The Effect of Climate Change on the Failure of Reservoir Operations to Supply Irrigation Water

The Case Study of Pandanduri Dam, West Nusa Tenggara, Indonesia

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ABSTRACT

Climate change is a natural phenomenon characterized by rapid changes in climatic elements. One impact of climate change is a long-term reduction in reservoir water volume. The research method includes climate change modeling with statistical tools and assessing reservoir operational performance based on the reservoir water balance concept, using indicators of reliability and failure to meet irrigation water needs. The data used in the modeling include reservoir capacity, irrigation service area, rainfall, climate, reservoir water level, and river baseflow. The analysis shows that climate change has affected the Pandanduri dam from 1994 to 2023. The main impact is a significant reduction in reservoir water volume, especially during both regular and dry seasons. During the dry season, the reservoir's water level nearly reaches its dead storage capacity of around 4 million m³. The reservoir's failure to supply enough water for irrigation during the October planting season ranged from 4.2% to 33.3%. The failure rates during the November planting season ranged from 4.2% to 34.1%, while those in December ranged from 4.2% to 35.8%. The 0% failure rate was observed exclusively during the rainy month, which lasted only three months, during which the reservoir water volume reached its standard capacity.

Keywords-climate change; reservoir operations; dams; failures; reliability

I. INTRODUCTION

The growth of industrialization across various sectors has driven job creation, economic development, and improved living standards. The Pandanduri Dam in East Lombok Regency, West Nusa Tenggara Province, Indonesia, is a crucial water resource infrastructure that supplies water to 5.168 hectares of irrigated land. However, in recent years, the dam's operational patterns have encountered serious challenges because of the impacts of climate change. Climate change has caused shifts in rainfall patterns, more frequent droughts, and reduced river flow into the Pandanduri Dam. These conditions have caused a decrease in reservoir volume, with the reservoir approaching near-dead capacity at times. These issues have failed to satisfy irrigation water needs, especially during the second planting season, a crucial period for agricultural productivity. Meanwhile, climate change has emerged as a significant threat to the utilization of natural resources [1].

The phenomenon of climate change has a significant impact, especially on the availability of water resources. Climate change has led to a notable increase in evaporation, significantly affecting local water pressure, particularly in arid and semi-arid areas. This has reduced the need for irrigation water [2]. A study showed that over the last 100 years, average annual temperatures rose by 0.72–3.92°C, while precipitation decreased by 2–3% [3]. The rise in average global temperatures since the mid-20th century is likely due to higher levels of greenhouse gases resulting from human activities. Using the linear regression method, a slight increase in the rain rate distribution at the 0.01% annual probability was observed across all regions, indicating a climate change effect on the distribution [4]. One indication of climate change is a shift in rainfall patterns driven by climate anomalies, such as tropical cyclones and El Niño and La Niña events. Generally, climate change causes a shorter rainy season and a longer dry season. The frequency of rainy days generally declines, whereas the highest daily rainfall and rainfall intensity tend to rise [5]. Various methods can be employed to predict climate change, particularly drought, which is often represented by index numbers [6] and by a drought index based on reservoir volume changes.

Furthermore, regional climate change can also be detected through changes in reservoir storage volume [7-8]. In most research on the impacts of climate change, General Circulation Models (GCMs) have served as the primary tools for global and regional climate simulations [9]. The second-generation Canadian Earth System Model (CanESM2) was used in Indonesia to analyze the annual frequency of daily rainfall under current and future climate conditions [10]. In predicting changes in climate parameters using the CanESM2 model in the Lar Dam Basin, the simulation results and observational data showed a strong relationship, with a correlation of 0.91 and an RMSE of 2.25 [11].

Dam infrastructure can store large amounts of reservoir water during the rainy season, which helps reduce flooding and supports flood management efforts downstream of the dam. Climate change has significantly reduced water availability in a series of reservoirs. As in the Monte Novo reservoir, the exceptionally high water demand has led to severe water scarcity [12]. Water storage in reservoirs can sustain the primary flow during dry seasons, thereby lessening drought impacts. Various strategies are used to meet water demands amid climate change. Given declining water supplies, the operational pattern implemented involves selecting the best alternative to meet water needs, particularly for irrigation [13]. The reservoir operation pattern model focuses on managing water use based on reservoir water availability and on distributing released water to meet irrigation needs [14]. Effective water management in reservoirs during climate change, especially during droughts, is vital to avoid dam damage. This involves regulating water releases mainly to keep reservoir water levels at capacity [15]. Reservoir operating patterns can be optimized using simulation and optimization methods to achieve optimal results [16].

Climatological disasters driven by climate change affect all sectors, including irrigation, necessitating dynamic water resource modeling that accounts for temporal changes. Reservoir water availability can help mitigate drought in river basins. By mitigating the decline of reservoir water levels driven by climate change, various water management efforts aimed at meeting demand can reduce associated impacts [17]. The effect of hydropower on a dam influences seasonal changes: during the rainy season, water availability decreases, while water demand increases during the dry season [18]. Because the hydrological system is changing rapidly, availability and demand are shifting rapidly as well. Climate change requires modeling reservoir operation patterns that account for these impacts [19].

II. METHODOLOGY

A. *Study Area*

The Pandanduri Reservoir is located in Sakra District, East Lombok Regency, West Nusa Tenggara Province. Geographically, it is positioned at coordinates 8° 42' 10" South Latitude and 116° 26' 1.27" East Longitude. The inflow to the reservoir is derived from the Palung River, which encompasses a watershed area of 64.51 km².

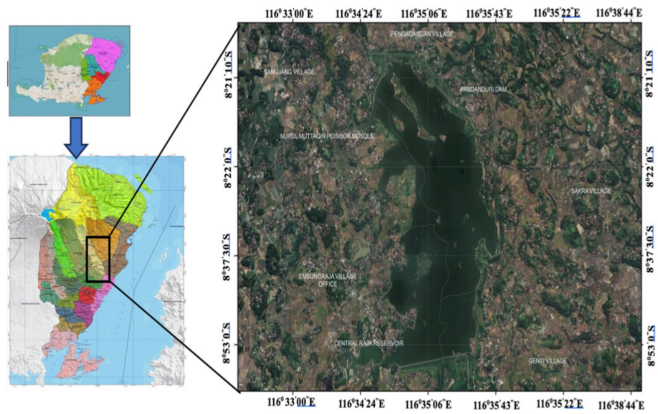

Fig. 1. Map of the study area (source: Nusa Tenggara I river basin center, West Nusa Tenggara province).

Fig. 2. Pandanduri dam.

B. *Research Data and Methods*

The data used in the analysis are secondary data collected from several agencies, including the Nusa Tenggara 1 River Basin Center, the Meteorology and Geophysics Agency of West Nusa Tenggara Province, and the Public Works Department of East Lombok Regency. The data collected include: Dam technical data; 30-year rainfall data from 4 stations (Pandanduri, Sepit, Prian, Geres Daya); 30-year dam water-level data; Irrigation area data; 30-year climatological data from 2 stations (Sambelia and Keruak); 30-year river water-level data; and reservoir catchment area. The stages of research are outlined as follows:

1) Data Collection Stage

Secondary data was gathered from relevant agencies, specifically the Nusa Tenggara I River Basin Office. This included data on Pandanduri Reservoir characteristics, climate data, rainfall records, historical inflow data, and the Pandanduri Reservoir operation manual.

2) Climate Change

Climate change analysis using climatological data from four stations on Lombok Island: Kediri, Sopak, Sambelia, and Kopang.

3) Reservoir Water Availability

Analysis of reservoir water availability based on inflow data to the Pandanduri Reservoir and available capacity.

4) Evapotranspiration

Evapotranspiration calculations use the Penman-Monteith method to determine the evapotranspiration rate, which helps assess irrigation water needs and reservoir evaporation. The data utilized include temperature, humidity, solar radiation, and wind speed from climatological sources.

5) Irrigation Water Requirements

Irrigation water requirements for rice and secondary crops are calculated based on the crop type, irrigated area, planting schedule, evapotranspiration, evaporation, percolation, and rainfall, with 80% considered for rice and 50% for secondary crops. The cropping pattern is rice–rice–secondary crops. Several alternative planting schedules are employed, including October, November, and December. The secondary crops are corn and tobacco.

6) Climate Change Analysis

The Mann-Kendall test, a nonparametric method commonly used to detect trends in time series data [20], was employed. The hypotheses of the test are defined as follows: the null hypothesis (H_0) states that the data exhibit no monotonic trend (S = 0), whereas the alternative hypothesis (H_1) states that a monotonic trend exists (S ≠ 0). Consider a time series $x_1, x_2, \dots, x_n$, where n represents the number of observations, and x_i and x_j are data values at times i and j, respectively. The Mann–Kendall test statistic S is computed as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sign}(x_j - x_i) \quad (1)$$

with:

$$sign\left(x_i - x_j\right) = \begin{cases} +1, \text{ if } x_j - x_i > 0 \\ 0, \ if \ x_j - x_i = 0 \\ -1, \ if \ x_j - x_i < 0 \end{cases} \quad (2)$$

$$Z = \begin{cases} \frac{S-1}{\sigma_s}, \ if \ S > 0 \\ 0, \ if \ S = 0 \\ \frac{S+1}{\sigma_s}, \ if \ S < 0 \end{cases} \quad (3)$$

If $S > 0$, there is an upward trend; if $S < 0$, there is a downward trend. If $S = 0$, there is no trend. Next, the variance value of S is calculated using:

$$\sigma_S^2 = \frac{1}{18}\left(n(n+1)(2n+5)\right) \quad (4)$$

The hypotheses used in this test are H_0, which indicates that there is no trend, and H_1, which suggests that a trend exists. The null hypothesis (H_0) is rejected if $|Z| > Z_{\alpha/2}$, where $F_N(Z_{\alpha/2}) = \alpha/2$, F_N is the standard normal cumulative distribution function, and α is the significance level.

7) Monthly Temperature Increasing Trend

Linear regression is commonly used to model the relationship between two variables by fitting a least-squares linear equation to the observed data. One variable is considered the independent variable (X), and the other is the dependent variable (Y). The functional relationship between the two variables can be expressed as:

$$Y = a + bx + e \quad (5)$$

where: Y is the dependent variable, a is the intercept, b is the slope of the regression line, and ε represents the random error term.

The parameters a and b are estimated using the following formulas:

$$a = \frac{\sum Y - b \sum X}{N} \quad (6)$$

$$b = \frac{N \sum XY - (\sum X)(\sum Y)}{N \sum X^2 - (\sum X)^2} \quad (7)$$

where: N is the number of observations, $\sum X$ and $\sum Y$ are the sums of the observed values, and $\sum XY$ and $\sum X^2$ are the sums of the cross-products and squared independent variable values, respectively.

With a constant term, the regression intercept represents the point where the regression line crosses the *Y*-axis, while *b* is the regression coefficient, indicating the magnitude and direction of the influence of *X* on *Y*. It represents the slope of the regression line. Simple correlation analysis is used to measure the strength and direction of the relationship between two variables. The correlation coefficient (*r*) is calculated using the following formula:

$$r = \frac{N \sum XY - (\sum X)(\sum Y)}{\sqrt{(N \sum X^2 - (\sum X)^2)(N \sum Y^2 - (\sum Y)^2)}} \quad (8)$$

8) Optimization of Reservoir Release Settings

The reservoir optimization methodology is implemented by identifying decision variables that satisfy the constraints for the maximization of the objective function [21]. The stages in reservoir optimization calculations start with identifying the constraints that must be met and implementing them through equations before finding the optimal conditions. Reservoir operation optimization is conducted using inflow scenarios for wet, normal, and dry years. The effectiveness of optimizing irrigation water, groundwater, and raw water release settings is evidenced by the k-factor value for each requirement [22]. To meet irrigation water needs, in addition to dams, water must come from various sources, including underground water and supplies from different river basins [23]. The success of irrigation water release is indicated by the minimum k-factor of 0.70. The minimum k-factor for raw water release is 0.85 [24].

The following presents the optimization formula for reservoir water release management. Decision variables are the parameters whose values are determined to achieve optimal results. In this model: M_a is the initial water level of the Pandanduri Reservoir (m), R_{it} is the actual release of irrigation water in the Pandanduri irrigation area during period *t* (mcm), and A_i is the irrigated area served by the Pandanduri Reservoir during the planting season (ha).

The objective function of the optimization model is to maximize the cropping intensity. It is formulated as follows:

$$MaxZ = \frac{AT_1+AT_2+AT_3}{A} \times 100\% \quad (9)$$

where: Z= objective function, expressed as annual cropping intensity (%), AT= planted area of irrigated crops per planting season (ha), A= total irrigated area (ha).

The constraint function limits the optimization of reservoir water release management. The following constraints are considered in this optimization. The planting areas during the first, second, and third planting seasons cannot exceed the standard irrigated area of the Pandanduri River Basin, which is 8,552 hectares. This constraint is expressed as follows:

$$A_i \leq A_I \quad (10)$$

where: A_i= planting irrigated area of the Pandanduri Reservoir during the *i*-th planting season (ha), I= planting season (I, II, or III), A_I= total irrigated area of the Pandanduri Reservoir (ha).

The following constraint ensures that the actual release of irrigation water from the reservoir during each period does not fall below the required minimum release level:

$$RI_t \geq RI_{min,t} \quad (11)$$

where: RI_t is the actual release of irrigation water from the Pandanduri Reservoir during period *t* (mcm), and $RI_{min,t}$ is the minimum irrigation water release required for period *t* (mcm).

Similarly, the release of raw water from the reservoir must also meet a minimum requirement, expressed as:

$$RB_t \geq RB_{min,t} \quad (12)$$

where: RB_t is the actual release of raw water from the Pandanduri Reservoir during period *t* (mcm), and $RB_{min,t}$ is the minimum raw water release required for period *t* (mcm).

Another constraint ensures that the ratio between the actual and target releases of irrigation and raw water (defined as factor *k*) meets the specified minimum values. These constraints are formulated as:

$$k_t = \frac{RI_t}{TI_t} \geq 0.70 \quad (13)$$

$$k_t = \frac{RB_t}{TB_t} \geq 0.85 \quad (14)$$

where k_t represents the fulfillment factor for irrigation and raw water requirements during the middle of month *t*. RI_t denotes the actual release of irrigation water for period *t* (mcm), TI_t is the target release of irrigation water for the same period (mcm), RB_t refers to the actual release of raw water for period *t* (mcm), and TB_t is the corresponding target release of raw water (mcm).

9) Reservoir Water Balance

The simulation of the water balance in a reservoir is a function of the input, output, and reservoir capacity, which can be expressed as:

$$I - O = \frac{dS}{dt} \quad (15)$$

where: I is the reservoir inflow, O is the reservoir outflow, and $\frac{dS}{dt}$ represents the rate of change in reservoir storage over time.

In a more detailed form, the water balance can be expressed as:

$$S_{\{t+1\}} = S_t + I_t + R_t - E_t - L_t - O_t - O_s \quad (16)$$

where: S_{t+1} is the reservoir storage during period $t+1$(m³), S_t is the reservoir storage during period t(m³), I_t is the reservoir inflow during period t(m³), R_t is the rainfall over the reservoir during period t(m³), E_t is the evaporative loss during period t(m³), L_t is the seepage loss during period t(m³), O_t is the total water released for operational demand (m³), and O_s is the water released through the spillway (m³).

10) Reservoir Failure and Reliability

Based on reservoir storage simulations, the probability of failure and the reservoir's reliability can be determined. According to [25], the probability of failure (P_e) is defined as the ratio of the number of time periods during which the reservoir fails to meet demand (i.e., becomes empty) to the total number of time periods in the analysis, expressed as a percentage:

$$P_e = \frac{P}{N}\, x\, 100\% \quad (17)$$

Reservoir reliability (R_e) is defined as the percentage of time the reservoir meets the planned water demand during its operational period [25]. In practice, no reservoir achieves 100% reliability. Reliability and failure probability are related through the following relationship:

$$R_e = 100 - P_e \quad (18)$$

where: P_e is the probability of failure (%), P is the number of time periods when the reservoir fails or becomes empty, N is the total number of time periods considered in the analysis, and R_e is the reliability of the reservoir (%).

III. RESULTS AND DISCUSSION

A. Climate Change Analysis with the Mann-Kendall Test

To assess data trends, the nonparametric Mann–Kendall test was used to determine whether the data exhibit a statistically significant increasing or decreasing trend. The analysis was conducted using climatological data from the Kediri Station. Two hypotheses were formulated: the null hypothesis (H_0) states that Z follows a normal distribution (no trend). In contrast, the alternative hypothesis (H_1) states that Z does not follow a normal distribution (there is a trend). The significance level (α) was set at 0.05, with the acceptance region defined as $-Z_{\alpha/2} < Z < Z_{\alpha/2}$, or numerically, $-1.96 < Z < 1.96$. The null hypothesis is rejected if $| Z |> Z_{\alpha/2}$. To calculate the $Z - value$, a relative rank is assigned to each temperature observation based on its position within the dataset, where P represents the number of rank values greater than the self-ranking value and M represents the number of rank values smaller than the self-ranking value.

TABLE I. MANN-KENDALL RESULTS OF TEMPERATURE DATA FROM KEDIRI AND SOPAK CLIMATOLOGY STATIONS

Climatology stations	Critical values	Value Z	Value |Z|	Result
Sambelia	1.96	4.64	4.64	Significant
Keruak	1.96	6.26	6.26	Significant

According to the Mann-Kendall test shown in Table I, the critical value of 1.96 and the Z-values of 4.64 for Kediri and 6.26 for Sopak indicate that the results are significant. This suggests that climate change took place from 1994 to 2023. To assess its effect on rainfall intensity, a multiple linear regression analysis was performed using SPSS V.25.0. The climate change review was divided into three periods: period I (1994-2003), period II (2004-2013), and period III (2014-2023). From these three periods, multiple linear regression coefficients will be derived from each climatological dataset on rainfall intensity. The analysis reveals changes in climatological parameters from period I to period II and from period II to period III, as shown in Table II.

TABLE II. RATE OF CHANGE OF CLIMATOLOGICAL PARAMETERS

Climatological variables	Period I to II (%)	Period II to III (%)
Temperature	55.6	78.2
Air humidity	45.7	76.5
Wind speed	21.7	52.6
Solar illumination	40.2	15.3

Table II shows a significant increase in temperature from Period I to Period II of 55.6%, and an even sharper rise from Period II to Period III of 78.2%. This increase signifies a consistent warming trend, one of the primary indicators of climate change. Elevated air temperatures directly influence increased evapotranspiration, drought conditions, altered precipitation patterns, and disruption of the hydrological cycle. Air humidity parameters increased by 45.7% from period I to period II and rose to 76.5% from period II to III. This humidity probably responds to rising temperatures, which boost water evaporation from the surface. While high humidity can lower drought risk, it may also lead to more extreme and uneven rainfall. Meanwhile, wind speed increased by 21.7% from period I to II, then by 52.6% from period II to III. This phenomenon can lead to more frequent storms and affect the distribution of water vapor and atmospheric pressure systems that greatly determine weather patterns. Solar radiation shows distinct fluctuations. It rose by 40.2% from period I to II but then fell to 15.3% from period II to III. This drop in solar radiation can impact photosynthesis, plant productivity, and local surface temperatures.

B. Changes in the Start of the Rainy Season

Climate change has caused shifts in the start of the rainy season. In East Lombok Regency, rainfall has primarily been observed in September over the past 30 years (1994-2023), with decreases in October and November. Analysis indicates that the rainy season began earlier in 1996, 1998, 1999, 2001, 2003, 2005, 2008, 2009, 2010, 2016, 2021, and 2022. Delays in the start occurred in 1994, 1997, 2002, 2006, 2003, 2004, 2005, 2018, 2019, and 2023. Figure 3 shows that over 30 years of rainfall data around the Pandanduri dam, the initial rainfall frequency was 10 times in September and 9 times in October and November.

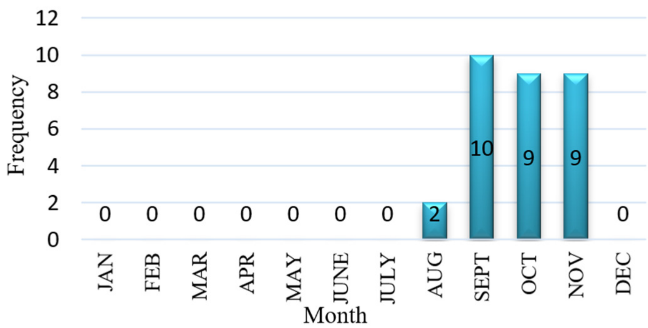

Fig. 3. Average frequency of the start of the rainy season.

C. Rainfall Depth Analysis

Climate change significantly influences rainfall patterns. An analysis of rainfall data from several stations in the Pandanduri Dam catchment area during the period 1994–2023 reveals a clear trend of increasing average daily rainfall depth. As shown in Table III, the pattern of change indicates an increase in average daily rainfall during the first period (1994–2003), a decrease during the second period (2004–2013), and a significant rise during the third period (2014–2023), demonstrating the substantial impact of climate change on rainfall variability in the region.

TABLE III. AVERAGE DAILY RAINFALL FOR EACH PERIOD

Period 1		Period 2		Period 3	
Year	Average Rainfall (mm)	Year	Average Rainfall (mm)	Year	Average Rainfall (mm)
1994	23.96	2004	45.28	2014	33.72
1995	36.85	2005	38.64	2015	63.77
1996	47.36	2006	40.96	2016	55.22
1997	27.04	2007	35.74	2017	65.29
1998	26.91	2008	25.66	2018	51.36
1999	50.43	2009	79.53	2019	53.40
2000	48.38	2010	19.05	2020	50.21
2001	36.16	2011	37.18	2021	53.22
2002	42.85	2012	29.61	2022	55.10
2003	47.52	2013	43.10	2023	60.45

D. Dependable Flow

The Pandanduri dam reservoir's inflow varies greatly between rainy and dry seasons (Figure 4). During drought periods, inflow mainly depends on the river, which greatly limits its ability to fill the reservoir for irrigation. The discharge reliability analysis employed the basic month method, with reliability thresholds set at 35% for wet years, 50% for normal years, and 65% for dry years.

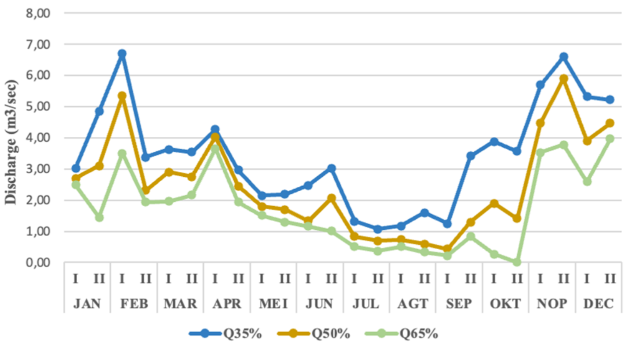

Fig. 4. Dependable flow of the Pandanduri dam.

E. Irrigation Water Requirements

An analysis of irrigation water requirements is conducted semi-monthly to ensure optimal water availability at each stage of plant growth. The technical irrigation area of the Pandanduri dam encompasses 8,552 hectares, with an average irrigation water requirement ranging from 1.5 to 1.97 liters per second per hectare. Due to climate change, the planting season is divided into three periods: October, November, and December. In October, demand for irrigation water tends to be relatively high, coinciding with the initial stage of plant development, requiring a substantial water supply from the Pandanduri reservoir. Meanwhile, under normal conditions, the demand for irrigation water in December, which comes from reservoirs, drops because it coincides with the rainy season. Water demand values serve as the foundation for controlling reservoir operations, including setting daily, weekly, and monthly water releases, especially during the growing season. Climate change leads to fluctuations in water availability due to changes in rainfall and temperature patterns, which are key considerations in adjusting dam operations. Tables IV, V, and VI. The following is a calculation of irrigation water requirements for each growing season.

F. Reservoir Operation Simulation

Reservoir operation simulations are performed to assess the reliability and potential failure of the reservoir's operating system in fulfilling water demand. In this study, reservoir operation was simulated every 15 days across various scenarios with planting seasons starting in October, November, and December. These different planting patterns were analyzed to determine the most sustainable configuration, which is characterized by the highest reliability and the lowest probability of water supply failure. The analysis of reservoir operation failure and reliability was conducted using Equations (16) and (17). The operation model considered three seasonal conditions: normal, wet, and dry. Results for the October planting season show that reservoir operation is sensitive to climate variability. Optimal performance occurs only at the start of the wet season. Conversely, during regular and dry seasons, reliability drops and the risk of failure increases, as shown in Figure 5 and Table VII.

TABLE IV. IRRIGATION WATER REQUIREMENTS FOR THE PANDANDURI DAM (OCT I & II)

No	Month	Period	Day	Water requirements (m^3) Oct I	Water requirements (m^3) Oct II
1	JAN	I	15	7.813.586	7.882.620
2		II	16	-	6.989.121
3	FEB	I	14	-	-
4		II	14	7.448.029	-
5	MAR	I	15	7.364.578	7.364.578
6		II	16	7.653.287	7.654.790
7	APR	I	15	7.419.956	7.397.829
8		II	15	7.642.665	7.660.175
9	MEI	I	15	7.710.668	7.729.104
10		II	16	7.931.886	7.979.068
11	JUN	I	15	6.771.167	7.921.301
12		II	15	6.570.272	6.784.072
13	JUL	I	15	6.147.577	6.439.045
14		II	16	6.836.229	6.240.343
15	AGU	I	15	7.277.312	6.405.181
16		II	16	7.363.762	6.557.603
17	SEP	I	15	7.555.208	6.693.591
18		II	15	6.292.545	6.495.679
19	OCT	I	15	9.517.250	-
20		II	16	9.774.641	9.774.670
21	NOV	I	15	8.410.264	8.410.264
22		II	15	8.309.688	8.158.938
23	DEC	I	15	7.883.278	7.914.727
24		II	16	8.219.667	8.252.733

TABLE V. IRRIGATION WATER REQUIREMENTS FOR THE PANDANDURI DAM PERIOD NOVEMBER I AND NOVEMBER II

No	Month	Period	Day	Water requirements (m^3) Nov I	Water requirements (m^3) Nov II
1	JAN	I	15	7.354.954	8.033.480
2		II	16	7.052.729	6.936.176
3	FEB	I	14	6.895.841	7.591.276
4		II	14	6.350.320	8.171.844
5	MAR	I	15	-	6.133.998
6		II	16	7.334.348	-
7	APR	I	15	7.131.265	7.436.148
8		II	15	7.321.408	7.638.048
9	MEI	I	15	7.516.828	7.725.654
10		II	16	7.708.040	8.000.508
11	JUN	I	15	7.686.656	8.176.688
12		II	15	7.444.526	7.942.468
13	JUL	I	15	6.649.518	7.950.337
14		II	16	6.526.080	6.852.779
15	AGU	I	15	6.626.777	6.650.118
16		II	16	6.806.463	6.266.091
17	SEP	I	15	7.252.716	6.507.604
18		II	15	7.029.965	6.510.285
19	OCT	I	15	6.848.680	6.432.287
20		II	16	-	6.071.845
21	NOV	I	15	7.766.060	-
22		II	15	7.637.394	8.158.938
23	DEC	I	15	7.411.298	7.834.067
24		II	16	7.732.709	8.124.457

TABLE VI. IRRIGATION WATER REQUIREMENTS FOR THE PANDANDURI DAM PERIOD DECEMBER I AND DECEMBER II

No	Month	Period	Day	Water requirements (m^3) Dec I	Water requirements (m^3) Dec II
1	JAN	I	15	7.834.115	7.836.705
2		II	16	7.121.707	6.851.763
3	FEB	I	14	7.413.569	7.443.119
4		II	14	8.239.899	8.269.660
5	MAR	I	15	8.010.799	8.072.871
6		II	16	6.522.711	8.444.719
7	APR	I	15	-	6.294.108
8		II	15	7.638.990	6.128.020
9	MEI	I	15	7.725.654	7.725.654
10		II	16	7.987.199	7.987.662
11	JUN	I	15	8.173.959	8.091.155
12		II	15	7.959.649	7.976.829
13	JUL	I	15	8.173.039	8.209.426
14		II	16	8.236.156	8.473.704
15	AGU	I	15	6.892.766	8.321.257
16		II	16	6.679.369	6.940.379
17	SEP	I	15	6.794.656	6.686.427
18		II	15	6.811.103	6.174.346
19	OCT	I	15	6.969.002	6.233.960
20		II	16	6.371.370	6.133.718
21	NOV	I	15	-	-
22		II	15	-	-
23	DEC	I	15	7.834.067	-
24		II	16	8.199.761	8.199.761

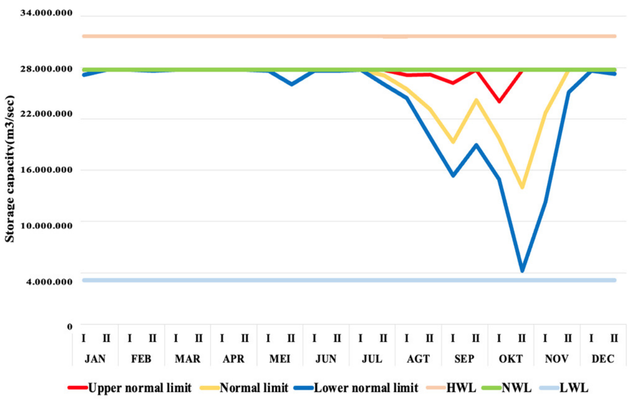

Fig. 5. Capacity curve model of Pandanduri reservoir for the October planting season.

Figure 5 and Table VII illustrate the dynamics of reservoir operations, which are strongly influenced by variations in climate conditions, particularly rainfall and water availability. The effects of climate change are evident in the reservoir's storage patterns and in the reliability of the irrigation water supply. Several key indicators of these impacts can be observed. In mid-October, the reservoir's capacity declined sharply, reaching 5 million m³, indicating a limited inflow from the catchment area due to reduced rainfall intensity at the beginning of the planting season, thereby constraining the reservoir's ability to meet irrigation demands. Failures in meeting water requirements occur under both normal and dry seasonal conditions. During regular seasons, failure rates range from 4.2% to 33.3%, suggesting increasing pressure on the water supply. However, reliability remains relatively high (66.7%–95.8%), indicating that irrigation needs can still generally be met despite fluctuations in water availability. In contrast, during dry seasons, failures increase to 8.3%-33.3%, and reliability decreases to 83.3%–91.7%. This decline demonstrates the reservoir's limited capacity to store and distribute water during periods of low rainfall, driven by increasingly unpredictable climate patterns. Similarly, in the November planting season, climate change has altered rainfall distribution, resulting in reduced reservoir storage volume and lower operational reliability.

TABLE VII. FAILURE AND RELIABILITY OF RESERVOIR OPERATION PATTERNS DURING THE OCTOBER PLANTING SEASON

Period	Season Crop (SC)	Early planting season: Oct I Failure	Oct I Reliabilty	Oct II Failure	Oct II Reliabilty
Wet	SC I	0.0%	100.0%	0.0%	100.0%
	SC II	0.0%	100.0%	0.0%	100.0%
	SC III	0.0%	100.0%	0.0%	100.0%
Normal	SC I	8.3%	91.7%	4.2%	95.8%
	SC II	8.3%	91.7%	8.3%	91.7%
	SC III	33.3%	66.7%	29.2%	70.8%
Dry	SC I	16.7%	83.3%	8.3%	91.7%
	SC II	8.3%	91.7%	12.5%	87.5%
	SC III	33.3%	66.7%	29.2%	70.8%

The analysis shows that climatic variability affects both the stability of reservoir storage and its ability to consistently meet irrigation demands, as illustrated in Figure 6 and Table VIII. In November, the Pandanduri Reservoir experienced considerable operational challenges, with failure rates ranging from 12.5% to 34.1%, indicating that during nearly one-third of the operating period, the available water volume was insufficient to meet irrigation requirements (Figure 6 and Table VII). One of the leading causes of this condition was a significant decrease in reservoir storage, which dropped to about 10 million m³, although it remained above the dead storage level. This reflects the impact of climate change, characterized by reduced inflows to the reservoir.

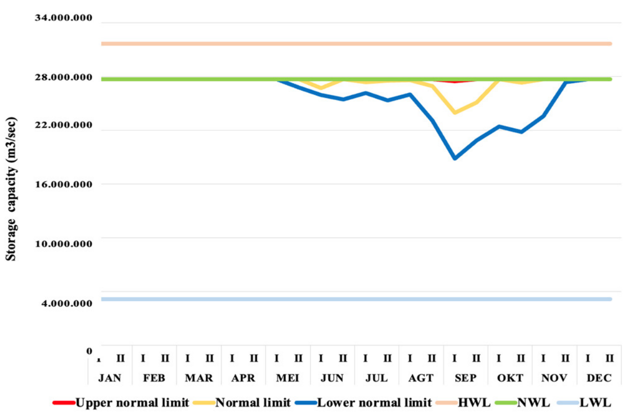

Fig. 6. Capacity curve model of Pandanduri reservoir for the November planting season.

TABLE VIII. FAILURE AND RELIABILITY OF RESERVOIR OPERATION PATTERNS DURING THE NOVEMBER PLANTING SEASON

Period	Season crop (SC)	Early planting season			
		Nov I		Nov II	
		Failure	Reliabilty	Failure	Reliabilty
Wet	SC I	0.0%	100.0%	0.0%	100.0%
	SC II	0.0%	100.0%	4.2%	95.8%
	SC III	0.0%	100.0%	0.0%	100.0%
Normal	SC I	0.0%	100.0%	0.0%	100.0%
	SC II	12.5%	87.5%	16.7%	83.3%
	SC III	25.0%	75.0%	20.8%	79.2%
Dry	SC I	0.0%	100.0%	0.0%	100.0%
	SC II	12.5%	87.5%	20.8%	79.2%
	SC III	33.3%	66.7%	29.2%	70.8%

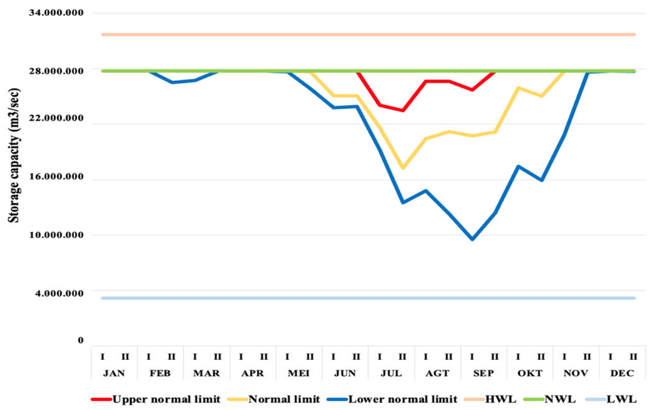

Fig. 7. Capacity curve model of Pandanduri reservoir for the December planting season.

In December, typically the peak of the rainy season, reservoir storage dropped sharply, nearing a dead storage capacity of around 4 million m³, as shown in Figure 7 and Table IX. This signals a serious climate anomaly, in which expected rainfall either does not occur at the anticipated intensity or is unevenly distributed across space and time. As a result, failures to meet irrigation water needs ranged from 4.2% to 35.8%, indicating that while irrigation requirements can be satisfied at times, the reservoir cannot supply enough water during periods of limited inflow or low storage reserves.

TABLE IX. FAILURE AND RELIABILITY OF RESERVOIR OPERATION PATTERNS DURING THE DECEMBER PLANTING SEASON

Period	Season Crop (SC)	Early planting season			
		Dec I		Dec II	
		Failure	Reliabilty	Failure	Reliabilty
Wet	SC I	0.0%	100.0%	0.0%	100.0%
	SC II	8.3%	91.7%	8.3%	91.7%
	SC III	4.2%	95.8%	0.0%	100.0%
Normal	SC I	0.0%	100.0%	4.2%	95.8%
	SC II	20.8%	79.2%	25.0%	75.0%
	SC III	16.7%	83.3%	12.5%	87.5%
Dry	SC I	4.2%	95.8%	8.3%	91.7%
	SC II	20.8%	79.2%	29.2%	70.8%
	SC III	25.0%	75.0%	20.8%	79.2%

G. Discussion

Climate change has significantly affected fluctuations in water availability at the Pandanduri Dam. Falling reservoir water levels strongly influence the stability of storage volume and the success of irrigation supply. Analyzing these effects reveals key conditions. From 1993 to 2023, there have been substantial changes in key climatic parameters, particularly an increasing trend in temperature and air humidity, along with noticeable shifts in wind patterns and solar radiation. Changes in climate parameters impact water, irrigation, and agriculture. Rising temperatures, a key climate change indicator, increase evapotranspiration, droughts, and alter rainfall, affecting productivity and the hydrological cycle. Increased air humidity occurs as temperatures rise because higher temperatures enhance evaporation of water from soil and vegetation surfaces. Although high humidity can help reduce the risk of drought, it also increases the potential for extreme and uneven rainfall. Wind speed changed by 21.7% from Period I to Period II and by 52.6% from Period II to Period III. Higher wind speeds can intensify storm frequency and intensity and influence the distribution of water vapor and the atmospheric pressure systems that shape weather patterns. Solar radiation exhibited a unique pattern, increasing by 40.2% from Period I to Period II but decreasing by 15.3% from Period II to Period III. This reduction may be attributed to higher vapor concentrations or cloud cover, which limit the amount of solar radiation reaching Earth's surface. The decline in solar radiation can negatively affect plant productivity.

The failure of the reservoir operation pattern during the October planting season shows that operational dynamics are greatly affected by changing climate conditions, especially rainfall. During this period, reservoir capacity fell sharply to 5 million m3, indicating a water shortage due to decreased rainfall. In the wet season, the water supply was sufficient, with a 0% failure rate in meeting irrigation water needs. This suggests that at the start of the rainy season, the reservoir's operating system was reliable, with steady inflow and outflow. During the primary planting season, the irrigation water supply falls short of demand by 4.2% to 33.3%, indicating pressure on water availability. Still, reliability remains relatively high, between 66.7% and 95.8%. Therefore, the reservoir's operational pattern shows it continues to reliably meet irrigation water needs, despite fluctuations in water availability. Meanwhile, during the dry season, the Pandanduri Dam's failure to supply irrigation water increases by 8.3% to 33.3%, and its reliability drops to 83.3% to 91.7%. This signifies a decline in reservoir water volume driven by increasingly unpredictable climate patterns. The decline in reservoir storage volume continued during the November planting season. It decreased by nearly 10 million m³, reflecting lower rainfall intensity and reduced reservoir inflows. In November, the reservoir's operating pattern, especially during the regular season, occurred in the second period, both at the beginning and end of the month. This suggests that even before the full dry season, water reserves were already insufficient to supply irrigation water. Failure rates ranged from nearly 12.5% to 34.1%, indicating that more than a quarter of water needs were unmet. However, during the wet season, reservoir reliability reached 100%, as rainfall and inflow maintained reservoir water levels within safe limits. This shows that reservoir operations were running efficiently with sufficient water supply to meet irrigation demands. The December planting season experienced a significant anomaly in water availability. December, usually the height of the rainy season, instead saw reservoir storage decrease by 4 million m³, reaching its dead storage limit. This shortfall ranges from 4.2% to 35.8% of irrigation water needs.

The validity of the optimization results depends on the irrigation area, planting water needs, and actual water availability from field data, which includes reservoir water volume and river inflow. The failure rate is determined by dividing the number of water shortages by the irrigation water demand (Figure 8).

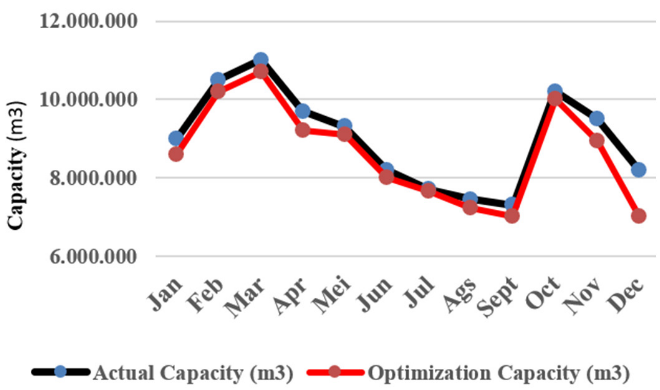

Fig. 8. Validation graph of the Pandanduri dam optimization.

IV. CONCLUSION

Based on the analysis of reservoir operation patterns, several key findings emerge. Climate change significantly impacts the operation of the Pandanduri Dam in meeting irrigation water needs, as shown by increases in temperature of 55.6% to 78.2% and other climatic parameters. These changes lead to greater rainfall variability, characterized by alternating periods of extreme wetness and dryness. Climate change also influences the frequency, intensity, and duration of rainfall. From 1994 to 2023, rainfall frequency decreased, and the rainy season shortened, ending in November. According to recorded inflow volume data at the Pandanduri Dam, during dry conditions, the reservoir's inflow reaches 1.8 million m³ per month, while the outflow is 3 million m³. Under such conditions, reservoir inflow becomes inadequate to meet water release requirements, resulting in reduced storage levels and a diminished capacity to fulfill irrigation demands. Failures during the October planting season ranged from 4.2% to 33.3%, while in November they ranged from 4.2% to 34.1%, and in December from 4.2% to 35.8%. During the November planting season, crops with moderate to high water requirements should be integrated with water-saving techniques such as rotational irrigation to extend the reservoir's capacity into subsequent seasons. In early November, crops with low water demand are preferable, supported by close coordination among irrigation managers; meanwhile, in early December, rice cultivation across the entire irrigated area is viable due to increased rainfall and reservoir storage.

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