%	-5%	3%	7%	10%	12%	12%
	3	-19%	-17%	-9%	-6%	4%	8%	8%	11%	14%
	2	-20%	-15%	-10%	-2%	3%	5%	7%	8%	13%
	1	-19%	-13%	-7%	-2%	1%	7%	7%	10%	12%
	0	-19%	-15%	-10%	-7%	0%	4%	10%	11%	14%
		-40	-30	-20	-10	0	10	20	30	40
		% Change in Precipitation								

Table -4.13 Total energy change surface for Marsyangdi Project

		Total Energy (GWh)								
Change in Temperature (°C)	5	-14%	-11%	-6%	-3%	0%	3%	3%	6%	8%
	4	-16%	-9%	-4%	-3%	1%	4%	5%	6%	6%
	3	-14%	-11%	-6%	-4%	3%	4%	4%	5%	6%
	2	-15%	-10%	-6%	-1%	1%	3%	3%	3%	6%
	1	-13%	-7%	-4%	-1%	1%	4%	5%	5%	6%
	0	-15%	-9%	-5%	-2%	0%	3%	5%	5%	6%
		-40	-30	-20	-10	0	10	20	30	40
		% Change in Precipitation								

Table -4.14 Total energy change surface for Chepe Khoal Small project

Change in Temperature (°C)	Total Energy (GWh)									
	5	-14%	-10%	-5%	-2%	0%	16%	18%	27%	30%
	4	-15%	-9%	-4%	-2%	2%	19%	21%	27%	29%
	3	-15%	-9%	-5%	-2%	1%	17%	20%	24%	30%
	2	-16%	-11%	-6%	-3%	1%	17%	19%	22%	29%
	1	-14%	-10%	-3%	-3%	0%	20%	20%	22%	28%
	0	-14%	-7%	-6%	-3%	0%	16%	25%	27%	31%
		-40	-30	-20	-10	0	10	20	30	40
	% Change in Precipitation									

4.4 High Flows

The Gumbel Method [40, 41] is used for the frequency analysis of annual maximum flow for baseline and CC cases for hydropower project. The Table 4.15 gives the changes in the floods for representative GCMs. The change in 1:100 years flood varies from 28% to 142%, from 40% to 118%, from 56% to 132% and from 49% to 114% for Upper Marsyangdi 'A', Middle Marsyangdi, Marsyangdi and Chepe Khola Small project. Where as from bottom-up approach the 1:100 years flood varies from -33% to 95%, from -29% to 71%, from -40% to 86% and from -42% to 108% for Upper Marsyangdi 'A', Middle Marsyangdi, Marsyangdi and Chepe Khola Small projects.

The Table **4.15** and **4.16** gives the 1:100 years flood change under bottom-up approach for Upper Marsyangdi 'A' and Marsyangdi project. The changes in the maximum flood for the different hydropowers, different RCPs and return periods are given in Table **4.17.** It is noted that the maximum flood magnitude is predicted by warm-wet climatic condition for RCP 4.5 and by cold-wet climatic condition for 8.5. Iinteresting to note that the flood will be increased with increased in temperature without increased in precipitation up to 3°C and then slowly decreased. That also shows the effect of temperature in flow and floods.

Table -4.15 Maximum flood 1:100 change surface for Upper Marsyangdi 'A' project

Change in Temperature (°C)	Flood 1:100 (m3/s)									
	5	-38%	-26%	-13%	-11%	8%	24%	37%	74%	83%
	4	-35%	-14%	-11%	-8%	14%	26%	38%	77%	90%
	3	-37%	-26%	-12%	-2%	15%	28%	42%	80%	95%
	2	-30%	-27%	-8%	-4%	6%	22%	32%	73%	75%
	1	-33%	-22%	-16%	-6%	5%	23%	30%	58%	72%
	0	-36%	-31%	-22%	-8%	0%	20%	28%	52%	56%
		-40	-30	-20	-10	0	10	20	30	40
	% Change in Precipitation									

Table -4.16 Maximum flood 1:100 change surface for Marsyangdi project

Change in Temperature (°C)		Flood 1:100 (m3/s)								
	5	-43%	-31%	-24%	-12%	3%	37%	51%	54%	72%
	4	-42%	-28%	-21%	-9%	4%	38%	58%	61%	76%
	3	-45%	-25%	-19%	-2%	1%	34%	53%	68%	86%
	2	-40%	-21%	-16%	-4%	2%	23%	46%	56%	65%
	1	-40%	-26%	-21%	-10%	1%	19%	37%	50%	58%
	0	-44%	-27%	-24%	-13%	0%	10%	34%	45%	53%
		-40	-30	-20	-10	0	10	20	30	40
		% Change in Precipitation								

5.0 CONCLUSIONS

The study has adopted a combined top-down and bottom-up climate change impact assessment on future water availability in the existing hydropower projects in the Marsyangdi basin using a well-calibrated and validated HEC-HMS hydrological model. Top-down information from four GCMs representing GCMs (warm-wet, cold-wet, cold-dry and warm-dry conditions for RCP 4.5 and RCP 8.5 emission scenarios were used to obtain the possible future climate condition. Additionally, bottom-up approach was used to analyze the impacts on water availability and energy generation for range of climate change (precipitation and temperature) scenarios. The precipitation and temperature were parametrically varied to enable the determination of problematic conditions in the performance indicators considered in this study, namely the water availability, energy generation and high floods. The precipitation and temperature for the period 2025 – 2050 is projected to increase in both RCPs compared with the baseline condition.

The monsoon flow is expected to increased significantly in the case of both RCPs. While the variation in the monthly flow from the base case values is found to be more in the post-monsoon season, December flow is expected to increase and April flow is expected to decrease. The increase in the 40th percentile flow is higher than the increase in the 60th percentile flow for each hydropower project. As expected, the RCP 8.5 projected higher flows than RCP4.5. The floods of different return periods are projected to be higher (28%-176%) than those of the base case floods for all climatic condition in both RCPs.

Also, the impact of precipitation and temperature changes from -40% to +40% and 0°C to 5°C, respectively, from the base case were used for assess the impacts on the water availability and energy generation of the hydropower project (dependable flow, energy, flood etc.). The result shows the sensitivity of impacts on the performance of the hydropower project with changes in future precipitation and temperature.

There is an uncertainty in the future climate scenarios that warrants considering a range of the probable future scenarios during the planning process. Existing hydropower project were traditionally designed based on a stationary hydrologic scenario with respect to time, which excluded the changing scenarios of climate. This research has presented the likely range of impacts of future climate scenarios using the GCM based top-down and the risk-based bottom-up approach. Hydropower projects need to bed design to both resilient and robust to the range of uncertain future condition.

Table -4.17 Maximum flood flow analysis under GCMs.

Name of Plant	Return Period	Baseline Flow (m3/s)	% Change in Flow RCP 4.5				Ensembled (4.5)	% Change in Flow RCP 4.5				Ensembled (8.5)
			CANESM2 (W-W)	CCSM4 (C-W)	HadESM2-CC (C-D)	MPI-ESM-LR (W-D)		CANESM2 (W-W)	CISRO-MK3-6-0 (C-W)	HadESM2-CC (C-D)	MIROC-ESM-CHEM (W-D)	
Upper Marsyangdi Hydropower	100	431	84	73	28	57	60	68	142	77	86	93
	500	491	99	90	38	70	74	81	167	95	105	112
	1000	516	104	96	42	75	79	86	176	102	112	119
Middle Marsyangdi Hydropower	100	535	65	65	40	46	54	74	118	89	72	88
	500	599	81	83	53	60	69	89	123	112	92	104
	1000	631	86	88	57	64	74	93	130	80	98	100
Marsyangdi Hydropower	100	874	85	79	56	61	70	74	132	119	129	113
	500	997	93	88	63	68	78	78	122	112	121	108
	1000	1050	98	94	68	73	83	82	130	120	129	115
Chepe Khola Small Hydropower	100	115	78	50	49	75	63	50	114	75	85	81
	500	143	82	49	55	76	65	52	97	79	89	79
	1000	155	83	49	56	75	66	53	97	80	90	80

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