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RESPONSE OF HYDROELECTRIC PROJECTS UNDER THE INFLUENCE OF CLIMATE CHANGE

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ABSTRACT

Hydropower is regarded as a low-carbon source of renewable energy and a reliable and cost-effective alternative to electricity generation by fossil fuels. However, its production is directly subjected to the effect of climate change (CC). Thus, this study focusses on the CC impact on the variation of discharge in the Karnali River and the subsequent effect in power generation in Mugu Karnali Storage Hydroelectric Project under study by NEA Engineering Company (NEC). Soil and Water Assessment Tool (SWAT) is applied in the Karnali basin to simulate the current and future hydrological regime. The model was calibrated for 2000-2005 and validated for 2007-2011. The future climate conditions at the basin are projected considering the outputs of five Global Circulation Models (GCMs) under two shared socioeconomic pathways (SSPs) for three future timeframes: 2021-2045, 2046-2070 and 2070-2100 (near, mid and far futures respectively) against the baseline period of 2000-2014. An ensemble of bias corrected GCMs under (SSP585) scenario shows the projected annual precipitation rises by 8.5% (7.9%), 14% (11.9%) and 9.6% (25.8%) in near, mid and far futures. For the same scenario for three future periods, the maximum temperature is projected to increase by 0.6°C (0.7°C), 1.1°C (1.7°C) and 1.6°C (2.9°C) respectively whereas the projected minimum temperature increases by 1°C (1.2°C), 1.9°C (2.7°C) and 2.5°C (4.6°C) respectively. Under these projected climate conditions, the annual streamflow is simulated to increase by 10% (10.6%), 17% (16.1%) and 14.5% (35.1%) in near mid and far futures. The reservoir simulation model is developed in excel spreadsheet to assess the effect in energy generation. Under the influence of climate change, the annual energy is projected to increase by 18.4% (21.9%), 26.2% (27.0%) and 22.1% (52.1%) in NF, MF and FF timeframes respectively under SSP245 (SSP585) scenario. This study provides the insight on climate change influence on currently under study hydropower and will assist in planning climate resilient hydropower projects.

1. INTRODUCTION

Nepal is endowed with abundant water resources draining approximately 222 billion m3 of water annually into the ocean (Sharma & Awal, 2013). Because of mountainous topography with wide variation of altitude in short stretch, and rivers flowing with high discharge favors the development of hydropower. But the utilization of the resources for sustainable development of hydropower is not to the optimum extent in Nepal. In the meantime, the country is able to harness only about 1900 MW of installed capacity in Integrated Nepal power system (INPS) (NEA, 2020).The INPS is dominant with Run-off River projects with only 106 MW of Storage project and 790 MW of peaking project.. Hence there is a wide alteration in energy production across seasons as ROR project produces only 16.66 % of the total installed capacity during dry months (Paudyal & Shrestha, 1970). Subsequently, imbalance is experienced in the supply as the production shrinkages when there is high demand. The peak demand has raised up to about 1700MW on December 2021. The problems of seasonal disparity in INPS expands further with the electricity demand projected to rise at 8.34% annually (NEA).

Thus, a storage project is envisaged as means of sustainable hydropower development. Given the unlimited extent of energy consumption spaces available in a country, hydropower has to be developed with intent and prospect of country's economic development. Mugu Karnali Storage Hydroelectric Project (MKHEP) is being studied by Vidhyut Utpadhan Company Limited (VUCL) in the upper part of the Karnali basin.

The water resource projects are sensitive to capital investment as well as climate. Moreover, the performance of hydropower projects is profoundly reliant on the hydrological conditions. Several studies have been conducted in Nepalese river basins (Bajracharya et al., 2018; Devkota et al., 2015; Pandey et al., 2019) reporting significant change in hydrological behavior under the influence of climate change (CC). The runoff changes subjected to climate change induced variation in rainfall, temperature, glacier retreat, drought etc. have caused diminishing effect in annual energy (Shrestha et al., 2021). The study on the impacts of CC in the Himalayan relating to GLOF, drought glacier melting etc. are extensive and richly available, however studies on CC impacts on hydropower in Nepalese context is limited. So, this study focuses on the probable impacts of climate change in hydropower projects with the case study of MKHEP.

2. STUDY AREA

The study area lies in Karnali and Sudurpaschim province in the north wester part of Nepal between latitude 29°41’22” N to 29°23’43” N and longitudes 81°57’13” E to 81°39’14” E. The proposed headwork site of the MKHEP is located at 29˚27’34.31” N and 81˚42’44.09” E. The catchment of the study region is about 16,083.6 km2.

Figure 1 presents the location and the catchment area of the Karnali River which is extended from Nepal to China. There is wide variation in the topography of ranging from 1,002m to 7,684m above the mean sea level with majority of the watershed lying above 3,000m elevation. There are 12 generic land use/ cover classes with dominance of grassland and barren lands and 12 soil classes with dominance of Gelic leptosols. The catchment has widely varying slopes, ranging from less than 1% to above 50% rise. The dominant slope class is above 50%. The average annual precipitation in the watershed is 792mm with 70.0% of rainfall occurring in wet season. The mean monthly temperature varies in range of -4.4 0C ~ 20.4 0C with maximum and minimum value recorded as 30 0C and -11 0C. The mean relative humidity varies in range of 67.7 ~ 87.7% with 75.9% annual average.

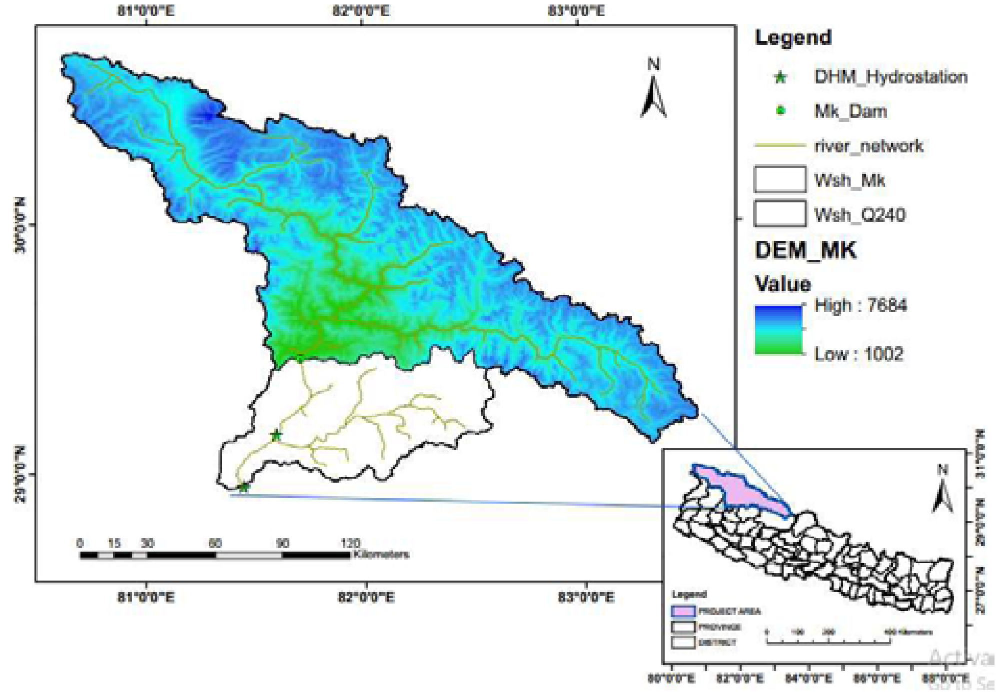

Fig. 1 : Study Area at the northwestern part of Nepal.

3. METHODOLOGY AND DATA

The overall conceptual methodological framework adopted is shown in Figure 2. The framework consists of data preparation, model setup, model calibration and validation, current hydrological characterization, future climate projection, energy simulation and CC impacts assessment on water availability and energy production using the validated SWAT and energy model. The methodology is elaborated in the following sub-sections.

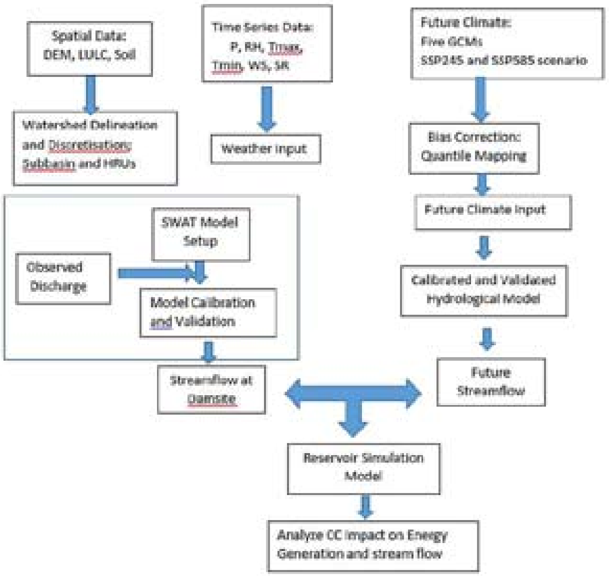

Fig. 2 : Overall Methodology

3.1 SWAT Theory

The SWAT model is a physically based semi-distributed hydrological model developed by Arnold et al., 1998 and the latest version available is SWAT 2012. In SWAT model, a watershed is divided into a number of sub basins which are associated with the river channels. The hydrological cycle of sub-basins is defined based on the following eight aspects, including climate, hydrology, sediment, soil temperature, plant growth, nutrients, pesticides and agriculture management (Arnold et al., 1998; Arnold & Fohrer, 2005). Each sub-basin is further subdivided into smallest calculation unit known as hydrologic response units (HRUs) according to the land use and soil type. The SWAT model runs a daily time step simulation on HRU. The SWAT simulates the hydrologic cycle based on the water balance equation (Neitsch et al., 2009):

$$SW_t = SW_0 + \sum_{i=1}^{t} R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw})$$

Where,

SW_t : Final soil water content (mm H2O),

SW_0 : Initial soil water content on day i (mm H2O), t is the time (days),

R_{day} : Amount of precipitation on day i (mm H2O),

Q_{surf} : Amount of surface runoff on day i (mm H2O),

E_a : Amount of evapotranspiration on day i (mm H2O),

W_{seep} : Amount of water entering the vadose zone from the soil profile on day i (mm H2O),

Q_{gw} : amount of return flow on day i (mm H2O)

3.2 Spatial Data preparation

SWAT requires three main spatial data viz. Digital Elevation Model (DEM), Soil and landuse (LULC) as inputs shown in Figure 3. The topographic surface and terrain relief is represented by the DEM. A 30m resolution DEM used in this study is downloaded from https://search.earthdata.nasa.gov/search . The slope map of the area is prepared using the DEM and classified into five categories. i.e., 0-1%, 1-5%, 5-25%, 25-50% and above 50% and majority of the catchment lies above 50% slope class. SWAT model requires LULC to delineate the HRUs and account the hydrological processes in land like runoff, evapotranspiration erosion and sediment transport. The MODIS land cover data with 300m spatial resolution is downloaded from www.earthexplorer.usgs.gov. There are 12 land cover type with grassland (46.91%) and barren areas (29.69%) as dominant land type. The properties of soil like soil hydrological group, soil texture, hydraulic conductivity, bulk density etc. for different layers of each soil type are required in SWAT model to replicate the hydrological processes like infiltration, deep percolation and subsurface/ groundwater flow into the river. The soil map is downloaded from International Soil Reference and Information Centre (ISRIC) official website (https://www.isric.org/projects/soil-and-terrain-soter-database-programme) in the form of Soil and Terrain (SOTER) map prepared by Food and Agriculture Organization (FAO). The scale of the map is 1:1,000,000. There are 15 soil classes with dominance of Gelic Leptosol (50%) and Eutric Regosols (22.1%).

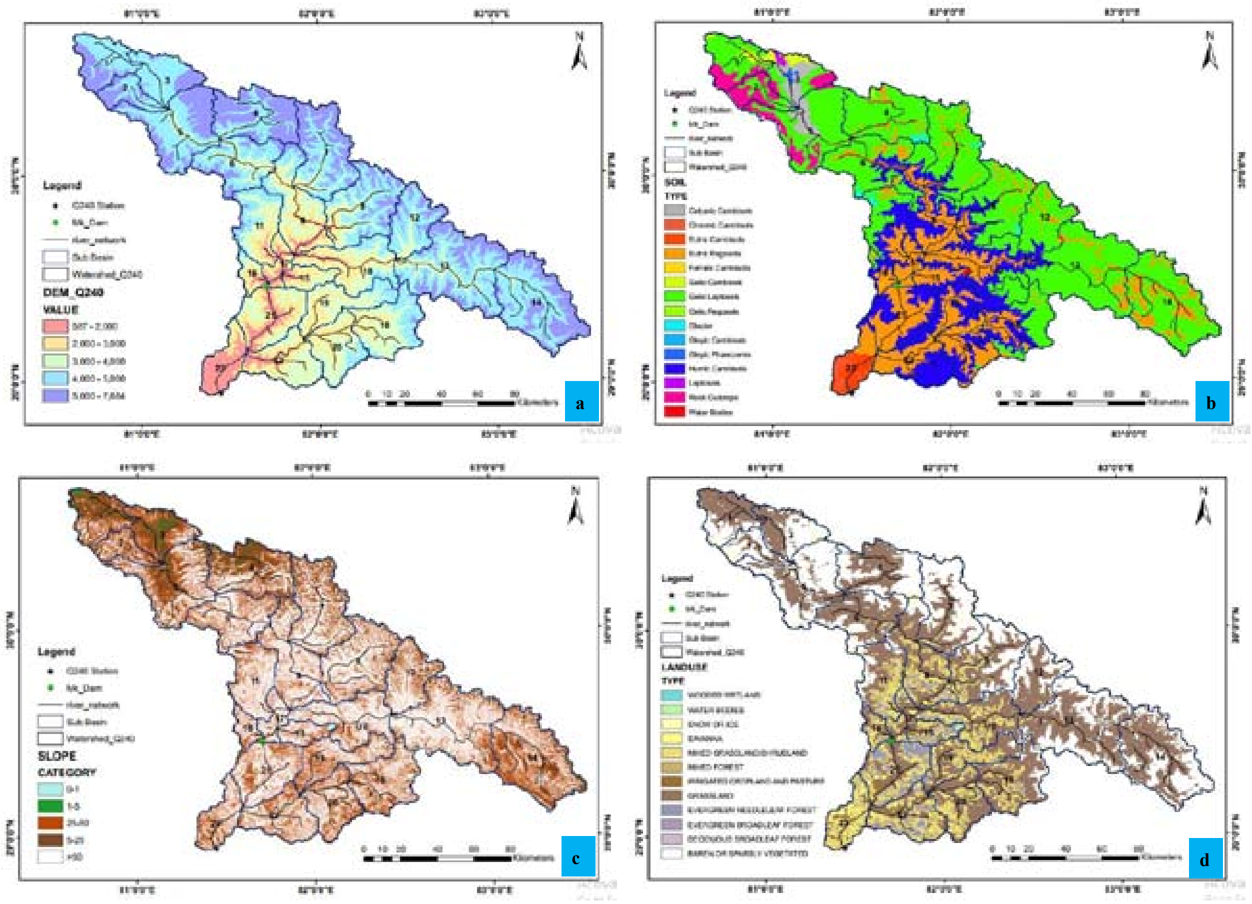

Fig. 3 : (a) Digital Elevation Model, (b) Soil, (c) Slope and (d) landuse map of the study area

3.3 Time Series Data Preparation

SWAT modelling requires five weather data i.e. daily precipitation (mm), minimum and maximum air temperature (°C), relative humidity (%), wind speed (m/s) and daily solar radiation (MJ/m2/day). The hydro-meteorological data of the study area is obtained from Department of Hydrology and Meteorology (DHM). The details of the stations are shown in Annex. The Aphrodite precipitation data is used for the portion of watershed lying in the upper reaches.. These data are downloaded from http://aphrodite.st.hirosaki-u.ac.jp/download/ and bias correction is applied with reference to the nearest DHM station.

3.4 SWAT model Setup

The model is formed in ArcGIS 10.3.1 with Arc SWAT extension. The whole basin was discretized into 23 sub basins based on the topographic characteristics. The sub basins are further sub divided into 271 HRUs by combining land use, soil and slope map with corresponding threshold areas defined as 15%, 10% and 5% respectively. Each sub basin in the model is segmented into five elevation bands to model the snowmelt and orographic temperature and precipitation distribution. Then daily time series of precipitation, temperature, relative humidity, wind speed and solar radiation are provided as weather input. The model is simulated by to evaluate the surface runoff, to compute potential evapotranspiration (PET) and to estimate the routing of flow.

The model calibration and validation were carried at Q240 (Asaraghat) station on daily and monthly scales. The model is calibrated for 6 years [2000-2005] and validated for five years [2007-2011]. The simulation is carried with two years of warmup period to develop adequate soil and groundwater conditions (Pandey et. Al 201). The calibration is done in three stages: Sensitivity analysis, Auto-calibration; and Manual calibration (Pandey et al., 2020). The simulated versus observed flow during calibration are examined visually in terms of hydrograph (peak, time to peak, shape and base flow), scatterplot, flow duration curve and statistical parameters. The statistical indices like coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE) and percent bias (PBIAS) are considered to evaluate the performance of the model. During the overall process of calibration, the values of the physically based parameters are ept within the reasonable range.

3.5 Future Climate Projection

The five GCMs viz. ACCESS-CM2, EC-EARTH3, INM-CM5-0, MPI-ESM1-2-HR and MRI-ESM2-0 developed under latest designed Coupled Model Intercomparison Project (CMIP6) is used to project the future climate. These GCMs are chosen based on its application in South Asian region by Almazroui et al., 2020 and Mishra et al., 2020. The outputs of these GCMs are considered for two shared socioeconomic pathways i.e. SSP245 and SSP585. The multi modal ensemble (MMEs) of these GCMs are used to analyze future climatic condition as MMEs reduces the uncertainties associated with model and generate outputs consistent with local (Ahmed et al., 2019; Hughes & Farinosi, 2020; Wang et al., 2018). There is considerable bias in GCMs outputs with the observation as a result of coarser spatial resolution, simplified physics, and imperfect conceptualization of the earth's climate system (Eden et al., 2012). Quantile Mapping (QM) is regarded as the best technique in reducing the error characteristics (Jakob Themeßl et al., 2011 and Enayati et al., 2021). After analysing various transformation functions to form quantile-quantile relation, RQUANT (robust empirical quantiles) is considered as a most preferable method to correct bias in rainfall data.

The calibrated and validated SWAT model was forced with the bias corrected projections for daily precipitation and temperatures (maximum and minimum). Simulations of futures were undertaken based on ensemble of five GCM outputs. The simulated streamflow based on the future projection were then synthesized in terms of long-term annual average and seasonal values for the three future periods: near-future (2021–2045), mid-future (2046–2070), and far-future (2071–2095). Finally, change in streamflow at annual and seasonal scales with respect to simulated baseline values are reported as an impact of CC on water resources availability.

3.6 Energy Generation

An excel spread sheet is developed to simulate the energy generation in storage project by using the principle of water balance of reservoir and power equation. The simulation requires daily streamflow (present or future), reservoir characteristics like volume-area elevation curve, project configurations like design discharge, Full supply level (FSL), Minimum Drawdown level (MDDL) etc. and operation rule. The basic operation rule is to fulfil the required water demand for hydropower as long as the reservoir level is above the MDDL, store excess inflows greater than design flow and when the water level reaches the FSL, the excess inflow in wet season is released via turbines to minimize the spill.

3.7 Data and Sources

The spatial and time-series data required in this study were collected from local and global sources. The datasets required for the energy simulation is obtained from NEA Engineering Company limited. The details of data required by SWAT, their description, and sources are provided in Annex.

4. RESULTS AND DISCUSSION

4.1 Evaluation of SWAT model

The SWAT model is calibrated and validated at Asaraghat station for a period of 2001-2005 and 2007-2011 respectively. The physical criteria (like mean and variance of discharge) of the validation period shall be more or less same with the calibration period (K. Abbaspour et al., 2017).

Based on the results of the global sensitivity analysis, auto-calibration of the model was carried in SWATCUP. The range of parameters are narrowed down by carrying several sequential iterations during the process of auto-calibration, until acceptable result in terms p-factor, r-factor and statistical indices is obtained. The simulation results for streamflow are acceptable if the p-factor > 0.7 and the r-factor < 1.5 (K. C. Abbaspour et al., 2015).

Manual calibration is carried by initially adjusting the highly sensitive parameters like TLAPSE, SMTMP, GWQMN, SOL_BD, CN2, CH_K2 and GW_DELAY and then the least sensitive parameters like ALPHA_BF, SOL_AWC and SOL_K to obtain the better result of statistical parameters like (NSE, R^2 and PBIAS) for evaluating Goodness of fit. The calibrated values of the parameters are presented in Annex.

The fitting of hydrological simulation at daily and monthly scales, scattering of observed versus simulated points from the mean, model capability to reproduce flow duration curve (FDC) and model performance indicators are shown in Figure 4. The simulated hydrographs correspond to the precipitation pattern and reasonably reproduce hydrological regime. The model well estimates the daily and monthly low flows while the higher flows with probability of exceedance of 15% or less are underestimated in daily and long-term average. However, average flows are well reproduced with PBIAS of around 3% for both calibration and validation periods. NSE values during calibration for daily and monthly scales are 0.84 and 0.94 respectively while for validation period, the respective values are 0.82 and 0.93. The values of R^2 for calibration and validation at daily scales are 0.85 and 0.82 respectively while at monthly scales these values are 0.97 and 0.96 respectively. The observed and simulated average annual values for calibration, validation and overall periods differ by less than 15%.

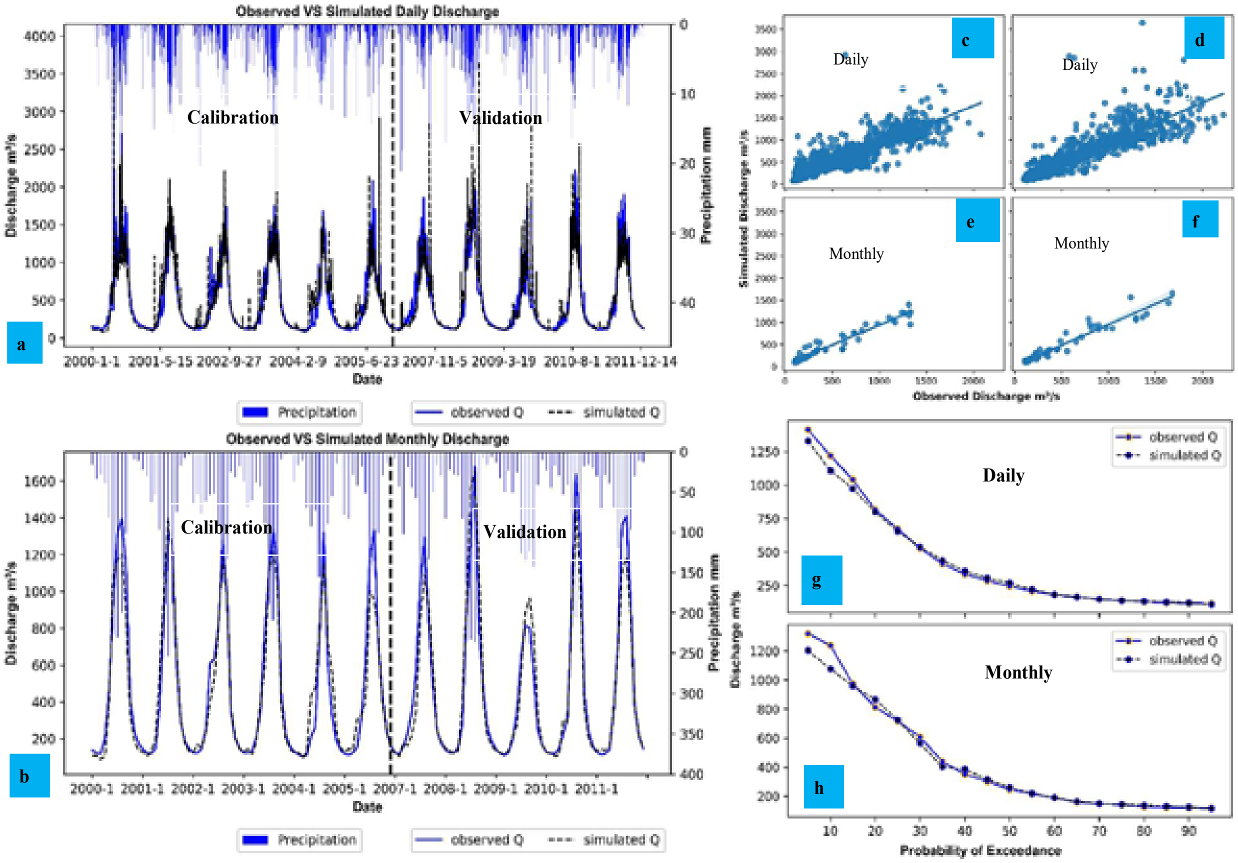

Fig. 4 : Comparison of observed versus simulated stream flows at Asaraghat (Index = Q240; River = Karnali) station: (a) Hydrograph for daily simulation, (b) hydrograph for monthly simulation, (c & d) scattered plots for daily calibration and validation, (e & f) scattered plots for monthly flow calibration and validation, (g & h) flow duration curve for daily calibration and validation

4.2 Future climate projection

The projected precipitation and min/max temperature are extracted at the all the meteorological stations from five GCMs under SSP245 and SSP585 scenarios and analyzed in terms of Three future timeframes: near future (NF, 2021–2045), mid-future (MF, 2046–2070), and far-future (FF, 2071–2100) against the baseline period of 2000-2014. The results of the future climate projections at a meteorological station (Index = 307) is discussed in the following section.

4.2.1 *Projected precipitation and temperatures*

The trend of projected annual precipitation is not clear as shown in Figure 5. The annual precipitation ranges from 754-1053 mm, 684-1067 mm, 679-1003 mm for NF, MF and FF respectively. The projected temperature unlike precipitation in both the scenarios as shown in Figure 5 (b) and (c) shows a rising trend for both the maximum and minimum temperatures. The projected precipitation is increasing across all seasons except DJF season under SSP245 and highest rise is observed in MAM season. The range of variation of the climate projection is shown in Figure 6.

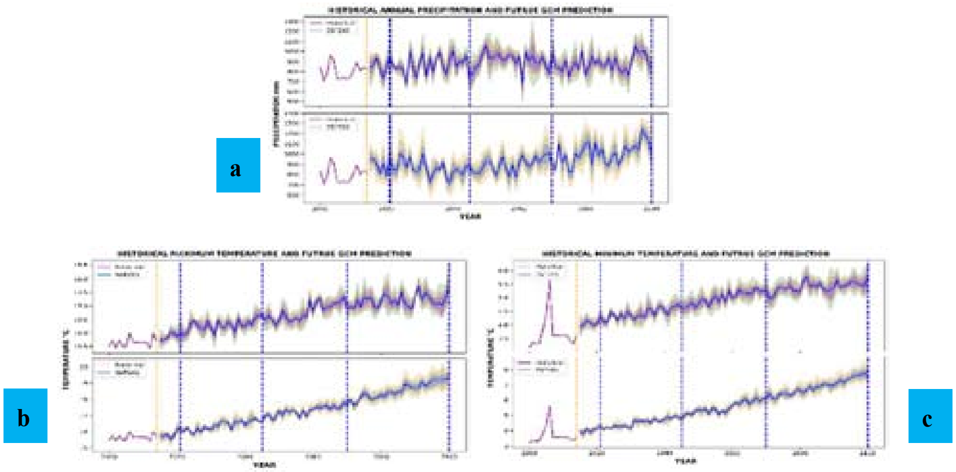

Fig. 5 : Trends in long-term average annual (a) total precipitation and (b) maximum temperature and (c) minimum temperature at station 307

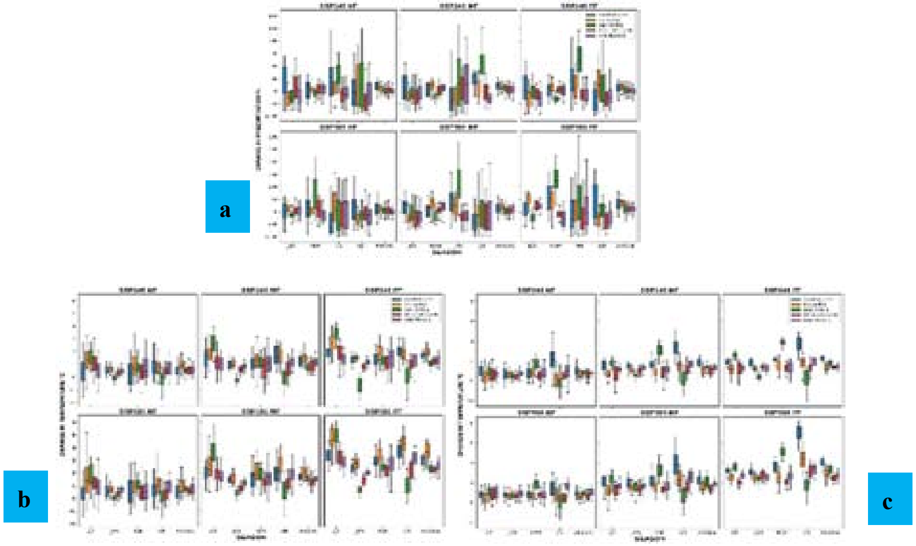

Fig. 6 : Range of projected change in future (a) precipitation (b) maximum temperature and (c) minimum temperature for different scenarios and GCMs for the study watershed

4.3 Hydrological Regime at the dam site

The calibrated and validated model is used to extract the daily stream flow at the dam site. The mean annual discharge is 321.9m^3/s and the maximum and minimum monthly discharge is 969.65m^3/s and 75.32 m^3/s respectively. The daily monthly hydrograph and FDC is shown in Figure 7.

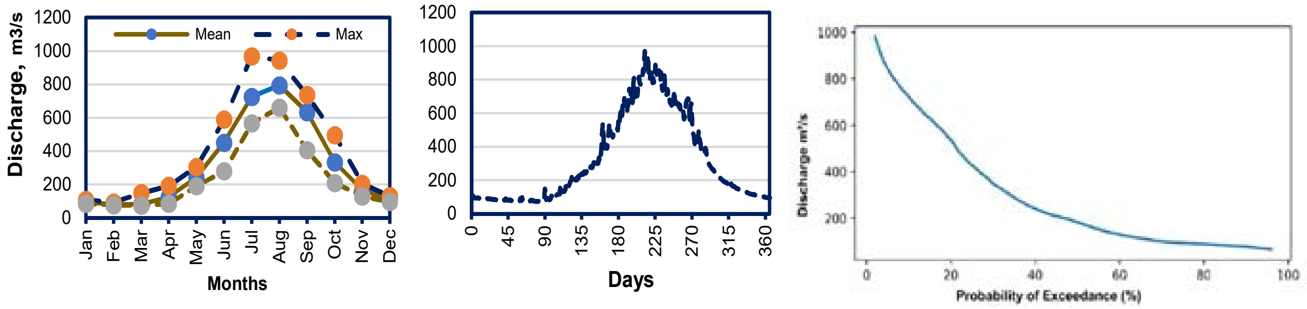

Fig. 7 : Monthly and Daily Hydrograph and FDC curve at damsite

4.4 Climate change impacts on water availability

The annual average discharge in the dam site is projected to increase under SSP245 and SSP585 scenario as shown in Figure 8. In SSP245 scenario, the projected annual average discharge at the project dam site is 354.12 m^3/s, 376.77m^3/s and 368.45 m^3/s against baseline flow of 321.9 m^3/s for NF, MF and FF periods respectively. The projection under SSP245 scenario shows the mean annual flow in three corresponding future periods are 356.03 m^3/s, 373.69m^3/s and 434.74 m^3/s against baseline flow. Figure 8 indicates continuous increasing trend in MF and FF with slight diminishing trend in NF for SSP585 scenario while the flow pattern in NF, MF and FF is in increasing, decreasing and again increasing respectively. The mean annual flows in three future periods increase by 10.0% (NF), 17.0%(MF) and 14.5% (FF) for SSP245 scenario while the SSP585 scenario shows increment by 10.6%, 16.1% and 35.0% in corresponding future periods. These results are similar to the study in other basin of Nepal that shows the rising trends (e.g. Immerzeel et al., 2013; Bajracharya et al., 2018:). The projected stream flows in the future periods are responsive to the trend of projected precipitation. It is clearly observed that the streamflow increases with the increase in precipitation and vice-versa (Pandey et al., 2019).

In both the scenario, the flows are consistently in increasing order across all seasons as shown in Figure 9(d). Based on deviation of mean seasonal flows from baseline period, it is observed that the pre-Monsoon (MAM) flows increases more and post monsoon (ON) flows varies least. The variation of flows in monsoon (JJAS) and winter (DJF) is more or less equal. The pre monsoon flows increases as a response to the higher increase in precipitation (Pandey et al., 2019) projected in that season projected under future climate scenario like SSP585 projecting 24.3% (NF), 32.6% (MF) and 52.3% (FF) as shown in Figure 9d) . But the increase of flow during DJF season contradicts with our above statement of increasing discharge with increasing precipitation as the precipitation during DJF season is decreasing. It is due to high percolation contributing to the stream flow as base flow during DJF season found by evaluating change in water balance components shown in Figure 9(c). The hydrographs and flow duration curves for the different periods are shown in Figure 9(a) and (b). It shows the projected mean monthly discharges over the future periods varies similar to the baseline period indicating no shift.

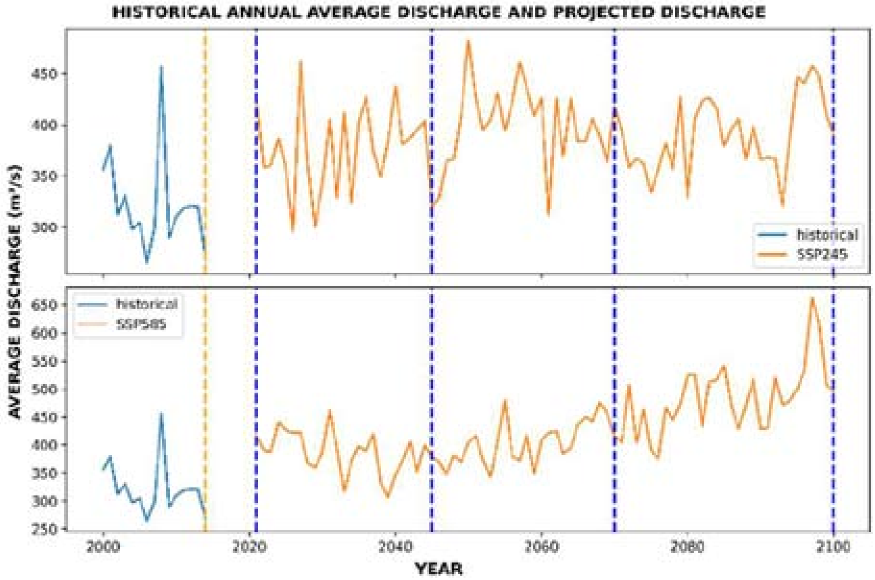

Fig. 8 : Trend of projected Average Annual stream flow under SSP245 and SSP585 scenario

4.5 Climate Change Impact on Energy Generation

There is a significant impact of climate change on hydropower projects especially storage type as its generation is dependent on the seasonal discharges and dominantly affected by climate change (Shrestha et al., 2021). The reservoir simulation is carried with the mean daily discharges of the baseline, NF, MF and FF periods for 8 hours of operation in dry season and maximum utilization of available water. The simulation results indicate the increment of energy across all seasons and months as shown in Fig 10. The annual energy increases by 18.4%, 26.2% and 22.1% in NF, MF and FF under SSP245 scenario compared to baseline generation of 5,581GWh. In case of SSP585, the annual energy production increases by 21.9%, 27% and 52.1% for three corresponding future periods. The energy generation is minimum at

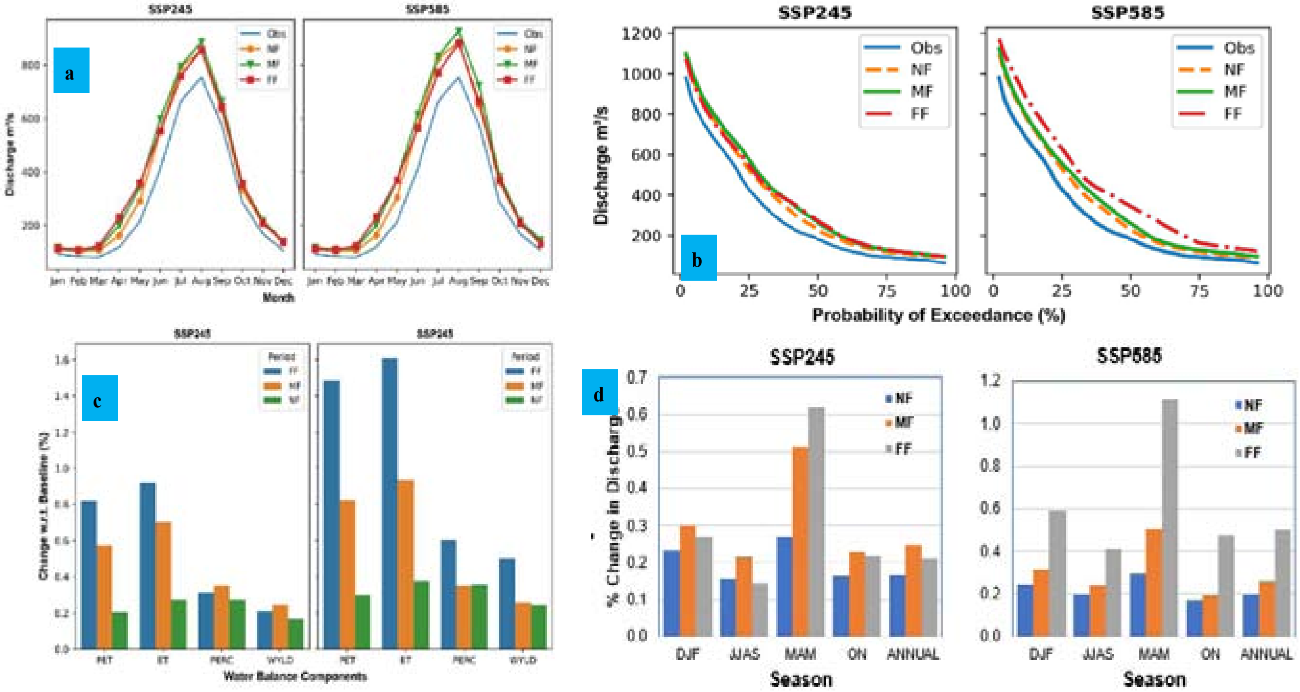

Fig. 9 :(a) Monthly Hydrograph, (b) flow duration curve, (c) change in water balance components and (d) seasonal change in streamflow under SSP245 and SSP585 scenario.

November and maximum energy at September. It is because the reservoir is full during this month and operated at maximum head i.e., at full supply level. Even though the reservoir is full till December, because of decreasing flow during October and November, the reservoir is operating with the inflow only causing minimum energy during November. And from December, the reservoir storage will be used to generate. The variation of reservoir level is shown in Figure 11(b). The operation hours during dry and wet seasons increases for all periods under SSP585 and SSP245 scenario of climate change.

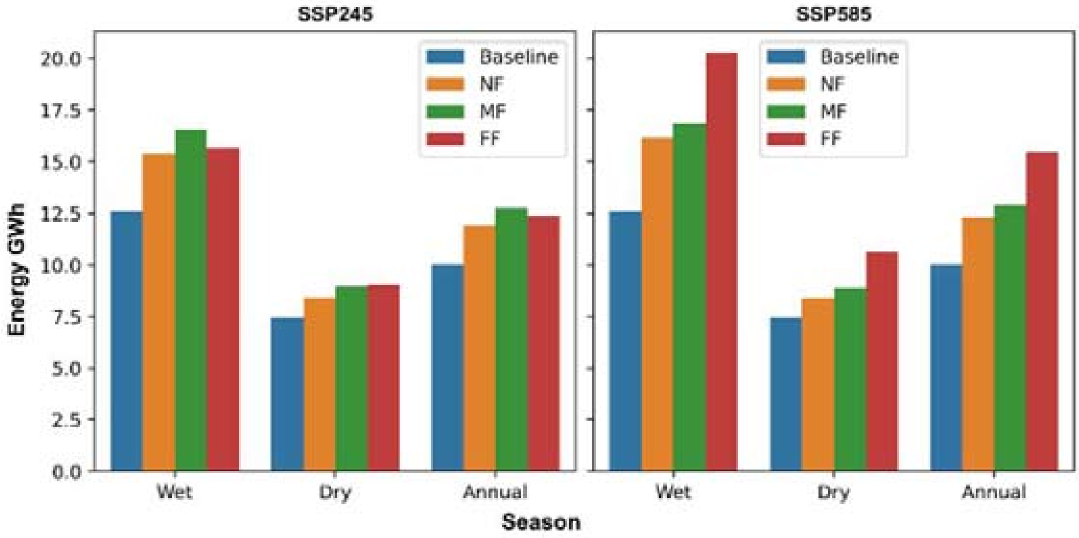

Fig. 10 : Seasonal Change in Energy generation under SSP245 and SSP 585 scenario.

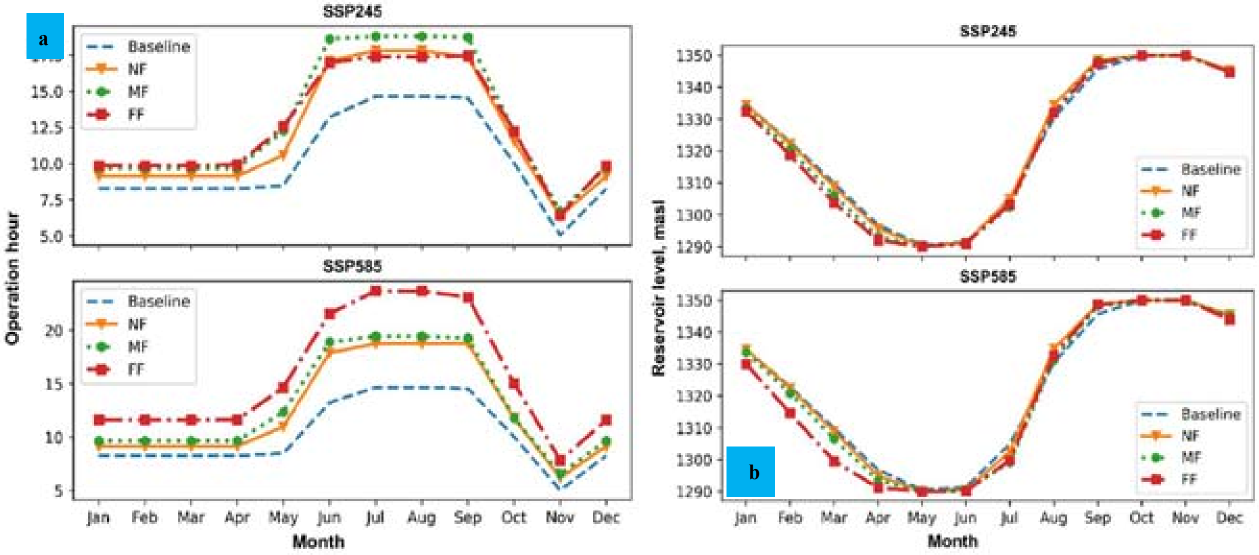

Fig. 11 : Variation of (a) Operation hour and (b) reservoir level under SSP245 and SSP585 scenario.

5. CONCLUSION AND RECOMMENDATION

The study was based on the projection of precipitation and temperature and the impact of change in climate on the discharge of the river followed by fluctuations in the hydropower generation. The mean annual and seasonal precipitation are expected to increase except for DJF season indicating drier winter and similar increasing trend is observed for the mean annual and seasonal temperature (min and max). The average annual discharge at the damsite is anticipated to increase from the baseline 321.9m^3/s differing by 10.0% (10.6%), 17.0% (16.1%) and 14.5% (35%) under SSP245 (SSP585) scenario in NF, MF and FF. The increasing tendency is steady across all seasons with higher difference projected in pre-monsoon (MAM). It seems that the projected discharge responds to the increase in precipitation. As a result, the energy production is anticipated to increase across all months and seasons as a result of increasing projection of stream flow. The annual energy will increase by 18.4% (21.9%), 26.2% (27.0%) and 22.1% (52.1%) from the baseline in NF, MF and FF under SSP245 (SSP585) scenario. Looking upon the reservoir operation, it is seen that the reservoir is filled quicker along with increased hours of plant operation. It is recommended to study the climate change impact on water resource project. This study only consider the stream flow and analyzed its impact on energy generation. The impact of sediment, extreme flow etc also need to be studied.

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