Studying the impact of climate change on hydroelectric energy production (Case study: Karun 4 Dam)

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ABSTRACT

In this manuscript, the primary goal is to assess how climate change affects the accessibility and fluctuation of aquatic reserves, which directly impacts the performance and reliability of hydroelectric energy production. The study aims to understand changes in precipitation patterns, snowmelt timings, and extreme weather events, which influence river flow dynamics, reservoir levels, and overall energy generation capacity. It also seeks to identify adaptive strategies to mitigate negative impacts and ensure sustainable hydropower development in the face of a changing climate. This study evaluates the performance of the Karun 4 Dam power plant, one of the country's most critical electricity generation facilities, under the impacts of climate change. A multi-criteria decision-making approach (TOPSIS) was used to identify the most reliable General Circulation Models (GCMs) and reduce uncertainty. Additionally, the IHACRES conceptual model was employed to simulate the runoff process, while the Differential Evolution (DE) algorithm was applied to optimize hydropower energy production. The findings show a projected temperature increase from 2040 to 2061 of 1.95°C and 2.34°C under the RCP 4.5 and RCP 8.5 scenarios, respectively, compared to the baseline period (1984-2005). Furthermore, the study predicts a reduction in inflow runoff to the Karun 4 reservoir by an average of 19% and 43% under the aforementioned scenarios. Based on the results, the decrease in reservoir inflow in future periods is expected to reduce annual electricity production by 9% under the RCP 4.5 scenario and 18% under the RCP 8.5 scenario relative to the plant's nominal capacity.

KEYWORDS

Climate Change, Hydropower Energy, Reservoir Operation, Uncertainty, Karun 4 Dam.

1. Introduction

Produced and consumed energy sources, especially renewable energy sources, have a very important value. Renewable energy sources such as solar, wind, hydro, and geothermal energy are sustainable methods that provide about 14% of the world's energy needs [1] [2] Among the stated options, hydroelectric power plants are known as the most important source of renewable energy due to their unique nature [3]. Switching from fossil fuels to renewable energy sources is essential for attaining global environmental sustainability. [4]. The current movement is further bolstered by transformations noted in geopolitical dynamics., which have led to disruptions in the supply chains of conventional fuels.

For instance, the 2022 conflict in Ukraine has demonstrated that natural gas is not a viable interim fuel for transitioning to a fully renewable energy system, particularly when its supply is unreliable. It has been stated that a worldwide Reducing carbon emissions in power systems is essential to meet the United Nations Sustainable Development Goals and the objectives of the Paris Agreement. [5] [6]. According to recent World Bank estimates, Out of the 38 countries in the Organization for Economic Co-operation and Development, fewer than 25% of their electricity is generated from ref14renewable sources. However, there are considerable variations among these countries. Wind, solar, and hydropower are acknowledged as the primary sources of variable renewable energy (VRES) due to their global availability and technological advancement. Also in a review climate change has significant impacts on hydropower potential, freshwater fisheries, and hydrological responses in snow-dominated basins. It discusses how global warming affects precipitation patterns, leading to earlier spring snowmelt and changes in river flow dynamics. The article highlights that small-scale, high-altitude hydropower reservoirs are especially susceptible to temperature variations. It also highlights the importance of considering these impacts for future hydropower projects and water resource management.[8]. Nevertheless, their variability is a challenge that scientists are working to address in order to enhance their contribution to power grids. [9]. While hydroelectric power plants have many advantages over fossil fuels and other renewable sources, they are directly dependent on the amount of water flow and are very sensitive to weather conditions. Therefore, the survival of hydropower projects in the current or planned state is affected by climate changes and spatial-temporal changes in river flow [10] [11]. The International Energy Agency has identified the reduction of access to water as one of the major risks associated with climate change for the energy sector. So, the effects of climate change could cause serious problems in future hydropower plant plans, making them unjustifiable from an economic point of view. Therefore, it is necessary to conduct studies on the effects of climate change during the useful life of the hydroelectric dam, with the results being vital in the long-term management of the dam and the production of hydroelectric energy [12].

In their study, Zapata et al. used two integrated evaluation models of data from four climate models to analyze the effects of climate change on global and regional energy consumption under two RCP 2.6 and RCP 6 scenarios [10]. The general results of this study pointed out a reduction in the use of fossil fuel resources for most regions, especially North America and Europe, under the RCP 6 scenario. It was also noted that under the RCP 6 scenario in Asia, except for China and India, climate change will increase the use of hydroelectric and wind energy. Emphasizing the share of renewable energy in the energy market and its increasing growth, Bhatt et al. investigated the impact of climate change on renewable energy production through new criteria [13]. Craig et al.'s study titled "Overcoming the Communication Gap Between Energy System and Climate Modeling" stated that since a system model's energy is the basis for decision-making by energy system planners and operators, energy system modeling has faced a transformation due to changes in weather conditions caused by climate change [14]. When Mirani et al. evaluated hydroelectric energy production and exploitation of the Kesem dam reservoir under the influence of climate change using a HEC-HMS hydrological model to estimate the river flow and the outputs of the MODSIM 8.1 simulator model using the information of RCP 4.5 climate scenario, they determined that the average production of hydroelectric energy will decrease by 0.64% in the short term (2050-2021) and 0.82% in the long term (2051-2080). Also, in the case of the RCP 8.5 climate scenario, it was found that energy production will decrease by 1.06% and 1.35% in the short term and long term, respectively. Even the RCP 4.5 scenario showed high energy production fluctuations in this basin and decreased energy production [15]. Acknowledging the lack of research on the impact of future stream drought on hydropower generation in China, Zhao and colleagues created a model to predict future hydropower output. Their research incorporated four global hydrological models and four global climate models across two emission scenarios. Findings revealed that, in comparison to the base period of 1951 to 2005, over 25% of hydropower plants are projected to see a 20% reduction in energy production relative to the base period average. [7].

Carlino et al. stated that more than 300 hydroelectric projects are ref18under consideration across the African continent to meet energy sector needs based on population growth and increased energy demand. They showed that due to the uncertainties related to weather, climate, social, and economic changes, only 40 to 68% of hydroelectric power plants will be economically suitable. They also stated that for reliability against climate change, an increase of 1.8 to 4 percent of investment in this continent is needed [16]. Gurriaran et al. used three climate scenarios, SSP 126, SSP 370, and SSP 585, aiming to determine climate change's impact on energy demand and carbon dioxide emissions in Japan from 2020 to 2100. They stated that the impact of climate change on carbon dioxide emissions from electricity generation has regional and seasonal differences. This study determined that the amount of future electricity demand in most regions of Japan will increase the most in May, June, September, and October [17]. Osman et al. (2023) explored various facets of renewable energy, including production costs, the impacts of climate change, the environment, the economy, and decarbonization efforts. They noted that in certain regions, hydroelectric and wind energy production could decline by as much as 40% due to the effects of climate change. [18]. figure 1 illustrates management and optimal exploitation of water resources systems with the aim of increasing productivity and the ability to meet future needs requires extracting the rules of exploitation of reservoirs and optimal allocation in climate change conditions. Determining and checking the status of a water resources system in a situation where a phenomenon such as climate change affects it increases the reliability of long-term plans and also increases the level of reliability of these systems in providing water to achieve their set goals. The important goals of the dams built in Iran’s Karun, Dez, and Karkheh basins include curbing severe floods, water storage and management, as well as the production of hydroelectric energy. Therefore, this study’s primary goal is to investigate the functioning of Karun Dam 4’s water resources system in the coming periods, the number of changes in the production of the power plant of this complex, and to optimize the amount of production. The progression of the study is outlined below in the flowchart in figure 1.

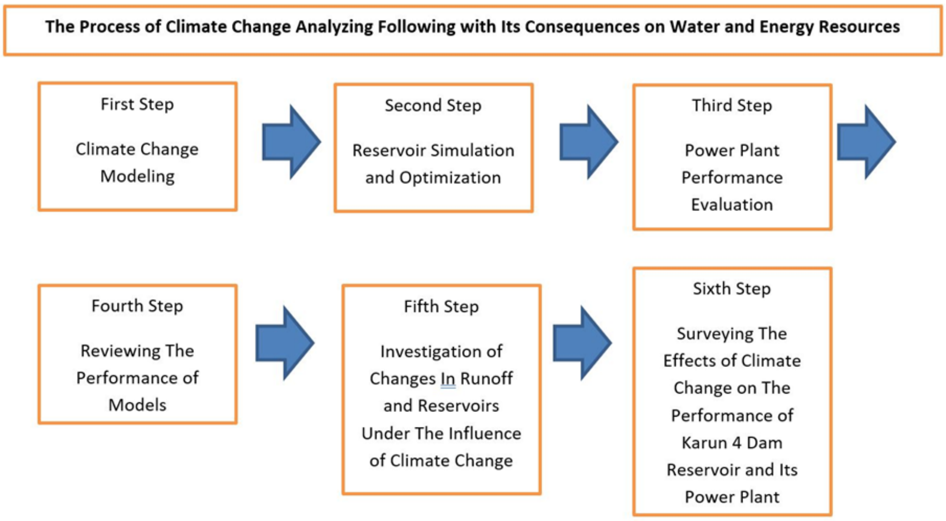

Figure 1. Flowchart of the Research Process

2. Materials and methods

2.1 Study area

Karun Dam 4 is the largest double-arched concrete dam in Iran and the fifth-highest dam in the world. Located in the Chaharmahal and Bakhtiari provinces in southwestern Iran, this dam covers an irrigation basin of approximately 14,500 square kilometers. Constructed with the objectives of regulating the Karun River's annual flow at 3.7 billion cubic meters, flood control, and hydroelectric energy production, the Karun 4 hydropower plant features four turbines, each with a capacity of 255 megawatts. This makes it one of the key hydroelectric power producers in Iran. The dam's strategic location and its significance in energy provision underscore the importance of its management and operation.

The four turbines at the plant each generate 255 MW, with a design height of 161.5 meters, and the plant's nominal output is 1000 MW. Notably, in the model presented, the power plant's load coefficient is treated as a separate variable for each month, typically higher in the warmer months than in the colder ones. Thus, effective management of this coefficient can enhance the balance in energy production and distribution. Table 1 details the characteristics of the studied stations.

Table 1. Characteristics of the Study Stations

No	Station Name	Geographic length	Geographic width	Elevation (meters)
1	Dokouheh	48.15	32.44	**280**
2	BashtAbad	48.24	32.24	**1686**
3	Dezk Abad	48.05	32.49	**2261**
4	Borogen	48.27	48.27	**2245**
5	Morghak	50.50	32.48	**949**
6	Manj	50.63	31.55	**2046**
7	Emam Gheys	51.30	31.75	**2125**
8	Kohrang	50.7	32.26	**2372**
9	Shahre Kord	50.85	32.28	**2057**

Figure 2. Location of Karun 4 Dam at the Basin Outlet and its Position within Iran

2.2 Research method

This research was conducted in four stages to achieve its objectives:

1- Climate change modeling,
2- Selection of the optimal scenarios,
3- Runoff simulation, and
4- Simulation and optimization of reservoir performance under the influence of climate change.

2.2.1. Climate change modeling

The first step involved downloading daily data from 20 selected models from the fifth report series (CMIP5). Following this, climate change data was processed, and the output of general circulation models (GCMs) was utilized. One critical pre-processing step when using GCMs is skew correction, which involves using observational and recorded regional data and statistical methods, such as fitting statistical functions and correcting potential errors. Table 2 displays the general characteristics of the selected general circulation models, along with their references and development centers.

Given that researchers prioritize achieving results with high accuracy and reliability, reducing the uncertainty in the output of the selected GCMs is essential. To enhance the precision of climate change studies, instead of randomly using all or a portion of the models, only those with better performance are utilized. Preacher and Merkle noted that in recent years, selecting models with superior performance to reduce uncertainty can lead to more dependable results.

Table 2. GCMs Used in this Study

N	Model	N	Model	N	Model	N	Model
1	ACCESS1.0	6	CESM1(BGC)	11	GFDL-ESM2G	16	MIROC-ESM
2	BCC-CSM1.1	7	CNRM-CM5	12	INM-CM4	17	MPI-ESM-MR
3	BNU-ESM	8	CSIRO-Mk3.6.0	13	IPSL-CM5A-LR	18	MPI-ESM-LR
4	CanESM2	9	GFDL-CM3	14	IPSL-CM5A-MR	19	MRI-CGCM3
5	CCSM4	10	GFDL-ESM2M	15	MIROC5	20	NorESM1-M

2.2.2 Selection of the best scenarios

The TOPSIS multi-criteria decision-making methods (further explained in the following section) were used to evaluate the performance of GCMs in this study. Because this approach necessitates selecting and ranking better-performing models, the models should be chosen based on better evaluation indices. Depending on the type of output data used (temperature and precipitation), the following indices have been utilized [19].

The Normalized Root Mean Square Error Index (NRMSE) is one of the most commonly used indices for evaluating simulated data in various. This index assigns a lower NRMSE value to any model with high accuracy in simulating data and whose values are closer to observational data.

In 2001, Taylor introduced the Taylor Index, one of the best evaluation indices. Due to its high efficiency and accuracy, the Taylor index was used in this study to evaluate the performance of models in estimating observational data during the baseline period. The advantage of the Taylor index over other evaluation indices is that it simultaneously utilizes evaluation criteria, correlation, standard deviation, and the squared differences of model estimation errors. The final Taylor index is calculated to assess the capability and performance of GCMs in simulating climatic variables as follows.

$$S_{Taylor} = \frac{4(1+R)^k}{(\sigma+\frac{1}{\sigma})^2(1+\mathrm{R}_0)^k} \qquad (1)$$

R_0 is the maximum value of the correlation coefficient, and if $\sigma \rightarrow 1$, then $R \rightarrow R_0$, and the Taylor index will reach its maximum value, meaning that the model's performance is completely identical. Conversely, the Taylor index approaches zero when the standard deviation of one model relative to another or observational data is higher. Taylor has suggested that penalty values should be considered for models with low correlation coefficients when simulating climatic variables (precipitation and temperature).

The TOPSIS multi-criteria decision-making method

Introduced by Hwang and Yoon in 1981, this method is among the most widely employed in multi-criteria decision-making. It prioritizes options based on their similarity to the ideal solution. Essentially, in the TOPSIS approach, the best option is the one closest to the ideal answer (efficient), while the worst is furthest from it (inefficient). This method's significant feature is its ability to simultaneously utilize both quantitative and qualitative criteria.

In this study, evaluation metrics were calculated after generating baseline rainfall and temperature data using 20 different climate models. The TOPSIS method was then applied to rank the performance of these climate models, and the top models were selected. Additionally, a composite state of the outputs from general circulation models was used to minimize uncertainty and offer a reliable range of results.

Given the critical importance of the Karun 4 Dam, this study employed RCP scenarios 4.5 and 8.5, representing pessimistic and medium emission levels, respectively. It assessed their impact on the incoming runoff volume to the dam and future hydropower generation. To extract large-scale climate scenarios and simulate variations from the top-performing GCMs identified in the previous stage, specific equations for temperature and precipitation were used to derive the relative differences.

$$\Delta T_i = (\bar{T}_{GCM,fut_i} - \bar{T}_{GCM,base_i}) \qquad (2)$$

$$\Delta P_i = \left(\frac{\bar{P}_{GCM,fut_i}}{\bar{P}_{GCM,base_i}}\right) \qquad (3)$$

In the above equations, ΔPi and ΔTi represent climate change scenario simulations for precipitation and temperature for a long-term average over 21 years in each month; in other words, the 21-year average of simulated precipitation for the future period (2061-2040) and the 21-year average of simulated precipitation for the baseline period (2005-1984) for each month. The same method was applied to temperature. In the previous stage, appropriately performing climate models were selected, and in this stage, using those models, temperature and precipitation data for both RCP 4.5 and RCP 8.5 scenarios were generated and prepared for input into the Lars model. The Lars model estimates the probability distributions governing the data periods, including wet and dry periods, precipitation, temperature (minimum and maximum), and daily radiation from a semi-empirical distribution [20].

2.2.3. Runoff simulation

The IHACRES rainfall-runoff model

Introduced in 1993 by Jakeman and Hornberger, this is a conceptual model for rainfall-runoff processes. This model consists of two main nonlinear modules: the reduction module and the linear hydrograph module. Figure 3 illustrates the general structure of this model. From the figure, it is clear that during the simulation process, precipitation r_k and temperature t_k are first converted to effective rainfall u_k by the nonlinear module at each time step k, and then in the linear section, the unit hydrograph is transformed into surface runoff at time step k.

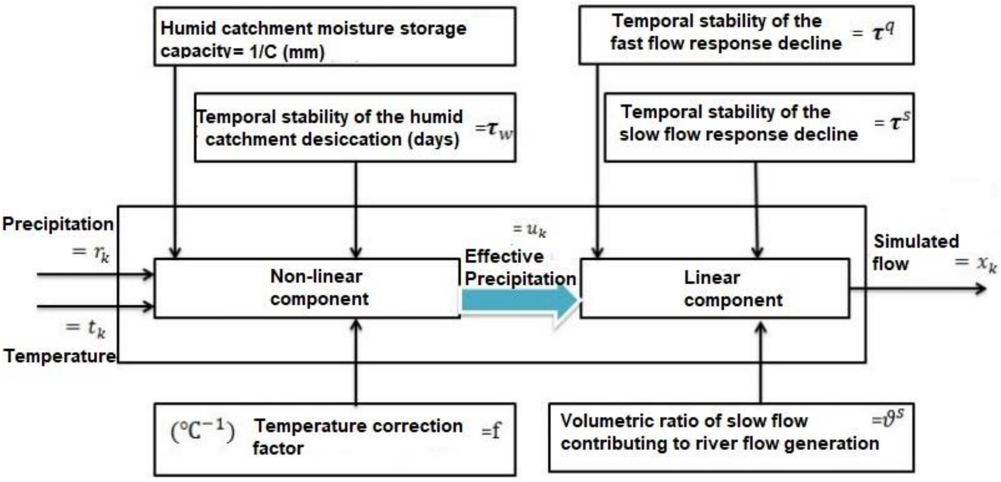

Figure 3. Schematic Representation of the Rainfall-runoff Simulation Process in the IHACRES Model (Sadeghi et al., 2015) [21]

To evaluate the performance of the IHACRES model in simulating the rainfall-runoff process of the Karun 4 dam basin, the model must first be calibrated and then validated. In this study, daily averages of rainfall and temperature data from the basin, along with recorded data from the Dukouheh hydrometric station at the basin outlet, are used to simulate river flow in the basin and assess the model's performance. Various criteria can be used in rainfall-runoff modeling to evaluate model efficiency, but the three most commonly employed criteria used to assess model accuracy are the Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and Nash-Sutcliffe efficiency coefficient. These are further explained in equations 4 to 6.

$$RMSE = \sqrt{\frac{1}{T}\sum_{t=1}^{T}(Q_o^t - Q_m^t)^2} \qquad (4)$$

$$MAE = \frac{1}{T}\sum_{t=1}^{T}|Q_o^t - Q_m^t| \qquad (5)$$

$$NS = 1 - \frac{\sum_{t=1}^{T}(Q_o^t - Q_m^t)^2}{\sum_{t=1}^{T}(Q_o^t - \overline{Q_o})^2} \qquad (6)$$

In the above equations, Q_o^t is the observed flow rate, $Q_m^t$is the estimated flow rate by the model, and t is the time step.

2.2.4. Reservoir Simulation and Optimization

Considering that the goal of this study is to examine the performance of the Karun 4 Dam reservoir in generating hydropower energy under climate change conditions, the performance of the dam's hydropower plant must be simulated and optimized.

After calibrating the precipitation-runoff model using recorded data from the baseline period and generating precipitation and temperature data under various climate scenarios for future periods, the river flow under different climate scenarios is calculated. However, a simulation of the hydropower production is required to estimate the impact of climate change on hydropower generation from the reservoir. Since the main purpose of the Karun 4 Dam is flood control and hydropower production, the power plant's capacity is determined using the following Equation as a function of water flow (Q) and reservoir water level (H) in a concave nonlinear equation.

$$PPW = f(Q,H) \tag{7}$$

The following objective function was used in this study to examine the effects of climate change on the amount of hydropower generated at the plant due to changes in reservoir inflow.

$$F = Min \quad \sum_{t=1}^{T}\left[1-\frac{PW_t}{PW_{max}}\right]^2 \tag{8}$$

In this equation, PW represents the production rate, as given by the equation below.

$$PW_t = Min \quad \left[9.81\times\frac{\gamma\times e\times o_t\times\overline{H_t}}{PF\times 1000}, PW_{max}\right] \tag{9}$$

Next, the average water level is calculated using the following equation.

$$\overline{H_t} = \frac{H_t + H_{t+1}}{2} - TW \tag{10}$$

In the above Equation, PF is the plant efficiency factor, and TW is the tailwater level. The objective function is based on the following continuity equations: overflow volume, evaporation, reservoir volume, and release amount.

$$V_{t+1} = V_t + IN_t - O_t - Spill_t - Ev_t \tag{11}$$

$$Spill_t = \left\{ \begin{matrix} V_{t+1}-V_{max} & V_{t+1}>V \\ 0 & otherwise \end{matrix} \right\} \tag{12}$$

$$Ev_t = Area_t \times H_t \tag{13}$$

$$V_{\min} \le V_t \le V_{\max} \tag{14}$$

$$O_{\min} \le O_t \le O_{\max} \tag{15}$$

2.2.5. Optimization of the Reservoir Plant's Performance Under Climate Change

This section uses an optimization algorithm to evaluate the objective function of Equation 13 and determine its optimal value. Among various optimization algorithms, the Differential Evolution (DE) algorithm has been used for this study. The Differential Evolution algorithm, introduced by Storn and Price in 1996, is a population-based metaheuristic optimization technique. This algorithm is similar to genetic algorithms in terms of its crossover and mutation operators, but it uses the difference of randomly chosen vectors instead. The DE algorithm consists of three main operators: mutation, crossover, and selection.

Furthermore, the DE algorithm uses a multi-strategy classification approach, denoted as DE/x/y/z, where x, y, and z correspond to the mutation vector and the type of crossover operator (either binomial or exponential).

Power Plant Performance Evaluation

To assess how the reservoir optimally allocates the required water in the baseline and future periods under climate change, two indices—reliability and vulnerability—are used and briefly explained below.

The reliability index is defined based on the probability of meeting the water demand in the simulation period using the available water, and it reflects the plant's ability to generate power at its nominal capacity over the long term [22].

$$R_e = \frac{N_{t=1}^{n}(D_t \le R_t)}{n} \quad t = 1,2,\ldots n \tag{16}$$

The vulnerability index is defined as the ratio of demand magnitude during periods of water shortage to the total production and reflects the probability that the plant will not be able to generate power at its nominal capacity.

$$V_u = \frac{\sum_{t=1}^{n}(D_t - R_t | D_t > R_t)}{\sum_{i=1}^{n} D_t} \quad t = 1,2,\ldots n \qquad (17)$$

3. Results and Discussion

3.1 GCM Performance Evaluation

To evaluate and select models of the Karun 4 Dam watershed with better performance in simulating climate variations with higher confidence during the baseline period (1984-2005), daily temperature and precipitation data from various General Circulation Models (GCMs) were compared with observed data averaged using the Thiessen method. The results of this comparison are shown in Table 3 using the NRMSE and S-Tylor indices.

Table 3. Evaluation Index Values for GCMs

		NRMSE		S-Tylor	
	GCM	P	T	P	T
1	GFDL-ESM2M	0.59	0.10	0.45	0.88
2	inmcm4	0.75	0.10	0.39	0.88
3	ACCESS1-0	0.71	0.09	0.43	0.90
4	bcc-csm1-1	0.70	0.09	0.40	0.89
5	BNU-ESM	0.67	0.09	0.39	0.89
6	CSIRO-Mk3-6-0	0.58	0.07	0.48	0.89
7	GFDL-CM3	0.67	0.10	0.37	0.88
8	GFDL-ESM2G	0.69	0.10	0.42	0.88
9	IPSL-CM5A-LR	0.71	0.10	0.28	0.83
10	IPSL-CM5A-MR	0.70	0.10	0.31	0.84
11	MIROC5	0.64	0.09	0.42	0.88
12	CanESM2	0.59	0.08	0.45	0.89
13	CCSM4	0.69	0.10	0.38	0.89
14	CESM1-BGC	0.69	0.09	0.35	0.88
15	CNRM-CM5	0.67	0.09	0.38	0.90
16	MPI-ESM-MR	0.63	0.08	0.42	0.90
17	MRI-CGCM3	0.66	0.14	0.40	0.88
18	NorESM1-M	0.64	0.10	0.42	0.88
19	MIROC-ESM	0.62	0.07	0.44	0.90
20	MPI-ESM-LR	0.75	0.08	0.42	0.89

The evaluation of the performance of GCMs using the TOPSIS method showed that the CSIRO-Mk3-6-0 and CanESM2 FIJ models performed the best in simulating climatic parameters. Based on all criteria, five models, including CSIRO-Mk3-6-0, CanESM2, GFDL-ESM2M, MIROC-ESM, and MPI-ESM-MR, were selected and used in this study. Figures 4 and 5 show the simulated temperature and precipitation changes under both RCP scenarios.

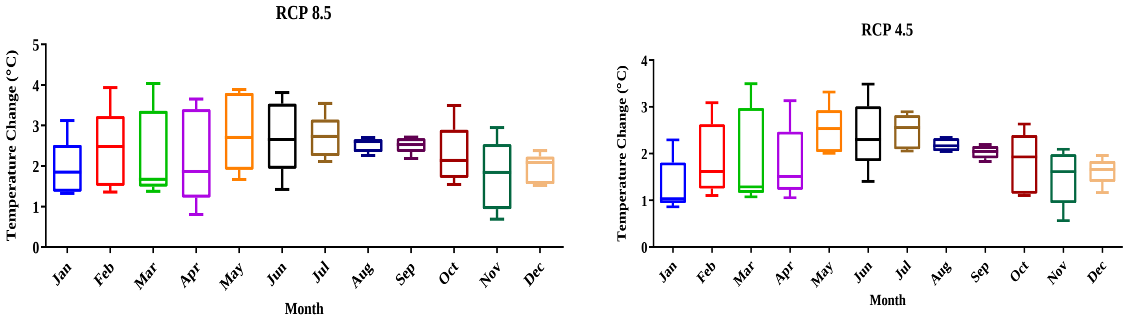

Figure 4. Boxplot Chart of the Average Increase in Expected Temperature using the Selected Five GCMs under RCP 4.5 and RCP 8.5 Scenarios

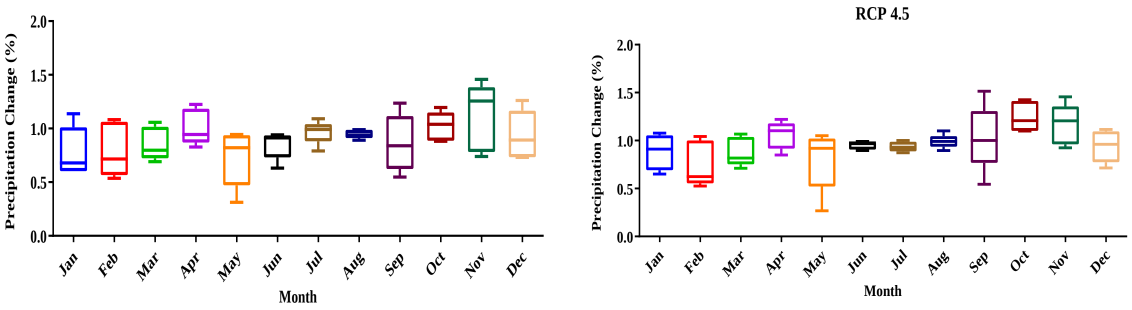

Figure 5. Boxplot Chart of the Average Expected Rainfall Changes using the Selected Five GCMs under RCP 4.5 and RCP 8.5 Scenarios

To reduce the existing uncertainty and increase confidence in the results, each of the five selected GCMs was weighted based on the method described in the previous section. The model whose simulated temperature and precipitation changes were closer to the observed changes during the baseline period at the watershed level was given a higher weight for that month. Based on the results from downscaled climate scenarios generated by the LARS model and the output of the GCMs (Table 4), the expected increase in annual average temperature is 1.95°C under RCP 4.5 and 2.34°C under RCP 8.5 at the Karun 4 Dam watershed. Regarding precipitation, a decrease of 3.52% is expected under RCP 4.5 and a 7.62% decrease under RCP 8.5 at the watershed.

Table 4. Results from Examining Seasonal and Annual Simulated Temperature and Rainfall Changes during the Future Period under Climate Change Influence

Season	**Simulated temperature changes (degrees Celsius)**		**Simulated rainfall changes (percentage)**	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Winter	1.99	2.26	1.34	-5.96
Spring	2.25	2.65	-7.5	-13.01
Summer	2.09	2.52	0	0
Fall	1.45	2.02	-6.45	-15.71
Annual	1.95	2.34	-3.52	-7.62

3.2 Results on Changes in Inflow Runoff Volume to the Reservoir Under Climate Change

To understand the changes in inflow runoff volume to the Karun 4 reservoir due to climate change, it is essential to evaluate the precipitation-runoff model's ability to simulate hydrological processes at the watershed level. The IHACRES model was employed for this purpose, with calibration and validation periods chosen to reflect both drought and wet conditions. The calibration period spanned from 1984 to 1998, while the validation period covered 1999 to 2005. The model demonstrated satisfactory performance in estimating the monthly runoff volume for the Karun 4 watershed, as illustrated in Figure 6.

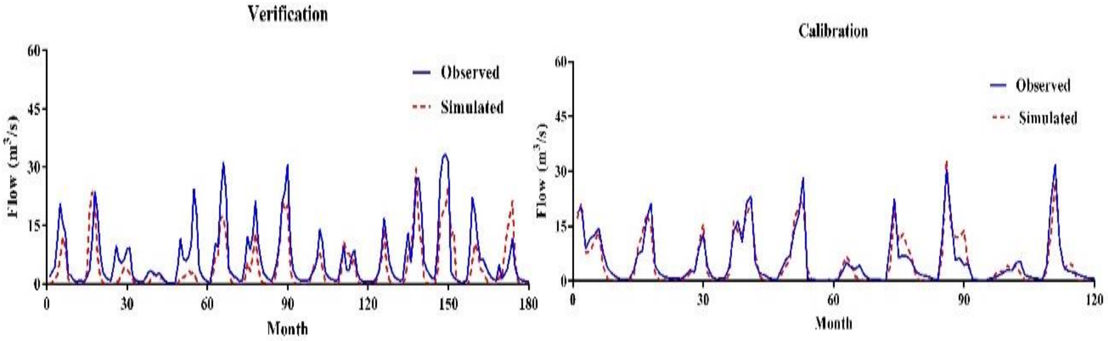

Figure 6. Evaluation of the IHACRES Model Performance in Simulating the Rainfall-runoff Process

The R2 value in the calibration period was 0.75 with RMSE = 80; in the validation period, R2 was 0.78 with RMSE = 40.

After confirming that IHACRES accurately simulates the precipitation-runoff process, the next step is to assess how changes in temperature and precipitation will impact the runoff volume entering the Karun-4 reservoir in the future, which is crucial for evaluating turbine performance. The simulated time series data of temperature and precipitation were used to model the runoff from the upper catchment of Karun-4 Dam. Considering the previous findings, which indicate an increase in temperature and a decrease in precipitation, it is predicted that the runoff volume entering the reservoir will decrease in the future compared to the baseline period. As illustrated in Figure 7, the total runoff volume is expected to decline under both scenarios. The projections indicate a 28% reduction in runoff volume under the RCP 4.5 scenario and a 43% reduction under the RCP 8.5 scenario.

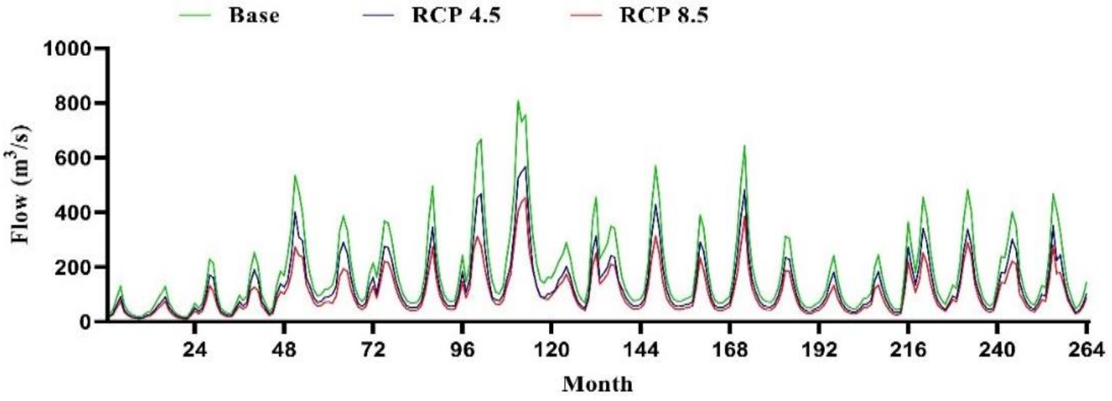

Figure.7 Comparison of the Baseline and Future Periods' Monthly Average Runoff Volume Entering the Reservoir under the Influence of Climate Change

Based on these results, the reduction in the volume of runoff entering the reservoir (outflow from the catchment) due to the increase in temperature and the decrease in precipitation will impact the performance of the reservoir as well as hydroelectric power generation in the future period.

3.3 Results of the Study on the Effects of Climate Change on the Performance of the Karun-4 Dam Reservoir and Hydroelectric Power Plant in Energy Production

After reviewing the long-term average changes in key climatic parameters (temperature and precipitation) at the catchment scale, as well as the volume of runoff entering the Karun-4 Dam reservoir—considered the most significant factor influencing the performance and amount of hydroelectric power production—the simulation of hydroelectric energy production has been conducted based on the results presented in the previous sections. Table 5 provides the specifications of the Karun-4 Dam turbine.

Table 5. Karun 4 Dam Power Plant Specifications

Specification	Number/Unit	Specification	Number/Unit
Turbine	4	Number and type of generators	4 synchronous generators
Turbine power	255 megawatts	Output power of each generator	263 megavolt-amperes
Nominal discharge	95.7	Nominal voltage of each generator	15.75 kilovolts
Design head	161.5 meters	Generator rotation speed	187.5 revolutions per minute
Nominal water outlet from turbine	171 cubic meters per second	Nominal generator current	12,500 amperes
Transformer	12 primary units / 1 reserve	Primary nominal voltage	15.75 kilovolts
Nominal power of each transformer	100 megavolt-amperes	Secondary nominal transformer voltage	410 kilovolts

Based on the results presented in Table 6 and the previous sections' findings, hydroelectric energy production is expected to decrease by 9% compared to the baseline under the RCP 4.5 scenario in the future period. Considering the assumptions of the RCP 8.5 scenario and the results from its application in the previous sections, the total reduction in power production at the Karun-4 Dam power plant in the future period is predicted to be 18%. Accordingly, the system's reliability is expected to decrease by 30% under the RCP 4.5 scenario and by 56% under the RCP 8.5 scenario in the future period compared to the baseline period. The table below presents the energy production, as well as the system reliability and vulnerability values for the Karun-4 Dam power plant in both the baseline and future periods under the stated climate change conditions. Figure 8 shows the monthly changes in electricity production under baseline conditions and considering climate change scenarios.

Table 6. Comparison of Electricity Production and Evaluation Criteria for the Karun 4Dam Turbine System during the Baseline and Future Periods under Climate Change Influence

	SumPower	Reliability	Vulnerability
Base	220549.53	49.62	0.16
RCP 4.5	200659.21	34.47	0.23
RCP 8.5	179049.60	21.59	0.32

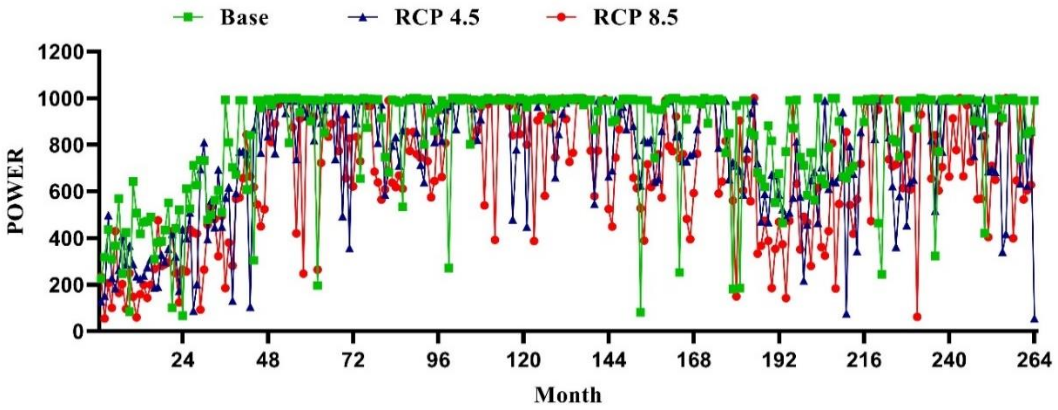

Figure 8. Comparison of the Total Average Monthly Energy Production during the Baseline and Future Periods under Climate Change Influence

4. Conclusion and Recommendation

Based on the results of this study, it is expected that, there will be an increase in temperature and a decrease in precipitation in the upstream catchment of Karun-4 in the future periods compared to the baseline period. Specifically, the annual average temperature is projected to increase by 1.95°C under the RCP 4.5 scenario and 2.34°C under the RCP 8.5 scenario. Additionally, annual precipitation is expected to decrease by 3.52% under the RCP 4.5 scenario and 7.62% under the RCP 8.5 scenario in the Karun-4 catchment area.

According to the results of this study, the volume of runoff exiting the catchment and entering the reservoirs, influenced by the effects of climate change on temperature and precipitation (two key factors affecting the precipitation-runoff process), is expected to decrease by an average of 19% under the RCP 4.5 scenario and by 43% under the RCP 8.5 scenario.

Given these results, assuming such a decrease in the average runoff volume entering the Karun-4 reservoir, the performance of this strategic reservoir will face significant challenges. It is certain that, in addition to the reduced reliability of the system's performance at the Karun-4 Dam, there will be an increase in the vulnerability of the dam's power plant in the future periods. The findings of this study indicate that the reduction in the volume of runoff entering the reservoir and changes in the seasonality of runoff can impact the operation and management of the reservoir and should be carefully considered by the operators.

Given this power plant's significance and strategic position in supplying a portion of the country's electricity, the reduction in total electricity production from the Karun-4 power plant is another important study result. Specifically, a reduction in the power plant's energy production of approximately 9% under the RCP 4.5 scenario and about 18% under the RCP 8.5 scenario should not be unexpected.

Additionally, it is suggested that in future studies, more detailed flowcharts are presented to show the correlation between parameters and climate changes so that deeper analyses can be achieved. The authors finish their paper on a positive note by talking about the benefits of their work and possible future work. With this limited study, it is not known whether this finding can be applied to all clinical scenarios. Notwithstanding these limitations, this study has proven that Ultrasound can potentially serve as a more efficient alternative to X-rays in diagnosis. Future directions include studying the effects of different ultrasound pulsing schemes on pain relief. Another interesting direction would be to consider applications in nonhuman primates.

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