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Optimizing performance assessment of multi-reservoir operations for sustainable water management in a semi-arid region

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ABSTRACT

Global challenges, such as population growth, rapid urbanization, and the impacts of climate change, are creating unprecedented demands on water resources in semi-arid regions. Meeting the surging needs for irrigation and water supply requires a departure from the limitations of single reservoir systems. Instead, the construction of multi-reservoir systems within semi-arid river basins is imperative. The research employs an integrated reservoir operation approach that facilitates the controlled release of surplus water from upstream reservoirs to downstream ones. The novel Teaching-Learning-Based Optimization (TLBO) model is utilized to determine optimal irrigation releases, subsequently forming the basis for evaluating reservoir operation performance through the lenses of reliability, resilience, and vulnerability. The findings of this study shed light on the performance of these reservoirs under different models. Notably, the Aji-2 reservoir operation exhibits higher levels of reliability and resilience when the TLBO model is employed, surpassing the outcomes of the Linear Programming (LP) model. Conversely, the vulnerability of the Aji-3 reservoir operation is more pronounced with the TLBO model, albeit reduced when compared to actual release years 2005, 2009, and 2013. This study adds to the development of reservoir operation policies that favor reduced vulnerability and increased reliability.

Key words: multiple reservoir system, reliability, reservoir operation measure, resilience, TLBO, vulnerability

HIGHLIGHTS

- Integrated reservoir operation measures were taken.
- TLBO algorithms were used in integrated reservoir operation.
- By recognizing the intricate connections between reliability, resilience, and vulnerability, decision-makers can navigate the complexities of water system planning with greater confidence and effectiveness.

1. INTRODUCTION

The worldwide population growth has resulted in a considerable increase in demand for water for a variety of uses. However, this demand is not dispersed uniformly over place and time, resulting in discrepancies in water supply and demand. Reservoirs have been built to solve these concerns by increasing water supply. As a result, it is critical for water resource planning and operational strategies to investigate alternative ways and evaluate the risks associated with them (Ren *et al.* 2020). Numerous optimization models have been created in the past to determine optimal operating methods for many reservoirs. For example, Lee *et al.* (2008) developed a multistage Stochastic Linear Programming (SLP) model to generate daily coordinated operating strategies for several reservoirs. Ajudiya *et al.* (2019) and Kumar & Yadav (2019) also used a Linear Programming (LP) monthly model to develop an integrated operational strategy for a multi-reservoir system in the semi-arid Saurastra river basin, with an emphasis on irrigation planning.

Various optimization approaches have been utilized to develop optimal operational policies for reservoirs. Kumar & Baliarsingh (2003) employed the Folded Dynamic Programming (FDP) model to derive optimal operation policies. Nagesh Kumar & Janga Reddy (2007) utilized the Particle Swarm Optimization (PSO) algorithm to formulate multipurpose reservoir operation policies. Jothiprakash *et al.* (2011) applied the Genetic Algorithm (GA) model to develop operational policies for multiple reservoir systems within Indian river basins. Arunkumar & Jothiprakash (2016) introduced a fully Fuzzy

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Linear Programming (FLP) hybrid approach to obtain operating policies for multiple reservoirs. Karnatapu *et al.* (2020) developed a Genetic Algorithm-Nonlinear Programming (GA-NLP) hybrid model to obtain multi-objective reservoir operation strategies. Kumar & Yadav (2018) used the Teaching-Learning-Based Optimization (TLBO) and Jaya models to derive real-time and discrete operation policies for multiple reservoir systems. Ajudiya & Yadav (2023) employed the TLBO algorithm to derive optimum rule curves for irrigation planning in the command area of a multiple reservoir system in a semi-arid region. Various other applications of optimization approaches in reservoir operation are GA (Chen *et al.* 2023; Mezenner *et al.* 2023), Invasive Weed Optimization (Trivedi & Shrivastava 2023), JA (Kumar *et al.* 2023), Artificial Bee Colony algorithm (Wang *et al.* 2023), and Improved Grey Wolf Optimizer (Choi *et al.* 2023).

Risk assessment typically involves quantifying the likelihood of specific undesirable outcomes (Rye *et al.* 2021). However, a major shortcoming in such assessments is that all undesirable outcomes are given equal weighting, without regard for the various degrees of severity or effect associated with each event. Furthermore, as Reddy & Kumar (2008) point out, these evaluations frequently address the consequences of several failures in isolation. Such assumptions are problematic since the amount and overall importance of failures might vary greatly. It is critical to get beyond these false preconceptions while analyzing reservoir operation regulations. To assess the efficiency of these policies, performance metrics such as reliability, resilience, and vulnerability, as defined by others (Jain & Bhunya 2008), must be considered. These metrics give a more comprehensive picture of reservoir operation techniques' performance and resilience. Notably, as noted by others (Kjeldsen & Rosbjerg 2004), the idea of dependability has been central to the design and study of water resource systems for over a century. This historical viewpoint emphasizes the ongoing need of examining the dependability of reservoir operation regulations in maintaining sustainable water resource management.

In recent years, there has been a noticeable change in the field of water resources management toward increasing the resilience of water systems. As described by Butler *et al.* (2017), this transition indicates a movement from a 'fail-safe' to a 'safe-fail' paradigm. This shift emphasizes the rising need of addressing not just dependability but also resilience and vulnerability when assessing water resource systems. In practice, however, the criteria for selecting and maintaining water resource systems frequently rely significantly on prior experiences. To bridge the gap between theory and practice, decision-makers must understand the interaction of three fundamental indices: reliability, resilience, and vulnerability, as stressed by Hashimoto *et al.* (1982). These indices are critical for understanding how different criteria interact, and they should help guide informed decisions about water system planning and management.

Previous research has looked on the relationship between dependability and resilience. Bayazit & Ünal (1990), for example, proposed a unique and complicated nonlinear link between these two elements. The narrow breadth of optimization solutions utilized in this research, on the other hand, has created gaps in our understanding of the full linkages between all three criteria. Several previous publications (Ecclestone & Lewis 2014; Spurway & Griffiths 2016; Schlosberg *et al.* 2017; Abdul & Yu 2020) have added other risk criteria into the discourse, such as resilience and vulnerability. According to the work of several authors (Kundzewicz & Kindler 1995) and (Srinivasan *et al.* 1999), research works have shown a good association between reliability and resilience in water supply reservoir systems under various operating conditions (Ahbari *et al.* 2019; Davidson *et al.* 2019; Kumar *et al.* 2021). Meanwhile, Vogel & Bolognese (1995) have recognized the relationship between dependability and resilience.

Furthermore, Butler *et al.* (2017) define reliability as the chance of failing to meet a given target release, underlining its importance. However, to gain a more comprehensive understanding of the relationships among these indices, further research and analysis are needed. The primary objective of this study is to foster a shared comprehension of reservoir operation measurement indices and to offer decision-makers a practical guideline for making well-informed choices in the management of water resource systems. By recognizing the intricate connections between reliability, resilience, and vulnerability, decision-makers can navigate the complexities of water system planning with greater confidence and effectiveness.

2. STUDY AREA

The multiple reservoir system is situated within the Aji river basin, located in the semi-arid region with geographic coordinates spanning from $22^\circ\ 18\,'0''\ N$ to $22^\circ\ 36'\ 0''\ N$ latitude and $70^\circ\ 36'\ 0''\ E$ to $70^\circ\ 48'\ 0''\ E$ longitude. This geographical context is visually depicted in Figure 1. This system comprises three reservoirs, namely Aji-2, Nyari-2, and Aji-3, which are situated in the Rajkot and Jamnagar districts of the Saurastra region. The primary crop seasons observed in the command area served by these reservoirs are Kharif and Rabi. Notably, Aji-2 and Nyari-2 reservoirs experience overflow events

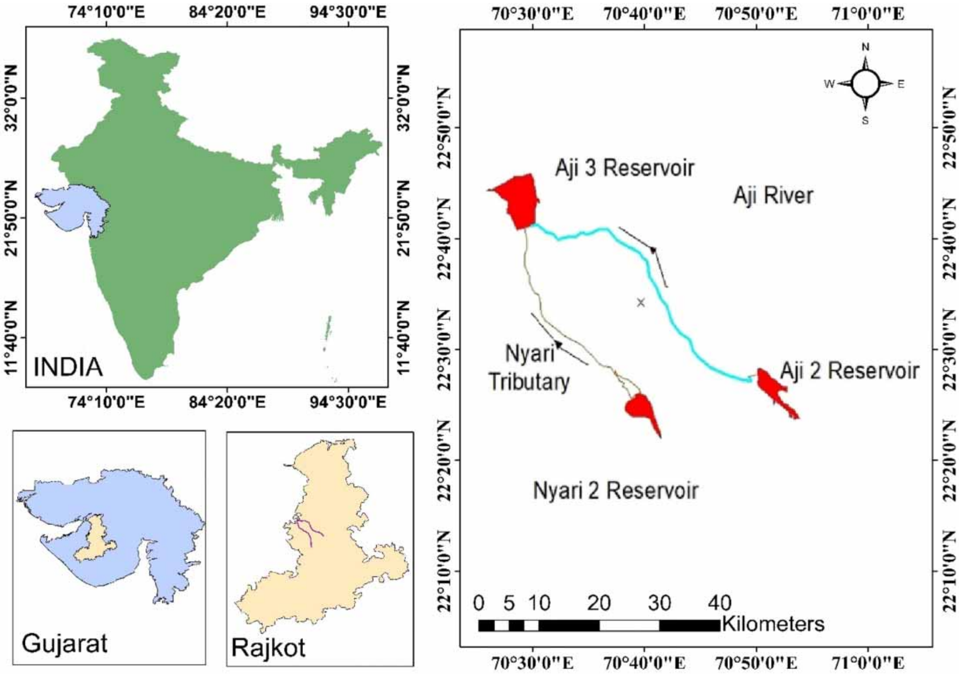

Figure 1 | Illustrates the geographical positioning of the Aji-2, Nyari-2, and Aji-3 reservoirs.

annually, while the Aji-3 reservoir rarely encounters such situations. This research investigates the possible advantages of irrigation in the semi-arid region by implementing a cooperative operation of numerous reservoirs to improve water resource usage and minimize the vulnerability of the Aji-3 reservoir. It specifically addresses the scenario depicted in Figure 2 in which the Aji-2 reservoir works in parallel with the Nyari-2 reservoir and in series with the Aji-3 reservoir. The Rajkot irrigation division provided relevant information and crucial data relative to the Aji-2, Nyari-2, and Aji-3 systems from 2005–06 to 2016–17 in order to undertake this study. These data sources form the basis for assessing the feasibility and benefits of coordinated reservoir operation in this semi-arid region.

The development of the Aji-2 reservoir was primarily intended to meet the need for irrigation. The Aji-2 irrigation project began in 1980 and was completed in 1987, resulting in the development of an effective canal system. Notably, the dam's essential parameters include a Full Reservoir Level (FRL) of 73.76 m and a High Flood Level (HFL) of 74.19 m, respectively. It has a gross storage capacity of 22.09 million cubic meters (MCM) and a live storage capacity of 20.76 MCM in terms of storage capacity. Furthermore, the Left Bank Main Canal (LBMC) connected to the Aji-2 reservoir has a Gross Command Area (GCA) of 2,529 ha and a Culturable Command Area (CCA) of 2,384 ha. These characteristics make the Aji-2 reservoir an essential component in satisfying the region's irrigation demands.

Construction on the Aji-3 irrigation project began in 1984 and was completed in 1988. Its major goal was to meet the demand for both irrigation and water supply. This reservoir has a gross storage capacity of 61.95 MCM, with a dead storage capacity of 4.75 MCM. The Aji-3 reservoir supports agriculture in the region by providing irrigation services to a 6635-hectare cultivable command area. This extensive irrigation coverage is made feasible by combining the LBMC and RBMC systems, which are integrated within the Aji-3 reservoir. This hybrid of LBMC and RBMC systems has given it the moniker composite bank main canal (CBMC). The CBMC system provides for 2.27 cubic meters per second (m^3/s) discharge through the RBMC and 4.5 m^3/s discharge through the LBMC, allowing for effective irrigation and water management in the region.

The Nyari-2 irrigation project was created with two goals in mind: to provide water to Rajkot and to assist agriculture activities. The Nyari-2 water resources project began construction in 1982 and was completed in 1986. The Nyari-2 reservoir has a gross storage capacity of 12.25 MCM, with a dead storage capacity of 0.75 MCM. This reservoir plays a vital role in fulfilling the water needs of both Rajkot city and agricultural irrigation. Within the command area, the LBMC serves a cultivated command area spanning 1,695 ha, while the GCA extends over 2,070 ha. The region receives an annual rainfall of 583 mm, which

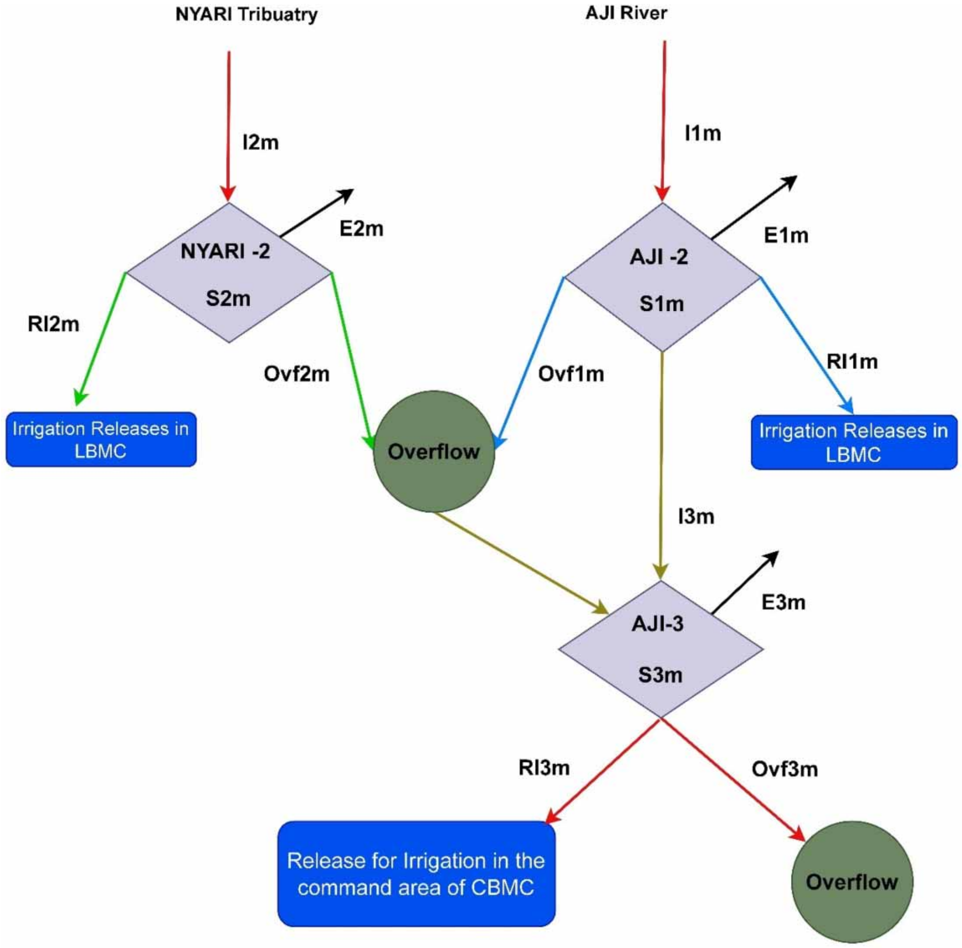

Figure 2 | Presents a schematic diagram outlining the operational configuration of the multiple reservoir system.

contributes to its water resources. The LBMC of the Nyari-2 reservoir has a discharge capacity of 3.06 m³/s, ensuring the efficient distribution of water resources for irrigation and other purposes within the project area.

3. METHODOLOGY OF TLBO ALGORITHM

The TLBO algorithm draws its inspiration from the teaching and learning dynamics observed in a classroom setting, as originally proposed by Rao *et al.* (2012). This algorithm comprises two distinct phases of learning: First, the 'teacher phase' involves an effort by the teacher to share their knowledge with the aim of enhancing the students' performance or grades. Second, the 'learner phase' entails the learners leveraging the knowledge imparted by the teacher and engaging in interactions with each other to collectively enhance their overall knowledge and understanding. In the context of optimization, the primary objective is to either maximize or minimize a given objective function, denoted as $f(X)$. Several parameters are predetermined for the algorithm, including the population size (equivalent to the number of students in the class) and the number of iterations.

Step-1: The initial solutions are generated randomly, in accordance with a specified equation Equation (1). From this set of solutions, the best solution is determined based on whether the optimization goal is to maximize or minimize the objective function. For maximization objectives, the best solution corresponds to the maximum value, while for minimization objectives, it corresponds to the minimum value.

$$\text{Randomly generated solution} = [L + r\,(U - L)] \quad (1)$$

where U is the upper limit of the variable; L is the lower limit of the variable; r is a random number generated from the interval [0, 1].

Step-2: In the teaching phase of the TLBO algorithm, the teacher endeavors to improve the overall performance of the class through a method known as the 'difference mean' approach, which can be mathematically expressed as shown in Equation (2):

$$\text{Difference mean} = r * (X_{\text{best}} - X_{\text{mean}}) \tag{2}$$

Here, X_{best} is the teacher's solution; X_{mean} is the mean value of all the student's solutions.

Using this approach, a modified solution, denoted as X_{new}, is derived based on the old solutions, as indicated in Equation (3):

$$X_{\text{new}} = (X_{\text{old}} + \text{Difference mean}) \tag{3}$$

Here, X_{old} represents the old solution, and X_{new} represents the modified solution. The better solution between X_{new} and X_{old} is then selected, and it replaces the previous X_{old} solution in the optimization process.

Step-3: During the learning phase of the TLBO algorithm, learners engage in random interactions with each other to enhance their knowledge. Consider two random learners represented as $X_{\text{old},i}$ and $X_{\text{old},j}$, where $X_{\text{old},i}$ interacts with $X_{\text{old},j}$. Two potential scenarios may arise, which can be mathematically expressed as follows in Equations (4) and (5):

$$\text{If, } f(X_{\text{old},i}) < f(X_{\text{old},j})\text{: Then } X_{\text{new}.i} = X_{\text{old},i} + r_1(X_{\text{old},j} - X_{\text{old},i}) \tag{4}$$

$$\text{If, } f(X_{\text{old},i}) > f(X_{\text{old},j})\text{: Then } X_{\text{new},i} = X_{\text{old},i} + r_1(X_{\text{old},i} - X_{\text{old},j}) \tag{5}$$

Here, $X_{\text{old},i}$ and $X_{\text{old},j}$ represent two random learners. $f(X_{\text{old},i})$ and $f(X_{\text{old},j})$ denote the objective function values associated with learners $X_{\text{old},i}$ and $X_{\text{old},j}$. r_1 represents a random number generated for the interaction.

In each interaction, only one of these two possibilities will occur at a given time, leading to the calculation of $X_{\text{new},i}$. The solution with the superior functional value among $X_{\text{new},i}$ options is retained and replaces the previous X_{new}.

Upon completing the first iteration, the algorithm checks if it has reached the maximum predefined number of iterations. If this limit is reached, the algorithm terminates and presents the optimum solution. However, if there are remaining iterations to be executed, the algorithm restarts from the teaching phase and continues its optimization process.

4. TLBO MODEL FORMULATION

The objective function, denoted as $f(X)$, aims to maximize the net benefits (NBs) obtained through the optimal allocation of crop areas for different seasons, including Kharif, Rabi, and biannual. It is represented as follows:

$$\text{Maximize NBs} = \sum_{j}^{3}\left(\sum_{i=1}^{n} C_i ak_{ji} + \sum_{i=1}^{n} C_i ar_{ji} + \sum_{i=1}^{n} C_i at_{ji}\right) \tag{6}$$

Here, NBs represents the NBs derived from the command area in Million Rupees. Reservoir index (j) can take values 1, 2, or 3. Crop index (i) ranges from 1 to n, encompassing various crop types. ak_{ji}, ar_{ji}, and at_{ji} signify the allocated crop areas for kharif, rabi, and biannual seasons, respectively, for the ith crop at the jth site (measured in hectares). C_i denotes the coefficient of NBs for the ith crop, measured in rupees per hectare.

This objective function quantifies the total NBs associated with crop area allocations across different seasons and reservoir sites. The optimization process seeks to maximize these NBs while adhering to specified constraints.

4.1. Land allocation constraint

The constraint for land allocation ensures that the cultivated area of crops during a specific season does not exceed the CCA available at site jth (ha). There are two seasons, Kharif and Rabi, with respective constraints as follows:

For Kharif season ($g_{1,j}(m)$) with operating period 'm':

$$g_{1,j}(m) = \sum_{i=1}^{n} (ak_{ji} + at_{ji}) - CCA_j \leq 0 \tag{7}$$

For Rabi season ($g_{2,j}(m)$) with operating period 'm':

$$g_{2,j}(m) = \sum_{i=1}^{n} (ar_{ji} + at_{ji}) - CCA_j \ \leq 0 \tag{8}$$

where CCA_j is the culturable command area at site jth (in hectares).

4.2. Storage continuity constraint

The storage continuity constraint maintains the monthly storage levels for the jth reservoir during an operating period 'm'. There are different equations for different reservoirs ($j = 1,\ 2,\ 3$) as follows:

For reservoir Aji-2 ($j = 1$):

$$g_{3,j}(m) = \mathrm{S}_m^1 + I_m^1 - \mathrm{RI}_m^1 - \mathrm{E}_m^1 - \mathrm{Ovf}_m^1 - \mathrm{S}_{m+1}^1 = 0 \tag{9}$$

For reservoir Nyari-2 ($j = 2$):

$$g_{3,j}(m) = \mathrm{S}_m^2 + I_m^2 - \mathrm{RI}_m^2 - \mathrm{E}_m^2 - \mathrm{Ovf}_m^2 - \mathrm{RW}_m^2 - \mathrm{S}_{m+1}^2 = 0 \tag{10}$$

For reservoir Aji 3 ($j = 3$):

$$g_{3,j}(m) = \mathrm{S}_m^3 + I_m^3 - \mathrm{RI}_m^3 + \mathrm{Ovf}_m^1 + \mathrm{Ovf}_m^2 - \mathrm{E}_m^3 - \mathrm{Ovf}_m^3 - \mathrm{RW}_m^3 - \mathrm{S}_{m+1}^3 = 0 \tag{11}$$

where m represents the operating month (1–12); S_m is the storage at the start of period 'm' (in MCM); S_{m+1}^1, S_{m+1}^2, and S_{m+1}^3 are the final storage levels at the end of month 'm' for the respective reservoirs; RI_m^j is the irrigation release during month 'm' (in MCM); Ovf_m^j represents overflow during month 'm' (in MCM); RW_m^j is the release for water supply during month 'm' (in MCM); E_m^j is the evaporation during month 'm' (in MCM); I_m^j represents the dependable inflow during month 'm' (in MCM) and is calculated using the Weibull method (Subramanya 2013) as per Equation (12).

$$P = \frac{M}{(N+1)} * 100 \tag{12}$$

where P is the percentage of time inflow is equal to or exceeds the threshold. N is the number of years. M is the rank of inflow.

4.3. Water allocation constraint

The water allocation constraint ensures that, during any given month 'm', the total water requirement for crops does not exceed the canal irrigation release available at the jth reservoir. This constraint is expressed as:

$$g_{4,j}(m) = \left(\sum_{i=1}^{n} \mathrm{NIR}_{jit} a_{ji} / \eta_s \right) - \mathrm{RI}_m^j \leq 0 \tag{13}$$

Here, NIR_{jit} is the net irrigation requirement of the i_{th} crop during month 'm'. a_{ji} is a parameter related to crop cultivation at site j_{th} and crop i. η_s represents the efficiency of the surface water system. RI_m^j is the canal irrigation release during month 'm'.

4.4. Evaporation calculation

To compute the monthly evaporation occurring from the j_{th} reservoir, the equation proposed by (Jothiprakash *et al.* 2011) is employed. This equation calculates evaporation as a function of various parameters and is represented as:

$$g_{5,j}(m) = a^j_m + b^j_m\ [\ (\mathrm{S}^j_m\ +\ \mathrm{S}^j_{m+1})/2] - \mathrm{E}^j_m = 0 \tag{14}$$

Here, a^j_m and b^j_m are regression coefficients specific to the j_{th} reservoir during month 'm'.

4.5. Overflow calculation

To account for the overflow in the optimization model, the equation proposed by (Jothiprakash *et al.* 2011) is utilized. This equation calculates the overflow by considering various factors, allowing for the release of excess water. The constraint for overflow is expressed as:

$$g_{6,j}(m) = \mathrm{S}^j_m + I^j_m - \mathrm{R}^1_m - E^j_m - K^j_m - Ovf^j_m >= 0 \tag{15}$$

where K^j_m represents the rule-level storage during month 'm' in MCM.

4.6. Penalty functions

Penalty functions $h_{1,j}(m)$, $h_{2,j}(m)$, $h_{3,j}(m)$, $h_{4,j}(m)$, $h_{5,j}(m)$, and $h_{6,j}(m)$ are applied to the respective constraint functions (Equations (7)–(11) and Equations (13)–(15)) when the solution is infeasible. These penalty functions are formulated as follows:

$$h_{1,j}(m) = \mathrm{sum}(10{*}abs(g_{1,j}(m))2) \tag{16}$$

$$h_{2,j}(m) = \mathrm{sum}(10{*}abs(g_{2,j}(m))2) \tag{17}$$

$$h_{3,j}(m) = \mathrm{sum}(10{*}abs(g_{3,j}(m))2) \tag{18}$$

$$h_{4,j}(m) = \mathrm{sum}(10{*}abs(g_{4,j}(m))2) \tag{19}$$

$$h_{5,j}(m) = \mathrm{sum}(10{*}abs(g_{5,j}(m))2) \tag{20}$$

$$h_{6,j}(m) = \mathrm{sum}(10{*}abs(g_{6,j}(m))2) \tag{21}$$

where $g_{1,j}(m)$ to $g_{6,j}(m)$ are the respective constraint functions at the j_{th} reservoir during period 'm'.

4.7. Penalized objective function

The penalized objective function $f'(X)$ is formulated as follows:

$$f'(X)\mathrm{Maximize\ NB} = f(X) - \sum_{j=1}^{3}\left\{\left(\sum_{t}^{12} h_{1(m)}\right) + \left(\sum_{t}^{12} h_{2(m)}\right) + \left(\sum_{t}^{12} h_{3(m)}\right) + \left(\sum_{t}^{12} h_{4(m)}\right) + \left(\sum_{t}^{12} h_{5(m)}\right) + \left(\sum_{t}^{12} h_{6(m)}\right)\right\} \tag{22}$$

Here, $f'(X)$ is the original objective function. The summations in the equation account for the penalty functions for each constraint and each reservoir over the 12-month period.

The TLBO model and the LP model are solved using MATLAB R2015b and LINGO 18 unlimited constraint version.

5. RESULTS AND DISCUSSION

The TLBO algorithm was developed and tested using various combinations of population size and iteration numbers, all of which were run independently in MATLAB R2015 with a 75% dependability level inflow scenario. The specific groupings for population size and iteration numbers used were as follows: 25–100, 25–150, 25–160, 25–200, 50–100, 50–150, 50–160, 50–200, 75–100, 75–150, 75–160, 75–200, 100–100, 100–150, 100–160, 100–200, 150–100, 150–150, 150–160, 150–200, 160–100, 160–150, 160–160, and 160–200. In total, the TLBO model was run 24 times independently. The analysis of the

NBs from these runs showed that NBs increase as both the number of iterations and population size increase. The maximum NBs of Rs. 1.283.67 $\times$ 10^6 were achieved when using a population size and iteration combination of 160–160 in the TLBO model. In comparison, the LP model resulted in maximum NBs of Rs. 1, 067.64 $\times$ 10^6. This indicates that the TLBO model improved maximum NBs by 20.24% compared to the LP model. Both the TLBO and LP models provided optimal irrigation releases, which were then used in the analysis of reservoir operation measures. Reservoir operation measures were based on irrigation demand as a threshold, the optimal irrigation release from both the TLBO and LP models, and actual release data for 12 years (2005–2016). The irrigation demand for the Aji-2 irrigation scheme was calculated using the Blaney-Criddle method, while the irrigation demand for Nyari-2 and Aji-3 irrigation schemes was obtained from a report from the office of the agronomist in Valsad, Gujarat. In the subsequent subsections, various operation performance measures, such as reliability, resilience, and vulnerability, were calculated and analyzed.

5.1. Reliability

Reliability is a crucial measure of how often a system operates satisfactorily (Reddy & Kumar 2008). It quantifies the likelihood that the system will function in a satisfactory manner (as defined by a specific threshold value). The formula for calculating reliability Y is as follows:

$$\text{Reliability}[Y] = \frac{\text{number of time periods}\,'t',\ Y_t \geq Y_T}{n} \tag{23}$$

In this formula: Y_T is the threshold value that defines system failure. n represents the total number of periods in the simulation.

It is important to note that reliability alone does not provide information about how quickly the system can recover from failure or the degree of unsatisfactory conditions when they occur (Anusha *et al.* 2017). Using the TLBO model, reliability values of 0.83, 0.58, and 0.58 were calculated for the Aji-2, Nyari-2, and Aji-3 reservoir operations, respectively. In contrast, the LP model yielded reliability values of 0.58, 0.58, and 0.42 for the same reservoir operations. The reliability analysis results for Aji-2, Nyari-2, and Aji-3 reservoirs are visually presented in Figure 3. It is evident from Figure 3 that Aji-2 reservoir operations are more reliable when using the TLBO model compared to the Nyari-2 and Aji-3 reservoir operations, especially when compared to the LP model.

5.2. Resilience

Resilience is a measure that quantifies the probability of a system transitioning from an unsatisfactory state to a satisfactory state, as defined by accepted values. The formula for calculating resilience Y is as follows:

$$\text{Resilience}[Y] = \frac{\text{Number of times an accepted value is followed by an unaccepted value}}{\text{Number of times an unaccepted value occurred}} \tag{24}$$

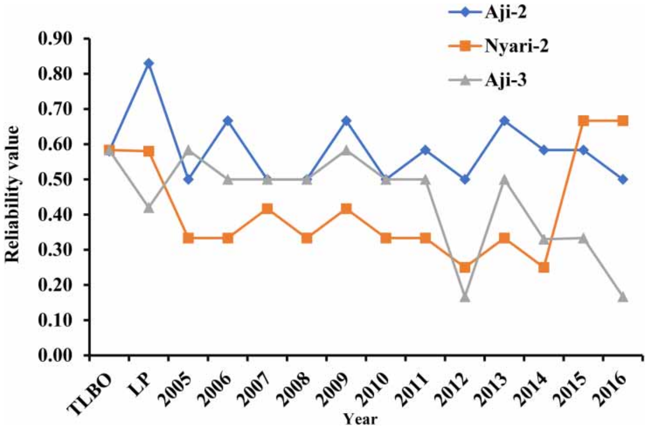

Figure 3 | Reliability measure for the release policy of a multiple reservoir system.

Resilience evaluates a system's ability to recover from an unsatisfactory state, indicating how quickly it can bounce-back from failure. It is worth noting that a system with lower reliability but higher resilience can be more satisfactory compared to a highly reliable system without resiliency (Anusha *et al.* 2017). Using the TLBO model, resilience values of 1.0, 0.40, and 1.0 were calculated for Aji-2, Nyari-2, and Aji-3 reservoir operations, respectively. On the other hand, the LP model resulted in resilience values of 1.0, 0.20, and 0.71 for the same reservoir operations. From Figure 4, it's evident that Aji-2 reservoir operations exhibit higher resilience compared to Nyari-2 and Aji-3 reservoir operations, regardless of whether the TLBO model or the LP model was used. Additionally, the Aji-3 reservoir operation demonstrates greater resilience for the actual years 2005 and 2009 compared to both the TLBO and LP release policies.

5.3. Vulnerability

Vulnerability is a critical measure that assesses the severity of failure or the degree of seriousness when a failure occurs. It quantifies the extent of damage or negative impact caused by failures. The formula for calculating vulnerability Y is as follows:

$$\text{Vulnerability}[Y] = \frac{\sum \text{of positive values of } (Y_T - Y_t)}{\text{Number of times an unaccepted value occurred}} \tag{25}$$

Vulnerability helps gauge how severe a failure can be or how significant the consequences of failure. Using the TLBO model, vulnerability values of 3.0, 1.30, and 4.51 were calculated for Aji-2, Nyari-2, and Aji-3 reservoir operations, respectively. In contrast, the LP model resulted in vulnerability values of 3.0, 1.07, and 2.57 for the same reservoir operations. From Figure 5, it's evident that the Aji-3 reservoir operation is more vulnerable when compared to Aji-2 and Nyari-2 reservoir operations, regardless of whether the TLBO model or the LP model was used. Additionally, the Aji-3 reservoir operation exhibits higher vulnerability across all actual years of irrigation releases. This indicates that Aji-3′s vulnerability to failure is more pronounced than the other reservoir operations studied.

5.4. Performance analysis

A performance analysis was conducted on the Aji-2, Nyari-2, and Aji-3 reservoirs using data on annual actual irrigation release, annual irrigation water demand, and annual optimum release obtained from both the TLBO model and the LP model. The data are summarized in Table 1. Furthermore, Table 2 presents the deficits in annual actual release compared to the annual optimum release generated by the TLBO and LP models. Upon examining Table 2, it becomes apparent that the reservoir operation performance for Nyari-2 and Aji-3 is significantly improved when using the TLBO model in comparison to the LP model. Conversely, the performance of the Aji-2 reservoir operation is found to be reduced by 31.61% when employing the TLBO model instead of the LP model. However, overall, the performance of multiple reservoir system operations is enhanced when utilizing the TLBO model. Additionally, it is worth noting that there were deficits in annual actual irrigation water supply across the state. These deficits were calculated by comparing the actual annual irrigation water releases with the annual irrigation water demand. The performance analysis highlights the benefits of the TLBO model for

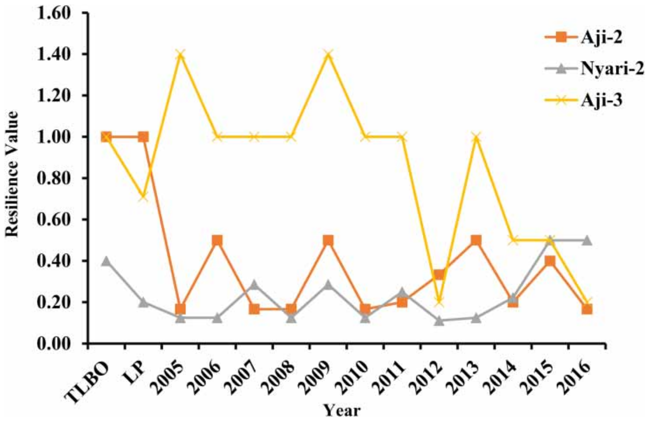

Figure 4 | Resilience measure for the release policy of a multiple reservoir system.

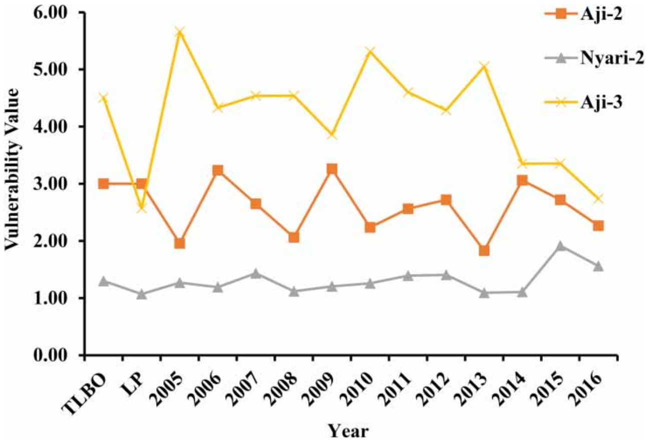

Figure 5 | Vulnerability measure for the release policy of a multiple reservoir system.

Table 1 | Annual actual release, annual optimum release with TLBO and LP model

	Annual actual irrigation release			Annual optimum release by TLBO at 75% dependability level			Annual optimum release by LP at 75% dependability		
Year	**Aji-2**	**Nyari-2**	**Aji-3**	**Aji-2**	**Nyari-2**	**Aji-3**	**Aji-2**	**Nyari-2**	**Aji-3**
2005–06	15.93	3.2	28.63	14.32	10.45	41.04	20.94	7.94	27.68
2006–07	17.56	3.65	28.01	14.32	10.45	41.04	20.94	7.94	27.68
2007–08	9.75	4.29	34.26	14.32	10.45	41.04	20.94	7.94	27.68
2008–09	17.93	5.44	34.26	14.32	10.45	41.04	20.94	7.94	27.68
2009–10	21.61	6.01	38.72	14.32	10.45	41.04	20.94	7.94	27.68
2010–11	14.93	3.37	36.61	14.32	10.45	41.04	20.94	7.94	27.68
2011–12	12.05	3.76	36.21	14.32	10.45	41.04	20.94	7.94	27.68
2012–13	12.27	0	0.00	14.32	10.45	41.04	20.94	7.94	27.68
2013–14	18.01	5.28	42.02	14.32	10.45	41.04	20.94	7.94	27.68
2014–15	13.45	3.46	29.31	14.32	10.45	41.04	20.94	7.94	27.68
2015–16	12.46	12.18	29.61	14.32	10.45	41.04	20.94	7.94	27.68
2016–17	11.13	11.665	15.49	14.32	10.45	41.04	20.94	7.94	27.68

certain reservoir operations, particularly Nyari-2 and Aji-3, while recognizing a reduction in performance for Aji-2. The results also underline the ongoing challenges related to annual actual irrigation water supply deficits within the state.

The findings of our study might be actually implemented in reservoir operations. This entails presenting solid recommendations and insights that water management authorities may quickly adopt into their policies and decision-making processes. The practical advantages that improved multi-reservoir operations, aided by the TLBO algorithm, may offer to real-world applications. This includes enhanced water usage efficiency, which is critical for long-term water consumption and aligns with wider environmental and conservation goals. Economic concerns will be addressed as well, giving light on the cost-effectiveness and financial feasibility of applying TLBO-based reservoir management measures. By delving into these practical features, the stakeholders, including local communities and decision-makers, to navigate and effectively execute sustainable reservoir operation regulations.

5.5. Environmental and economic implications

a) Environmental implications

- Ecosystem health: Consider the possible consequences of improved reservoir operations on downstream ecosystems, aquatic habitats, and biodiversity.

Table 2 | The deficit in annual actual irrigation release, annual optimum release with TLBO and LP model

	Annual irrigation water demand			Deficit in annual optimum release with TLBO			Deficit in the annual actual release			Deficit in annual optimum release with LP		
Year	**Aji-2**	**Nyari-2**	**Aji-3**	**Aji-2**	**Nyari-2**	**Aji-3**	**Aji-2**	**Nyari-2**	**Aji-3**	**Aji-2**	**Nyari-2**	**Aji-3**
2005–06	18.31	12.65	42.87	−3.99	2.20	1.83	−2.38	−9.45	−14.24	2.63	−4.71	−15.19
2006–07	18.31	12.65	42.87	−3.99	2.20	1.83	−0.75	−9.00	−14.86	2.63	−4.71	−15.19
2007–08	18.31	12.65	42.87	−3.99	2.20	1.83	−8.56	−8.36	−8.61	2.63	−4.71	−15.19
2008–09	18.31	12.65	42.87	−3.99	2.20	1.83	−0.38	−7.21	−8.61	2.63	−4.71	−15.19
2009–10	18.31	12.65	42.87	−3.99	2.20	1.83	3.29	−6.64	−4.15	2.63	−4.71	−15.19
2010–11	18.31	12.65	42.87	−3.99	2.20	1.83	−3.38	−9.28	−6.26	2.63	−4.71	−15.19
2011–12	18.31	12.65	42.87	−3.99	2.20	1.83	−6.27	−8.89	−6.66	2.63	−4.71	−15.19
2012–13	18.31	12.65	42.87	−3.99	2.20	1.83	−6.05	−12.65	−42.87	2.63	−4.71	−15.19
2013–14	18.31	12.65	42.87	−3.99	2.20	1.83	−0.30	−7.37	−0.85	2.63	−4.71	−15.19
2014–15	18.31	12.65	42.87	−3.99	2.20	1.83	−4.86	−9.19	−13.56	2.63	−4.71	−15.19
2015–16	18.31	12.65	42.87	−3.99	2.20	1.83	−5.85	−0.47	−13.26	2.63	−4.71	−15.19
2016–17	18.31	12.65	42.87	−3.99	2.20	1.83	−7.18	−0.98	−27.38	2.63	−4.71	−15.19

- Water quality: Investigate how changes in release patterns affect water quality, focusing on sediment movement, nitrogen levels, and downstream water availability.
- Climate resilience: Take into account the optimized operations' flexibility to probable climate change scenarios, guaranteeing resilience in the face of unknown future conditions.

b) Economic implications

- Agricultural productivity: Evaluate the economic advantages of optimal irrigation releases on agricultural productivity, taking into account possible changes in crop yields and water-use efficiency.
- Infrastructure costs: Discuss any potential cost consequences associated with infrastructure upkeep or changes necessary to perform the improved reservoir operations.
- Social and economic equity: Think about the socioeconomic ramifications, such as benefit distribution and any potential inequities among various stakeholders.

5.6. Limitations and uncertainties of the TLBO model

a) Sensitivity to initial settings: The TLBO model, like many optimization techniques, may be sensitive to initial settings. Need to explore how differences in beginning solutions might affect convergence and ultimate outcomes, stressing the need of strong initialization procedures.

b) Model calibration and validation: Addressing uncertainties in model calibration and validation is critical. Here need to go over the methodologies utilized for TLBO model and integrated reservoir operating approach calibration and validation, as well as freely addressing errors and their consequences.

c) Parameter sensitivity: Explore the sensitivity of the TLBO algorithm and the integrated reservoir operating model to various factors. Acknowledge the possible impact of parameter settings on optimization outcomes, with a focus on methods to reduce these impacts.

d) Reservoir operations inherent uncertainties: Reservoir operations are inherently unpredictable due to climatic variability and shifting water needs. Look at how this method takes these uncertainties into account and analyze the consequences for the robustness of the suggested reservoir management strategy.

6. CONCLUSION

This study has delved into the optimization of multi-reservoir operations within irrigation systems, employing the TLBO algorithm as a novel approach. The results obtained from this research have unveiled several key insights. Notably, the TLBO model exhibited a remarkable improvement in NBs by 20.24% when contrasted with the LP model. This financial advantage indicates the viability of the TLBO algorithm for optimizing reservoir operations in the context of irrigation, thereby enhancing the overall economic feasibility of such systems. The reliability analysis presented a favorable outcome, particularly in the case of Aji-2 reservoir operations, demonstrating an enhanced capacity to consistently meet irrigation demands. In parallel, resilience analysis pointed to improved bounce-back capabilities for Aji-2, with Aji-3 showing higher resilience during specific years, regardless of the optimization model employed. This implies that the TLBO algorithm can effectively contribute to the robustness and adaptability of reservoir operations in the face of fluctuating conditions. However, vulnerability analysis sounded a cautionary note by highlighting the heightened vulnerability of Aji-3 operations, indicating the potential severity of failures in this specific context. This underscores the importance of further examining and mitigating vulnerabilities in reservoir systems, especially those optimized using the TLBO algorithm. A meticulous performance analysis across multiple reservoir systems corroborated the advantages of the TLBO model, notably improving the operational efficiency of Nyari-2 and Aji-3. Conversely, a 31.61% reduction in performance was noted for Aji-2 when transitioning from the LP model to the TLBO model. This variation in performance underscores the need for tailored optimization approaches based on the unique characteristics and requirements of each reservoir.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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