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Assessment of the Climate Change Impact on Hydropower Water Footprint in Kenyir Lake

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Abstract: The Hydropower Water Footprint (HWFP) is a key metric for assessing historical water use and predicting future trends. This assessment is becoming increasingly important as greenhouse gas (GHG) concentrations rise, leading to greater heat retention, and consequently affecting the availability of water in reservoirs for hydropower generation. This study contributes to the long-term development of the HWFP by specifically considering the impact of long-term evaporation in Kenyir Lake, Terengganu. To project the HWFP, it is essential to consider climate variables (such as rainfall, temperature, evaporation, and relative humidity) and electricity supply (ES), as the HWFP equation is linked to both reservoir evaporation rates and the amount of electricity produced by hydropower plants. For this purpose, the Statistical Downscaling Model (SDSM) version 4.1 was employed to analyze climate variation and forecast future evaporation rates from 2025 to 2100. The Representative Concentration Pathways (RCP2.6, RCP4.5, and RCP8.5) from the IPCC Fifth Assessment Report (AR5) provided future climate scenarios under three different radiation levels. Additionally, an ES equation was developed using multiple linear regression. The HWFP was then calculated based on the projected ES data, along with rainfall and evaporation rates. Both the Gross Hydropower Water Footprint (GHWF) and Net Hydropower Water Footprint (NHWF) methods were applied to determine the long-term HWFP pattern. The results indicate significant increases in projected electricity supply during February, July, and October from 2025 to 2100. Meanwhile, the future HWFP is expected to exhibit negative values, implying a situation that more water will be entering the reservoir than being lost through evaporation. The GHWF between 1997 and 2020 ranged from 2.5 m^3/GJ to 5 m^3/GJ, and is projected to increase in the future, particularly in February, September, October, and November. These findings are crucial for improving hydropower plant performance and supporting future development.

1. Introduction

According to the International Energy Agency (IEA, 2023), hydropower is projected to grow at a rate of about 4% per year until 2030, maintaining its position as the largest renewable source of electricity among all energy technologies. Hydropower has long been a significant global energy source, recognized for its wide availability and reliable output. Also referred to as hydroelectricity, it harnesses the potential energy of water to generate electricity.

A typical hydropower system operates by utilizing the gravitational force of water stored in a reservoir behind a dam. The water flows through a channel (penstock) to the turbines, whose spinning motion produces mechanical energy. This energy is then converted into electricity by generators. After passing through the turbines, the water is released back into the river, re-entering the natural hydrological cycle.

Despite being the largest renewable energy source, global hydropower generation declined in 2021 by about 0.4% due to extreme droughts in many major hydropower-producing countries, including China, Canada, and Brazil (IEA, 2023). This issue is primarily caused by climate change, which has led to increasingly variable and unpredictable rainfall patterns. Consequently, there is a growing need to enhance sustainable operation, output, and maintenance of existing hydropower plants. Each hydropower plant must generate a specific amount of electricity to meet local energy demand.

The long-term emission of greenhouse gases (GHGs) is expected to have a strong impact on local climate conditions. Increasing concentrations of GHGs, particularly carbon dioxide, cause more heat to be trapped in the atmosphere, thereby raising global temperatures. As temperatures rise, the evaporation rate on the surface of reservoir water also increases.

In Kenyir Lake, weather patterns are strongly influenced by the monsoon seasons, namely the Northeast Monsoon (November–March), the Southwest Monsoon (May–June), and two inter-monsoon periods. As climate change affects weather patterns and climate components, the amount of rainfall has become unpredictable (Loo et al., 2015). Due to fluctuations in surface temperature, evaporation rates can vary significantly, affecting water availability in hydropower

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reservoirs. Consequently, as water levels decrease, the electricity output from hydropower plants is also reduced.

The climate in Malaysia is characterized by high humidity, heavy rainfall, and an average annual temperature of 24.5°C. These conditions lead to increased electricity consumption, as people rely more on electrical energy to cope with high temperatures and uncomfortable conditions. As future energy demand is expected to rise, hydropower production will also increase. Therefore, estimating electricity supply (ES) in the coming years based on climate variables has become a significant area of study for hydropower plant planning and management.

As demonstrated by Maaouane et al. (2021), an energy demand model was successfully developed using the multiple linear regression method, which considered five macroeconomic independent variables as significant parameters. However, to date, no standardized method has been established for analyzing the relationship between climate change and electricity production. Further investigation into the impact of climate change on hydropower generation is thus essential, emphasizing the importance of assessing the Hydropower Water Footprint (HWFP).

The HWFP quantifies the amount of water evaporated from a reservoir's surface during hydroelectric power generation. Previous studies have shown that the choice of method used to calculate HWFP can significantly influence the results (Mekonnen & Hoekstra, 2011; Herath et al., 2011; Marence, 2013). Typically, HWFP calculations only account for consumptive water use, focusing on gross evaporation from the reservoir surface, which may lead to overestimation. However, it is also important to consider the volume of water entering the reservoir when analyzing HWFP. Therefore, the objective of this study is to evaluate the implications of climate change on HWFP through changes in evaporation up to 2100.

1.1 Study Area

Fig. 1 shows the location of the Sultan Mahmud Power Station on Kenyir Lake, Terengganu. Constructed between 1978 and 1986, the Sultan Mahmud Power Station is located approximately 40 km inland from Hulu Terengganu, Terengganu, at a latitude of 5º 1' 20" N and a longitude of 102º 54' 30" E. Previously known as the largest dam in Malaysia before the opening of the Bakun Dam in Sarawak, this 369 km² reservoir, formed by a rock-fill clay core dam, has a gross storage volume of 13.6 billion m³ and a catchment area of 2,600 km².

The reservoir receives water from six major tributaries: Sungai (Sg.) Terengganu (the main river), Sg. Cacing, Sg. Petang, Sg. Tembat, and Sg. Petuang (Chow, 2020). Table 1 presents the hydrological stations included in this analysis.

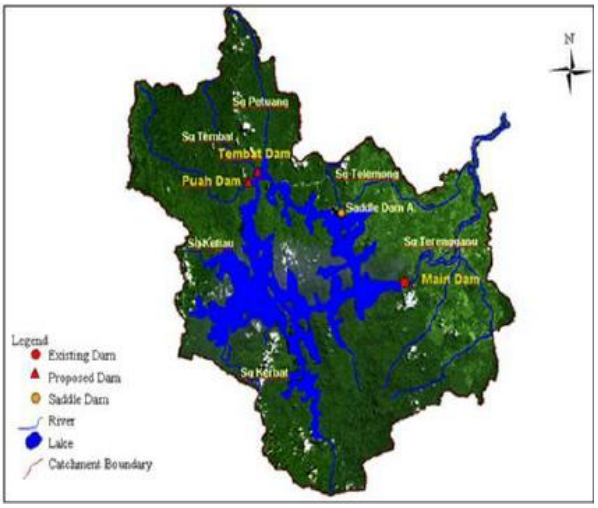

Fig. 1 - Sultan Mahmud Power Station at Kenyir Lake, Hulu Terengganu

Table 1 - List of Hydrological Stations

Type of data	Station name	Date Range (Year)	Source of data
Rainfall	Kg. Embong Sekayu Kg. Dura Sg. Gawi	1989-2020	Department of Irrigation and Drainage (DID)
Temperature	Kuala Terengganu		Malaysia Meteorological Department (MMD)
Evaporation	Kuala Terengganu		
Relative humidity (RH)	Kuala Terengganu		
Electricity supply (ES)	Sultan Mahmud Power Station		Tenaga Nasional Berhad (TNB)

2. Methodology of the Study

Fig. 2 illustrates the methodological framework of this study. Initially, data were collected for both climate variables and electricity supply. To achieve the first objective, climate analysis was conducted using the SDSM model. The projections generated by the SDSM model were then used in the multiple linear regression (MLR) analysis of electricity supply. Finally, the hydropower water footprint (HWFP) was assessed for both historical and future scenarios.

The HWFP was evaluated using two commonly applied methods: the Gross Hydropower Water Footprint (GHWF) and the Net Hydropower Water Footprint (NHWF). Projections of climate variables, electricity supply (ES), and HWFP were performed under three different Representative Concentration Pathway (RCP) climate scenarios from Canadian Earth System Model, version 2 (CanESM2) — RCP2.6, RCP4.5, and RCP8.5—throughout the century, divided into three-time phases: short-term (2025–2039), mid-term (2040–2069), and long-term (2070–2100).

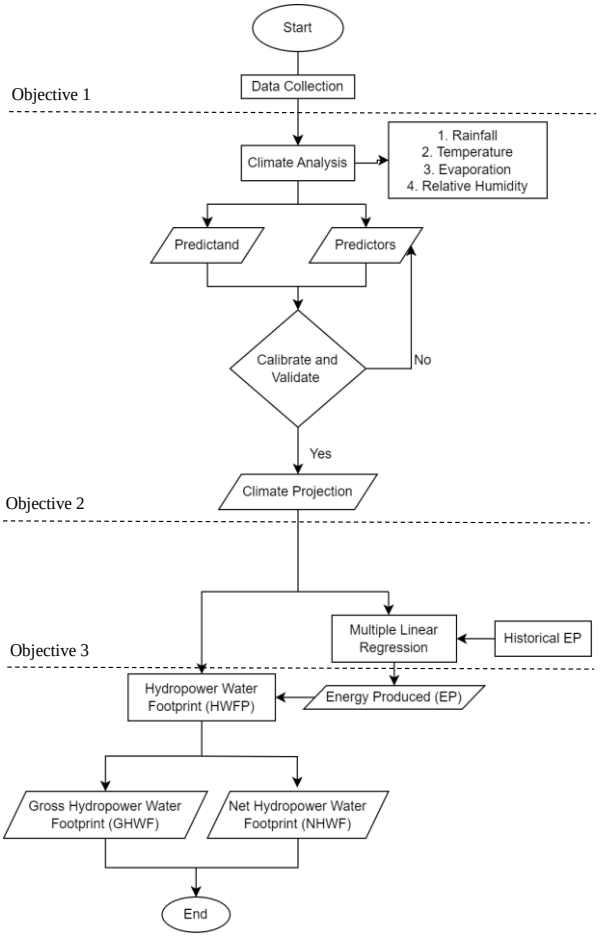

Fig. 2 - Flow of Methodology

2.1 HWFP Determination

The general equation for the hydropower water footprint (HWFP) is defined as the ratio between the amount of water evaporated from the reservoir (m^3/yr) and the electricity supplied during the same period (GJ/yr). Two key factors determine the hydropower water footprint: the rate of evaporation from the reservoir surface and the amount of electricity generated by the plant (Marence, 2013). In this study, the electricity supply data for the hydropower plant were obtained from the local hydropower authority.

Water loss from a reservoir is primarily associated with seepage and surface evaporation. In hydropower plants, seepage is not included in the calculation of the water footprint, as the water that seeps from the reservoir remains within the same river basin (Marence, 2013). Therefore, only evaporation is considered in the HWFP equation. Once the evaporation rate from the reservoir surface is determined, the HWFP can be calculated.

As there is ongoing debate regarding the most accurate approach for determining the hydropower water footprint, several studies have explored different methods. To date, however, no universally accepted methodology has been established for quantifying the water footprint of hydroelectricity (Herath et al., 2011). In this study, the HWFP was assessed using two commonly applied methods: the gross evaporation method and the net water balance method. After determining the historical HWFP of the hydropower plant, the same methods were applied to future projections, in which the evaporation (Eva) and electricity supply (ES) values were derived from earlier stages of analysis

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Gross HWFP

This method follows the earlier definition of hydropower water footprint by M. Mekonnen and A. Hoekstra (2011) where the water loss by evaporation on the surface of reservoir is divided by electricity supply by the hydroelectricity plant. This approach only considers the water consumed without considering the evapotranspiration losses before the construction of the hydropower plant. The equation of GHWF is given in Equation 1 and Equation 2.

$$GHWF = E_0 / ES \quad \text{…Eq 1}$$

$$E_0 = (10 \times \sum_{t=1}^{365} Eva) \times A \quad \text{…Eq 2}$$

The value of gross evaporation, E_0 is the annual surface water evaporation of the reservoir (mm^3) while ES is the annual electricity supply of the power plant in Giga Joules (GJ). Meanwhile, Eva refers to daily evaporation (mm/day) and A is area of reservoir (ha).

Net HWFP

A water balance equation was used to estimate the water footprint by accounting for the inputs and outputs of the reservoir (Herath et al., 2011). In this method, water losses from seepage are not considered a consumptive use of water. However, seepage and evaporative losses differ significantly in their qualitative effects. Water loss through evaporation typically leaves the hydrological basin and is therefore regarded as a true loss, whereas water lost through seepage generally remains within the same basin.

The Net Hydropower Water Footprint (NHWF) method analyzes the net water balance by considering the water leaving and entering the reservoir surface—specifically, evaporation as the output and rainfall as the input. Accordingly, the net water balance was calculated using Equation 3. In this equation, **RF** represents the annual rainfall (mm/day) over the reservoir.

$$NHWF = (E_0 - RF) / ES \quad \text{…Eq 3}$$

Statistical Analysis

To determine the disparity in future electricity supply, a statistical analysis based on percentage difference was conducted as shown in Equation 4. A positive (%) value indicates an increase, while a negative (%) value indicates a decrease. Meanwhile Equation 5 to 7 were used to assess the validation accuracy.

$$\%\ Difference = \frac{\hat{y} - y}{y} \times 100 \quad \text{…Eq 4}$$

$$MAE = \frac{\sum_{i=1}^{n}|X_0 - X_s|}{n} \quad \text{…Eq 5}$$

$$r = \frac{\Sigma(x_o - \bar{x})(x_s - \bar{x_s})}{\sqrt{\Sigma(x_o - \bar{x})^2 \Sigma(x_s - \bar{x_s})^2}} \quad \text{…Eq 6}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_0 - x_s)^2} \quad \text{…Eq 7}$$

Where:

$\hat{y}$ = monthly predicted electricity supply
y = monthly actual electricity supply
n = number of sample data
x = observed data
x_s = simulated data
$\overline{x_o}$ = mean observed data
$\bar{x_s}$ = mean simulated data

3. Results and Discussions

3.1 Changes Pattern of Climate Variables

In this study, the analysis of changes in hydrological components including rainfall, temperature, evaporation, and relative humidity was conducted using the Statistical Downscaling Model (SDSM) to project future climate changes in the study area. Historical climate data were obtained from three sources: the Department of Irrigation and Drainage (DID) Malaysia, the Malaysian Meteorological Department (MMD), and the management of the Sultan Mahmud Hydropower Station, Terengganu, depending on data type and availability.

Rainfall data were collected from three stations: Kg. Embong Sekayu, Kg. Dura, and Kg. Gawi. Temperature, humidity, and evaporation data were collected from the Kuala Terengganu station. The hydrological components, known as predictands, and the predictors from the National Centers for Environmental Prediction (NCEP) were screened to identify the most suitable predictors for each station.

The selection of predictors was based on the correlation between predictands and predictors within the SDSM. Among the 26 available predictors, a maximum of five predictors were selected for each climate variable according to their correlation coefficients as shown in Table 2. The combination of these five predictors effectively modeled the relationships among the climate variables. The wind-related variables—divergence (zh), airflow strength (f), and vorticity (z)—showed a stronger correlation with rainfall in this catchment. As supported by Luan et al. (2023) and Sheng et al. (2022), changes in these potential variables can lead to variations in rainfall intensity. However, the air temperature at 2 m (temp) exhibited a greater influence on temperature formation and evaporation processes.

For calibration and validation, the historical data (predictands) for each climate variable from 1989 to 2020 were divided into calibration (1989–2005) and validation (2006–2020) periods. Table 3 presents the performance results of the calibration and validation for all stations.

After simulating the model for each predictand, projections were carried out under three emission scenarios RCP2.6, RCP4.5, and RCP8.5 from 2025 to 2100. The calibrated and validated rainfall, temperature, evaporation, and relative humidity showed patterns consistent with the observed historical data. For the projected data, rainfall tended to decrease during the inter-monsoon and Southwest Monsoon seasons and increase during the Northeast Monsoon. The projection of maximum temperature indicated a gradual increase under all RCPs, peaking between February and October, with an annual rise ranging from 4.5% to 6.5%. The projection of relative humidity showed a general decline for all RCPs, particularly under RCP4.5, which decreased by approximately 4.5% between 2070 and 2100 from November to January.

Table 2 – Predictors Selection

Predictors Variables	Rainfall			Temperature			Eva
	Kg ES	Kg Dura	Sg Gawi	Tmax	Tmean	Tmin	Mean
ncep_mslp.dat	√		√				
ncep_p__f.dat	√	√					√
ncep_p__u.dat							
ncep_p__v.dat				√			
ncep_p__z.dat							
ncep_p_th.dat				√			
ncep_p_zh.dat				√	√		√
ncep_p500.dat					√	√	√
ncep_p5_f.dat							√
ncep_p5_u.dat		√					
ncep_p5_v.dat						√	
ncep_p5_z.dat	√	√					
ncep_p5th.dat							
ncep_p5zh.dat							
ncep_p850.dat							
ncep_p8_f.dat	√		√				
ncep_p8_u.dat							
ncep_p8_v.dat							
ncep_p8_z.dat			√				
ncep_p8th.dat			√				
ncep_p8zh.dat	√	√	√				
ncep_prec.dat							
ncep_r500.dat							
ncep_r850.dat		√					
ncep_shum.dat					√	√	
ncep_temp.dat				√	√	√	√

As shown in Fig. 3, projected monthly evaporation increased steadily throughout the year, gradually rising toward the end of the year. Surface evaporation from the reservoir is influenced by temperature, wind speed, and humidity in the area. The temperature projections indicate that November experiences the lowest mean temperature and the highest average relative humidity, resulting in the lowest evaporation rates during that month. Evaporation projections for September and November showed the largest differences, with

evaporation under all RCPs expected to decrease by approximately 22% and 24%, respectively.

Table 3 - Performance of the Calibrated and Validated Results

Predictand	r		MAE		RMSE	
	Calibrate	Validate	Calibrate	Validate	Calibrate	Validate
Rainfall						
Kg Embong Sekayu	0.99	0.99	33.98	23.69	2.20	1.84
Kg Dura	0.99	0.98	34.77	17.48	7.64	2.42
Sg Gawi	0.98	0.99	42.22	44.53	9.72	6.23
Temperature						
Tmax	0.99	0.97	0.20	0.26	0.10	0.11
Tmeann	0.99	0.99	0.20	0.23	0.04	0.01
Tmin	0.97	0.88	0.26	0.27	0.10	0.11
Evaporation						
Kuala Terengganu	0.96	0.97	3.64	3.39	0.68	0.73
Relative Humidity						
	R		MAE		RMSE	
Kuala Terengganu	0.99		0.37		0.11	

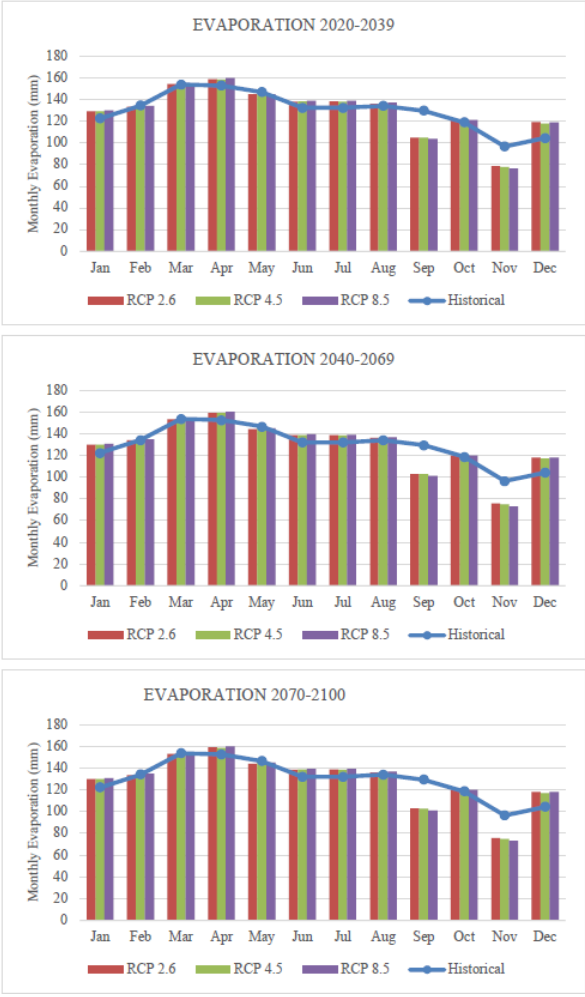

Fig. 3 - Projection of Evaporation until 2100

3.2 Projection of Electricity Supply (ES)

Electricity supply is significantly dependent on various climate variables (Vu et al., 2014). In this study, the climate variables considered include rainfall, minimum temperature, maximum temperature, mean temperature, relative humidity, and evaporation. These variables were analyzed to investigate their effects on electricity supply.

First, the Pearson correlation matrix was employed to examine the relationships among all variables. Then, a multiple linear regression (MLR) model was applied to analyze the data using the significant variables and to predict electricity supply. The final electricity supply (ES) equation was developed and is presented in Equation 8:

$$\hat{y} = 15407.99 + 357.15x_1 - 881.77x_2 + 8.32x_3 \quad \ldots \text{Eq } 8$$

Where:

$\hat{y}$= monthly predicted electricity supply
x_1= monthly maximum temperature
x_2= monthly mean temperature
x_3= monthly evaporation

The equation was used to compute the simulated values of monthly electricity supply (ES). The simulated ES was then compared with the actual ES, as shown in Fig. 4. The plot illustrates a strong correspondence between the simulated and actual ES values, confirming the capability of the selected climatic variables to accurately estimate ES or electricity demand.

In the regression analysis, the standard error represented the dispersion of data points around the regression line. The closer the data points are to the regression line, the higher the accuracy of the model. The standard error value obtained in this analysis was 113.8, which is relatively high. However, the acceptable range of standard error largely depends on the context of the regression model. In this case, the regression model was applied to electricity supply values ranging from 3,300 to 4,000 GWh.

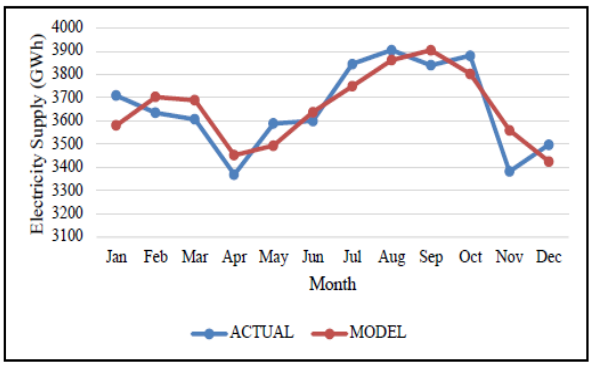

Fig. 4 - Comparison between actual and simulated ES

Meanwhile, Fig. 5 illustrates the disparity in the projected electricity supply (ES) among the three RCP scenarios from 2025 to 2100. The percentage differences are clearly shown, highlighting RCP8.5 as the scenario with the greatest increase. While RCP8.5 exhibits the highest rise, the other two scenarios, RCP2.6 and RCP4.5, display moderate upward trends especially during July and October. Although

the changes in these two scenarios are less pronounced, both follow a similar increasing pattern in projected ES between 2070 and 2100.

The modelling of ES, based on climate variables, indicates that future changes are significantly influenced by shifts in climatic conditions. The projected ES trends align closely with the variations in climate variables. For instance, in October, the projected ES reaches its peak, which can be attributed to the lowest predicted evaporation rates during that month, resulting in a higher volume of stored water in the reservoir. The reduced evaporation enhances the ES generated by the hydropower plant. Additionally, the projected increase in rainfall during October contributes further to the greater water volume in the reservoir. The projected ES results were subsequently applied in the assessment of the long-term hydropower water footprint.

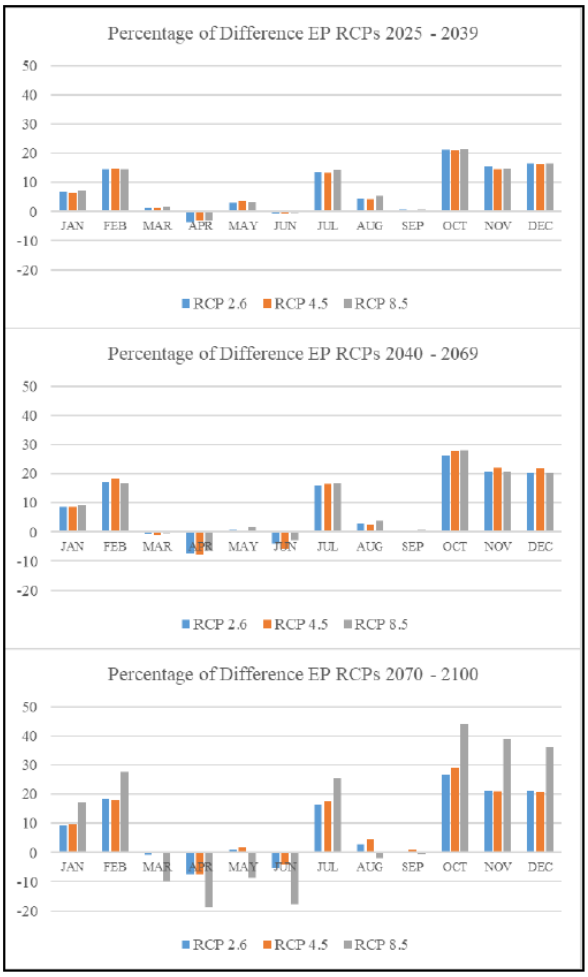

Fig. 5 - Percentage Changes of Future ES

3.3 Evaluation of HWFP

In this study, the projection of long-term Hydropower Water Footprint (HWFP) was carried out using two methods: the gross and net HWFP approaches. Both methods utilized the projected data for climate variables—rainfall and evaporation—as well as electricity supply (ES) from 2025 to 2100. The projections were also analyzed across three time phases and visualized under the climate scenarios RCP2.6, RCP4.5, and RCP8.5 to provide a clearer understanding of the results. The assessment of long-term gross and net HWFP is presented in Fig. 6 and Fig. 7.

Based on Fig. 6, the projected gross HWFP closely follows the same pattern as the historical gross HWFP, gradually decreasing from September to November. A significant drop is also observed in February, followed by an increase until April. This pattern is influenced by the direct proportional relationship between evaporation and the gross HWFP. As evaporation is projected to increase from January to April, the gross HWFP follows a similar trend.

From Fig. 7, the projected net HWFP displays a similar pattern across all time periods and RCP scenarios. The net HWFP increases from January to February and then fluctuates slightly at lower values. Starting from August, the net HWFP begins to decline toward the end of the year. The results from this method clearly demonstrate the effect of accounting for water entering the reservoir, which in some periods exceeds the amount of water evaporated and leaving the reservoir surface.

The assessment of both gross and net HWFP methods reveals that future climate changes exert a substantial impact. Climate change not only affects the electricity supply of the hydropower plant but also intensifies weather conditions—particularly rising temperatures and increasing evaporation rates—which significantly influence reservoir water availability. However, the analysis using the net HWFP method indicates that climate conditions have a less pronounced effect on HWFP. This is attributed to the region's tropical climate and relatively consistent rainfall throughout the year. Although some months experience lower rainfall, the overall impact on HWFP remains comparatively minimal

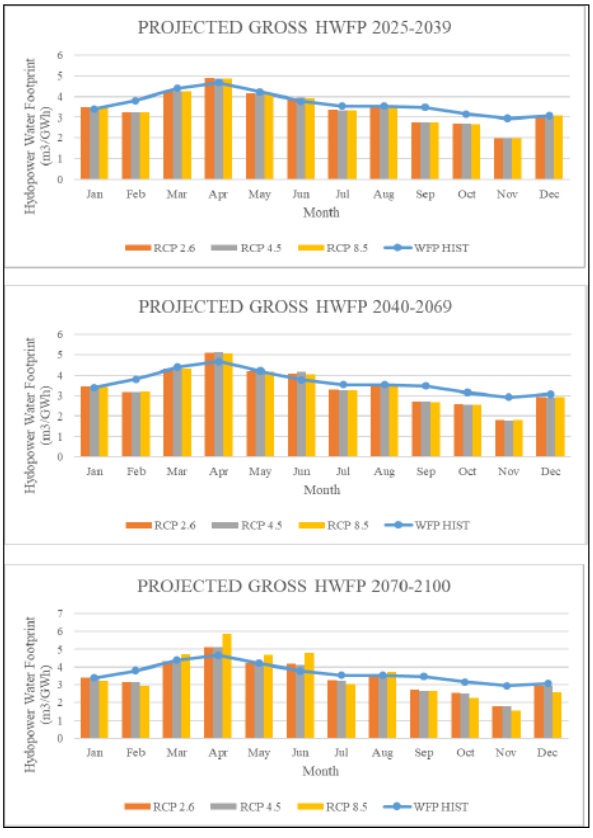

Fig. 6 - Projection of gross HWFP until 2100

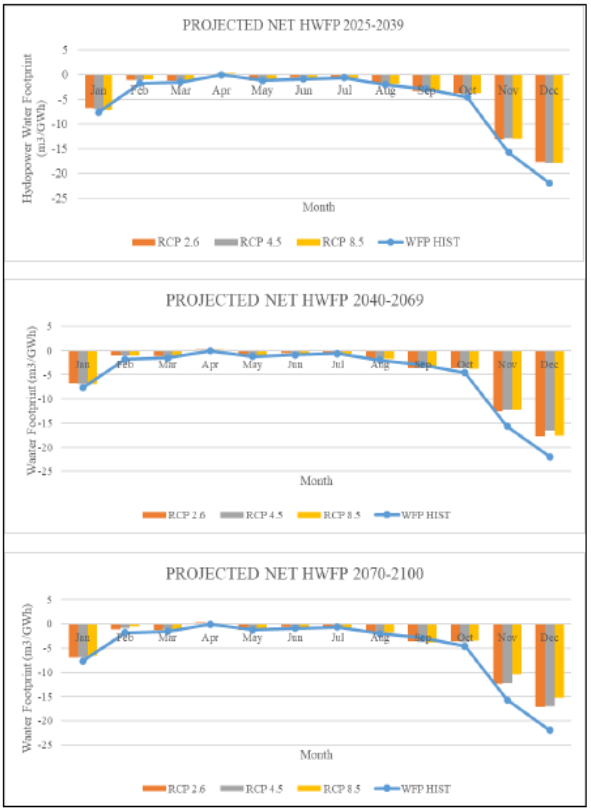

Fig. 7 - Projection of net HWFP 2100

4. Conclusions

Climate change has significant implications for the Hydropower Water Footprint (HWFP). As shown in the climate projection data, rainfall is expected to increase during the Northeast Monsoon period. Meanwhile, the projection of maximum temperature indicates that all RCP scenarios gradually peak between February and October, rising by approximately 4.5% to 6.5% each year. The projection of relative humidity (RH) shows a general decrease across all RCPs, with RCP4.5 exhibiting the greatest reduction—approximately 4.5% between 2070 and 2100, particularly from November to January. Evaporation projections for September and November display the most notable differences, with evaporation under all RCPs expected to decrease by about 22% and 24%, respectively.

As a result, there is a significant projected increase in electricity supply (ES) during February, July, and October. This increase is attributed to higher projected rainfall during these months, which raises the water level in the reservoir. Additionally, the projected decline in evaporation during the same period contributes to this trend. The combination of lower evaporation rates and higher rainfall results in an overall increase in ES values.

The gross HWFP is expected to rise only in April, by an average of 4.5% for RCP2.6 and RCP4.5, while the highest increase of about 25% is observed under RCP8.5. Conversely, the net HWFP considers the balance between water input (rainfall) and output (evaporation) from the reservoir. According to historical data, the net HWFP of the hydropower plant is generally negative, indicating that more water enters the reservoir than leaves or is consumed in electricity production. Future projections follow a similar pattern, with a slight increase observed from October to December each year.

Although carbon and greenhouse gas (GHG) emissions are expected to rise in the future, their impact on the hydropower water footprint is considerably greater under the gross HWFP method, while the effect remains minor under the net HWFP method. However, results from the regression analysis clearly show that certain climate variables significantly influence fluctuations in the electricity supply generated by the hydropower plant.

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