Performance Measurement on the Existing Operation Pattern of the Multi-Purpose Ladongi Reservoir

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Received: 16 April 2025 | Revised: 31 May 2025 | Accepted: 7 June 2025

 DOI: https://doi.org/10.48084/etasr.11535

ABSTRACT

This study aims to assess the current operational framework of the multi-purpose Ladongi reservoir, which serves various functions including providing 120 L/s of raw water, irrigating 3,600 ha of land, controlling floods, potentially generating 1.3 MW via a Mini Hydro Power Plant, and supporting the tourism sector. The evaluation utilizes measurements of the reservoir's capacity to satisfy various requirements classified by three indexes: reliability, resilience, and vulnerability. The results indicate that the existing framework of the Ladongi reservoir has a reliability of 92.72% with an average deficit ratio of 7% based on 23 years of historical data. Based on the current operational scheme, the reservoir has a fairly high level of reliability and resilience translating to a considerable recovery duration from a failed period. Additionally, the maximum deficit ratio reaches 100% suggesting that in that period the reservoir cannot meet the target despite that the average deficit ratio is small, highlighting the variables that need to be optimized in the operation framework.

Keywords-Ladongi reservoir; optimization; reservoir operation; multi reservoir

I. INTRODUCTION

Effective water resource management remains crucial to address issues between water availability and demand, which can be accomplished through the optimized allocation of the available resources [1]. In this context, water management refers to the control of water resources with a focus on distribution patterns. However, nationwide water resource management presents considerable challenges. The latter intensify with the unpredictable climatic conditions and events [2, 3]. Effective management relies on a factual foundation of system information, processing methodologies, and interpretive analysis [4]. The main objective of water resource management is to address the formulation of water resource supply and demand in critical areas, considering spatial, temporal, environmental, economic, political, and other relevant aspects. Furthermore, water management also involves the reconciliation of all users, water preservation, the related land resources, and having previously ensured that there is enough water for the constantly expanding needs [5].

The limitations in surface water resources, particularly during the dry season, highlight the importance of optimizing the operation and capacity of multi-purpose reservoir systems [6, 7]. Moreover, monitoring the surface water resources in terms of quantity is essential to determine the water availability, assessing the substance load leaving the catchment, and verifying the consumption norms [8]. Consequently, an efficient distribution of water demand is necessary through a system model for optimization. The optimization analysis can provide further insights into the water allocation for each objective function [9].

The order of priority is contained in the Law of the Republic of Indonesia No. 17, 2019 concerning the Water Resources Article 28, paragraph 1. That is, water resources are intended to be utilized in a sustainable manner with the main priority being the fulfillment of water for the basic daily needs of the community. In addition, according to paragraph 2, in the event that there is still sufficient availability of water resources for the needs referred to in paragraph 1, priority should be given to covering the irrigation water needs for small holder agriculture.

The reservoir operation aims to redistribute the water resources, minimize the risk of drought and flooding, and maximize the water utilization, which is guided by the operation pattern [10]. The operation involves a complex decision-making process that seeks to balance various and often conflicting objectives of other reservoir benefits [11]. Similarly, authors in [12] stated that the operating scheme addressed the relationship between the optimal set of releases, reservoir state variables, and hydrological inputs, such as storage and inflow.

The Ladongi reservoir is located in the east Kolaka District southeast Sulawesi. The current raw water allocation of 120 L/s is considered insufficient for the projected population needs for 2024, estimated at 132 L/s. Furthermore, the reservoir provides irrigation water for an area of 2,212 ha and is planned to develop an additional 1,392 ha. Consequently, research into optimizing the Ladongi Reservoir's operation scheme is necessary. Reservoir operations must adhere to the established service priorities, as mandated by existing regulations, and therefore multiple scenarios must be developed [13]. The resulting scenario model will inform the direction of the Ladongi Reservoir's operational policy in both the short and long run. This paper focuses on analyzing the existing operating pattern of the Ladongi Reservoir to support its optimization model.

II. MATERIALS AND METHODS

A. Study Area and Methodology

The Ladongi reservoir is located in the Ladongi District, East Kolaka Regency of southeast Celebes province in Indonesia, as illustrated in Figure 1. It is utilized for: (a) irrigation water supply of 3,604 ha; (b) raw water supply of 120 L/s; (c) mini hydro electrical generation potential of 1.3 MW; (d) tourism; and (e) flood control. The dam reaches a height of 66 m, creating a water surface area of 185.87 ha. The most recent Ladongi's reservoir operation framework is presented in Figure 2. Figure 2 displays the upper reservoir operation boundary (BON A), lower reservoir operation boundary (BON B), Normal Water Level (NWL), and Low Water Level (LWL). The reservoir's scheme is conducted based on a water irrigation supply of 3,604 ha and 100 L/user/day for 70,829 users.

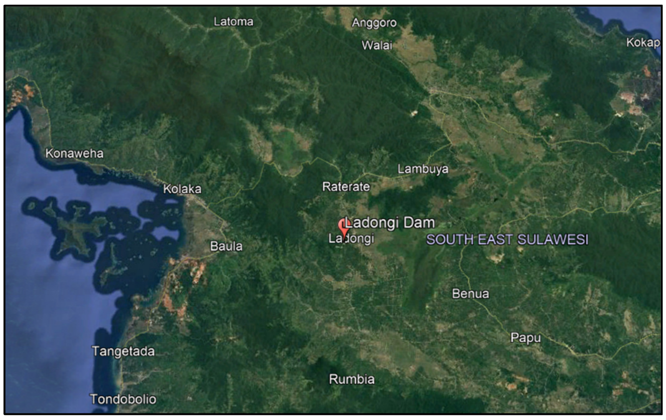

Fig. 1. Location of Ladongi Reservoir in East Kolaka Regency.

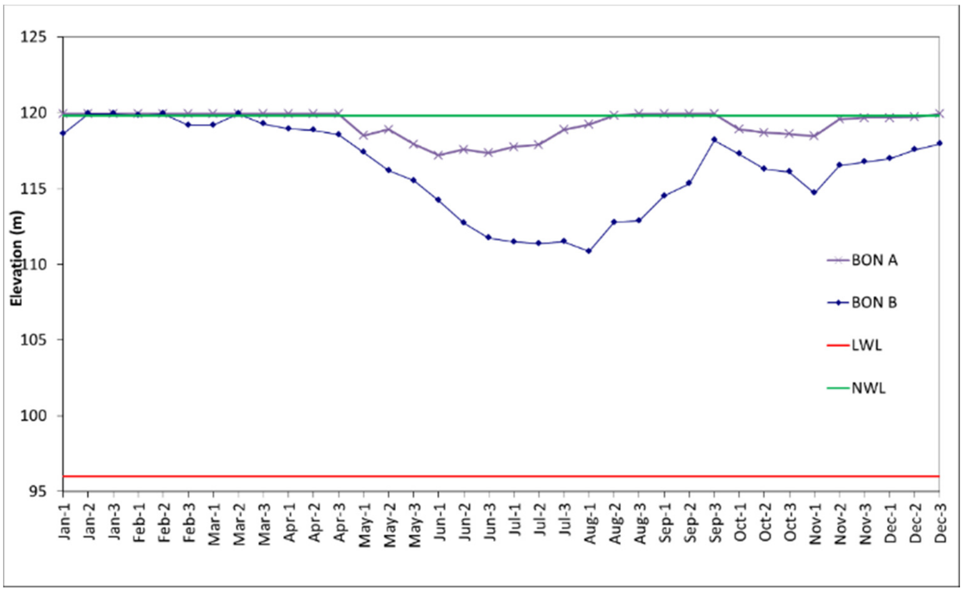

Fig. 2. Existing operation framework of Ladongi reservoir.

The research method deployed to assess the existing scheme of the Ladongi reservoir includes the following methods: (a) method of reliability, (b) method of resilience, and (c) method of vulnerability [14].

B. Method of Reliability

Reliability (Z_t) is an indicator to determine the level of the reservoir ability to meet the demands that are to be achieved. There are two kinds of reliability definitions [15, 17]. The first refers to the instance percentage in which the reservoir can fulfill its needs. The definition of reliability is often related with its failure to address the target demand, as presented in:

$$Z_t = \begin{cases} 1, \text{ for } \mathrm{R_t} \geq \mathrm{D_t} \\ 0, \text{ for } \mathrm{R_t} < \mathrm{D_t} \end{cases} \quad (1)$$

where R_t is the release from the reservoir for period *t* and D_t is the target demand for period *t*.

The second definition considers the average percentage of the reservoir discharge compared to the target demand. Even in the event of the reservoir's supply being unable to meet its demand, the reservoir is not considered a total failure. On the contrary, it is regarded as being able to supply a part of its needs, which is mathematically depicted in:

$$Z_t = \begin{cases} 1, \text{for } \mathrm{R_t} \geq \mathrm{D_t} \\ \frac{\mathrm{R_t}}{\mathrm{D_t}}, \text{for } \mathrm{R_t} < \mathrm{D_t} \end{cases} \quad (2)$$

The long-term reliability (α) for both definitions can be calculated by [17]:

$$\alpha = \lim_{n \to \propto} \frac{1}{n} \sum_{t=1}^{n} Z_t \quad (3)$$

where *n* is the operating time period and $\sum_{t=1}^{n} Z_t$ is the overall time the reservoir can meet its demand.

C. Method of Resilience

Resilience (W_t) measures the ability of a reservoir to return to a satisfactory state from a failed state. The faster the reservoir returns to a satisfactory state, the smaller is the failure. The transition period from a failed state to a satisfactory one is calculated by [15]:

$$W_t = \begin{cases} 1, for\ R_t \geq D_t \text{ and } R_{t-1} < D_t \\ 0, \text{otherwise} \end{cases} \quad (4)$$

The long-term sustainability for the definition above can be calculated by:

$$\rho = \lim_{n \to \infty} \frac{1}{n} \sum_{t=1}^{n} W_t \quad (5)$$

The average period of the reservoir in a continuous failed (T_{failed}) state is formulated in (6) and (7):

$$T_{failed} = \frac{\frac{1}{n}\sum_{t=1}^{n}(1-Z_t)}{\frac{1}{n}\sum_{t=1}^{n} W_t} \quad (6)$$

$$E[T_{failed}] = \frac{1-\alpha_t}{\rho} \quad (7)$$

where $\sum_{t=1}^{n}(1 - Z_t)$ refers to the total number of times that the reservoir fails, ρ is the probability or average frequency, and *E* refers to the "expectation". The clarity (γ) performance is depicted in [18]:

$$\gamma = \frac{1}{E[T_{failed}]} \quad atau \quad \gamma = \frac{1}{T_{failed}} \quad (8)$$

D. Method of Vulnerability

Vulnerability (DEF_t) is a measure of the potential damage and its magnitude in a failure event. Relevant strategies must be adopted to address the low-probability and high-magnitude failure events. Vulnerability can also be defined by system defects that allow attackers to circumvent the security measures [14]. Enhancing system efficiency and reliability can increase vulnerability and lead to costly failures. For example, flood control measures, like reservoirs and levees can create a false sense of security, encouraging development in vulnerable areas and increasing the potential for substantial losses in the event of a major flood or levee breach. To measure the magnitude of a failure, so that the level of vulnerability can be determined, we use [16]:

$$DEF_t = \begin{cases} \mathrm{D_1} - \mathrm{R_t}, \text{if } \mathrm{R_t} < \mathrm{D_t} \\ 0, \text{if } \mathrm{R_t} \geq \mathrm{D_t} \end{cases} \quad (9)$$

Vulnerability can be defined by metrics, such as the average value of deficit ratio, which is defined as the average percentage of shortages where failures occur in certain months and is described by:

$$v_1 = \frac{\sum_{i=t}^{n} \frac{DEF_t}{D_t}}{\sum_{i=t}^{n} W_t} \quad (10)$$

Another metric is the maximum value of the deficit ratio, which is defined as the maximum value of the shortage percentage at which failures occur in certain months, and is described by:

$$v_2 = max_t \left\{\frac{DEF_t}{D_t}\right\} \quad (11)$$

An additional metric is the maximum value of "*deficit*", which is defined as the maximum value of the shortage of the occurrence of failures in certain months, and is described by:

$$v_3 = max_t\{DEF_t\} \quad (12)$$

III. RESULTS AND DISCUSSION

The existing operation framework of the Ladongi reservoir, presented in Figure 2, was evaluated by the simulation of the reservoir operations utilizing 24 years of historical data. To evaluate its performance, the parameters Z_t, W_t, and DEF_t are calculated. Their calculations for 1998 and 2000 are presented in Tables I and II and the performance indicators for all 24 years are summarized in Table III. Table I demonstrates that the framework's reliability is 100% due to sufficient $\mathrm{R_t}$ to fulfill $\mathrm{D_t}$. The indicator W_t is constantly 0, reflecting a zero need for recovery from failure, and DEF_t is also 0, suggesting no recorded deficit.

Table II reveals that in 2000, reliability reached 96% with the minimum Z_t of 0.4 observed on March 3rd. Consecutive failed periods followed from March 1st to April 1st in which W_t returned to 1. Table III and Figure 3 display an inverse relationship between reliability and resilience.

TABLE I. PERFORMANCE INDICATORS OF RESERVOIR OPERATION SCHEME ON 1998

1998	R_t	D_t	Z_t	W_t	DEF_t	DEF_R (%)
Jan-1	29.49	6.65	1.0	0	0.0	0
Jan-2	24.50	7.08	1.0	0	0.0	0
Jan-3	19.84	5.89	1.0	0	0.0	0
Feb-1	15.19	3.72	1.0	0	0.0	0
Feb-2	13.36	4.21	1.0	0	0.0	0
Feb-3	12.10	3.55	1.0	0	0.0	0
Mar-1	9.36	4.41	1.0	0	0.0	0
Mar-2	7.23	4.00	1.0	0	0.0	0
Mar-3	6.44	4.50	1.0	0	0.0	0
Apr-1	5.51	3.09	1.0	0	0.0	0
Apr-2	7.93	4.02	1.0	0	0.0	0
Apr-3	15.28	2.88	1.0	0	0.0	0
May-1	25.83	2.65	1.0	0	0.0	0
May-2	30.23	6.17	1.0	0	0.0	0
May-3	26.92	6.47	1.0	0	0.0	0
Jun-1	31.50	3.39	1.0	0	0.0	0
Jun-2	31.00	2.77	1.0	0	0.0	0
Jun-3	38.14	3.31	1.0	0	0.0	0
Jul-1	38.57	4.09	1.0	0	0.0	0
Jul-2	34.03	4.14	1.0	0	0.0	0
Jul-3	33.94	5.09	1.0	0	0.0	0
Aug-1	31.03	4.63	1.0	0	0.0	0
Aug-2	28.93	4.46	1.0	0	0.0	0
Aug-3	32.42	4.71	1.0	0	0.0	0
Sep-1	32.05	3.50	1.0	0	0.0	0
Sep-2	30.60	2.89	1.0	0	0.0	0
Sep-3	32.07	1.91	1.0	0	0.0	0
Oct-1	37.15	1.94	1.0	0	0.0	0
Oct-2	30.51	2.66	1.0	0	0.0	0
Oct-3	33.51	2.75	1.0	0	0.0	0
Nov-1	36.59	2.55	1.0	0	0.0	0
Nov-2	38.36	2.80	1.0	0	0.0	0
Nov-3	30.58	2.16	1.0	0	0.0	0
Dec-1	28.63	2.38	1.0	0	0.0	0
Dec-2	28.23	3.19	1.0	0	0.0	0
Dec-3	25.71	6.11	1.0	0	0.0	0

TABLE II. PERFORMANCE INDICATORS OF RESERVOIR OPERATION SCHEME ON 2000

2000	R_t	D_t	Z_t	W_t	DEF_t	DEF_R (%)
Jan-1	13.97	6.63	1.0	0	0.0	0
Jan-2	13.95	7.06	1.0	0	0.0	0
Jan-3	12.62	5.87	1.0	0	0.0	0
Feb-1	10.73	3.71	1.0	0	0.0	0
Feb-2	8.86	4.21	1.0	0	0.0	0
Feb-3	4.99	3.55	1.0	0	0.0	0
Mar-1	2.79	4.40	0.6	0	1.6	37
Mar-2	2.83	3.99	0.7	0	1.2	29
Mar-3	1.72	4.49	0.4	0	2.8	62
Apr-1	4.71	3.09	1.0	1	0.0	0
Apr-2	6.84	4.01	1.0	0	0.0	0
Apr-3	8.81	2.87	1.0	0	0.0	0
May-1	11.34	2.64	1.0	0	0.0	0
May-2	12.76	6.15	1.0	0	0.0	0
May-3	14.26	6.45	1.0	0	0.0	0
Jun-1	11.41	3.38	1.0	0	0.0	0
Jun-2	29.97	2.76	1.0	0	0.0	0
Jun-3	43.66	3.31	1.0	0	0.0	0
Jul-1	38.57	4.09	1.0	0	0.0	0
Jul-2	29.13	4.14	1.0	0	0.0	0
Jul-3	31.84	5.09	1.0	0	0.0	0
Aug-1	32.07	4.63	1.0	0	0.0	0
Aug-2	27.77	4.46	1.0	0	0.0	0
Aug-3	25.95	4.71	1.0	0	0.0	0
Sep-1	21.24	3.49	1.0	0	0.0	0
Sep-2	20.71	2.88	1.0	0	0.0	0
Sep-3	20.60	1.90	1.0	0	0.0	0
Oct-1	20.24	1.93	1.0	0	0.0	0
Oct-2	21.89	2.65	1.0	0	0.0	0
Oct-3	21.52	2.74	1.0	0	0.0	0
Nov-1	24.29	2.54	1.0	0	0.0	0
Nov-2	25.05	2.79	1.0	0	0.0	0
Nov-3	25.92	2.15	1.0	0	0.0	0
Dec-1	24.05	2.38	1.0	0	0.0	0
Dec-2	23.45	3.19	1.0	0	0.0	0
Dec-3	21.59	6.10	1.0	0	0.0	0

TABLE III. PERFORMANCE RESERVOIR INDICATOR SUMMARY

Year	α (%)	γ (%)	ν_1 (%)	ν_2 (%)
1998	100	0	0	0
1999	100	0	0	0
2000	96	3	4	62
2001	100	0	0	0
2002	77	3	23	100
2003	88	6	12	95
2004	83	3	17	100
2005	97	3	3	77
2006	79	3	21	100
2007	95	3	5	57
2008	90	3	10	99
2009	82	3	18	100
2010	98	3	2	66
2011	95	6	5	100
2012	97	3	3	74
2013	95	3	5	67
2014	99	3	1	41
2015	82	6	18	100
2016	95	3	5	71
2017	100	0	0	0
2018	100	0	0	0
2019	86	0	14	100
2020	98	6	2	51
2021	100	0	0	0

TABLE IV. PERFORMANCE INDICATORS OF THE EXISTING OPERATION SCHEME

No	Indicator	Score
1	Z_t	92.72%
2	W_t	22.22%
-	Operation Period	828
-	Successful Period	729
-	Failed Period	99
-	Failure to Success Transition	22
-	T_{failed}	4.5
3	DEF_t	-
-	Average deficit (MCM)	0.26
-	Maximum deficit (MCM)	6.46
-	Average deficit ratio	7%
-	Maximum deficit ratio	100%

The overall operation scheme of Ladongi reservoir exhibits a high reliability rate of 92.72%. However, the criticality indicator value of 22.22% indicates a prolonged period of operation in a failed state.

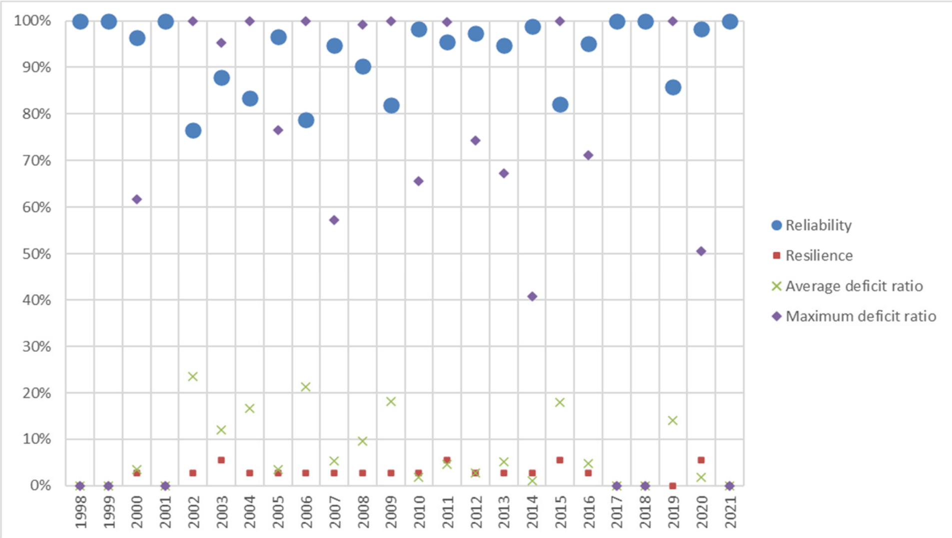

Fig. 3. Performance reservoir indicators per year.

The average deficit ratio value is low at 7% even though there is a maximum deficit ratio of 100%. The performance indicators of the reservoir operation framework are presented in Table III. Table IV depicts the performance indicators of the existing operation pattern of Ladongi reservoir.

IV. CONCLUSIONS

The Ladongi reservoir serves multiple purposes, including providing 120 L/s of raw water, irrigating 3,600 ha of land, managing flood control, offering a potential 1.3 MW mini hydro power plant, and supporting the tourism sector. This research aims to evaluate the reservoir's reliability (Z_t), resilience (W_t), and vulnerability (DEF_t). The performed analysis indicated that the current operating scheme of the Ladongi reservoir demonstrates a reliability of 92.72%, with an average deficit ratio of 7%, based on 24 years of historical data. The Ladongi reservoir exhibits a relatively high level of reliability and resilience under the existing operating pattern.

The current operational framework of the Ladongi reservoir exhibits a reasonably high reliability rate in addition to its high resilience rate, suggesting an extended recovery period following failures. Furthermore, the maximum deficit ratio reaches 100% indicating instances where the reservoir is entirely unable to meet its intended targets despite a small average deficit ratio. These findings reveal the presence of modifiable variables within the Ladongi reservoir's operational framework that could be optimized.

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