Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 10 Issue 08, August-2021

Development of A Rainfall Run off Model for An Ungauged Location Under Climate Change Scenarios: A Case Study of Kabeli Khola, Nepal

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Abstract— **The discharge prediction at ungauged hydropower intake site is crucial thing in mountainous country like Nepal. This influences the management of generated energy corresponding to different flows in different seasons to balance between demand and supply. Among various methods available for determination of discharge at ungauged site, rainfall runoff modelling is fairly accurate over others. First, the DEM data was collected and analyzed in Arc GIS for extraction of watershed hydrological and physical parameters. Then the semi-distributed HEC-HMS rainfall runoff model was calibrated and validated taking hydrological, meteorological, climatological data as well as physical parameters in a Tamor basin, which is a gauged catchment with two hydrological stations at Majhitar and Mulghat. The calibration was performed for the period 1996 to 2001 and validation was conducted for period 2002 to 2006. The performance of the model was evaluated using Nash-Sutcliff Efficiency (NSE) and Coefficient of Determination (R^2). The obtained values of NSE and R^2 are 0.858 and 0.8681 for Majhitar station and 0.808 and 0.853 respectively for Mulghat station during calibration period. Similarly, the values of NSE and R^2 for validation period are 0.671 and 0.8694 for Majhitar and 0.823 and 0.8273 for Mulghat. The performance of model achieved was good and acceptable. The model with optimized parameters of the gauged catchment was then used to predict discharge at intake site of proposed Kabeli Khola Hydropower Project during calibration and validation period. Four CMIP6 climate scenarios ACCESS-CM2-SSP585, ACCESS-CM2-SSP245B, EC3-EARTH-SSP245B and EC3-EARTH-SSP585B were taken and discharge simulation was performed for the years 2015 to 2100 at same site. Similar trend was observed for maximum and minimum annual flow for four climate scenarios during the period. However, there is variation in annual peak flow during the period with maximum peak flow 494.9 m^3/s in June 26, 2077 for EC3-EARTH-SSP585B scenario and minimum peak flow 50.9 m^3/s in August 20, 2033 for ACCESS-CM2-SSP585B scenario. Mean monthly hydrographs have been plotted for calibration and validation period as well as for period 2015-2100 for all climate scenarios. The maximum mean monthly flow obtained was 59.9 m^3/s for EC3-EARTH-SSP585B scenario. The simulated peak discharge could be utilized in the design of headworks and flood management structures at headworks site. The consistency of the energy generation from the proposed hydropower project could be assessed through the prepared hydrographs for the period 2015-2100.**

Keywords*— *Climate Projections, Discharge Prediction, Flood Management, HEC-HMS, Hydrologic Model, Tamor

I. INTRODUCTION

Nepal is one of the richest countries in the world water resources, accounting for more than 2.27% of the world's water resources (HEMS, 2015). The total hydropower potential of Nepal was assessed as 83,500 MW in 1966 by Dr. Hari Man Shrestha during his PhD research work in former USSR (R. Jha, 2011). However, various rough estimates shows that only half of this total potential is technically feasible. Nepal Electricity Authority (NEA) and Department of Electricity Department (DoED) are responsible for power development, licensing and policy making with reference to this potential within our country. The total installed generation capacity in Nepal is only 1,182 megawatts (MW) against a peak electricity demand of 1,320 MW in fiscal year 2018–2019 (ADB, 2020). The reasons behind the huge hydropower potential are topography of Nepal with high relief and river with abundant water flow. Although snow fed river in Nepal has less problem with discharge due to perennial in nature, rivers in mid hills depend more on rainfall. Therefore, discharge prediction in such rivers plays great role as power production from Run-off-River hydropower schemes solely rely on river flow due to fixed head.

Nepal is mountainous country and most of the gauged catchments are located at low altitudes and most of the higher altitudes catchments are ungauged. The discharge prediction of ungauged river can be made with the calibrated and validated model within the gauged river.

Rainfall runoff modeling is one of the most paramount hydrological modeling that is used to investigate the relationship between the rainfall and direct runoff generated under the influence of different watershed physical parameters (Salwa and Wardah, 2015 and Kishor et al., 2014).

Tamor catchment with outlet at Mulghat, Dhankuta has been chosen as a study area. Tamor basin has two discharge gauging stations at Majhitar and Mulghat. The calibrated and validated rainfall runoff model at this catchment could be applied for discharge prediction at the intake site of Kabeli Khola Hydropower Project which takes supplies from Kabeli Khola of Taplejung district, Nepal.

The Tamor River is the major river of eastern part of Nepal and major tributary of Sapta Koshi River. The basin with outlet at Mulghat has an area of 5864 km^2 with elevation range 233 to 8422 m. The geographical coordinate range of the basin is of 26°59’9.6” N and 88°16’40.8” E to 27°50’34.8” N to 88°11’52.8” E.

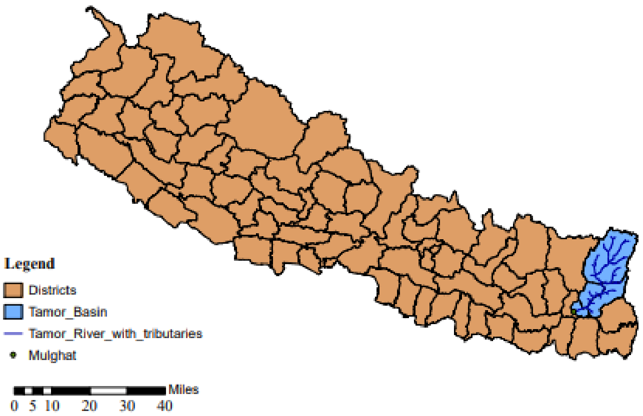

Fig 1. District Map of Nepal showing Tamor basin outlet at Mulghat, Dhankuta

The intake site of Kabeli Khola Hydropower Project is proposed at Kabeli river in Panchthar and Taplegunj district with geographical coordinates 27°27'29.23"N and 87°55'18.29" E.

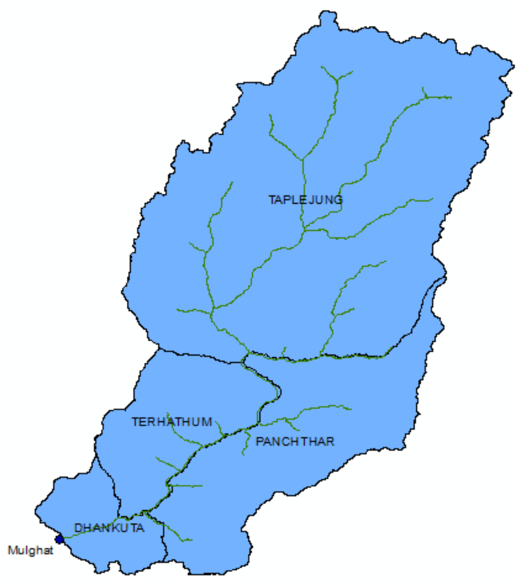

Fig 2. Tamor basin with outlet at Mulghat, Dhankuta

The main objective of the study is to develop rainfall runoff model for the Tamor basin outlet at Mulghat, Dhankuta. The other specific objectives are to simulate runoff from ungauged catchment at proposed headworks point of Kabeli Khola Hydropower Project and to develop climate model to simulate future discharge data at that point.

This study is believed to be useful in analyzing discharge at the intake point of the proposed headworks of Kabeli Khola Hydropower Project. The predicted discharge could be utilized in assessing efficiency of the hydropower project in hydroelectricity generation as well as supply capacity of the project could be assessed with respect to the demand. The flood management study could be done in advance and potential future risks could be mitigated.

II. MATERIALS AND METHOD

The overall research methodologies adopted are described in following points.

A. GIS data collection, processing and basin creation

DEM of Nepal of 30 m resolution has been collected and processed in Arc GIS 10.2.1 to obtain the DEM of the study area. Terrain preprocessing, watershed processing and flow path tracing has been performed for the study area using Arc Hydro tools of Arc GIS. The shape file of Tamor basin with outlet at Mulghat station at Dhankuta district was thus created with number of sub basins and stream networks.

After preparing the basin, sub basins and stream networks with flow path tracing in Arc GIS, the project required for HEC-HMS modelling was created and generated using HEC GeoHMS interface in Arc GIS.

The merging and the splitting of the sub basins created earlier was done considering the location having available flow data and location where flow data have to be simulated.

There are two hydrological stations available within the basin, namely Mulghat and Majhitar. As basin was already cut through lower outlet point Mulghat, sub-basin has been also formed through Majhitar. Moreover, sub-basin has been also created through the proposed location of proposed headworks of Kabeli Khola Hydropower Project, where discharge data are to be simulated.

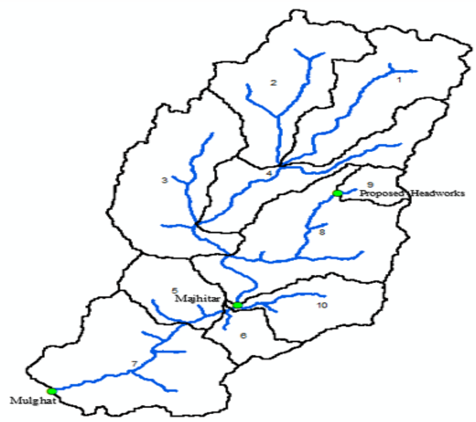

Fig 3. Tamor basin with outlet at Mulghat station divided into ten sub basins with stream networks

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 10 Issue 08, August-2021

The Basin characteristics, River Length, River Slope, Basin Slope, Longest Flow Path, Basin Centroid, Centroidal Elevation and Centroidal Longest Flow Path were determined using charactersitics tool of HEC-GeoHMS interface in GIS.

The Land Use Land Cover Map of Nepal has been collected and extracted for the study area. The occupancy of land use type of entire sub basins were then determined using GIS.

TABLE I. Details of the Sub-basins created

Sub basin	Altitude (m)	Latitude (m)	Longitude (m)	Area (Sq km)
1	5343	27.727	88.005	743
2	4901	27.753	87.815	763
3	1713	27.492	87.591	889
4	3328	27.522	87.866	545
5	2079	27.194	87.580	326
6	1606	27.075	87.732	181
7	647	27.000	87.503	990
8	1046	27.326	87.860	930
9	3188	27.476	87.995	123
10	2347	27.154	87.875	374

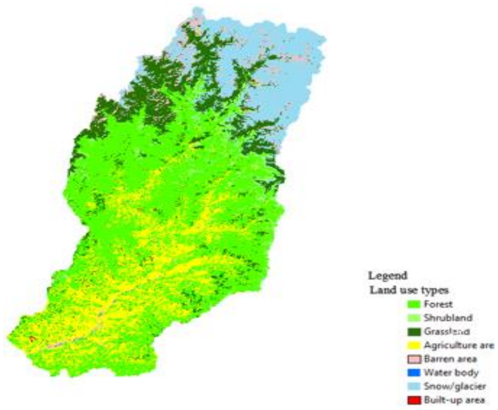

Fig 4. Land Use Land Cover Map of Tamor basin outlet at Mulghat station

TABLE II. Land use type in Tamor basin

Landuse type	Area (Sq. km)	% Area of basin	Remarks
Forest	2671.65	45.56 %	**Maximum**
Shrubland	198.90	3.39 %	
Grassland	809.63	13.81 %	
Agricultural Area	1105.05	18.84 %	
Barren Area	186.32	3.18 %	
Water Body	5.56	0.09 %	
Snow/Glacier	883.85	15.07 %	
Built-up Area	3.04	0.05 %	**Minimum**
Total	**5864**	**100 %**	

Table II shows land use coverage in percentage in Tamor basin. Forest covers most of the land with moderate coverage by snow, agricultural area and grass land and minor coverage by shrubland, water body and built-up area.

B. *Meterological data collection, processing and PET calculation*

The daily precipitation data has been collected for the available rainfall stations within the study area from Department of Hydrology and Meteorology (DHM) for the study period (1996-2006). The average daily precipitation for each sub-basins was then calculated by Thiessen Polygon method in Arc GIS 10.2.1.

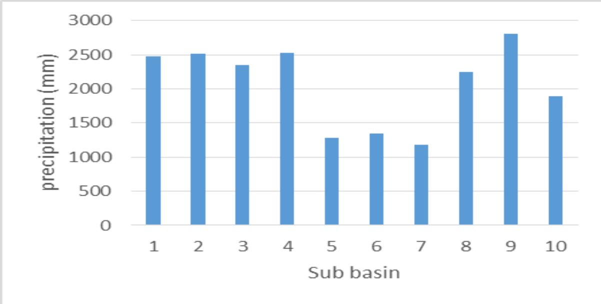

Fig 5. Average annual precipitation for sub basins for years 1996 to 2006

Figure 5 shows that sub basin 9 received maximum annual average precipitation of 2777.88 mm and sub basin 7 received minimum average annual precipitation of 1174.072 mm with in the study period.

The daily temperature, sunshine hours, wind velocity data were also collected and averaged for the study period for each sub-basins. The monthly average values were then calculated from the daily data averaged over the period. For the sub basin not having the stations within its boundary, data of the station at the least distance from centroid of the sub basin were used.

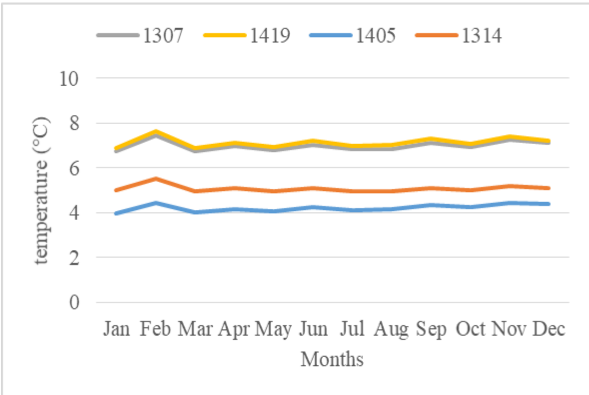

Fig 6. Average monthly minimum temperature of stations for the study period

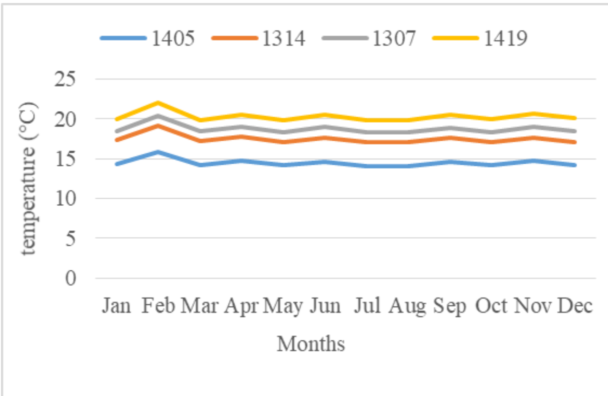

Fig 7. Average monthly maximum temperature of stations for the study period

International Journal of Engineering Research & Technology (IJERT)
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Figure 6 shows that average minimum temperature of station 1405 is comparatively lesser as it lies in Himalaya region and Figure 7 shows average maximum temperature of 1419 is higher as it lies in middle Terai region.

The average monthly humidity data for the chosen stations for the study period has been presented in Figure 8. It shows that station 1307 has lesser humidity throughout the year as it lies in lower Middle Terai region and station 1314 has higher humidity throughout the year as it lies in Middle Himalaya region.

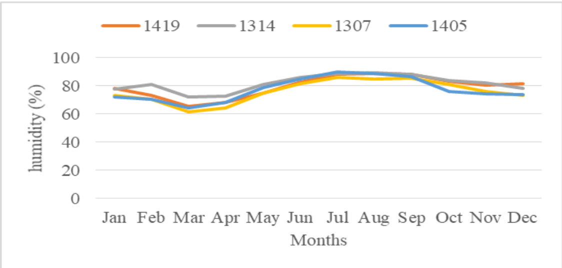

Fig 8. Average Monthly Humidity data of stations for the study period

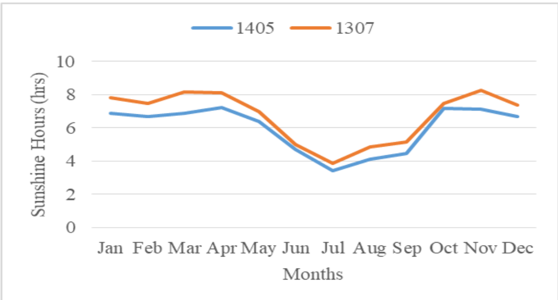

Fig 9 . Average Monthly Sunshine hours of stations for the study period

There are only two stations available that measure sunshine hours within the study area namely station 1405 and 1307. The data from station 1405 has been assigned to sub basins 1, 2,3,4,5,6,8,9 and 10. Similarly data from station 1307 has been assigned to sub basin 7. The average monthly sunshine hours of these stations for the study period are shown in Figure 9.

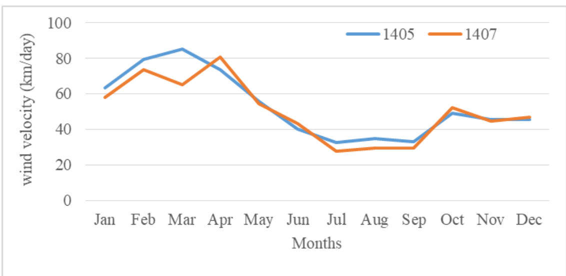

Fig 10. Average Monthly Wind Velocity of stations for the study period

The average wind velocity for available stations within the study area during the study period are presented in Figure 10.

From Figure 10, it can be clearly seen that for stations 1405 and 1407, during months of March and April wind has maximum velocity, while wind has minimum velocity in July for both the stations.

The average monthly minimum and maximum temperature, average monthly humidity, average monthly sunshine hours and average monthly wind velocity data were used to calculate Average Daily Potential Evapotranspiration through each sub basins during study period in CROPWAT 8.0. The average daily values were then converted into average monthly values.

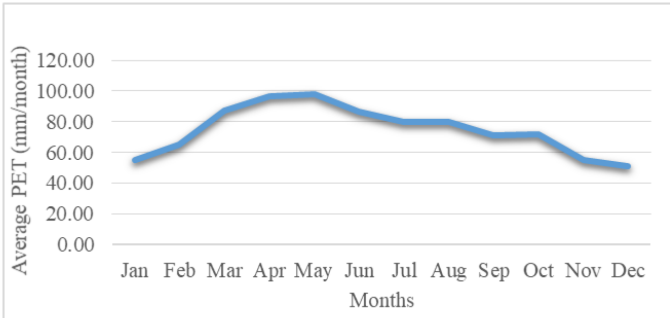

Fig 11. Average Monthly Potential Evapotranspiration (PET) during the study period

C. Hydrological data collection and preparation

The daily flow data observed at two hydrological stations; Mulghat at Dhankuta district and Majhitar at Terhathum district have been collected from DHM for the study period.

The minimum monthly value for each months for each year was then determined from the daily flow data of Mulghat station and averaged over the study period to get minimum monthly average flow value. Thus obtained flow data were then distributed to all of the sub basins in proportion to the area of sub basins to obtain average monthly base flow contribution from each sub basin during the study period.

The base flow calculated from daily flow data for the Mulghat station has been presented in Table III. Table III shows that sub basin 9 have minor base flow contribution of 1.08 m^3/s in the month of March while sub basin 7 has major contribution of base flow of 122.57 m^3/s in the month of August.

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TABLE III. Average monthly base flow (m^3/s) for subbasin for the study period

Sub basin	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1	7.26	6.79	6.55	7.71	13.11	27.50	78.96	91.99	60.47	25.65	13.97	10.10
2	7.45	6.97	6.72	7.92	13.46	28.24	81.08	94.46	62.10	26.34	14.34	10.37
3	8.68	8.12	7.83	9.23	15.69	32.90	94.47	110.06	72.35	30.69	16.71	12.08
4	5.32	4.98	4.80	5.66	9.62	20.17	57.92	67.47	44.35	18.82	10.24	7.41
5	3.18	2.98	2.87	3.38	5.75	12.06	34.64	40.36	26.53	11.26	6.13	4.43
6	1.77	1.65	1.59	1.88	3.19	6.70	19.23	22.41	14.73	6.25	3.40	2.46
7	9.67	9.05	8.72	10.28	17.47	36.64	105.20	122.57	80.57	34.18	18.61	13.45
8	9.08	8.50	8.19	9.65	16.41	34.42	98.83	115.14	75.69	32.11	17.48	12.64
9	1.20	1.12	1.08	1.28	2.17	4.55	13.07	15.23	10.01	4.25	2.31	1.67
10	3.65	3.42	3.29	3.88	6.60	13.84	39.74	46.30	30.44	12.91	7.03	5.08

D. HEC-HMS modelling

GIS map of sub-basins and river network created in Arc GIS 10.2.1 was imported in basin model manager interface of HEC HMS 4.2.1.

Sub-basins, junctions, reaches and sinks were defined in the basin model. Downstream elements for each sub-basins, junctions and reaches were then assigned.

Metrologic model was then added in the HEC HMS interface and prepared precipitation, flow and PET data were given for each of the sub basins.

Parameters that define the basin processing to simulate the discharge through each sub basins were then given. The parameters were set for the phenomenon like canopy, surface, loss, transform, base flow, and routing.

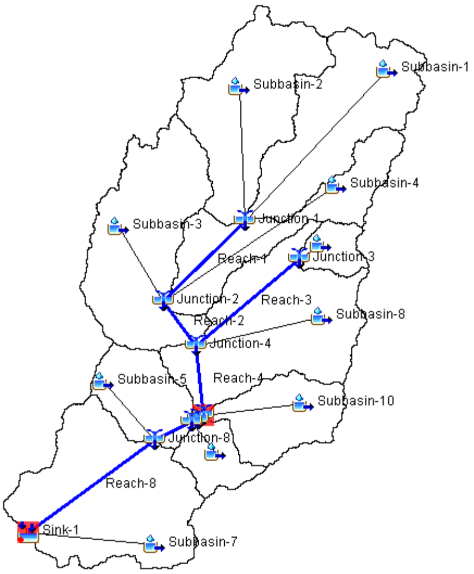

Fig 12. HEC HMS model with junctions, reaches and sink

The stream flow data are available for 11 years period from 1996 to 2006. Therefore first six years period from 1996 to 2001 has been chosen for calibration and remaining five years from 2002 to 2006 has been chosen for validation. The control specifications has been added in HEC HMS interface and time period has been defined as chosen for calibration.

The model was then run for the calibration period. The results of observed flow data and simulated flow data for both the outlet stations was compared. The discrepancy obtained between observed and simulated data shows the error in the model and the sensitive parameters affecting the run off from the sub basins were changed till the hydrograph of observed and simulated hydrograph matched and till the performance criteria governing the efficiency of model is within acceptable range as good as possible. The calibrated model was used to simulate discharge at outlet stations for the validation period and again the simulated flows were compared with the observed flows. The performance of the model was evaluated comparing hydrographs of the simulated and observed flows as well as evaluating the values of performance criteria obtained.

E. Flow simulation at the headworks point

The flow of Kabeli Khola at the proposed headworks point of Kabeli Khola Hydropower Project was simulated for the calibration and validation period.

Moreover, among the different Global Climate Models (GCMs) presented by the Coupled Model Intercomparison Project Phase-6 (CMIP6), two GCMs; ACCESS CM2 and EC3 EARTH were downscaled into Regional Climate Models (RCMs). Each model contain two climate scenarios SSP245B and SSP585B. The daily precipitation, maximum and minimum temperature data for historical period 1989 to 2014 and for climate projections period 2015 to 2100 were downloaded for these scenarios from CMIP6 database (https://esgf-node.llnl.gov/search/cmip6/) for the same meteorological stations selected for the HEC-HMS model of the Tamor basin as explained earlier.

The RCMs data for each stations were bias corrected using Quantile mapping method. Daily precipitation data were determined for the each of the ten sub basins using station average technique applied for the HEC HMS model calibration and validation for the year 2015 to 2100. Similarly, daily precipitation data for each of the sub basins were determined. Potential Evapotranspiration (PET) for all of the sub basins were then calculated from monthly average minimum and maximum temperature for the years 2015 and 2100 with previous humidity, sunshine hours and wind velocity data.

The calibrated and validated model was then run separately for four climate scenarios with new precipitation and PET data. The simulated flow at the proposed headworks point of the Kabeli Khola Hydropower project was then obtained

III. RESULTS AND DISCUSSIONS

A. Model Calibration

The Model was calibrated for the period 1996 to 2001 using the parameters affecting the run off through the sub basins. The different phenomenon selected that stimulate the rainfall runoff from the basin were simple canopy, simple surface, Green and Ampt Loss, SCS unit hydrograph and Muskingum routing. These phenomenon uses different parameters for rainfall run off response from the sub basins. Those parameters are initial storage and maximum storage for simple canopy, initial storage and maximum storage for simple surface, initial content, saturated content, suction, hydraulic conductivity and imperviousness for Green and Ampt Loss, lag time for SCS unit hydrograph and Muskingum K and Muskingum x for routing. The initial value of lagtime and maximum surface storage was done based on Curve Number value estimated from CN grid generated from Land use map and Soil Map. The other parameters were assumed based on the land use and soil type. These parameters were assigned to each sub basins. The most sensitive parameters were hydraulic conductivity and maximum surface storage.

The model parameters were changed with a view to get maximum efficiency both manually and optimization simulation techniques. The Nash-Sutcliff Efficiency (NSE) value was observed and Coefficient of Determination (R^2) was calculated from scatter plot diagram between observed and simulated flows as presented in Figure 15 and Figure 16.

Figure 13 and Figure 14 shows that there is well simulation between observed and simulated flows during the calibration period for both Majhitar and Mulghat stations. Moreover, the date of peak discharge for Majhitar station concurred for both simulated and observed data, only three days variation for Mulghat station. The statistical parameters Nash-sutcliff Efficiency (NSE) and Coefficient of Determination (R^2) obtained to be 0.858 and 0.8681 for Majhitar station and these values came to be 0.808 and 0.853 respectively for Mulghat station.

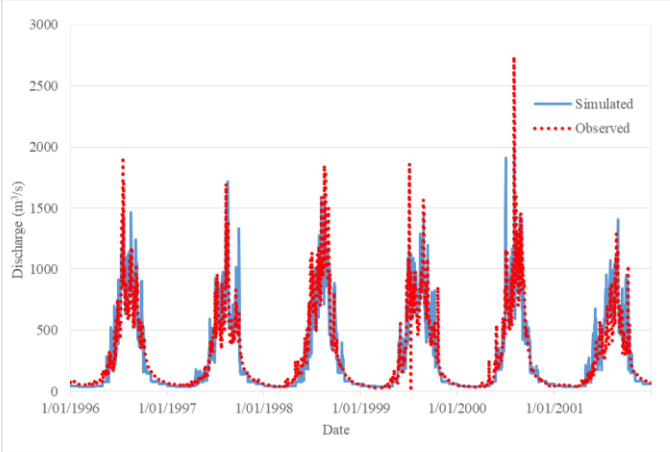

Fig 13. Simulated and Observed Flow hydrograph for Majhitar for Calibration period

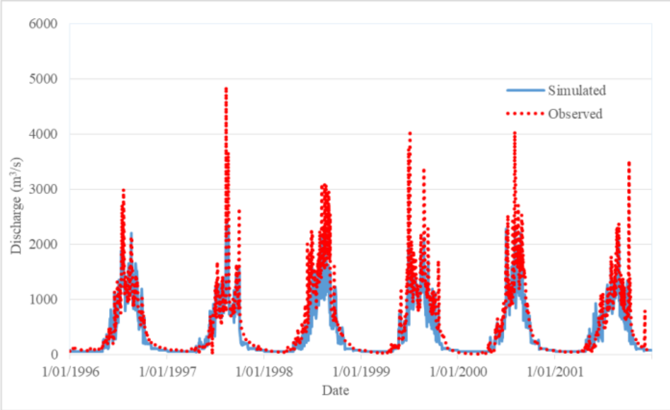

Fig 14. Simulated and Observed Flow hydrograph for Mulghat for Calibration period

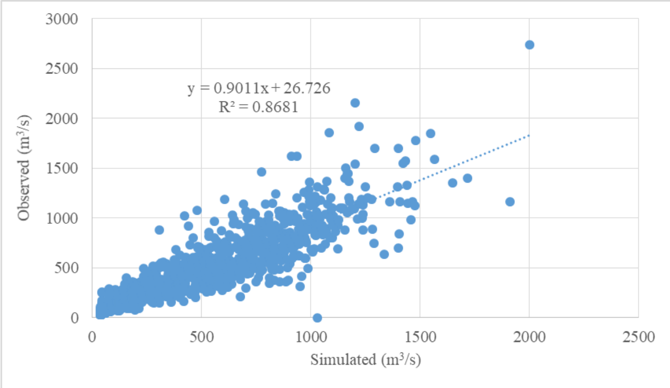

Fig 15. Comparison of Simulated and Observed Flow for Majhitar for Calibration period

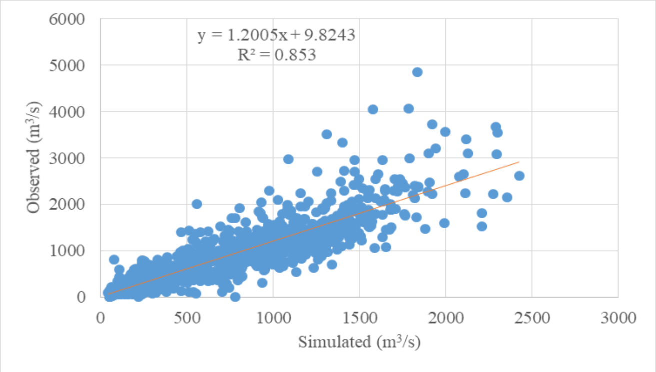

Fig 16. Comparison of Simulated and Observed Flow for Mulghat for Calibration period

This shows model performance is good during calibration period from both qualitative and quantitative analysis. However, the peak discharge obtained is under predicted for the both the stations.

B. Model Validation

The model with calibrated parameters was validated for the period 2002 to 2006 and the performance of the model was checked. The Figure 17 and Figure 18 show the hydrograph of simulated flow well-coordinated with the observed flow.

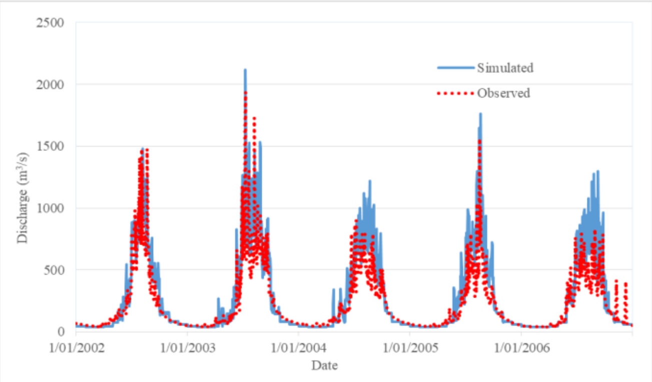

Fig 17. Simulated and Observed Flow hydrograph for Majhitar for Validation period

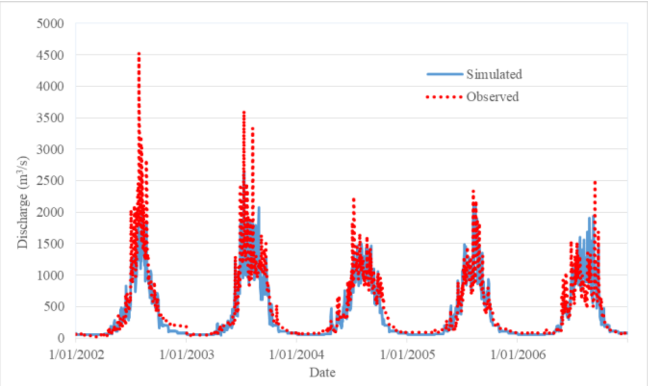

Fig 18. Simulated and Observed Flow hydrograph for Mulghat for Valibration period

The Nash-Sutcliff Efficiency (NSE) and Coefficient of Determination (R^2) obtained for Majhitar station were 0.671 and 0.8694. These values were 0.823 and 0.8273 respectively for Mulghat station. These values showed the model performing in acceptable range for both stations in validation period as well. The date and time of peak flow exactly coincide for Majhitar station but variation for the Mulghat station. Likewise in calibration period, the simulated peak flow is lower than observed ones for both the stations.

The scatter plot diagram determining R^2 for both the stations are presented in Figure 19 and Figure 20.

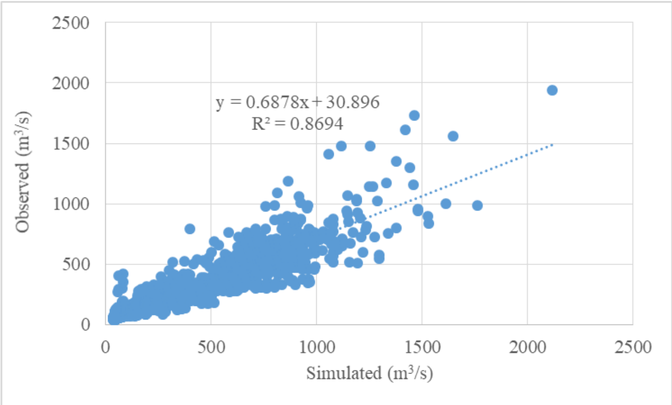

Fig 19. Comparison of Simulated and Observed Flow for Majhitar for Validation period

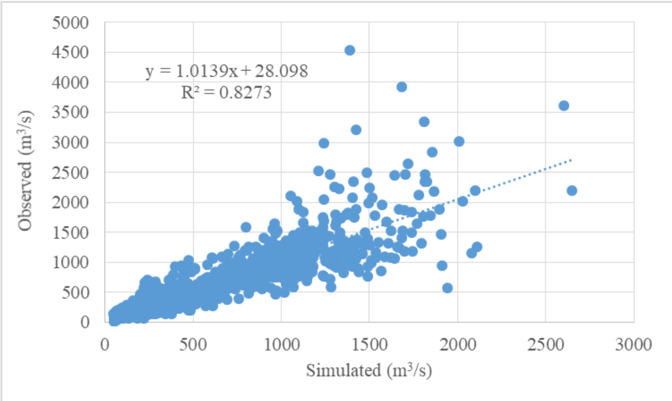

Fig 20. Comparison of Simulated and Observed Flow for Mulghat for Validation period

C. Analysis of Annual Mean Flow and Peak Flow

1) Annual Mean Flow

Figure 21 shows the graph comparing the simulated and observed annual mean flow during the period 1996 to 2006 for the Majhitar station. The graphs for both the observed and simulated data are alike with minimum flow deviation of 1.52 m^3/s in the year 1996 and maximum flow deviation 85.79 m^3/s in the year 2002.

Similarly, the comparison of simulated and observed mean annual flow for Mulghat station for the period has been presented in Figure 22. This graph also shows harmonious relation between simulated and observed data with 172.07 m^3/s (maximum) flow deviation in the year 1998 and 8.09 m^3/s (minimum) flow deviation in 2005.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
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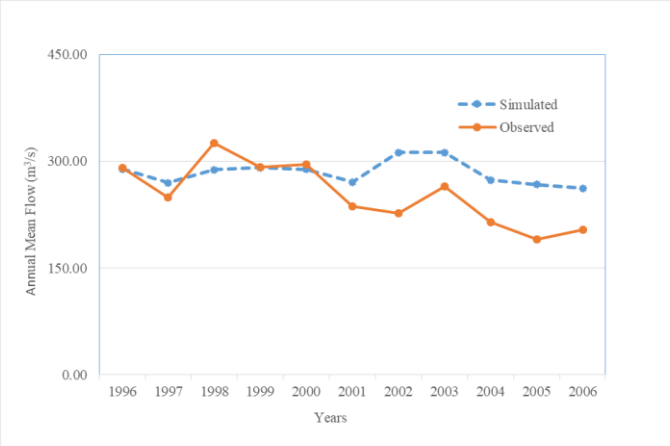

Fig 21. Comparison of Simulated and Observed Annual Mean Flow for Majhitar for the years 1996 - 2006

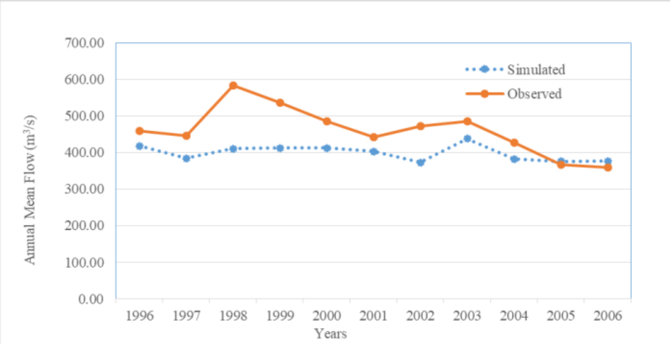

Fig 22. Comparison of Simulated and Observed Annual Mean Flow for Mulghat for the years 1996 – 2006

The simulated and observed annual mean flows for both the outlets are presented in Table IV and Table V.

TABLE IV. Simulated and Observed Annual Mean Flow data for Majhitar during 1996-2006

Year	Annual Mean Flow (m^3/s)	
	Simulated	**Observed**
1996	289.32	290.85
1997	269.96	249.14
1998	287.94	325.76
1999	291.18	292.10
2000	288.83	295.29
2001	270.90	237.13
2002	312.54	226.75
2003	312.54	264.77
2004	273.59	214.71
2005	267.33	190.75
2006	261.85	203.55

TABLE V. Simulated and Observed Annual Mean Flow data for Mulghat during 1996-2006

Year	Annual Mean Flow (m^3/s)	
	Simulated	**Observed**
1996	418.14	460.05
1997	384.17	446.24
1998	410.90	582.97
1999	412.95	536.21
2000	412.95	485.69
2001	403.02	442.01
2002	372.48	473.22
2003	438.11	485.94
2004	382.71	427.20
2005	375.29	367.20
2006	377.05	359.76

2) Annual Peak Flow

The graph showing the comparison between simulated and observed annual peak flow for Majhitar station for the period 1996 to 2006 has been presented in Figure 23 and the data have been presented in Table VI.

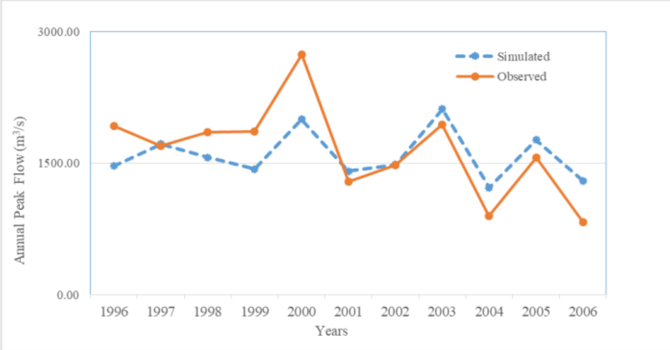

Fig 23. Comparison of Simulated and Observed Annual Peak Flow for Majhitar for the years 1996 – 2006

Figure 23 shows that simulated and observed peak flow data are well coordinated with maximum flow deviation of 454.40 m^3/s in the year 1996 and minimum flow deviation of 2.10 m^3/s in the year 2002.

Likewise comparison between simulated and observed annual peak flow for Mulghat station for the period 1996 to 2006 has been presented in Figure 24 and the data have been presented in Table VII. The graph also shows similar pattern for observed and simulated data with more deviation. The maximum flow deviation is 2502 m^3/s in the year 2002 and minimum flow deviation is 576.2 m^3/s in the year 2006.

The comparison of simulated and observed annual peak flow as well as annual mean flow data during calibration and validation period resembles the acceptable and good performance of the model during both period.

TABLE VI. Simulated and Observed Annual Peak Flow data for Majhitar during 1996-2006

Year	Annual Peak Flow (m^3/s)	
	Simulated	**Observed**
1996	1465.60	1920.00
1997	1719.10	1700.00
1998	1565.70	1850.00
1999	1433.40	1860.00
2000	2000.70	2740.00
2001	1409.50	1290.00
2002	1482.10	1480.00

2003	2118.30	1940.00
2004	1222.00	898.00
2005	1765.00	1560.00
2006	1298.10	828.00

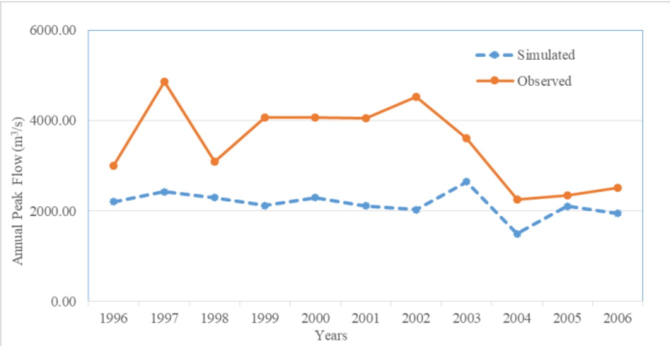

Fig 24. Comparison of Simulated and Observed Annual Peak Flow for Mulghat for the years 1996 – 2006

TABLE VII. Simulated and Observed Annual Peak Flow data for Mulghat during 1996-2006

Year	Annual Peak Flow (m^3/s)	
	Simulated	**Observed**
1996	2208.50	3000.00
1997	2425.00	4860.00
1998	2293.40	3100.00
1999	2117.50	4070.00
2000	2298.50	4070.00
2001	2113.40	4050.00
2002	2027.80	4530.00
2003	2649.60	3610.00
2004	1498.10	2250.00
2005	2109.30	2340.00
2006	1943.80	2520.00

The date of incident of peak discharge for calibration and validation period for the both stations are shown in Table VIII. The peak discharge date coincides for Majhitar during both calibration and validation period while three days variation for Mulghat during calibration period and about a year variation for validation period. Although some peak discharge date variation for Mulghat during validation period, performance analysis discussed above as well as peak discharge date matching, good qualitative and statistical performance of upper altitude outlet Majhitar station suggests the developed model performed well for upper catchments.

TABLE VIII. Simulated and Observed Peak discharge date for both stations

Outlet	Calibration Period (1996-2001)		Validation Period (2002-2006)	
	Peak discharge date			
	Simulated	**Observed**	**Simulated**	**Observed**
Majhitar	8/3/2000	8/3/2000	10/7/2003	10/7/2003
Mulghat	8/14/1997	8/11/1997	7/28/2002	7/11/2003

D. Flow simulation at proposed headworks point of Kabeli Khola Hydropower Prject

1) Calibration and Validation Period

The flow data at the proposed headworks point of Kabeli Khola Hydropower project were obtained for the calibration and validation period from the developed HEC-HMS model. The time series data for the period 1996 to 2001 are presented in Figure 25.

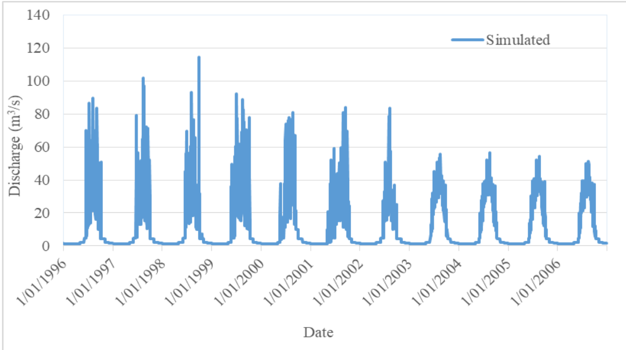

Fig 25. Simulated time series flow data at the proposed headworks point of Kabeli Khola Hydropower Project for the years 1996-2006

The calculated annual mean flow and annual peak flow values presented in Table IX. The graphs for the Annual Mean Flow and Annual Peak flow for the period have been presented in Figure 26 and Figure 27.

TABLE IX. Simulated Annual Mean Flow and Annual Peak Flow data at the proposed headworks point for the years 1996 – 2006

Year	Simulated	
	Annual Mean Flow (m^3/s)	**Annual Peak Flow (m^3/s)**
1996	11.30	89.80
1997	10.75	101.70
1998	11.20	114.60
1999	12.75	92.10
2000	11.77	80.80
2001	10.82	83.80
2002	8.85	83.50
2003	10.93	55.80
2004	10.93	56.40
2005	10.76	54.60
2006	10.63	51.40

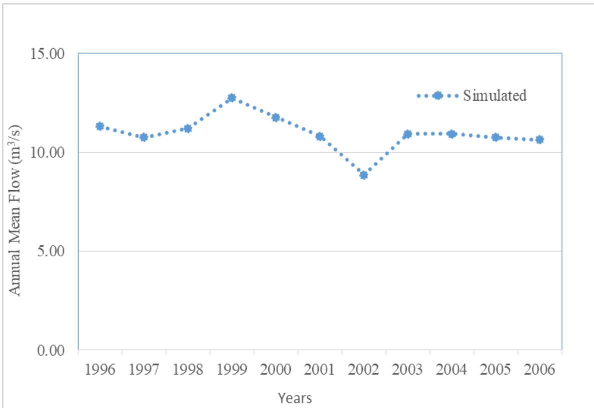

Fig 26. Simulated Annual Mean Flow at the proposed headworks point of Kabeli Khola Hydropower Project for the years 1996 – 2006

The Figure 26 shows similar values of Annual Mean Flow at the headworks point during the calibration and validation period with maximum flow 12.75 m^3/s in the year 1999 and minimum flow 8.85 m^3/s in the year 2002.

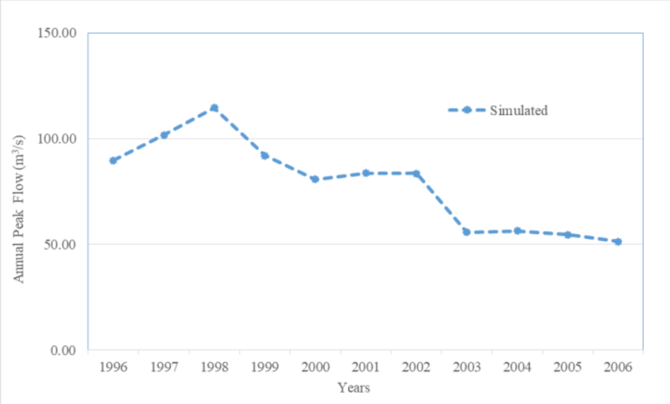

Fig 27. Simulated Annual Peak Flow for at proposed headworks point of Kabeli Khola Hydropower Project for the years 1996 – 2006

The Figure 27 shows that variation in Annual Peak Flow is more or less in decreasing order with maximum value 114.60 m^3/s in the year 1998 and minimum value 51.4 m^3/s in the year 2006. Although Annual Mean Flow during the period shows similar pattern, fluctuation of Annual Peak Flow replicates the change in precipitation amount in the catchment with time.

The mean monthly hydrograph has been also plotted for the calibration and validation period using average monthly flow calculated from the monthly average flow of each year. The hydrograph has been presented in Figure 28 and the flow is equal to base flow during dry seasons (January to April and October to December), then the hydrograph starts to rise in May with peak value 39 m^3/s in August and descends to meet base flow again in October.

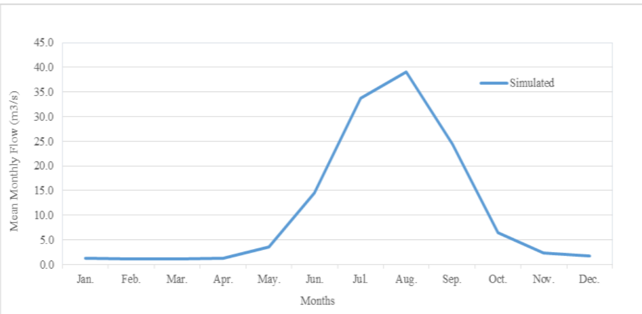

Fig 28. Mean Monthly Flow Hydrograph at the proposed headworks point for the years 1996–2006

2) Future Flow Simulations

Similarly, the flow at the headworks point were obtained for four climate scenarios; ACCESS-CM2-SSP245B, ACCESS-CM2-SSP585B, EC3-EARTH-SSP245B and EC3-EARTH-SSP585B using the developed model. The graphs of Annual Mean Flow for these scenarios are presented in Figures 29, 30, 31 and 32 respectively. Similarly, graphs of Annual Peak Flow are presented in Figures 33, 34, 35 and 36 respectively. The comparison of Annual Peak Flow and Annual Mean flow for these scenarios are presented in Tables X and XI.

TABLE X. Comparison of Annual Mean Flow for different Climate Scenarios for period 2015-2100

Climate Scenarios	Annual Mean Flow (m^3/s)		Year
ACCESS-CM2-SSP245B	Minimum	7.00	2088
	Maximum	15.70	2036
ACCESS-CM2-SSP585B	Minimum	5.70	2027
	Maximum	18.10	2092
EC3-EARTH-SSP245B	Minimum	8.40	2074
	Maximum	16.90	2098
EC3-EARTH-SSP585B	Minimum	8.20	2018
	Maximum	22.80	2100

TABLE XI. Comparison of Annual Peak Flow for different Climate Scenarios for period 2015-2100

Climate Scenarios	Annual Peak Flow (m^3/s)		Date
ACCESS-CM2-SSP245B	Minimum	64.90	8/26/2098
	Maximum	266.80	5/15/2082
ACCESS-CM2-SSP585B	Minimum	50.90	8/20/2033
	Maximum	430.80	8/10/2080
EC3-EARTH-SSP245B	Minimum	80.00	8/05/2031
	Maximum	431.20	8/11/2093
EC3-EARTH-SSP585B	Minimum	70.70	8/18/2022
	Maximum	494.90	6/26/2077

From Table X, similar values are obtained for maximum and minimum Annual Mean Flow during the period 2015-2100 for different climate scenarios. However, Table XI shows variation in Annual Peak Flow during the period with maximum Peak Flow 494.9 m^3/s in June 26, 2077 for EC3-EARTH-SSP585B scenario and minimum Peak Flow 50.9 m^3/s in August 20, 2033 for ACCESS-CM2-SSP585B scenario.

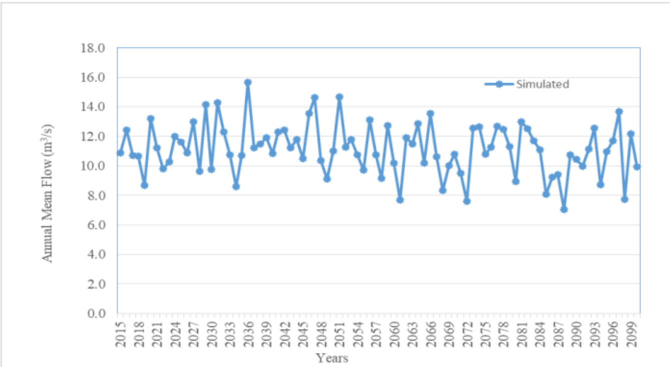

Fig 29. Simulated Annual Mean Flow at proposed headworks point of Kabeli Khola Hydropower Project for the years 2015-2100 considering ACCESS-CM2-SSP245B climate scenario

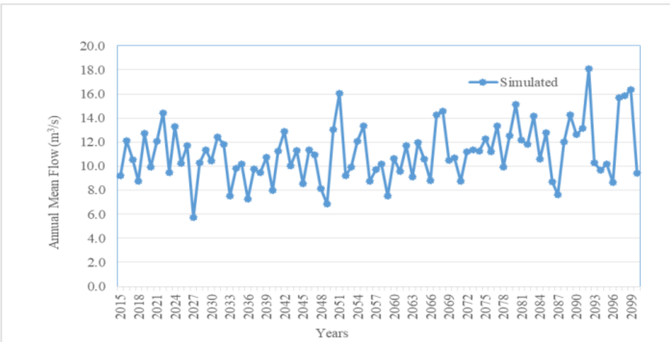

Fig 30. Simulated Annual Mean at proposed headworks point of Kabeli Khola Hydropower Project for the years 2015-2100 considering ACCESS-CM2-SSP585B climate scenario

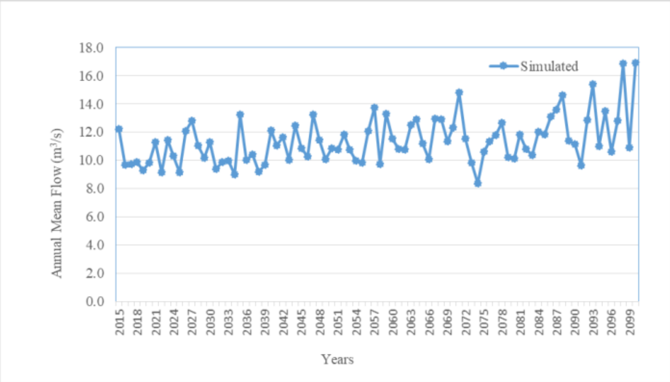

Fig 31. Simulated Annual Mean Flow at proposed headworks point of Kabeli Khola Hydropower Project for the years 2015-2100 considering EC3-EARTH-SSP245B climate scenario

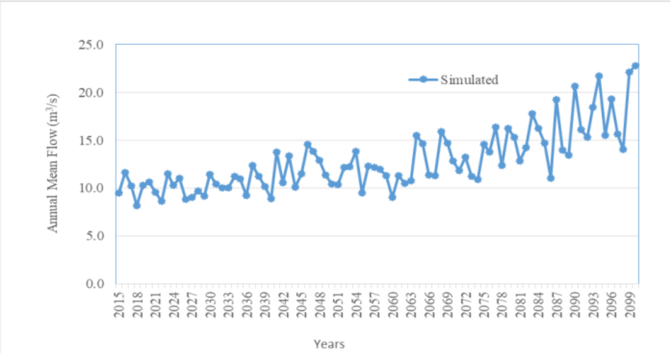

Fig 32. Simulated Annual Mean Flow at proposed headworks point of Kabeli Khola Hydropower Project for the years 2015-2100 considering EC3-EARTH-SSP585B climate scenario

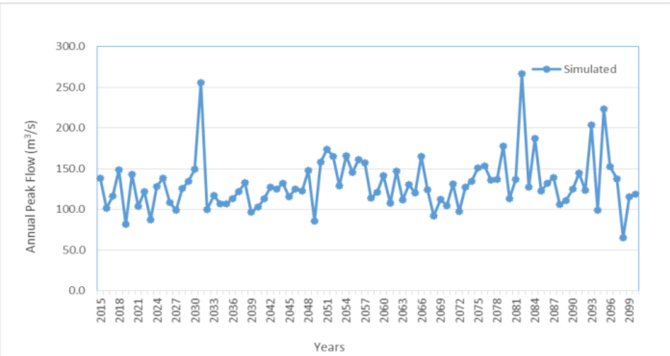

Fig 33. Simulated Annual Peak Flow at proposed headworks point of Kabeli Khola Hydropower Project for the years 2015-2100 considering ACCESS-CM2-SSP245B climate scenario

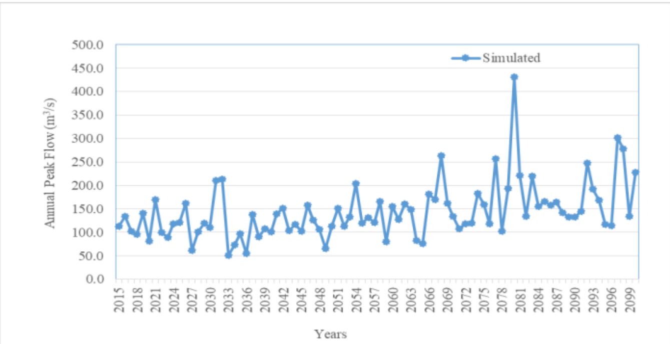

Fig 34. Simulated Annual Peak proposed headworks point of Kabeli Khola Hydropower Project for the years 2015-2100 considering ACCESS-CM2-SSP585B climate scenario

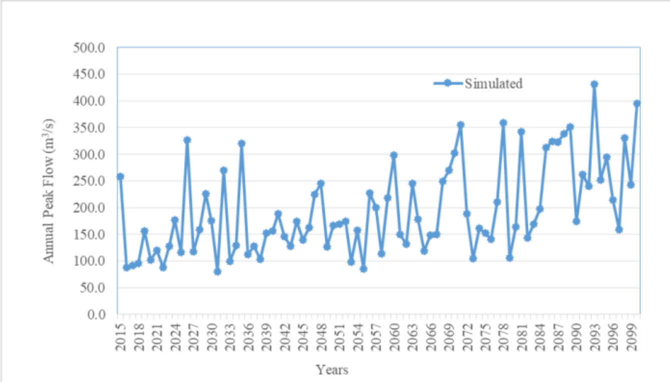

Fig 35. Simulated Annual Peak Flow at proposed headworks point of Kabeli Khola Hydropower Project for the years 2015-2100 considering EC3-EARTH-SSP245B climate scenario

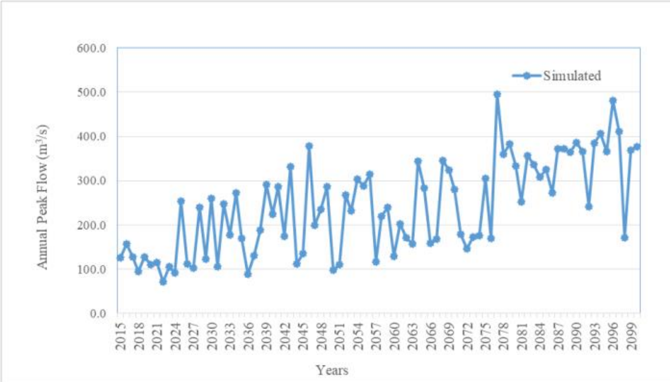

Fig 36. Simulated Annual Peak Flow at proposed headworks point of Kabeli Khola Hydropower Project for the years 2015-2100 considering EC3-EARTH-SSP585B climate scenario

The entire duration from 2015-2100 was divided into three periods; 2015-2040, 2041-2070 and 2071-2100. Mean monthly hydrographs have been plotted for each period for four climate scenarios from the simulated time series flow data. These hydrogaphs have been presented in Figures 37-48.

Fig 37. Mean Monthly Flow Hydrograph at proposed headworks point of Kabeli Khola Hydropower Project for the years 2015–2040 considering ACCESS-CM2-SSP245B climate scenario

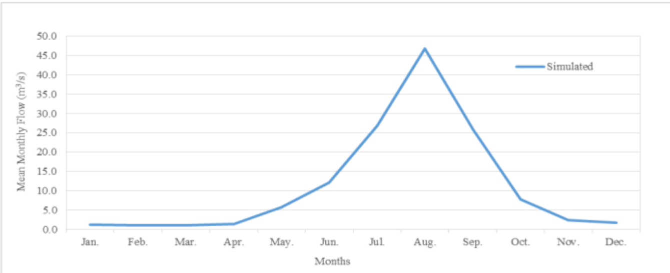

Fig 38. Mean Monthly Flow Hydrograph at proposed headworks point of Kabeli Khola Hydropower Project for the years 2041-2070 considering ACCESS-CM2-SSP245B climate scenario

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 10 Issue 08, August-2021

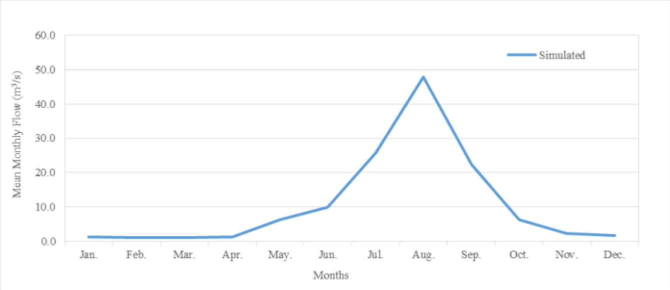

Fig 39. Mean Monthly Flow Hydrograph at proposed headworks point of Kabeli Khola Hydropower Project for the years 2071-2100 considering ACCESS-CM2-SSP245B climate scenario

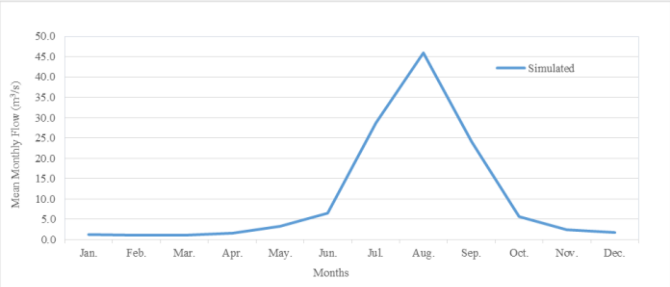

Fig 40. Mean Monthly FlowHydrograph at proposed headworks point of Kabeli Khola Hydropower Project for the years 2015-2040 considering ACCESS-CM2-SSP585B climate scenario

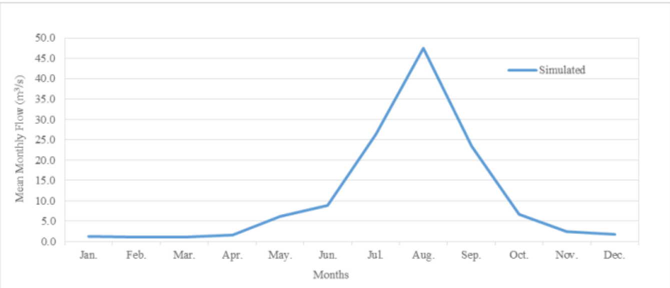

Fig 41. Mean Monthly Flow Hydrograph at proposed headworks point of Kabeli Khola Hydropower Project for the years 2041-2070 considering ACCESS-CM2-SSP585B climate scenario

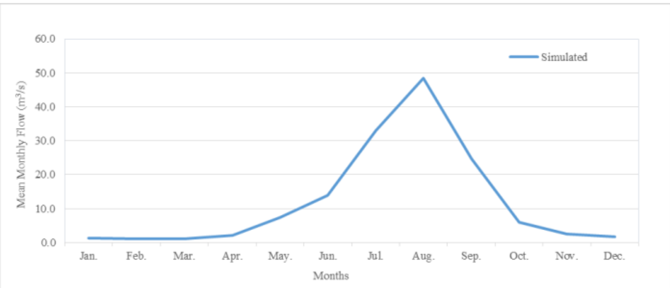

Fig 42. Mean Monthly Flow Hydrograph at proposed headworks point of Kabeli Khola Hydropower Project for the years 2071-2100 considering ACCESS-CM2-SSP585B climate scenario

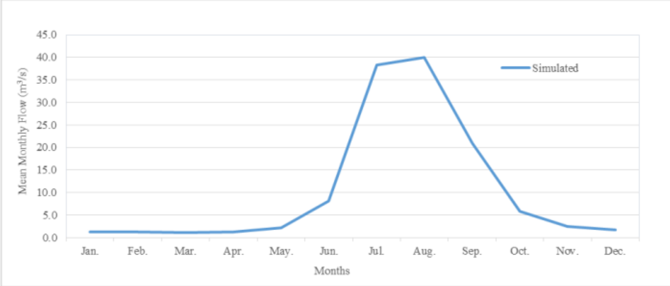

Fig 43. Mean Monthly Flow Hydrograph at proposed headworks point of Kabeli Khola Hydropower Project for the years 2015-2040 considering EC3-EARTH- SSP245B climate scenario

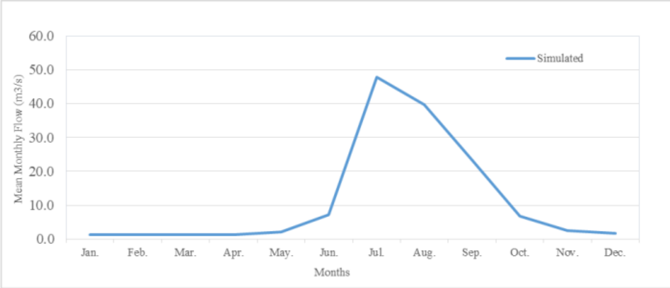

Fig 44. Mean Monthly Flow Hydrograph at proposed headworks point of Kabeli Khola Hydropower Project for the years 2041-2070 considering EC3-EARTH- SSP245B climate scenario

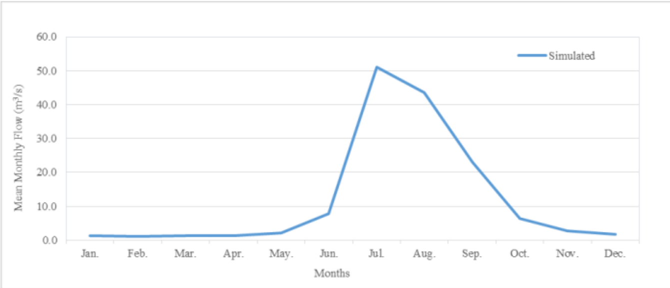

Fig 45. Mean Monthly Flow Hydrograph at proposed headworks point of Kabeli Khola Hydropower Project for the years 2071-2100 considering EC3-EARTH-SSP245B climate scenario

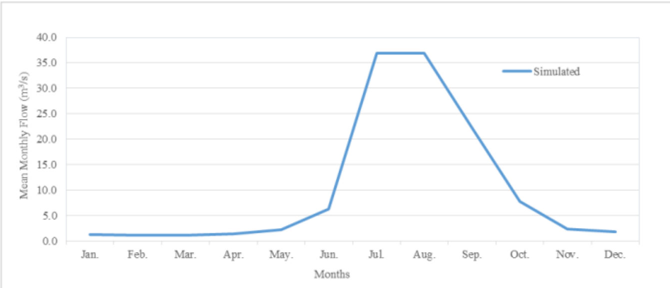

Fig 46. Mean Monthly Flow Hydrograph at proposed headworks point of Kabeli Khola Hydropower Project for the years 2015-2040 considering EC3-EARTH-SSP585B climate scenario

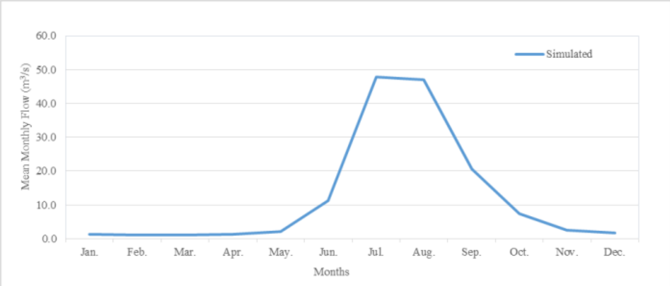

Fig 47. Mean Monthly Flow Hydrograph at proposed headworks point of Kabeli Khola Hydropower Project for the years 2041-2070 considering EC3-EARTH-SSP585B climate scenario

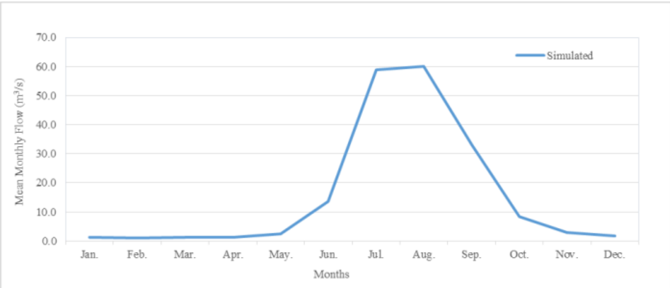

Fig 48. Mean Monthly Flow Hydrograph at proposed headworks point of Kabeli Khola Hydropower Project for the years 2071-2100 considering EC3-EARTH-SSP585B climate scenario

Figures 37-48 describe similar trend of mean monthly flow during the period 2015-2100 for all four climate scenarios with low flow during dry seasons and high flow during rainy season alike mean monthly flow hydrograph during calibration and validation period. However, it has been observed that for six cases of EC3-EARTH climate scenarios, from Figures 43-48, high flows concentrated to two months July and August while for other scenarios high flows seem to concentrate in August only. The maximum mean monthly flow was observed to be 59.9 m^3/s and occurs in August for EC3-EARTH-SSP585B climate scenario during 2071-2100 period.

IV. CONCLUSION

River flow study has a great importance pertinent to the use of water resources for hydropower, irrigation, navigation and many other purposes as well as river flood management. Future prediction of discharge at required section of river provides demand and supply management of electric energy as per public needs during the planning and design phase. Kabeli Khola as flow through the mountainous relief of our country has huge hydropower potential and future discharge prediction at the proposed headworks site obviously provides some ideas in advance.

The HEC-HMS model has been calibrated and validated at two outlet stations Majhitar and Mulghat for the period 1996-2001 and 2002-2006 respectively. The maximum surface storage and hydraulic conductivity are the most sensitive parameters. The statistical quantities Nash-Sutcliff Efficiency (NSE) and Coefficient of Determination (R^2) were evaluated to check the performance of the model during calibration and validation period. The obtained values of NSE and R^2 are 0.858 and 0.8681 for Majhitar station and 0.808 and 0.853 respectively for Mulghat station during calibration period. Similarly, the values of NSE and R^2 for validation period are 0.671 and 0.8694 for Majhitar and 0.823 and 0.8273 for Mulghat. These values are within the satisfactory and acceptable range and provided well simulation of discharge at both stations during both calibration and validation period. Although the developed model consists usual downside of hydrological model of under predicting the discharge, the obtained results could be useful. The simulated maximum Annual Peak Flow 494.4 m^3/s obtained from EC3-EARTH-SSP585B climate scenarios during the period 2015-2100 at the proposed headworks point of Kabeli Khola Hydropower Project could be employed in planning and design of headworks structure. Similar trends observed in average monthly flow hydrographs during 2015-2100 period comparing with the average monthly flow hydrograph of 1996-2006 period for different climate scenarios might favour consistency and sustainability of hydropower in generation of electric energy for future period also.

The upper catchments of Tamor basin lie in the Himalaya region of Nepal and snow fall contributes the major portion of run-off. Therefore this study can be extended to use the snow fall parameters for developing climate model.

ACKNOWLEDGEMENT

Authors would like to thank Department of Hydrology and Meteorology, Nepal for providing hydrological and meteorological data.

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