

Application of the CMIP6 Approach for Determination of Climate Change Impact on Inflow to Malampuzha Reservoir, India

ABSTRACT

Optimal operation of a reservoir is important for the efficient planning and management of water resources. Inflow estimation into the reservoir is the basic information needed by a policy maker for the optimal planning of the reservoir operation. Climate change has become a major cause for the changes in the hydrological phenomena. An attempt was made to analyse the impact of climate change on Malampuzha reservoir inflow for the future using recent Shared Socioeconomic Pathways (SSP) scenarios. Two SSP scenarios, SSP 245 and SSP 585 were considered for the evaluation of changes in the meteorological variables for the future period. Rainfall-runoff modelling of the catchment area of the Malampuzha reservoir was done with IHACRES model for the period 2003-2022. The model performance was accepted in calibration (2003-2016) and validation (2017-2022) periods with R^2 of 0.90 and 0.91 and RMSE 2.63 and 4.53 m^3/s respectively. The outputs of SSP245 and SSP585 scenarios were given to the developed runoff model to estimate the future inflow volume into Malampuzha reservoir for the period of 2023 to 2042. From the results, the change in monthly temperature varies from $-0.88^\circ C$ to $3.3^\circ C$ and change in monthly precipitation varies from -0.64% to 1.73% which indicates a decrease in the inflow of water into the reservoir for future period by 2.6% and 9.3% than the base period (2003– 2022) for SSP245 and SSP585 scenarios, respectively. The results of the study implies that better planning of the reservoir operation is needed for meeting the future demands.

Keywords: IHACRES, CMIP6, Climate change, reservoir inflow

INTRODUCTION

Estimation of inflow volume of water into the reservoirs plays a major role in water resources planning and management. Reservoirs are the manmade structures used to store the inflow volume of water from upstream catchment area and later released to the downstream command area for different purposes (Sun *et al.*, 2023). It is very much important to predict the inflow to get an idea about how much quantity of water can be stored in the reservoirs and can be released to the downstream command area to satisfy the crop water and drinking water demand

(Yu *et al.*, 2014). Rainfall-runoff modelling helps in understanding the behaviour of the catchment area and also can be used to model the runoff volume with the help of several catchment descriptors (Naz *et al.*, 2018). Most of the rainfall runoff models are in need of large amount of input data such as meteorological variables, land use, soil type, and digital elevation model data (Jakeman and Hornberger, 1993; Post and Jakeman, 1996). But it is not always possible to get sufficient amount of data due to lack of availability. So, hydrologists have developed several rainfall-runoff models which are empirical in nature that can be used with the limited quantity of input data (Littlewood, 2021). One can apply these models to their respective study areas on the basis of proper validation criteria.

Climate change is the one important factor that affects the watershed hydrology. Due to rapid industrialization, urbanization, rise of greenhouse emission concentration, increase in population and diminution of natural resources, several changes have been occurring in hydrological cycle. Increase in temperature, shift of rainfall patterns and occurrence of intense rainfall are some major factors that adversely affect all water balance components of watershed including runoff (Korobkina and Filippova, 2021; Prasanchum and Kangrang, 2018). So, it is important to evaluate the climate change impact on meteorological variables to understand the changes in inflow volume into the reservoir for future period (Visweshwaran, 2021; Parmas *et al.* 2023; Taehyeong Kim and Boosik Kang, 2023). General Circulation Models (GCMs) are used to project future climate data based on CO₂ emission scenarios. In 2021, Intergovernmental Panel on Climate Change (IPCC) has released new set of emission scenarios, based on socioeconomic conditions and greenhouse gases concentration which are popularly called as SSP's.

Varughese and Hajilal, (2020) predicted a decrease in the south west monsoon and increase in the north east monsoon over Bharathapuzha river basin using CMIP5 scenarios. After thorough understanding of the literature available, we found that no previous studies are available on the inflow modelling of the Malampuzha reservoir in Kerala India. An attempt was made to analyse the climate change impact on the inflow to Malampuzha reservoir which is situated in Palakkad district of Kerala. Rainfall-runoff model of the catchment area of the Malampuzha reservoir was developed with the help of IHACRES model using data available for the period of 20 years (2003 to 2022). The outputs of CNRM-CN-6-1 general circulation model under IPCC CMIP6 SSP245 and SSP585 emission scenarios were downscaled for the study area

for the period of 2023 to 2042. These outputs were given to the developed runoff model to get the future inflow volume of water into the reservoir.

Materials and Methods

Study area: Malampuzha reservoir is situated in Palakkad district of Kerala, on the western side of Western Ghats of India. The catchment area of this multipurpose reservoir (Fig.1) is around 146 km² which is mostly covered with dense vegetation and forest area and has a humid tropical region. The maximum storage capacity is 226 Mm³ and dead storage is 2.4 Mm³. The Malampuzha reservoir area receives an annual rainfall between 2000 to 2800mm. South-west monsoon is the major contributor to the reservoir which arrives in June and contributes up to the onset of North East monsoon. The water stored in the reservoir is used for the irrigation, drinking water and hydropower generation. The cultural command area of the reservoir is around 22000 ha. Palakkad district is considered as the rice bowl of Kerala state as it contributes 40% of rice production. Malampuzha reservoir is the main source for irrigation and drinking water of the Palakkad district.

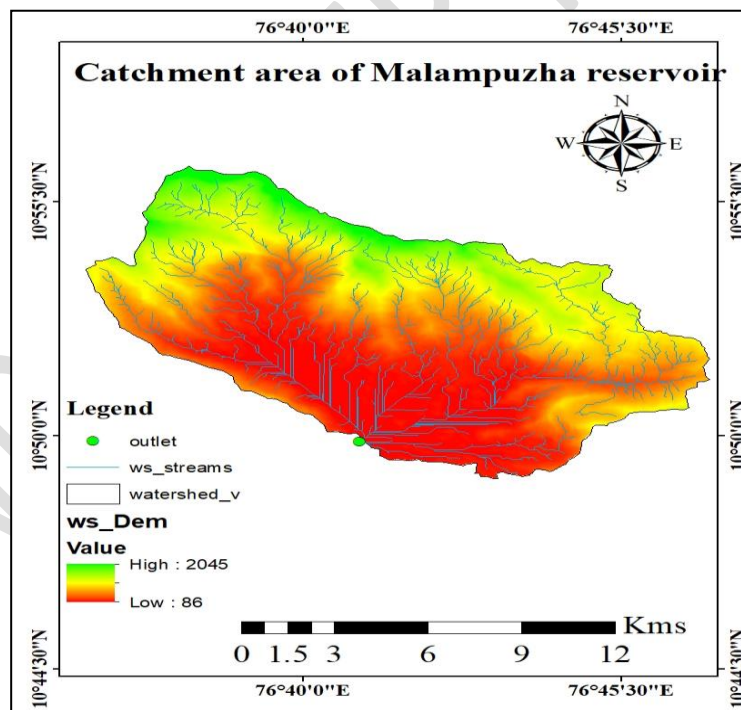


Fig.1 Catchment area of Malampuzha reservoir

Climate change scenarios: Sixth assessment report of IPCC has released five pathways in which the effect of societal choices on greenhouse emission concentration is explained and

finally the results of climate extremes are described. These SSP scenarios are on the basis of their earlier version of emission scenarios (RCPs) but an addition of the factor of socioeconomic conditions has been done. These include, a world of sustainability-focused growth and equality (SSP1); a “middle of the road” world where trends broadly follow their historical patterns (SSP2); a fragmented world of “resurgent nationalism” (SSP3); a world of ever-increasing inequality (SSP4); and a world of rapid and unconstrained growth in economic output and energy use (SSP5).

IHACRES: Identification of unit hydrograph and component flows from rainfall, evaporation and streamflow data is a spatially lumped conceptual rainfall runoff model developed by UK Institute of hydrology and Centre for Resource and Environmental studies at the Australian national University (Jakeman *et al.* 1990). Scientists across the globe have used IHACRES model and have pointed out that the IHACRES model is an efficient, straight forward and simple tool for rainfall-runoff modelling that requires very limited data for the runoff simulation.

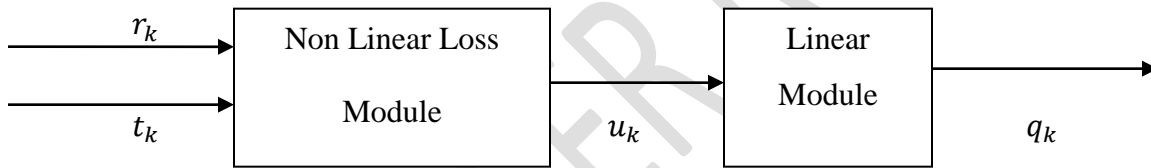


Fig.2 Structure of IHACRES rainfall-runoff model

IHACRES model needs only precipitation and temperature/evaporation data for the rainfall-runoff modelling. Streamflow data need to be provided to the model for the purpose of calibration and validation. This model requires quantitative data, so it can be used in many watersheds where there is scarcity in data availability (Dye and Croke, 2003). The model consists of two modules namely nonlinear module and linear module. With the data of temperature or evaporation of a watershed, the nonlinear module converts rainfall into effective rainfall whereas the linear module relates the effective rainfall to modelled streamflow.

$$s_k = \frac{r_k}{c} + \left[1 - \frac{1}{\tau_w \exp[(20-t_k)f]} \right] s_{k-1} \quad \text{Eq.(1)}$$

For each time step k , a soil moisture wetness index of the catchment s_k is calculated using Eq(1), where r_k is the observed rainfall (mm); t_k is the observed temperature ($^{\circ}\text{C}$); f is a temperature modulation parameter; c is a factor which equates the effective rainfall and observed

streamflow over a period of calibration also popularly called as mass balance term of a basin. τ_w is the time parameter for the decline in s_k . The larger the value of τ_w , the longer the effect of antecedent rainfall on s_k .

$$\text{Effective rainfall can be calculated as } u_k = \begin{cases} r_k s_k^p & r_k > l \\ 0 & r_k < l \end{cases} \quad \text{Eq.(2)}$$

Where, p is the exponential loss parameter and l is the streamflow threshold value for producing flow. Effective rainfall will be calculated only if the rainfall is in excess of the moisture threshold value to produce the flow. To account the fluctuation in evapotranspiration, the observed rainfall r_k is replaced in above equations by r_k^* which can be calculated with the help of reference temperature t_m .

$$r_k^* = \left(1 - \frac{t_k}{t_m}\right) r_k \quad \text{Eq.(3)}$$

In IHACRES, the linear module considers the entire catchment as a combination of two parallel stores, one for quick flow another is for slow flow (Croke and Jakeman, 2004). For each time step k , the streamflow (q_k) is the sum of both the quick flow (x_k^q) and slow flow (x_k^s) components.

$$q_k = x_k^q + x_k^s \quad \text{Eq.(4)}$$

$$x_k^q = \exp\left(\frac{-\Delta}{\tau_q}\right) x_{k-1}^q + v_q \left[1 - \exp\left(\frac{-\Delta}{\tau_q}\right)\right] u_k \quad \text{Eq.(5)}$$

$$x_k^s = \exp\left(\frac{-\Delta}{\tau_s}\right) x_{k-1}^s + v_s \left[1 - \exp\left(\frac{-\Delta}{\tau_s}\right)\right] u_k \quad \text{Eq.(6)}$$

Where, Δ is the time constant, τ_q and τ_s are the decay time constants and v_q and v_s are the relative volumetric proportions for quick flow and slow flow respectively.

Performance indices such as mean bias error, root mean square error, mean absolute error, R^2 and Nash Sutcliffe Efficiency (NSE) are used as the base for the consideration of the model for the runoff simulation. Monthly data of rainfall, temperature and inflow volume of Malampuzha reservoir is given to the model for the period of 20 years (2003 to 2022). Calibration was done using data for the period 2003 to 2016, and validation using the data of 2017 to 2022.

$$MBE = \frac{\sum(O_i - S_i)}{n} \quad \text{Eq.(7)}$$

$$NSE = 1 - \frac{\sum_{i=1}^n (O_i - S_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2} \quad \text{Eq.(8)}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (O_i - S_i)^2}{n}} \quad \text{Eq.(9)}$$

$$MAE = \frac{\sum_{i=1}^n |O_i - S_i|}{n} \quad \text{Eq.(10)}$$

$$R^2 = \frac{[\sum_{i=1}^n (O_i - \bar{O}) \cdot (S_i - \bar{S})]^2}{\left[\left[\sum_{i=1}^n (O_i - \bar{O})^2 \right]^{0.5} \cdot \left[\sum_{i=1}^n (S_i - \bar{S})^2 \right]^{0.5} \right]^2} \quad \text{Eq.(11)}$$

Where O_i is the observed values and S_i is the simulated data

Results and Discussion

The main aim of this research is to develop a more reliable model for the estimation of inflow into the Malampuzha reservoir. Rainfall, temperature and inflow data of Malampuzha reservoir was provided to the IHACRES model for the period 2003 to 2022 on monthly basis. The required parameters were determined in both nonlinear and linear modules and their optimal values were obtained which are presented in Table 1 and 2.

Table 1 Non-linear module calibration parameters

Mass balance term (c) (1/mm)	0.000555
Drying rate at reference temperature (τ_w) (days)	12
Temperature dependence of drying rate (f) ($1/^\circ\text{C}$)	1.00
Reference temperature (t_m) ($^\circ\text{C}$)	28.00
Moisture threshold for producing flow (l)	0.000
Power on soil moisture (p)	1.000

Table 2 Linear module calibration parameters

Recession rate 1 ($\alpha^{(s)}$)	-0.148	Time constant 1 ($\tau^{(s)}$)	523
Peak response 1 ($\beta^{(s)}$)	0.945	Volume proportion 1 ($v^{(s)}$)	0.809
Peak response 2 ($\beta^{(q)}$)	0.109	Volume proportion 2 ($v^{(q)}$)	0.191

The parameter f accounts for evapotranspiration effects based on temperature. Higher values indicate greater influence of temperature on runoff. τ_w describes how fast the soil moisture responds to rainfall events. A short time constant means rapid changes in soil moisture

conditions. $v^{(q)}$ is the proportion of the total flow that comes from the quick-flow reservoir. $v^{(s)}$ is the proportion of the total flow coming from the slow-flow reservoir (i.e., base flow). From the Table 1 and Table 2, it was clear that there is no much effect of temperature on the inflow into the reservoir and also the contribution of base flow component towards reservoir inflow is more than the quick flow component.

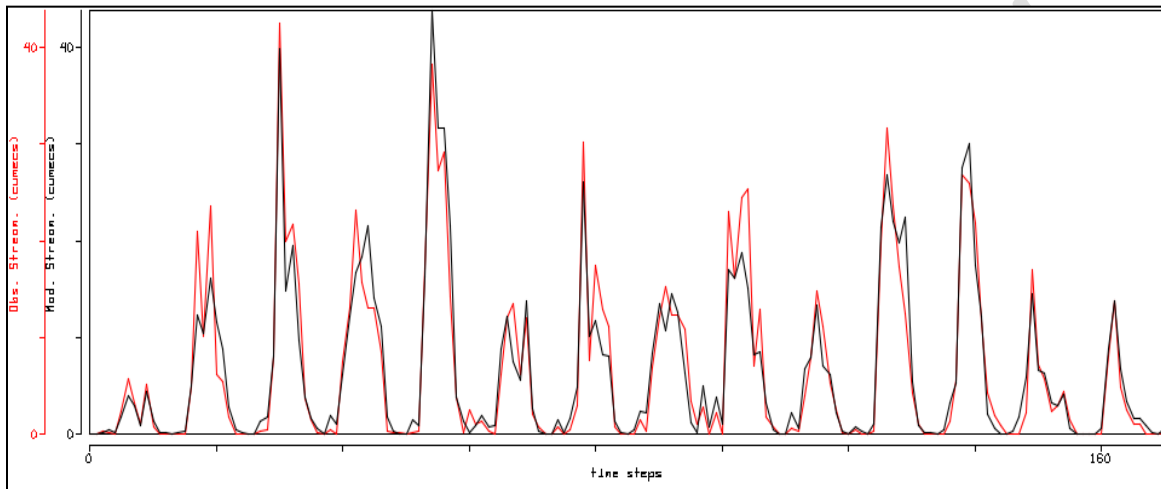


Fig.3 Calibration results of IHACRES

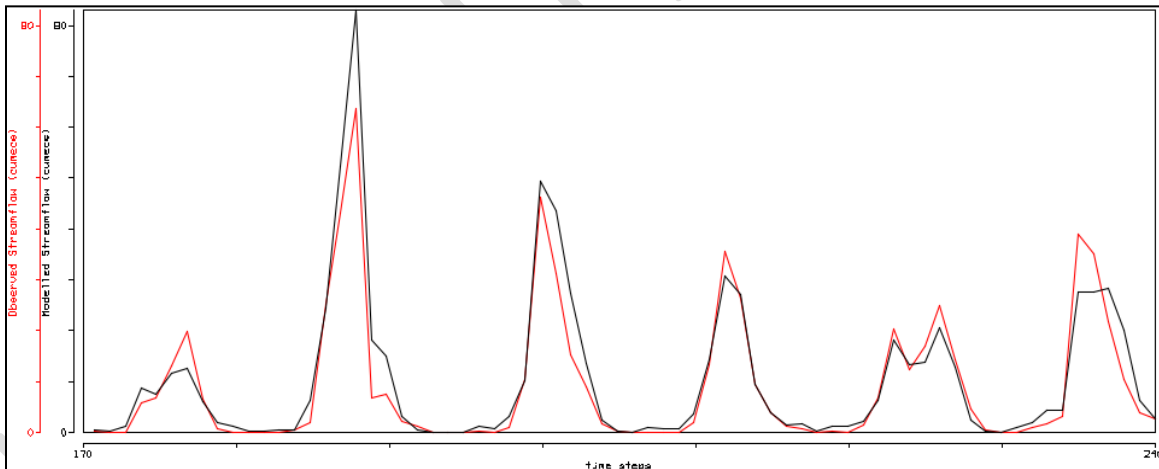


Fig.4. Validation (2017-2022) results of IHACRES

The comparison of observed and simulated inflow from IHACRES model of Malampuzha reservoir are shown in the Fig.3 and Fig.4 for calibration and validation periods respectively. From these figures it can be observed that the developed model has performed well and is suitable to simulate monthly inflows of Malampuzha reservoir. The monthly time series

plot of observed and modelled inflow values was shown in the Fig. 5. The monthly error plot was also drawn between actual and simulated inflow data and are presented in Fig.6.

The maximum error of around $19 \text{ m}^3/\text{s}$, was obtained in the month of August of the year 2018 where the reservoir was completely filled with the water because of the extreme precipitation in the catchment area.

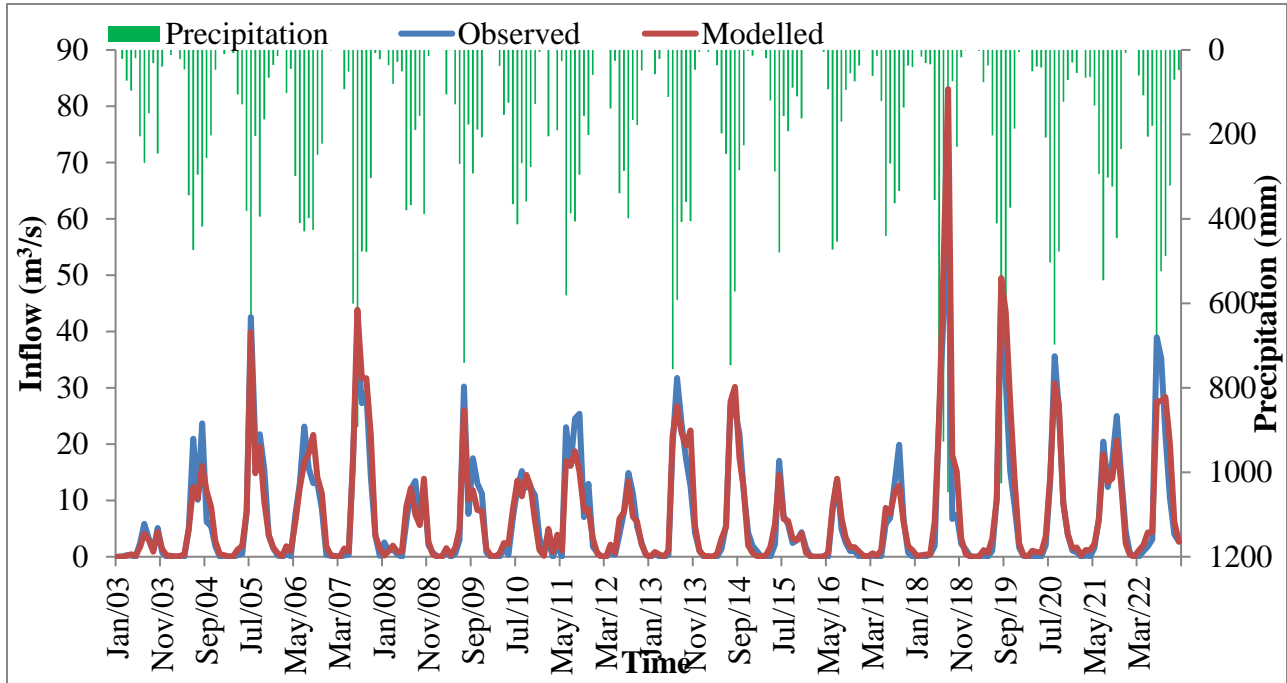


Fig.5 Comparison of observed and simulated monthly inflows of Malampuzha reservoir

For better understanding of the ability of the developed rainfall-runoff model, observed inflow values were plotted against simulated inflow values in both calibration and validation periods with their respective coefficient of correlations. In Fig.6, the points which are related to inflow with small values are positioned at a smaller distance from 1:1 line in both calibration and validation phases. This indicates that the developed model has simulated smaller inflows in a better way than the large inflow values. Different performance indices were also calculated and presented in the Table 3.

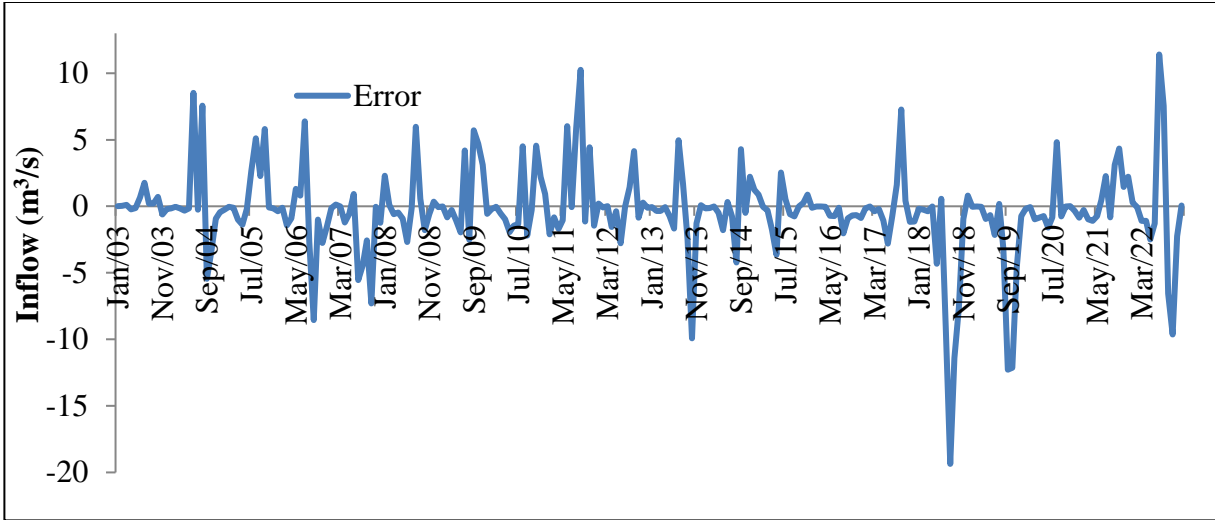


Fig.6 Time series error plot between observed and simulated inflow

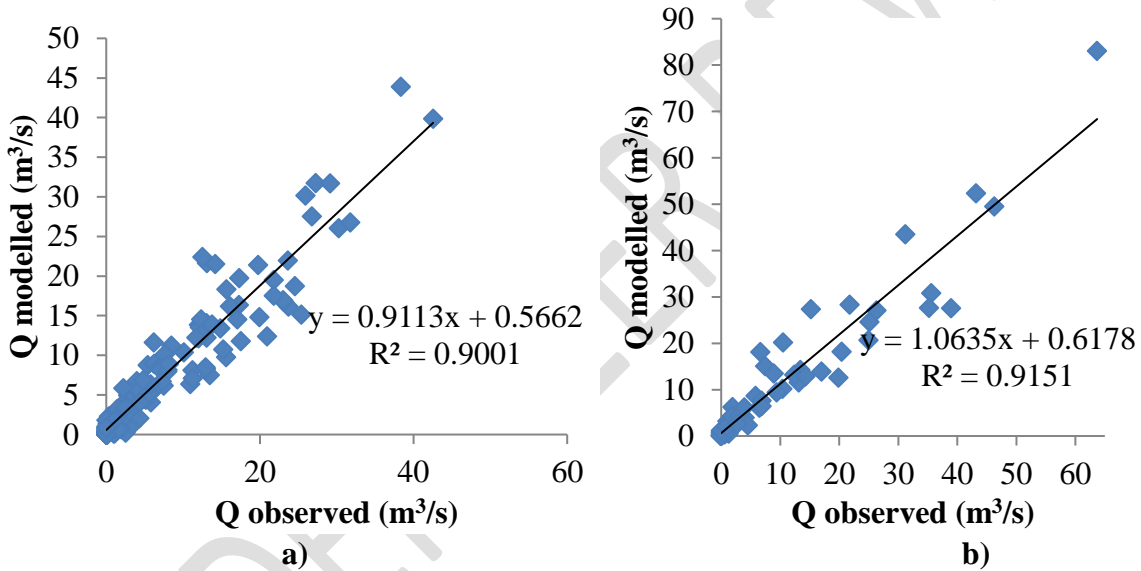


Fig.7. Scatter plots for monthly inflow a) calibration period b) validation period

Table 3: Evaluation of developed rainfall-runoff model

Performance indicator	Calibration (2003-2016)	Validation (2017-2022)
R²	0.9001	0.9151
NSE	0.9100	0.8831
MBE	6.9598	20.5916
RMSE	2.6381	4.5378
MAE	1.6150	2.5335

The R² value in calibration period was 0.91 and in the evaluation period it increased a little. The developed model also exhibited lower values of RMSE, MAE and MBE with the

actual inflow values. Based on the performance indices it can be inferred that the developed rainfall-runoff model using IHACRES, performed well in both calibration and validation periods and can be used to simulate inflow into the Malampuzha reservoir for future period.

Estimation of future inflow: The meteorological data of CNRM-CM-6-1 AOGCM model was selected for this study since many recent literatures have used the model for prediction. The period of 2023-2042 was considered as a future period. The daily data of temperature and precipitation of CNRM-CM-6-1 model for the period of 2023 to 2042 was downscaled for the study area for the SSP 245 and SSP585 scenarios. As we can see from the Fig.8, when compared to the base period (2003-2022) the precipitation of the future period of Malampuzha catchment is going to be decreased based on SSP 245 and SSP 585 scenarios. SSP 585 scenario predicted more decrease in the precipitation in all months for the future period than SSP 245 scenario. The comparison of temperature between base period and future scenarios was presented in Fig.9. In majority of the months, both scenarios had predicted an increase in the temperature for the future period. Being a high emission scenario, SSP 585 has predicted more increase in the temperature when compared to SSP 245 predictions.

Temperature and precipitation data of CNRM-CM-6-1 GCM model for the period of 2023 to 2042 was given to the developed IHACRES model to simulate the future inflow. The monthly inflow estimation of two prior considered scenarios were compared with the base period inflow and was presented in Fig.10.

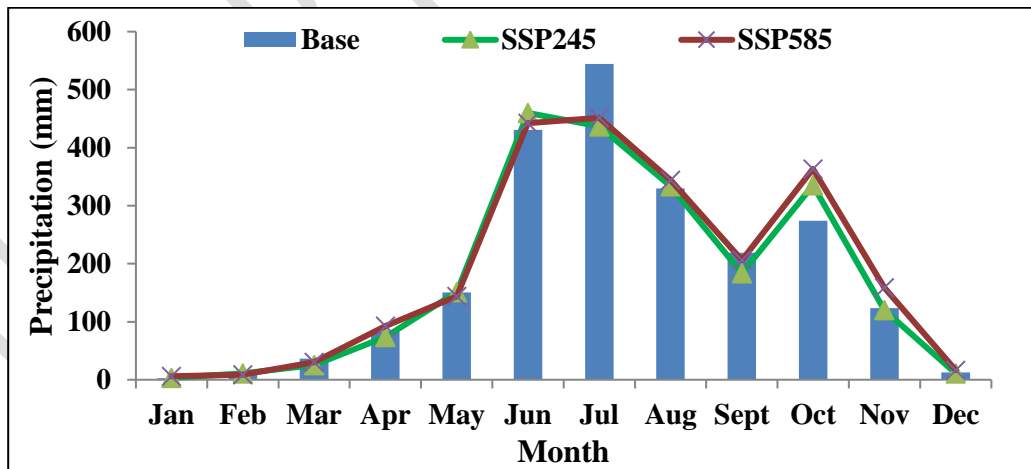


Fig. 8 Comparison of monthly precipitation between base period and future period

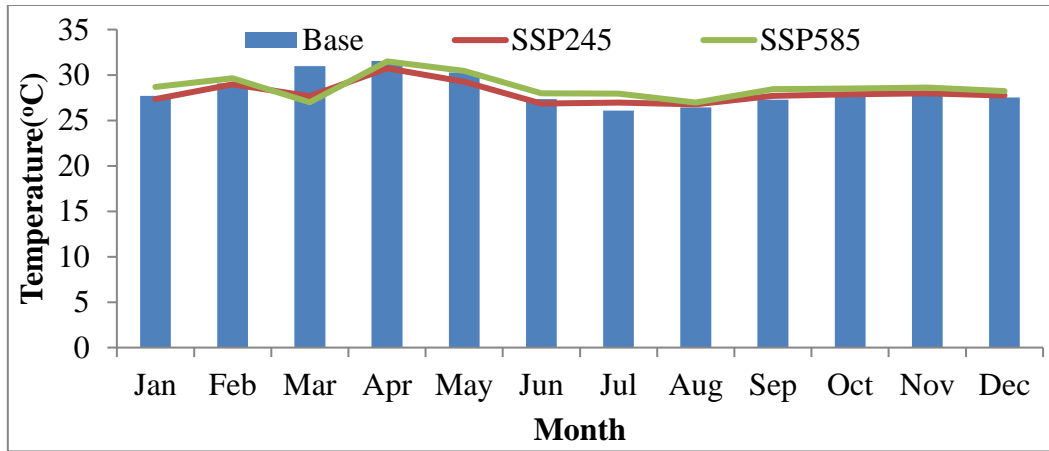


Fig.9 Comparison of monthly temperature between base period and future period.

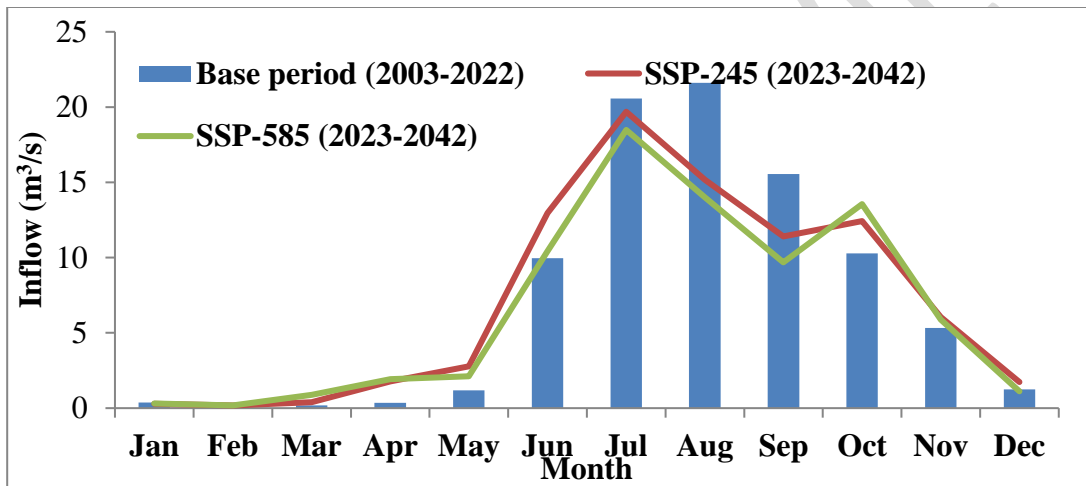


Fig.10 Comparison of Inflow between base period and future period

From Fig.10, it can be said that the inflow volume of water is decreasing in the months of July, August and September. In these months, SSP 585 scenario has predicted a more decrease in the inflow for future period than SSP 245 scenario. An increase in inflow during the month of October is also predicted. It is observed that the monthly temperature change varied from -0.88 to 3.3 °C and the monthly precipitation change varied from -0.64 to 1.73% in the future. Since, there was a decrease in the precipitation and increase in the temperature for of the Malampuzha reservoir catchment in the future period, the inflow volume of water that will join the reservoir will be reduced which indicates the urgent need of better planning and management of reservoir operation.

Conclusion

Climate change effect on Malampuzha reservoir inflow was evaluated with the support of IHACRES hydrological model under CMIP6 scenarios. Rainfall runoff model was developed for the period of 20 years (2003 to 2023) with R^2 , RMSE of 0.91, 2.63 for calibration (2003-2016) and 0.91, 4.53 for validation (2017-2022) periods respectively. The developed IHACRES model was provided with future temperature and precipitation data to get future inflow of malampuzha reservoir. The average annual inflow into the reservoir for future period (2023 – 2042) will decrease by 2.6% and 9.3% than the base period (2003– 2022) for SSP245 and SSP585 scenarios. The results of the research will give an insight to the experts in the field for planning of future development projects to reduce the harmful effects that can occur due to climate change in the area. The predictions of climate change in the study was done on the basis of only one GCM, and more detailed research based on multiple GCM's is needed to make better conclusions.

Acknowledgements

The author would like to sincerely thank the Department of Science and Technology (DST) for continuous monetary assistance during the research work. The author acknowledges the KCAET, Kerala Agricultural University for the constant support and guidance.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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