submitted: 15.06.2026. *https://doi.org/10.62683/ZRGAF41.7*
corrected: 24.06.2026. *Research paper*
accepted: 26.06.2026.

THERMAL STRATIFICATION AS AN OPERATIONAL INDICATOR FOR MULTIPURPOSE RESERVOIR MANAGEMENT: A SCADA-BASED CASE STUDY OF THE ĆELIJE RESERVOIR

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Abstract

Reservoir thermal stratification is often described as a physical and limnological process, but its direct relevance for day-to-day reservoir operation is less frequently quantified using routinely available monitoring data. This paper investigates whether high-frequency Supervisory Control and Data Acquisition (SCADA) records can be used to identify periods in which thermal stratification becomes operationally significant for the Ćelije multipurpose reservoir in Serbia. The analysis combines hourly water-temperature measurements at six elevations, 255, 265, 268, 271, 274 and 277 m a.s.l., with reservoir level and outflow data for the period September 2022–September 2023. Thermal conditions were quantified using a vertical stratification index, $\Delta T = T277 - T255$, while reservoir operation was interpreted through level–outflow relationships and total discharge intensity. Strong stratification, defined as $\Delta T \geq 10°C$, occurred for 109 days, with a maximum daily value of 17.38°C recorded on 17 July 2023. The longest uninterrupted strongly stratified period lasted 64 days, from 30 June to 4 September 2023. The results show that discharge intensity was primarily governed by reservoir level, but the ΔT index provided essential additional information for identifying periods when increased release coincided with a strongly stratified water column. These operating windows are particularly relevant for assessing outlet use, withdrawal depth and potential thermal effects on released water. The study demonstrates that simple indicators derived from SCADA data can support thermally informed reservoir operation and provide a practical basis for future selective-withdrawal and water-quality assessments.

Key words: *Ćelije Reservoir, SCADA Monitoring, Thermal Stratification, Reservoir Operation, Selective Withdrawal, Water Temperature*

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1. INTRODUCTION

Multipurpose reservoirs are complex hydraulic and water-management systems in which water supply, flood mitigation, environmental flow requirements and water-quality protection must be coordinated within a single operational framework. In stratified reservoirs, vertical temperature differences introduce an additional management dimension because the temperature and quality of withdrawn or released water may depend on the depth, timing and intensity of operation. Consequently, reservoir management cannot rely only on hydrological indicators such as inflow, storage and discharge, but increasingly requires high-frequency thermal observations that can be interpreted in an operationally meaningful way.

Recent studies have demonstrated that high-frequency temperature monitoring can objectively track the temporal evolution of stratification in reservoirs [1] and support near-term reservoir management platforms [2]. Other studies have examined how seasonal operation schemes affect stratification in monomictic reservoirs [3], how reservoir optimization may incorporate thermal regulation [4], and how selective withdrawal can improve in-reservoir and downstream thermal or ecological conditions [5, 6]. In drinking-water reservoirs, vertical thermal and chemical stratification are also directly relevant to dissolved oxygen conditions, nutrient dynamics and treatment requirements [7]. These studies confirm that reservoir thermal structure is both measurable and operationally relevant. However, many existing approaches are either primarily diagnostic, model-based, or dependent on detailed hydraulic and outlet-geometry information. A remaining practical challenge is to convert routinely collected SCADA measurements into a small set of simple indicators that can be used as a first operational screening tool.

The Ćelije reservoir is a strategic component of the Rasina–Pomoravlje regional water-supply system. Previous research on the Rasina River Basin has documented the importance of the reservoir and its catchment for long-term water management, sediment control and storage sustainability [8]. Nevertheless, the operational use of high-frequency temperature, level and outflow data for identifying thermally sensitive reservoir states has not been systematically examined. This makes the reservoir a suitable case study for testing whether existing SCADA records can be transformed from monitoring archives into operationally interpretable indicators.

The novelty of this paper is not the introduction of a new thermodynamic parameter, but the operational coupling of a simple stratification index with reservoir level and outflow indicators. Compared with high-frequency monitoring studies focused mainly on thermal-structure description [1, 2], this study uses ΔT as a management-oriented screening variable. Compared with optimization and selective-withdrawal studies [3–6], the proposed framework does not require a full numerical model as a first step but identifies periods in which such detailed analysis would be most relevant. The practical advantage of ΔT is that it can be calculated directly from routinely available temperature records and interpreted together with discharge intensity. The paper therefore aims to: quantify the duration and intensity of thermal stratification, examine the level–outflow relationship, and identify operating windows in which strong stratification coincides with increased release.

2. METHODOLOGY

2.1. Study Area, Monitoring Data and Data Preparation

The study focuses on the Ćelije multipurpose reservoir on the Rasina River. The analysis was based on time series that directly describe three components of the system: the vertical water-temperature profile, the operational outflow regime and the reservoir level.

Water-temperature data were available at fixed monitoring elevations of 255, 265, 268, 271, 274 and 277 m a.s.l. All elevations are referenced to metres above sea level, while the actual depth of each measurement point below the free water surface varies with reservoir level.

The outflow data included the main evacuator, pipe I, pipe II and the biological-minimum pipe. Daily and hourly reservoir-level information was used to examine the hydraulic-operational context of discharge changes. A schematic representation of the reservoir location, the monitored temperature elevations and the outlet components used in the analysis is given in Figure 1.

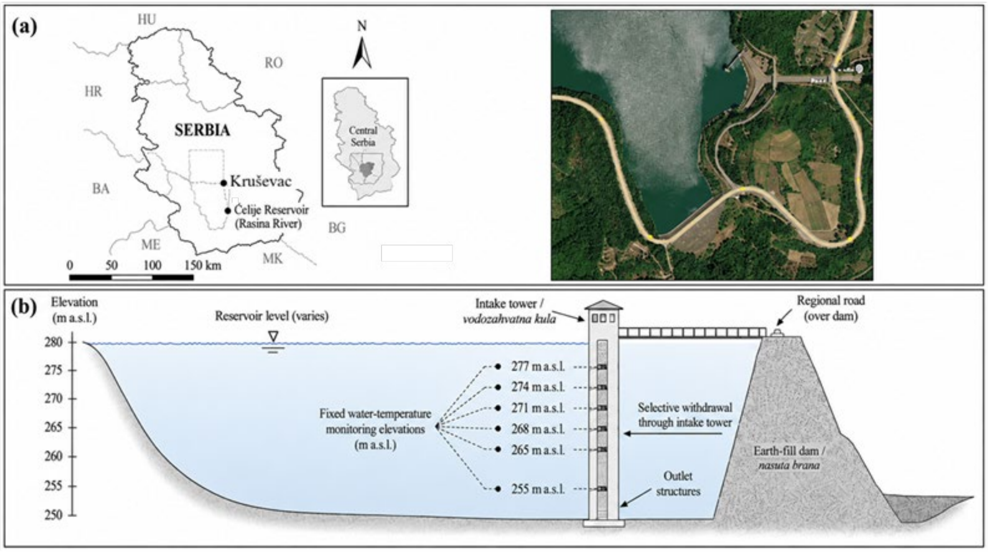

Figure 1. Study area and monitoring scheme of the Ćelije Reservoir: (a) location of the reservoir, aerial view of the dam area; and (b) schematic vertical profile showing water-temperature monitoring elevations, the intake tower and outlet structure

The monitoring data were obtained from the operational SCADA system of the Ćelije reservoir. The reservoir level was recorded using the electronic measuring equipment associated with the intake tower, while outflow components were registered for the main outlet structures and subsequently combined into the total outflow for the operational analysis. Water-temperature measurements were available at fixed monitoring elevations within the reservoir profile, enabling the assessment of vertical thermal differentiation. The intake structure enables withdrawal from several elevations, which makes the relationship between thermal stratification and reservoir operation particularly relevant. Detailed manufacturer specifications and sensor-accuracy data were not available in the analysed dataset; therefore, the study relies on screened operational SCADA records and daily aggregated indicators rather than isolated hourly observations.

Table 1. Data groups used in the analysis

Data group	Temporal resolution	Period	Role in the analysis
Water temperature at elevations 255, 265, 268, 271, 274 and 277 m a.s.l.	Hourly	05/09/2022–30/09/2023	Calculation of ΔT and stratification assessment
Outflow through the main evacuator, pipe I, pipe II and biological-minimum pipe	Hourly	01/09/2022–30/09/2023	Analysis of discharge intensity and outlet structure
Reservoir level	Daily and hourly control series	01/09/2022–30/09/2023	Level–outflow relationship and operational response
Precipitation and inflow	Daily/monthly	2022–2023	Contextual interpretation of increased-release periods

Before the analytical calculations, all hourly SCADA series were converted to a common time axis and screened for missing values, duplicate time stamps, physically implausible values and isolated outliers. Water-temperature observations were retained when they were within the physically plausible range of 0–35°C and when no isolated one-hour spike was detected without support from adjacent records.

Table 2. Summary of data-quality control

Series	Number of time steps	Used/valid time steps	Comment
Reservoir level (SCADA)	9480	8398	Control series; an independent daily level series was used for the level–outflow relationship
Total outflow / outlet components	9480	9459	Hourly outflow components were summed into total outflow
Water temperature at elevations 255–277 m a.s.l.	9480	8640	Basis for the stratification index $\Delta T = T277 - T255$
Daily reservoir level	638	638	Independent daily series used for the level–outflow relationship

Outflow values were required to be non-negative, while reservoir-level observations were checked against the observed operating range of the reservoir. Records failing these criteria, as well as missing observations, were excluded from the corresponding calculation.

After screening, 8640 valid hourly temperature records were retained from 9480 time steps, corresponding to 91.1% data availability. For outflow records, 9459 of 9480 time steps were retained, corresponding to 99.8% data availability. The hourly SCADA level series had 8398 valid time steps, while the independent daily reservoir-level series used for the level–outflow analysis was complete.

This procedure reduced the influence of isolated sensor or communication errors on the calculated stratification and operation indicators.

Data preparation and preliminary inspection were performed in Microsoft Excel, while statistical calculations and graphical visualization were carried out in Python.

2.2. Thermal stratification index

The basic stratification indicator was defined as the temperature difference between the upper measurement elevation and the deeper measurement elevation:

$$\Delta T = T_{277} - T_{255} \quad (1)$$

where:

- T_{277} – the water temperature at elevation 277 m a.s.l. (°C),
- T_{255} – the water temperature at elevation 255 m a.s.l. (°C), and
- ΔT – the vertical temperature difference used as the stratification index (°C).

A larger positive value of ΔT indicates stronger thermal differentiation between the upper and deeper part of the monitored water column.

For interpretation, four ΔT classes were defined as empirical operational classes for the analysed dataset: isothermal or weak stratification, $\Delta T < 2°C$; transitional state, $2°C \leq \Delta T < 5°C$; moderate stratification, $5°C \leq \Delta T < 10°C$; and strong stratification, $\Delta T \geq 10°C$.

These thresholds are not proposed as universal limnological boundaries, but as practical screening classes for separating near-mixed conditions from progressively stronger vertical thermal differentiation. The $\Delta T < 2°C$ class represents conditions in which vertical temperature differences are small for operational interpretation. The 2–5°C and 5–10°C classes describe transitional and developed stratification, respectively. The $\Delta T \geq 10°C$ threshold was selected to identify strongly stratified conditions in which different withdrawal or release elevations could plausibly be associated with substantially different water temperatures. Therefore, the thresholds are used as operational screening criteria rather than regulatory limits.

The threshold $Q > 20$ m³/s was selected empirically as an increased-release criterion. In the screened hourly dataset, this threshold corresponds approximately to the upper 10.5% of outflow observations and is substantially higher than routine release values observed during the most frequent operating-level class. Its purpose is to distinguish ordinary release conditions from operating states in which discharge intensity is high enough for the thermal consequences of outlet use to become operationally relevant. The threshold is therefore used as a screening value for identifying thermally sensitive operating windows, while sensitivity to alternative discharge thresholds should be examined in future applications.

Accordingly, both $\Delta T \geq 10°C$ and $Q > 20$ m³/s should be interpreted as preliminary screening criteria and decision-support indicators, rather than as validated operational guidelines. Reservoir operation was examined using three indicators:

1. the relationship between daily reservoir level and total outflow through outlet structures,
2. the variation of total outflow across reservoir-level classes and
3. an operational matrix combining the stratification index with total outflow.

Days with $\Delta T \geq 10°C$ and $Q > 20$ m³/s were treated as thermally sensitive operating windows. These windows do not by themselves define an operational guideline but identify situations in which outlet selection and withdrawal depth may need to be interpreted together with the thermal profile.

3. RESULTS

3.1. Temporal dynamics of water temperature and stratification

After data-quality screening, daily values of the ΔT index were available for 373 days.

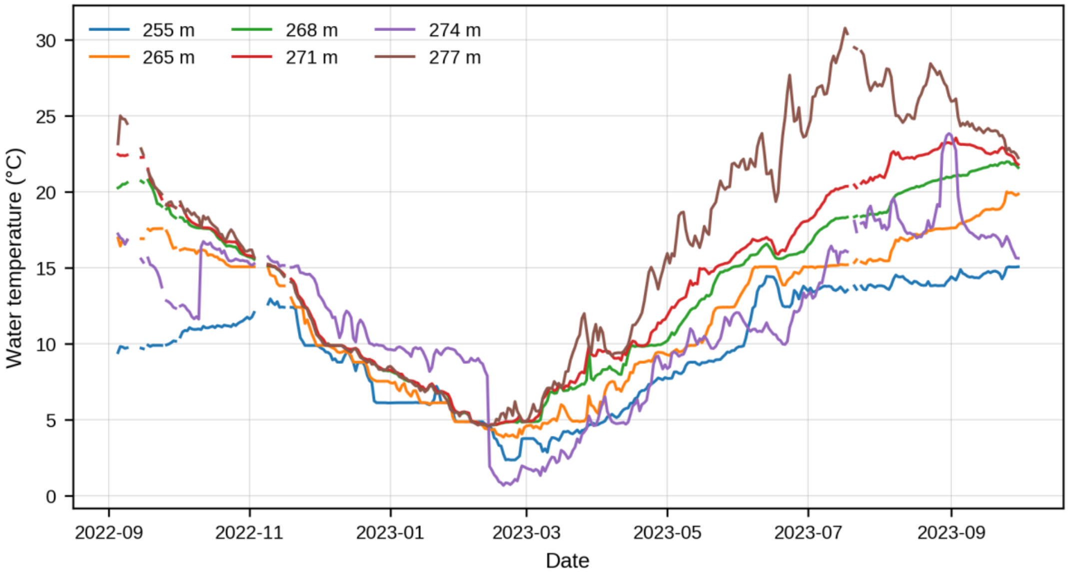

Figure 2. Temporal evolution of daily mean water temperature at six monitoring elevations, 255–277 m a.s.l., in the Ćelije Reservoir during September 2022–September 2023

Figure 3. Daily stratification index ΔT = T277 − T255, with threshold lines indicating moderate stratification, ΔT = 5°C, and strong stratification, ΔT = 10°C

The mean value of ΔT over the analysed period was 6.76°C, while the maximum daily value was 17.38°C on 17.07.2023. The maximum hourly value was 19.54°C and was recorded on 17.07.2023 at 20:00. These values indicate a clearly developed seasonal thermal structure, particularly during the summer period of 2023. Strong stratification, defined by ΔT ≥ 10°C, occurred for 109 days. In total, 221 days had ΔT ≥ 5°C, indicating that a substantial part of the warm season was characterized by the vertical thermal differentiation. The longest continuous period of strong stratification lasted 64 days, from 30.06.2023 to 04.09.2023.

Table 3. Duration of thermal stratification classes based on the daily ΔT index

Stratification class	Days	Share (%)	Mean ΔT (°C)	Range ΔT (°C)
Isothermal/weak (<2°C)	83	22.3	0.79	-0.47–1.96
Transitional (2–5°C)	69	18.5	3.30	2.02–4.98
Moderate (5–10°C)	112	30.0	7.66	5.12–9.98
Strong (≥10°C)	109	29.2	12.57	10.03–17.38

3.2. Relationship between reservoir level and total outflow

The operational analysis shows that total outflow increases at higher reservoir levels.

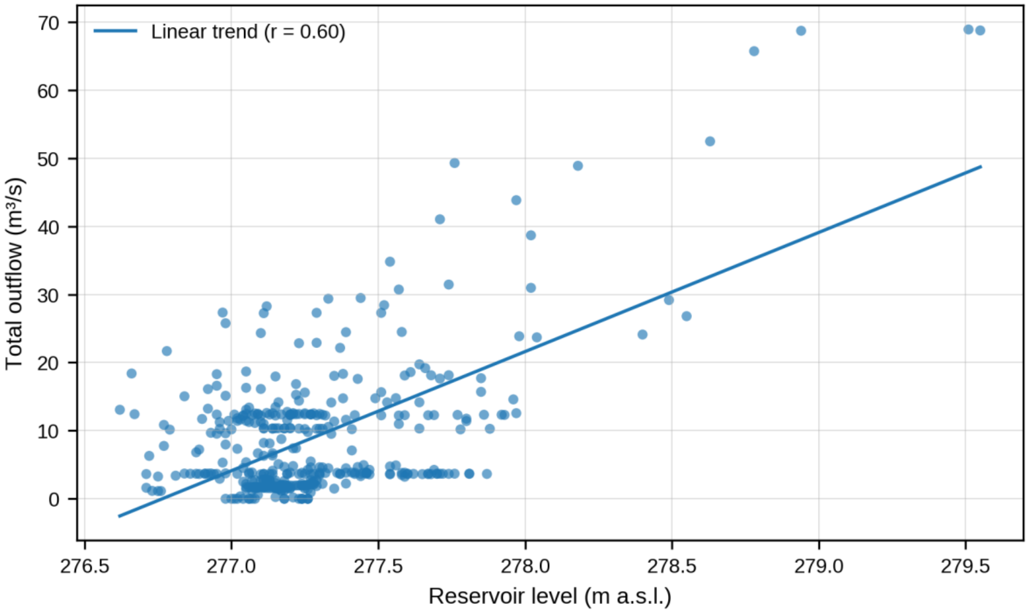

Figure 4. Relationship between daily reservoir level and total outflow through outlet structures, illustrating the operational dependence of discharge on reservoir storage conditions

At the daily scale, the relationship between reservoir level and total outflow was statistically significant. Using 395 matched daily observations, the Pearson correlation coefficient was $r = 0.60$, with a 95% confidence interval of 0.53–0.66 and $p < 0.001$.

The Spearman rank correlation coefficient was $\rho = 0.28$, with an approximate 95% confidence interval of 0.19–0.37 and $p < 0.001$.

The difference between the Pearson and Spearman coefficients indicates that the relationship is not purely monotonic across the full range of operation. Instead, more intensive release is concentrated in higher-level zones, suggesting threshold-like operational behaviour.

Table 4. Total outflow through outlet structures by reservoir-level class

Level class (m a.s.l.)	Days	Mean Q (m³/s)	Median Q (m³/s)	Max. Q (m³/s)
<277.0	50	8.60	7.49	27.33
277.0–277.5	268	6.50	3.67	29.47
277.5–278.0	65	13.13	12.25	49.28
≥278.0	12	45.56	43.77	68.88

The results in Table 4 indicate threshold-like operational behaviour. In the most frequent level zone, 277.0–277.5 m a.s.l., mean total outflow was 6.50 m³/s. When the reservoir level exceeded 278.0 m a.s.l., mean total outflow increased to 45.56 m³/s, with a median value of 43.77 m³/s. This confirms that discharge intensity was primarily activated as a response to the reservoir-level increase.

Figure 5 combines the two screening dimensions used in this study. The x-axis represents the daily stratification index ΔT, while the y-axis represents the daily total outflow. The vertical dashed line at ΔT = 10°C separates strong stratification from lower stratification classes, whereas the horizontal dashed line at Q = 20 m³/s separates routine from increased-release conditions.

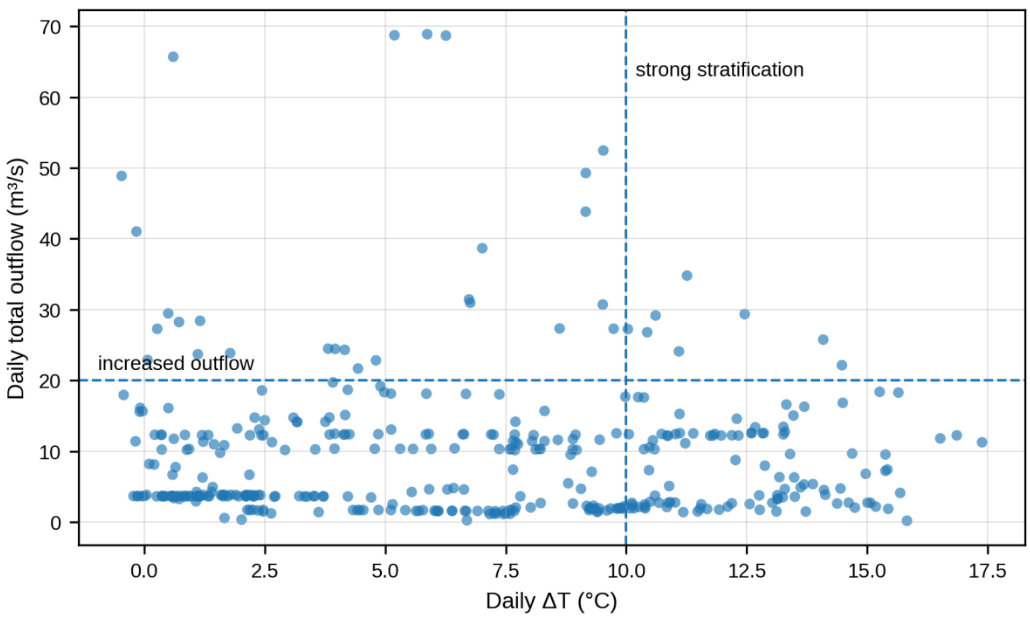

Figure 5. Operational matrix linking daily stratification intensity, represented by ΔT, and daily total outflow, with threshold lines defining strong stratification and increased-release conditions

The upper-right quadrant therefore represents thermally sensitive operating windows, where a strong vertical thermal differentiation occurs simultaneously with an increased discharge.

These points do not define a validated operating guideline, but identify periods in which the outlet selection, withdrawal elevation and released-water temperature may be evaluated with additional attention.

The strength of stratification did not directly determine the amount of the released water. The hourly relationship between ΔT and the total outflow was weak, which is consistent with the fact that discharge decisions are primarily driven by hydrological and operational needs. Nevertheless, stratification changes the interpretation of operational consequences: the same outflow could lead to different thermal and water-quality outcomes under isothermal conditions and under a strong vertical thermal differentiation.

Under the strong stratification, 242 hours with Q > 20 m³/s were recorded. At the daily scale, 8 days were identified in which the strong stratification and increased outflow occurred simultaneously. These days represent the most relevant operating windows for thermally informed management.

Table 5 summarizes total outflow statistics by stratification class using hourly data.

The results indicate that the frequency of increased outflow, defined as Q > 20 m³/s, was relatively similar across ΔT classes, confirming that the stratification intensity did not directly control the discharge quantity.

Table 5. Total outflow by stratification class based on hourly data

ΔT class	Hours	Mean Q (m³/s)	Median Q (m³/s)	Max. Q (m³/s)	Hours with Q > 20 m³/s
Isothermal/weak (<2°C)	2025	9.66	3.71	67.63	226 (11.2%)
Transitional (2–5°C)	1550	9.73	6.97	69.75	162 (10.5%)
Moderate (5–10°C)	2581	10.65	9.45	69.88	278 (10.8%)
Strong (≥10°C)	2460	9.21	4.90	117.07	242 (9.8%)

Table 6 lists the days identified as thermally sensitive operating windows, defined as days when the strong stratification, ΔT ≥ 10°C, coincided with an increased total outflow, Q > 20 m³/s.

Table 6. Days with simultaneous strong stratification and increased outflow

Date	ΔT (°C)	Total Q (m³/s)	Level (m a.s.l.)	Dominant outlet component
04/06/2023	11.09	24.11	278.40	main evacuator
05/06/2023	10.43	26.80	278.55	main evacuator
06/06/2023	10.61	29.17	278.49	main evacuator
11/06/2023	10.03	27.25	277.11	main evacuator
20/06/2023	11.26	34.80	277.54	main evacuator
21/06/2023	12.46	29.36	277.33	main evacuator
22/06/2023	14.09	25.76	276.98	main evacuator
05/08/2023	14.47	22.15	277.37	main evacuator

Table 6 is important for practical interpretation because it identifies the intersection of two operationally relevant conditions: strong thermal differentiation and increased release. During such periods, the outlet selection and the depth of withdrawal or release may have a greater influence on the temperature of released water and on the stability of the reservoir thermal regime.

Figure 6 provides a time-based example of the level–outflow response during June 2023. Unlike Figure 3, which presents the general statistical relationship between level and outflow, Figure 6 illustrates how short-term changes in reservoir level were followed by changes in total outflow during an increased-release period.

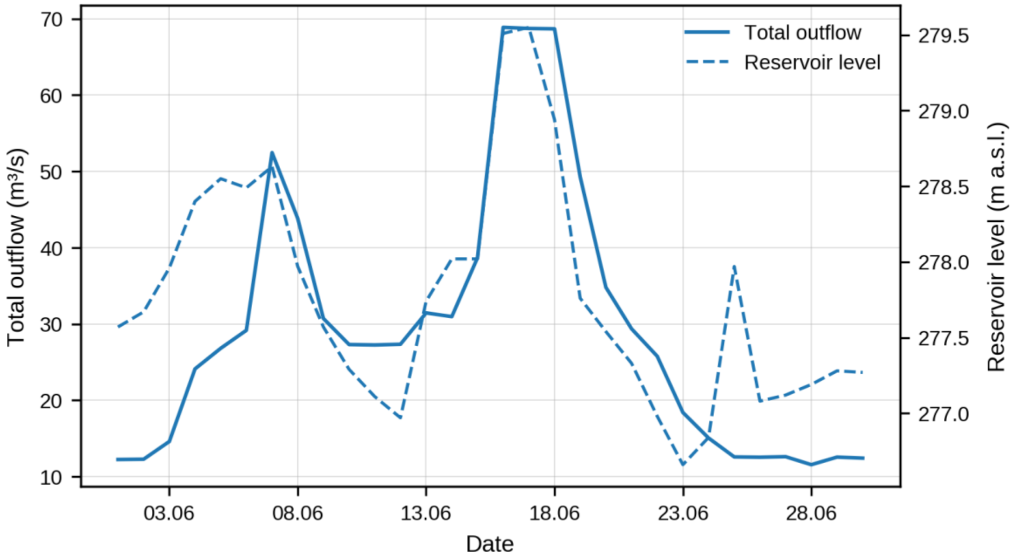

Figure 6. Example of the operational response in June 2023, showing the temporal relationship between total outflow and reservoir level during an increased-release period

4. DISCUSSION

The results show that the operation of the Ćelije reservoir can be interpreted through two complementary dimensions: a hydraulic-operational dimension, represented by reservoir level and total outflow, and a thermal dimension, represented by vertical temperature differentiation. Compared with studies that use high-frequency measurements primarily to reconstruct or classify the thermal structure [1, 2], the present framework uses the thermal signal as an operational screening variable. Its purpose is not to replace the detailed thermal modelling, but to identify periods when reservoir operation should be evaluated not only in terms of discharge quantity, but also in terms of possible thermal consequences.

The operational relevance of this approach is consistent with previous studies showing that reservoir operation schemes can modify the onset, strength and duration of stratification [3, 4], while selective withdrawal can influence both in-reservoir thermal structure and downstream water-temperature conditions [5, 6]. The difference is that the present study does not start from an optimization model or a predefined selective-withdrawal configuration. Instead, it proposes a preliminary screening step: identifying when the thermal state of the reservoir is strong enough, and the release intensity high enough, for selective withdrawal or outlet-depth analysis to become operationally important.

For drinking-water reservoirs, the practical significance of strong stratification extends beyond the water temperature alone. Previous studies have shown that a persistent thermal separation can affect the dissolved oxygen distribution, internal nutrient cycling, chemical stratification and the vertical variability of raw-water quality [7]. In such conditions, the same discharge rate could lead to different thermal and water-quality outcomes depending on the depth from which water is withdrawn or released. Therefore, the identification of strongly stratified and increased-release periods may support enhanced monitoring, interpretation of raw-water quality observations and the assessment of whether selective withdrawal could improve operational flexibility.

The most important finding is not merely the existence of stratification, but its persistence and overlap with the increased outflow. During summer 2023 the reservoir remained strongly stratified over a long continuous period, while several days with increased release occurred under strongly stratified conditions.

This supports the use of a simple operational screening criterion: when ΔT ≥ 10°C, increased release may be interpreted together with information on the depth and type of outlet being used.

International literature on the selective withdrawal and water-temperature management shows that different intake or outlet elevations can produce different thermal responses in the reservoir and in downstream reaches [3–6].

The present study does not prescribe the optimal outlet configuration for the Ćelije reservoir because detailed intake elevations, bathymetry, vertical water-quality profiles and released-water temperature measurements were not included in the analysis.

However, this limitation also defines the practical relevance of the work: existing SCADA data are sufficient to identify when the thermal criterion should become part of the operational decision-making.

4.1. Operational interpretation of ΔT–Q classes

- When ΔT < 5°C, the water column may be considered weakly to moderately thermally differentiated, and the operational relevance of the vertical temperature profile is relatively lower.
- When 5°C ≤ ΔT < 10°C, the trend of the index may be monitored as an indication that the reservoir is entering a state of moderate stratification and increased thermal sensitivity.
- When ΔT ≥ 10°C, the reservoir may be considered strongly stratified; increased release can therefore be interpreted together with outlet depth and the expected temperature of released water.
- When ΔT ≥ 10°C and Q > 20 m^3/s occur simultaneously, the period may be treated as a thermally sensitive operating window, representing a condition in which enhanced monitoring and additional operational attention may be beneficial.

The identified operating windows are interpreted as decision-support indicators rather than direct prescriptions for the outlet operation. During such periods, reservoir operators may verify which outlet or intake structure is active, compare its elevation with the observed thermal profile and increase attention to released-water temperature where such monitoring is available.

If several outlet levels are available, the ΔT–Q matrix can help prioritize when selective-withdrawal decisions may be most relevant. If outlet geometry is fixed or unknown, the same matrix still has practical value because it indicates when additional monitoring of released-water temperature and water-quality variables may be prioritized.

4.2. Limitations

The results should be interpreted in relation to several limitations. First, the ΔT index is calculated from two measurement elevations, 277 and 255 m a.s.l., and therefore does not describe the full thermal stability of the water column or the exact position of the thermocline. A complete stability analysis would require bathymetry, density profiles and a more detailed vertical temperature structure. Second, the analysis does not include the exact elevations, hydraulic characteristics or operating rules of all intake and outlet structures. For this reason, the study identifies thermally sensitive operating windows, but does not prescribe an optimal outlet configuration. Third, released-water temperature and vertical water-quality variables, such as dissolved oxygen, nutrients or algal indicators, were not available. The findings should therefore be understood as an operational assessment of SCADA monitoring potential and as a first step toward more detailed thermohydrodynamic and selective-withdrawal analysis.

Consequently, the proposed ΔT–Q approach should be regarded as a preliminary decision-support tool and not as a substitute for site-specific operating rules or detailed thermohydrodynamic modelling.

5. CONCLUSIONS

This study demonstrates that routinely collected SCADA data can be transformed into a practical screening framework for thermally informed reservoir operation. The main contribution is the coupling of a simple vertical thermal indicator with reservoir level and outflow variables, rather than treating temperature profiles and discharge records as separate monitoring datasets.

The results for the Ćelije reservoir confirm that the strong summer stratification represents an important seasonal management condition. Although the total outflow was primarily governed by reservoir level, the stratification index provided additional information for identifying periods when release decisions may have increased the thermal relevance. The overlap between the strong stratification and increased outflow defines operating windows in which outlet selection, withdrawal depth and released-water temperature should be considered together with discharge quantity.

The proposed framework is intentionally simple and transferable. It can be applied to other reservoirs where multilevel temperature measurements, reservoir level data and outflow records are available, even before a full thermohydrodynamic model is developed. In practical terms, the approach can support enhanced monitoring, prioritization of selective-withdrawal assessment and improved interpretation of water-temperature conditions and related water-quality observations during stratified periods.

Future research should integrate bathymetry, intake and outlet elevations, vertical water-quality profiles and direct measurements of released-water temperature. Such data would allow the proposed screening approach to be further developed toward quantitative decision-support procedures for selective withdrawal and thermally informed reservoir management.

SUSTAINABLE DEVELOPMENT GOALS

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ACKNOWLEDGEMENT

This research was supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia, under the Agreement on Financing the Scientific Research Work of Teaching Staff at the Faculty of Civil Engineering and Architecture, University of Niš - Registration number: 451-03-34/2026-03/200095 dated 05/02/2026.

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