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Decision support system for selective withdrawal in water supply reservoirs: an approach based on thermal stratification

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ABSTRACT

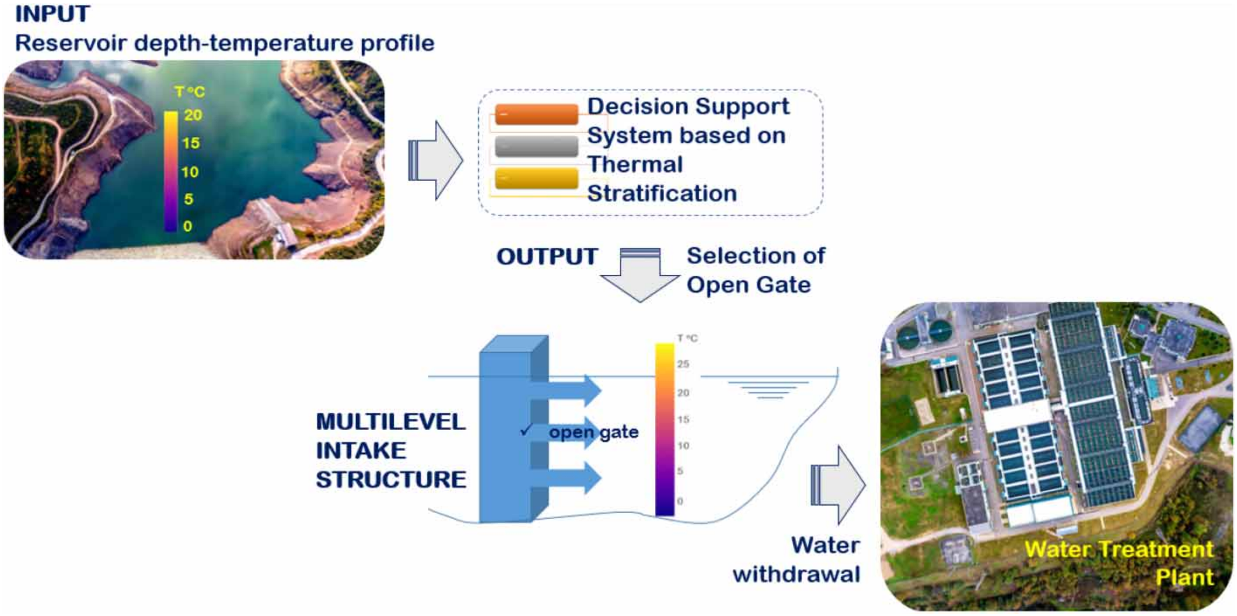
We consider the problem of determining water withdrawal depth in water supply reservoirs with multilevel intakes in an effective and systematic manner. In the traditional way, operators decide which intake port to use based on their own experience and water samples taken from various depths. Our goal is to provide assistance to operators in the decision-making process and establish a systematic approach for determining the appropriate water withdrawal level in a stratified reservoir. To achieve this, we propose an algorithmic approach as a decision support system for estimating the water withdrawal level. We validate our approach using long-term data collected from a water supply reservoir and compare the results with those of the operator's decisions. The results reveal that when the depth tolerance is set to 10 m, the approach and operator's decisions match at an 80% rate. However, when the depth tolerance is increased to 15 m, the matching percentage improves to over 90%.

Key words: decision support system, selective withdrawal, thermal stratification, water inlet structure, water quality, water supply reservoirs

HIGHLIGHTS

- A new approach was designed to act as a decision support system for selective withdrawal in stratified water supply reservoirs.
- The system takes a depth-temperature profile as input and automatically determines the location of thermal stratification, which is used to recommend the depth of water withdrawal to the operator.
- The approach was validated using long-term (22 years) data collected from Yuvacık Reservoir in Turkey.
- The consistency of withdrawal depths determined by the approach and the operator was investigated.
- The depth decisions made by the approach comply with the operator's decision up to 90%.

GRAPHICAL ABSTRACT



INTRODUCTION

Reservoirs are artificial lakes built to store water. These standing water basins are usually formed by constructing dams across rivers. Besides being constructed for supplying drinking and potable water, reservoirs are also used for the generation of hydroelectric power and water storage for irrigation or flood protection. Storing water in a dam causes some physical, chemical, and biological changes in its quality (AWWA 2010, 2011; Raven *et al.* 2012). Winton *et al.* (2019) summarize the physical, chemical, and ecological effects of damming on water quality under two main groups: (i) stratification-related effects and (ii) effects observed due to the trapping of sediment. Thermal stratification and mixing patterns are observed in a lake or reservoir annually. This physical process is governed by warming and cooling cycles due to incoming solar energy and the variability of water density. As a result of thermal stratification, vertical movement in water is restricted and three layers are observed: (i) epilimnion layer: warm, less dense water near the surface, (ii) hypolimnion layer: cooler, denser deep layer, and (iii) thermocline or metalimnion: the transitional zone between the surface and the bottom layers.

Water quality parameters can significantly vary in types and concentrations depending on the depth of water in the reservoir. Their relative importance and effects are also determined by seasonal changes, especially in thermal stratification periods. Stratification alters the thermal regime and prevents the mixing of epilimnetic and hypolimnetic waters, which results in (i) depletion of dissolved oxygen in bottom layers (hypoxic stress), (ii) increase in algal growth (eutrophication), and (iii) presence of toxic and/or negative effects due to increased concentrations of reduced compounds such as hydrogen sulfide, iron, and manganese (Lewis & Edelmann 1994; Winton *et al.* 2019). Constituents are likely to be present throughout all the depths of the reservoir during turnover periods, i.e. when the reservoir is completely mixed.

Assessments regarding water withdrawn from water supply reservoirs are crucial in delivering adequate quantities of water in the best available quality. Although water taken is treated at the plant, the location of withdrawal or selected depth determines the number of chemicals needed and directly affects treatment processes and operational problems. This could be more significant if the reservoir has a high hydraulic residence time and is at risk of nutrient inflow due to agricultural eutrophication (Ashby & Kennedy 1999). Wastewater originating from domestic or industrial sources, as well as water with high salinity such as brine from desalination systems, may be released into the ocean following advanced treatment. Failure to implement advanced treatment methods can result in the effluent from these treatment plants significantly degrading the quality of the receiving water body. In order to keep the negative effects on water resources at the lowest level and to determine the financial investments required, various alternatives such as advanced methods for treating pollutants, minimal liquid discharge, and zero liquid discharge are studied in the literature (Panagopoulos 2022a, 2022b).

The treatment train for a conventional surface water treatment plant includes aeration, pre-oxidation, and pH adjustment, coagulation–flocculation–sedimentation, granular filtration, and disinfection processes. The fundamental parameters considered in these treatment processes are turbidity and color, taste and odor, algae count, iron and manganese, pH, dissolved oxygen, and volatile constituents (Crittenden *et al.* 2012).

Utilities capable of depth profiling have operational flexibility since the data collected with depth sampling assist operators in the selection of optimal depth for the intake. Flexible operation considerations are based on reservoir stratification, physical and chemical water quality process parameters, algae count and blooms, and trihalomethane formation potential together with raw water chlorine demand (Davis *et al.* 1987; Qasim *et al.* 2000; AWWA-ASCE 2005). Turbidity is among the water quality parameters monitored during depth-wise measurements. Winton *et al.* (2019) evaluate several turbidity control mechanisms to prevent New York City's drinking water reservoir system from experiencing high levels of turbidity during extreme storms. These control mechanisms include (i) enhancing the multilevel intake capability at the existing basin intakes and (ii) constructing a new multilevel intake downstream of the current intake location to allow for selective diversion of the highest-quality water. Since the reservoir has high-quality water, the system does not add any chemicals under normal conditions. However, when turbidity increases with precipitation, the system adds alum to achieve treatment objectives. The control mechanism with multilevel intake was found to provide approximately a 15% reduction in the number of alum days. The analysis of water quality at various depths can aid in mitigating the deterioration of taste and odor. Such parameters are often a result of the metabolites and toxins produced by cyanobacteria cells. The identification of depths with low cyanobacterial levels is crucial in developing an operational response, where water withdrawal is conducted at different depths (Chinyama *et al.* 2016). Elçi (2008) performed a vertical profiling of eight distinct water quality parameters in a drinking water lake, evaluating variations in these parameters across different layers and assessing their interrelationships. The lake's stratification was analyzed via non-dimensional parameter analysis.

These studies have revealed that treatment plant operators must consider various parameters when selecting the depth from which water is extracted for treatment. However, determining the optimal depth can be challenging due to the plant's continuous operation. There are studies focusing on developing approaches using scenario-based models to investigate the effects of abstracting raw water from varying levels (such as the deepest region or the bottom of the dam) or from varying levels of different reservoirs on water quality as well as on the problems observed during operation of the treatment plant and its processing costs (Slavik *et al.* 2013; Bertone *et al.* 2018). These studies have led to the understanding that conducting detailed hydrological–ecological modeling and simulation is necessary to accurately evaluate water withdrawal depth. Furthermore, artificial neural network-based modeling is employed, incorporating past usage of various chemicals and dosages under differing conditions by the company, to determine depth assessments along with cost calculations. Çalışkan & Elçi (2009) stated that a one-dimensional model was insufficient and a three-dimensional numerical model was used to investigate the effects of selective withdrawal on the hydrodynamics of a stratified reservoir. Separate simulations were carried out for four different water withdrawal depths of the lake and the depth which encourages vertical mixing the most was suggested. They did not specifically recommend what elevation of water should be taken at any given time. In another study, aiming both to provide warmer water downstream and to avoid anoxia in the deep hypolimnetic layer, Weber *et al.* (2017) employed a one-dimensional General Lake Model (GLM). The fate of contaminants entering into the reservoir during an accident or a spill may be serious and different operating practices depending on whether the lake is stratified are required (Jeznach *et al.* 2016). According to Jeznach *et al.* (2016), developing hydrodynamic and water quality models for water resources at risk of contamination can help to prepare for operational approaches and measures. However, our proposed approach in this study is simpler and does not require a lake model or complex inputs. Instead, it entails determining the presence and degree of stratification via temperature measurements performed along the lake's depth and then recommending a water withdrawal depth based on these measurements.

Determining the temperature stratification of a lake is crucial due to its impact on water quality. For instance, in a lake utilized as a drinking water source, in situ monitoring of chlorophyll-a profiles has revealed that the concentration of chlorophyll-a is highest in the upper gate located immediately below the photic zone, while the middle and lower gates (hypolimnion) exhibit low and consistent concentrations (AWWA 2010). Similarly, Barbiero *et al.* (1997) aimed to reduce phytoplankton populations in a water supply reservoir via entrapping phosphorus in the hypolimnion by strengthening thermal stratification or removing algae from the water body by discharging epilimnetic water. Selective water withdrawal from hypolimnion, especially during summer months with thermal stratification taking place, surpasses the negative effects of increased dissolved solids, nutrients, and metal concentrations such as iron and manganese (Lewis & Edelmann 1994;

Benskin & Linder 2004). Withdrawing water hypolimnion or epilimnion also has an important effect on the coagulant dosage required for coagulation. For instance, Benskin & Linder (2004) demonstrate that, at the beginning of early spring months, the required alum dosage when water is taken from hypolimnion becomes half of the dosage used when water is taken from epilimnion. Furthermore, since water is supplied from under the photic zone, the organic matter load is lowered and chlorine demand is reduced. The coagulant dosage used for treatment is decreased because of stable algae and chlorophyll-a levels and this allows the filter operating times to be extended in the plant. High-quality hypolimnetic water withdrawal is continued until the dissolved oxygen levels decrease dramatically. When anoxic conditions occur and Mn values start to increase, the utility decides to blend epilimnetic and hypolimnetic water by daily monitoring Mn values. In raw water, the maximum Mn concentration is kept around 0.15 mg/L with this operating mode.

Identifying an optimal withdrawal strategy is of great significance in terms of long-term operational concerns and reservoir management, as well as minimizing the environmental impacts when water is taken from a certain level and released to a downstream river. Thermal simulation models were studied to meet downstream water temperature objectives (Fontane *et al.* 1981). Dortch & Holland (1984) utilized a model that solely assesses intake level to achieve the desired downstream temperature from a reservoir. They concluded that this technique could be valuable for those involved in hydraulic design. In these studies, while the temperature stratification is calculated by modeling, in our study, thermal stratification is determined over the real water temperatures monitored *in situ* along the depth.

All these studies given above reveal that decisions for the overall treatment should start from the very start of the water intake. One of the important decisions is to choose the depth of water withdrawal if the reservoir has multilevel intake ports.

The aim of this study is to develop a new approach that can aid in the decision-making process for determining water withdrawal depth and ensuring the supply of high-quality water to drinking water treatment plants via the open gate in the intake structure. The main contributions of the paper include the following:

- Developing an algorithmic approach as a decision support system for recommending water withdrawal elevation,
- Validating the approach using long-term data collected from a water supply reservoir,
- Comparing the approach with the decisions made by the operator.

METHODS

In this section, we explain an algorithmic approach developed for determining the depth from which water is supplied to the treatment plant. We then apply this approach to a real-world case.

Decision-making in operation: an algorithmic approach

We develop an algorithmic approach to the problem of determining the location of thermal stratification and recommending depth for water withdrawal. The approach is outlined in Algorithm 1. The approach requires as inputs (i) an array (*Temp_List*), which contains water temperatures measured at all consecutive depths from the reservoir and (ii) a temperature threshold (*Temp_Threshold*) for determining whether there occurs thermal stratification. Thermal stratification is the marked layering, characterized by how far light penetrates, and it results in an abrupt temperature transition occurring between the upper warm layer and the bottom cold layer (Raven *et al.* 2012).

The first step is to detect if thermal stratification has occurred for a given day. For this purpose, we assume that if the difference between the minimum and maximum temperature values is greater than the temperature threshold *Temp_Threshold*, then a thermal stratification exists. The idea behind the selection of this threshold is based on the generally accepted profile of temperature variation by depth in temperate lakes. Once the stratification is detected, the mean temperature across the overall depth is calculated (*Strafication_MidPoint_Temp*).

In the next step, the two separate average temperature values, *Stratification_UpperLevel_Temp* and *Stratification_LowerLevel_Temp*, are found for the zone above the temperature *Strafication_MidPoint_Temp*, and for the zone below the temperature *Strafication_MidPoint_Temp*, respectively.

Subsequently, the nearest depths corresponding to these temperature averages are assigned as *Stratification_UpperLevel* and *Stratification_LowerLevel*. *Stratification_LowerLevel* is chosen as the depth at which the temperature is closest to and just above the temperature *Stratification_LowerLevel_Temp*.

Some of the water quality constituents gradually increase over the stratification season since they accumulate in the lower depths (hypolimnion/stagnant zone) of the reservoir. However, when the stratification is broken in winter, top layers are enriched in nutrients from hypolimnion, full circulation occurs, and an almost uniform distribution of chemical and biological water quality parameters is observed throughout the overall depths. Therefore, during the stratification season, it is important to implement an effective and timely withdrawal of some constituents such as Fe and Mn, algae and phytoplankton, phosphorus, and other water quality parameters (Casamitjana *et al.* 2003; Bertone *et al.* 2015).

As a result, Algorithm 1 returns the boundaries of thermocline (transition zone comprising water layer in which water temperature changes rapidly) as:

- *Stratification_UpperLevel*: Depth corresponding to the bottom of the warm-water layer standing at top of the reservoir, i.e bottom level of epilimnion,
- *Stratification_LowerLevel*: Depth representing the top level of the cold-water layer lying at the bottom of the reservoir, i.e top level of hypolimnion. Regarding the discussion outlined above, we choose the *Stratification_LowerLevel* as the recommended depth for water withdrawal.

Algorithm 1: Determine_Thermal_Stratification_Depths

```
Inputs: * Temp_List // an array of temperature values for each depth
          * Temp_Threshold // temperature threshold for thermal stratification
// Initialize upper and lower levels of the stratification
Stratification_UpperLevel ← ∅
Stratification_LowerLevel ← ∅
// Check whether a thermal stratification occurs
If max(Temp_List) – min(Temp_List) > Temp_Threshold
    Strafication_MidPoint_Temp ← mean(Temp_List)
    Stratification_UpperLevel_Temp ← average of the temperatures in Temp_List which are greater than Strafication_MidPoint_Temp
    Stratification_LowerLevel_Temp ← average of the temperatures in Temp_List which are less than Strafication_MidPoint_Temp
    Stratification_UpperLevel ← depth at which the temperature is closest to Stratification_UpperLevel_Temp
    Stratification_LowerLevel ← the depth at which the temperature is closest to and just above Stratification_LowerLevel_Temp
End If
Return Stratification_UpperLevel, Stratification_LowerLevel
```

An example of determining the location of thermal stratification and its boundaries on the real temperature data is shown in Figure 1. Using the temperature data recorded along the depth, the differences between the surface water temperature and the water temperature in the region close to the base of the dam are shown in Figure 1 (right). The greatest temperature difference across the depth occurs between July and September and is above 15 °C. It is also observed that the maximum water temperature difference can be as high as 20 °C. On the day shown in Figure 1 (left), using Algorithm 1, the average temperature (*Strafication_MidPoint_Temp*) in the reservoir is calculated to be 15.6 °C with corresponding surface and bottom temperatures being 22.3 and 6.9 °C, respectively. The warm upper layer which has been formed by incoming solar radiation and heat conduction from warm air was observed across the first 15 m of surface depth. The cold lower layer stretching across the depths of 100–115 m is separated from the surface by a transition zone. *Stratification_LowerLevel_Temp* is obtained by taking the average of the temperatures which are less than 15.6 °C and are found to be 11.9 °C. Similarly, Algorithm 1 calculates a *Stratification_UpperLevel_Temp* of 20 °C, which is the average of temperature values greater than 15.6 °C. Based on the values of *Stratification_LowerLevel_Temp* and *Stratification_UpperLevel_Temp*, the corresponding stratification lower (*Stratification_LowerLevel*) and upper levels (*Stratification_UpperLevel*) are then evaluated to be between 115 and 130 m, respectively. The recommended water intake depth is the lower boundary of this transition zone (115 m) and corresponds to a water temperature of 12 °C. Evaluating in detail all the water quality parameters measured along the depth, the treatment plant operator decided that the water intake depth should be 110 m. The raw water was taken to the plant from this depth on the same day.

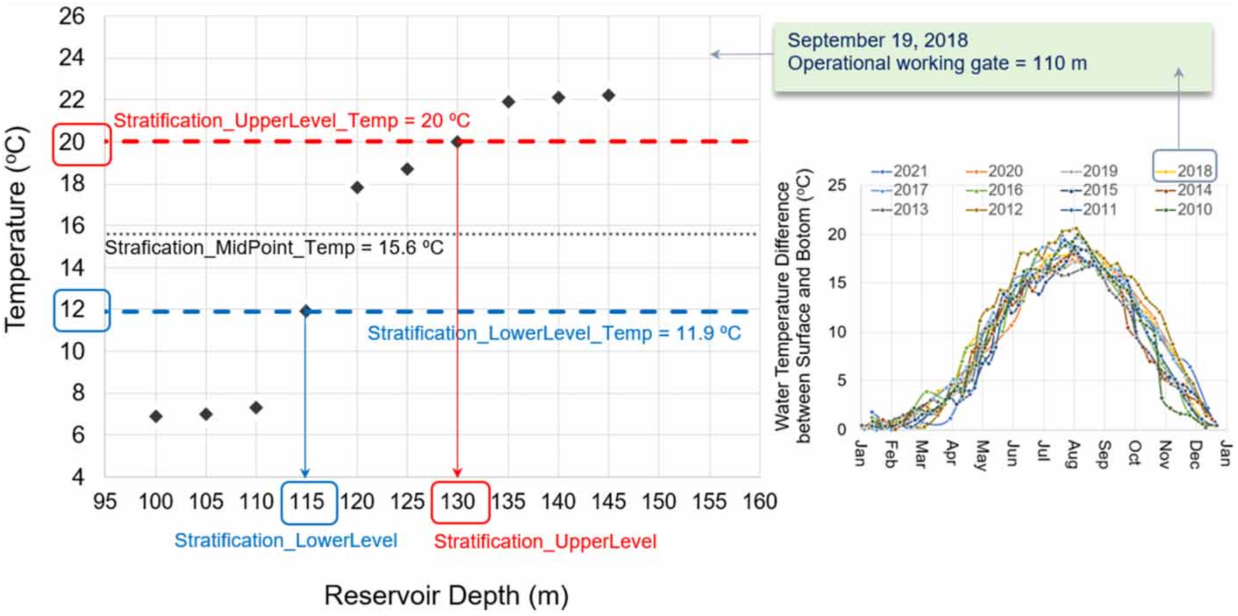


Figure 1 | Left: Water temperature variation with reservoir depth, location of thermal stratification (19 September 2018), and terminology used in Algorithm 1. The black dots denote the temperature measurements at each depth. Right: Temperature variation between 2010 and 2022 in Yuvacık Reservoir.

Case study: Yuvacık reservoir

Yuvacık Reservoir (40.6741 °N, 29.9694 °E) is located in Kocaeli, Turkey, and is fed by Kirazdere, Kazandere, and Serindere creeks. Yuvacık water basin with a catchment area of 258 km^2 covers Kocaeli, Sakarya, and Bursa provinces. A satellite image of Yuvacık Reservoir and a photo of the multilevel intake structure (İSAŞ 2022) are shown in Figure 2.

The minimum and maximum operational water levels of the dam are 112.5 and 169.3 m, respectively. The useful volume of the reservoir is 51 million m^3 and it has an annual capacity of 142 million m^3 of water (İSAŞ 2022). In order to optimize water quality parameters and ensure process efficiencies in the treatment plant, the intake structure was configured with several withdrawal depths vertically. These are located between 110 and 160 m relative to the sea level.

Manually sampled and laboratory-analyzed data from the surface (maximum being 169.3 m) to a depth of 100 m for the period of 2000–2022 was provided by Izmit Water Company (İSAŞ). The parameters monitored include temperature, pH, turbidity, conductivity, dissolved oxygen, iron, manganese, color, chlorophyll-a, ammonium, nitrate nitrogen, phosphates, UV254 absorbance, silicates, and light penetration. These 15 water quality parameters were measured at least twice per month from 2000 to 2022 in the reservoir between the depths of 100 and 160 m at 5-m intervals. Some of them, such as pH, temperature, conductivity, turbidity, dissolved oxygen, iron, manganese, and chlorophyll-a, were monitored three times a month.

In Yuvacık Reservoir, at discrete depths of 5-m intervals through 60-m overall depth, water temperature and dissolved oxygen concentration were recorded with equipment measuring them together. Water temperature (together with dissolved oxygen) was measured with a YSI 52 model microprocessor-based instrument designed for field and laboratory use until 2014. Starting from 2014 to the end of the first half of the year 2019, the WTW ProfiLine Oxi 197i Model oxygen meter, equipped with a built-in temperature sensor, was used. After 2019, starting from the second half of the year, the YSI ProSolo ODO Model optical dissolved oxygen meter was employed for monitoring. It is also paired with the latest optical dissolved oxygen and temperature (OTO/T) probe. Since the temperature was monitored three times a month on average, a total of 801 temperature data were included in the analysis.

We determined stratification at upper and lower levels using the approach in Algorithm 1. By using these levels, we defined hypolimnion, thermocline, and epilimnion layers. For each layer, we calculated the mean, standard deviation, and minimum and maximum values of the water quality parameters (Table 1).

The water quality parameters measured in raw water directly influence water treatment processes. These parameters encompass suspended and particulate matter, turbidity, algae, dissolved oxygen, iron, manganese, and pH. Notably, these

Figure 2 | Satellite image of Yuvacık Reservoir (Google Earth, June 2022) and intake structure at the construction time (İSAŞ 2022).

Table 1 | Variations of water quality parameters within layers

Parameter	Hypolimnion	Thermocline	Epilimnion
pH	7.79 ± 0.16 [7.41–8.17]	7.93 ± 0.20 [7.46–8.43]	8.37 ± 0.23 [7.69–8.96]
Turbidity (NTU)	3.6 ± 3.1 [1.0–18.8]	3.6 ± 3.9 [0.5–32.3]	2.2 ± 1.3 [0.6–8.9]
Temperature (°C)	7.5 ± 1.4 [5.1–11.5]	15.2 ± 3.3 [7.7–22.5]	21.2 ± 2.7 [13.3–27.4]
Conductivity (μS/cm)	234 ± 15 [186–269]	234 ± 15 [190–268]	220 ± 14 [180–264]
Dissolved oxygen (mg/L)	6.8 ± 2.6 [0.3–13.2]	6.3 ± 2.6 [0.8–14.0]	7.7 ± 1.7 [2.8–12.4]
Mn (mg/L)	0.026 ± 0.020 [0.0005–0.121]	0.019 ± 0.017 [0.0005–0.100]	0.012 ± 0.006 [0.001–0.037]
Chlorophyll-a (mg/L)	0.70 ± 0.53 [0.047–2.5]	2.35 ± 1.53 [0.047–8.0]	3.11 ± 1.89 [0.15–12.2]
Fe (mg/L)	0.034 ± 0.022 [0.005–0.150]	0.030 ± 0.027 [0.005–0.205]	0.019 ± 0.012 [0.005–0.070]
Color (Pt-Co)	4.7 ± 2.3 [1–12]	4.1 ± 2.2 [1–11]	3.5 ± 1.7 [0.3–9]
NH_4 (mg/L)	0.037 ± 0.028 [0.001–0.14]	0.039 ± 0.028 [0.002 - 0.13]	0.035 ± 0.021 [0.005–0.11]
NO_3 (mg/L)	3.4 ± 1.7 [0.25–8.2]	2.95 ± 1.6 [0.25–7.7]	2.4 ± 1.6 [0.10–7.1]
Orthophosphate (mg/L)	0.028 ± 0.025 [0.003–0.14]	0.029 ± 0.034 [0.001–0.21]	0.022 ± 0.023 [0.0007–0.11]

Data for a 22-year period are given in the following format: 'mean value ± standard deviation [minimum – maximum]'.

parameters exhibit variations along the depth and show interrelationships within the lake or reservoir. Specifically, (i) turbidity and clarity are bidirectionally related to algal biomass. Chlorophyll-a concentration, a measure of algal cells, is high near the surface where algae receive enough light to grow, but the presence and growth of algae can also reduce water clarity. (ii) Atmospheric diffusion serves as the primary mechanism for water oxygenation/aeration, resulting in lower oxygen concentrations in the hypolimnetic layer during stratification, causing the release of Fe and Mn into the water as dissolved substances. (iii) High pH values near the surface (epilimnion) are attributed to photosynthesis reactions where dissolved carbon dioxide is consumed. In contrast, the lower pH values in deeper layers are due to organic decomposition processes.

Upon examining Table 1, it becomes apparent that the water quality of the lake exhibits distinct variations due to thermal stratification, which is consistent with the previously explained trends. Specifically, (i) the concentration of chlorophyll-a is high near the surface where light penetration is intense, accompanied by high water temperature that decreases with depth, and increased turbidity toward the stagnant middle and deep layers. (ii) Dissolved oxygen levels are higher in the surface water compared to the middle and bottom layers, whereas iron and manganese concentrations increase with depth. (iii) As expected, the pH value of surface water is higher than that of the deeper layers.

In the Yuvacık Water Treatment Plant, the operators monitor water quality parameters throughout all the elevations in the reservoir and evaluate them separately while determining the elevation of the working gate on the intake structure. Besides, based on the operator's experience in achieving treatment objectives, variations in a certain group of parameters are examined in more detail. Among these parameters are pH, temperature, iron, manganese, algae, dissolved oxygen, and turbidity.

Various chemicals are used in the treatment train. Their required concentration and types differ with the incoming raw water. Yuvacık Water Treatment Plant carries out coagulation using aluminum sulfate and the process is accomplished by pH adjustment to work within the optimum pH range of alum. From the operating side of the facility, it is observed that there might be problems in ensuring the residual aluminum standards in the treated water, especially during summer when water is taken into the facility at high temperatures, therefore, low-temperature water is preferred. To avoid this kind of problem, it is crucial to withdraw water from the cold-water region below the stratified layer, hence the water taken will have a lower temperature and lower pH.

In some cases, the decision on the selection of withdrawal depth is made due to various operational restrictions rather than the water quality parameters explained above. Among them are: (i) the presence of few alternate depths in the gated inlet structure due to a decrease in water level, (ii) aiming for destratification, i.e. disruption of a stratified zone to prevent accumulation of some constituents at the bottom of the reservoir, such as iron and manganese, (iii) avoiding the acceptance of very low-temperature water into the plant especially in warm air temperatures because this acceptance creates condensation problems on the equipment and causes mechanical problems.

Considering these operational experiences and source-specific characteristics of Yuvacık Reservoir, it is understood that the recommended water intake depth (*Stratification_LowerLevel*) obtained by the proposed approach coincides with the probable region of the choice made by the operator after evaluating all parameters separately by extreme care and effort.

We observe from the dataset that stratifications occur mostly when the difference between the maximum and minimum temperatures is higher than 10 °C. Hence, the temperature threshold value (*Temp_Threshold*), defined in Algorithm 1, was chosen as 10 °C in this case study conducted for Yuvacık Reservoir. The stages defined in the decision-making process were carried out and the results obtained are given in the following Results and Discussion Section.

RESULTS AND DISCUSSION

In our study, we proposed an approach for determining the optimal depth for raw water treatment in a water treatment plant. This approach is based on temperature measurements taken throughout the depth of the lake. Using the algorithm that calculates the stratification depths in the lake based on these temperature measurements, we determine the hypolimnion, thermocline (metalimnion), and epilimnion layers. In addition to recommending a depth for water intake, our approach also statistically analyzes the variation in water quality across these layers. The water quality parameters we consider include pH, turbidity, dissolved oxygen, iron, manganese, and chlorophyll-a.

The processes utilized for water treatment depend on the quality of raw water. Several water quality parameters must be considered during the treatment process: (i) turbidity refers to the amount of particulate matter in water, such as soil particles, microorganisms, algae, and plankton. Coagulants are used to remove turbidity from water and their dosage is adjusted based on the turbidity of the water entering the treatment plant. (ii) Chlorophyll-a concentration is generally measured to determine the algal biomass responsible for imparting taste and odor to the source water. (iii) Dissolved Fe and Mn concentrations exhibit seasonal and vertical changes in lake waters. Water from hypolimnion with low dissolved oxygen exhibits high concentrations of Fe and Mn. The treatment of these compounds requires oxidants such as chlorine, ozone, or permanganate. (iv) pH and temperature have a direct impact on the removal of pollutants through coagulation–flocculation. To ensure effective treatment, it is crucial to routinely monitor the pH of the source water since it significantly affects the chemical species and performance of the treatment processes. It also plays a critical role in the oxidation of Fe, Mn, taste, and odor compounds. The reaction time may also vary depending on the temperature.

Water treatment plant operators should monitor both the waterbody and critical points within the treatment process to assess their effectiveness. However, establishing the appropriate approach for data collection and assessments can be complex, expensive, and time-consuming.

In this study, 22 years of temperature measurements collected at 5-m depth intervals in a reservoir of a water treatment plant were analyzed. This historical dataset indicates that temperature stratifications exist from late April and mostly around the beginning of May through late October. It becomes more apparent during summer, especially in August, when an obvious thermocline develops (Figure 3). Water depth in the reservoir may fall 20–25 m below the maximum possible water level during the months of September and October due to precipitation patterns and changes in water requirements.

Figure 4 shows the lower and upper depths of the stratified region for the days when a thermal stratification is expected to take place in the reservoir. The operator's preferences for withdrawal depth and the recommended depth determined by the approach are also displayed in Figure 4. When the lower and upper boundaries of the stratified region are examined in terms of depth and temperature change, it is seen that this layer becomes wider and more diffused especially from July to August and the temperature difference between the upper and lower levels takes the greatest values in this period. When the reservoir is thermally stratified, the agreement between the depth suggested by the approach developed here and the depth selected by the operator is very high, either being the same or remaining within 10 m of error.

Our developed model utilizes temperature measurements collected every 5 m along the depth of the lake. Reducing this 5-m measuring range further, in other words collecting more data along the depth, can improve the accuracy of the model. Figure 1 shows the calculation of the lower and upper levels of the stratification on a day with temperature stratification. In addition, we analyze the effect of taking more temperature data along the depth on the performance of the developed algorithm. In this analysis, we consider the case in Figure 1, and the temperature is measured at 2-m intervals instead of 5-m intervals. Consequently, the lower and upper limits of the stratification will be 114 and 130 m, respectively. The depth the model recommends as the water withdrawal is the depth at which the temperature is closest to and just above

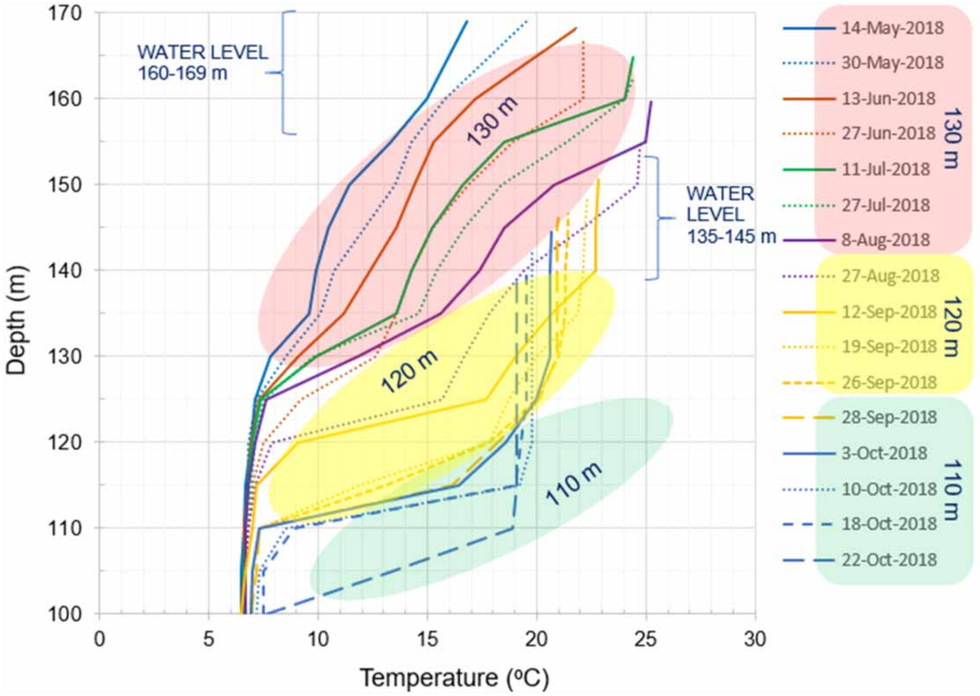


Figure 3 | Temperature profiles in Yuvacık Reservoir between 14 May 2018 and 22 October 2018 (withdrawal depths determined by the operator are colored pink, yellow, and green, and enclosed by oval-shaded regions). Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wqrj.2023.030.

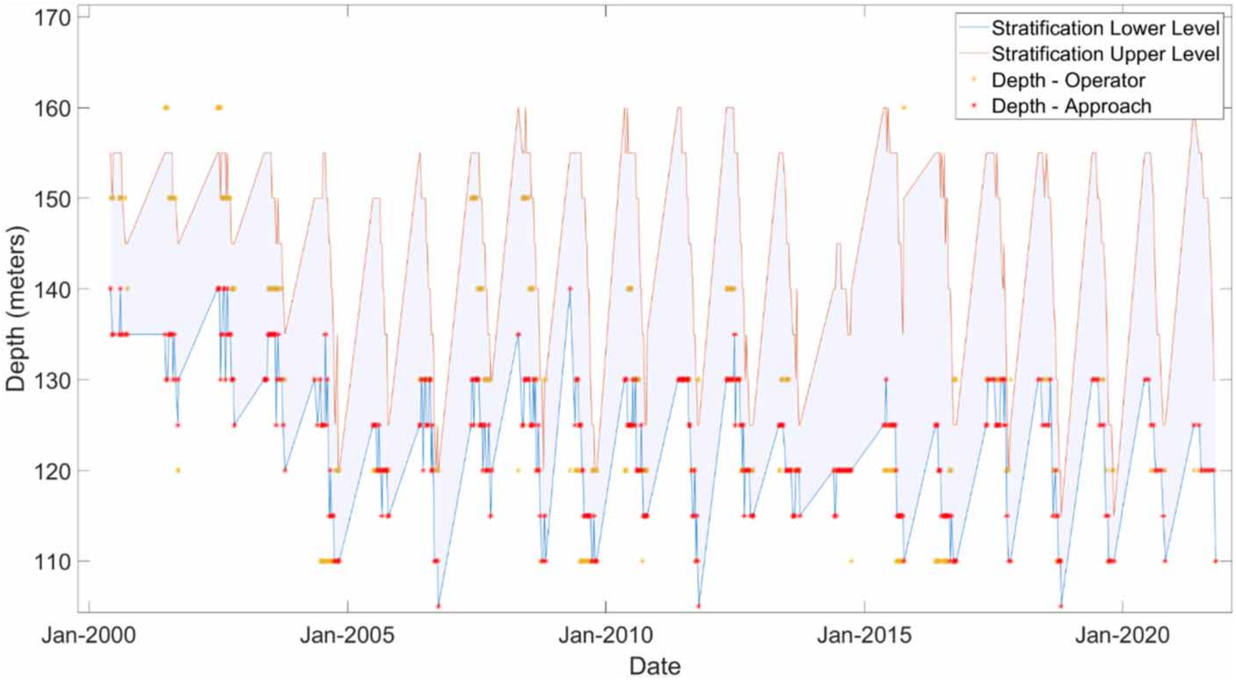


Figure 4 | Location of the stratified layer and withdrawal depth (depth tolerance = 10 m).

stratification lower level temperature. As a result, the model offers to draw water from a depth of 114 m. However, since the gates that can withdraw water to the facility are placed every 10 m, the model will produce the same decision of opening the 115-m-gate as in Figure 1. Thus, increasing the water temperature measurement points along the depth will increase the accuracy of the predictions of lower and upper levels of the stratification, but will not eliminate the need for the model.

Water quality monitoring at the inlet of a drinking water treatment plant is more frequent than at the source. Certain parameters are recorded and evaluated twice a day, and the treated water must meet specified standards as per regulations. The plant operator adjusts the dosage of chemicals used to achieve these standards before releasing the effluent to the distribution system. The plant operator made only two changes to the water withdrawal depth over a 22-year span, both occurring 2 days after the plant's operation. Other than these instances, the plant consistently operates at the same depth determined by the operator between two consecutive sampling periods for a long period of time. This indicates the operator's confidence in their decision, as the water quality is constantly monitored. To achieve the same withdrawal depth decision as the operator, our approach utilizes temperature stratification and resulting layer depths. The model works effectively, producing results that align with those obtained from analyzing a multitude of water quality parameters simultaneously.

Figure 5 clearly demonstrates that the decisions made by the approach and the operator are highly consistent. Matching percentages are also reported for 5, 10, and 15 m of error, i.e. deviations between the approach's result and the working gate. As an example, 61.2% of all estimates show that the depth decision made by the approach developed in this study overlaps with the decision made by the operator by ± 5 m. When the depth tolerance is increased from 5 to 15 m, the matching percentage becomes more than 90%.

In late summer and fall, progressive mixing occurs along the depth of the reservoir due to declining air temperatures. Temperature differences between the surface and bottom of the reservoir become insignificant and hence stratification is not observed. In such cases, since Algorithm 1 does not detect thermal stratification, it will not provide any recommendation for water withdrawal depth and the treatment plant operator will base his/her decision on individual assessment of water quality parameters.

CONCLUSIONS

This paper considered the problem of determining the water withdrawal depth for water supply reservoirs with a multilevel intake. We presented a decision support-based approach for estimating the location of thermal stratification and water

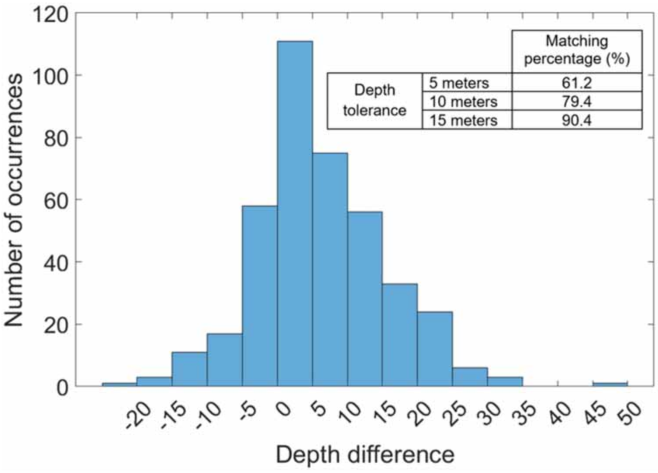


Figure 5 | Histogram of depth differences between the operator's decision and the approach and the table for the percentage of the approach's decisions consistent with the operator (top-right).

withdrawal level in a stratified reservoir. Our proposed method utilizes water temperature measurements taken at various depths within a lake. By analyzing the average temperature values and the fluctuations above and below the mean, we can identify the boundaries of the thermal stratification layers. The algorithm's output is then used to provide the user with a recommended depth for withdrawing water.

We validated our approach by utilizing data collected over a 22-year period from Yuvacık Reservoir, which serves as a water supply reservoir in Kocaeli, Turkey. We then compared the decisions made by our approach with those of the operator.

The operator makes decisions regarding facility operations based on their assessments of the water quality data and their cumulative past experiences. These assessments are used to determine the optimal depth for water withdrawal. Following this, water is extracted and the facility is operated. Additionally, both the raw and treated water quality at the facility is continuously monitored.

It is uncommon for the operator to adjust the open gate soon after an operational decision has been made (this has only occurred twice). Thus, the agreement between our proposed approach and the operator's decisions provides evidence supporting the feasibility of our approach.

When comparing the operator's decision with the estimation generated by our algorithm, the two decisions coincide with an 80% matching percentage when the depth tolerance is 10 m. If the depth tolerance is increased to 15 m, the matching percentage becomes more than 90%.

We are currently working on developing machine learning-based techniques for estimating the withdrawal depth. In addition to the temperature data, we plan to make use of other water quality parameters in this estimation. Furthermore, we aim to incorporate the changes in water quality into our model by adjusting the upper limit of the hypolimnion layer, which currently determines the recommended water withdrawal depth based on vertical temperature profiles of the water. We will also explore the potential of utilizing alternative gate levels within the hypolimnion layer for water withdrawal during operation.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Ashby, S. L. & Kennedy, R. H. 1999 *Water Quality Assessment for the Proposed Water Supply Reservoir, Duck River, Cullman, Alabama*. Technical Report EL-99-5. US Army Corps of Engineers.

AWWA 2010 *Algae: Source to Treatment, Manual of Water Supply Practices M57*, 1st edn. American Water Works Association, Denver, CO.

AWWA ASCE 2005 *Water Treatment Plant Design*, 4th edn. McGraw-Hill, New York, NY.

AWWA, Edzwald, J.K. 2011 *Water Quality and Treatment: A Handbook on Drinking Water*, 6th edn. McGraw-Hill, New York, NY.

Barbiero, R. P., James, W. F. & Barko, J. W. 1997 The effects of a change in withdrawal operations on phytoplankton and nutrient dynamics in Eau Galle Reservoir, Wisconsin (USA). *Internationale Revue der gesamten Hydrobiologie und Hydrographie* **82** (4), 531–543.

Benskin, P. & Linder, K. 2004 Hypolimnion withdrawal renews reservoir. *Opflow AWWA* **30** (5), 12–15.

Bertone, E., Stewart, R. A., Zhang, H., Bartkow, M. & Hacker, C. 2015 An autonomous decision support system for manganese forecasting in subtropical water reservoirs. *Environmental Modelling & Software* **73**, 133–147.

Bertone, E., O'Halloran, K., Bartkow, M. & Mann, K. 2018 Autonomous intake selection optimisation model for a dual source drinking water treatment plant. *Water Science and Technology: Water Supply* **18** (1), 279–287.

Çalışkan, A. & Elçi, Ş. 2009 Effects of selective withdrawal on hydrodynamics of a stratified reservoir. *Water Resources Management* **23**, 1257–1273.

Casamitjana, X., Serra, T., Colomer, J., Baserba, C. & Pérez-Losada, J. 2003 Effects of the water withdrawal in the stratification patterns of a reservoir. *Hydrobiologia* **504** (1), 21–28.

Chinyama, A., Ochieng, G. M., Snyman, J. & Nhapi, I. 2016 Occurrence of cyanobacteria genera in the Vaal Dam: implications for potable water production. *Water SA* **42** (3), 415–420.

Crittenden, J. C., Trussell, R. R., Hand, D. W., Howe, K. J. & Tchobanoglous, G. 2012 *MWH's Water Treatment: Principles and Design*, 3rd edn. John Wiley & Sons, Inc., Hoboken, NJ.

Davis, J. E., Holland, J. P., Schneider, M. L. & Wilhelms, S. C. 1987 *SELECT: A Numerical one-Dimensional Model for Selective Withdrawal*. Instruction Report E-87-2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Dortch, M. S. & Holland, J. P. 1984 *A Technique to Optimally Locate Multilevel Intakes for Selective Withdrawal Structures*. Department of the Army, Waterways Experiment Station, Corps of Engineers, Vicksburg, MS.

Elçi, S. 2008 Effects on thermal stratification and mixing on reservoir water quality. *Limnology* **9**, 135–142.

Fontane, D. G., Labadie, J. W. & Loftis, B. 1981 Optimal control of reservoir discharge quality through selective withdrawal. *Water Resources Research* **17** (6), 1594–1602.

İSAŞ 2022 *İzmit Su A.Ş. Tanıtım Kitapçığı*. (Company Brochure), In Turkish. İzmit Su, Kocaeli.

Jeznach, L. C., Jones, C., Matthews, T., Tobiason, J. E. & Ahlfeld, D. P. 2016 A framework for modeling contaminant impacts on reservoir water quality. *Journal of Hydrology* **537**, 322–333.

Lewis, M. E. & Edelmann, P. 1994 *Physical, Chemical, and Biological Characteristics of Pueblo Reservoir, Colorado*. U.S. Geological Survey, Denver, Colorado.

Panagopoulos, A. 2022a Brine management (saline water & wastewater effluents): sustainable utilization and resource recovery strategy through minimal and zero liquid discharge (MLD & ZLD) desalination systems. *Chemical Engineering and Processing-Process Intensification* **176**, 108944.

Panagopoulos, A. 2022b Techno-economic assessment and feasibility study of a zero liquid discharge (ZLD) desalination hybrid system in the Eastern Mediterranean. *Chemical Engineering and Processing-Process Intensification* **178**, 109029.

Qasim, S. R., Motley, E. M. & Zhu, G. 2000 *Water Works Engineering: Planning, Design, and Operation*. Prentice- Hall, Inc., Hoboken, NJ.

Raven, P. H., Hassenzahl, D. M. & Berg, L. R. 2012 *Environment*, 8th edn. John Wiley & Sons, Hoboken, NJ.

Slavik, I., Uhl, W., Skibinski, B., Rolinski, S., Petzoldt, T., Benndorf, J., Scheifhacken, N., Paul, L., Funke, M., Lohr, H., Völker, J. & Borchardt, D. 2013 A decision support procedure for integrative management of dammed raw water reservoirs. *Water Science and Technology: Water Supply* **13** (2), 349.

Weber, M., Rinke, K., Hipsey, M. R. & Boehrer, B. 2017 Optimizing withdrawal from drinking reservoirs to reduce downstream temperature pollution and reservoir hypoxia. *Journal of Environmental Management* **197**, 96–105.

Winton, R. S., Calamita, E. & Wehrli, B. 2019 Reviews and syntheses: dams, water quality and tropical reservoir stratification. *Biogeosciences* **16**, 1657–1671.

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