



Effects of the water withdrawal in the stratification patterns of a reservoir

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Abstract

The change in the stratification pattern in Boadella Reservoir (Catalonia, Spain) due to the switch in water withdrawal was investigated for a 6-month period in the year 2000. A numerical one-dimensional model (DLM) was used to predict the thermal structure of the reservoir during the period of maximum water demand. The model was found to satisfactorily predict the basic trends of the thermal stratification of the water column of the reservoir. We used this model to investigate various possible water withdrawal scenarios. When thermal stratification has been completely developed, the location of the main thermocline coincides with the depth of the outlet, in the various withdrawal scenarios considered. The possible effect of the switch between outlets on the water quality of the reservoir is discussed.

Introduction

Reservoirs, or man-made lakes, are usually built to store water for later use, water supply, flood control or power generation. Inflow and withdrawal lead to a decrease in the reservoir's water retention time compared to a lake with the same morphometry (Ford, 1990). For this reason, reservoirs are usually considered as intermediate water bodies between rivers and lakes, sharing some characteristics with both. A deeper and large reservoir behaves more like a lake or a river depending mainly on the residence time (Armengol et al., 1999). The stratification of a lake is the result of various physical processes that distribute heat from the lake surface to its deeper layers. These processes depend not only on meteorological variables such as wind velocity, and short and long wave radiation, but also on the biochemical characteristics of the water body. For example, the penetration of short wave radiation depends on the particulate matter in the water. Particulate matter in lakes has two distinct origins – biological and physical. Inorganic particles generally consist of finely ground quartz sand, clay minerals or metal oxides. Organic particles grow and reproduce and can occur in many forms: viruses, colloids, bacteria, phytoplankton or large particles such as zooplankton (Mobbley, 1990).

An important difference between lakes and reservoirs is the location of the outflow. In a natural lake, water usually overflows from the water surface. In a reservoir, the outflow is released from a fixed outlet, or several selective outlets at different depths. From the point of view of management of the reservoir, it is important to know the possible effects of the water extraction level on the reservoir. When multiple outlets exist, each different throughflow option can produce a suite of positive and negative effects, with the overall result depending on the particulars of the reservoir in question (Straskraba, 1986).

Temperature distribution is fundamental to understanding the performance and functioning of reservoir ecosystems (Kimmel et al., 1990). The effects of water withdrawal have been found important in determining thermal stratification in reservoirs (Martin & Arneson, 1978; Ford, 1990). Surface withdrawal generally dissipates heat because the heated water layer is directly removed, resulting in the preservation of cooler, denser hypolimnetic water. In contrast, bottom withdrawal tends to store heat because the release of cool hypolimnetic water results in an expansion of the epilimnion layer heated by solar radiation (Kennedy, 1999).

Selective withdrawal of hypolimnetic water can increase the net export of phosphorus from reservoirs experiencing anoxia (Martin & Arneson, 1978). A

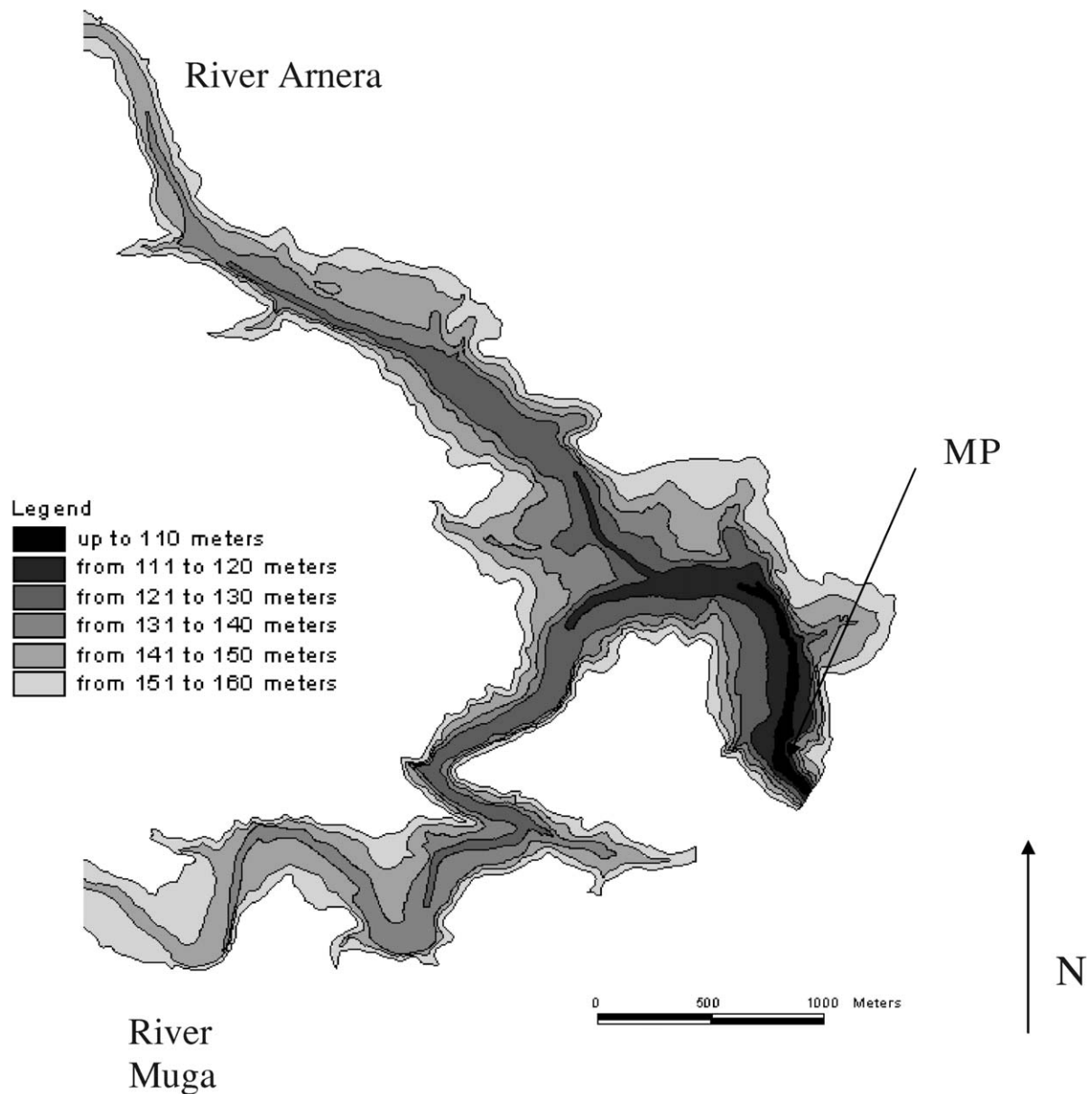


Figure 1. Bathymetric map of Boadella Reservoir showing the location of the measurement station (MP). Contour intervals (height above the sea level) are in meters.

shortened hypolimnetic residence could also reduce the potential for the development of anaerobic conditions, therefore further reducing phosphorus release (Cooke et al., 1993). However, by selectively releasing hypolimnetic water, discharges can lead to warming of the hypolimnion, and a resulting decrease in the thermal stability of the water column. Decreased stability can promote vertical entrainment of nutrients in the epilimnion (Effler et al., 1986).

This paper deals with the effects of the water withdrawal level in the thermal stratification of the water column of a reservoir. After validating the model by comparing simulations with experimental withdrawal data for summer 2000, other possible reservoir management scenarios are investigated. Finally, the possible effects of the water withdrawal on the water quality of the reservoir are discussed.

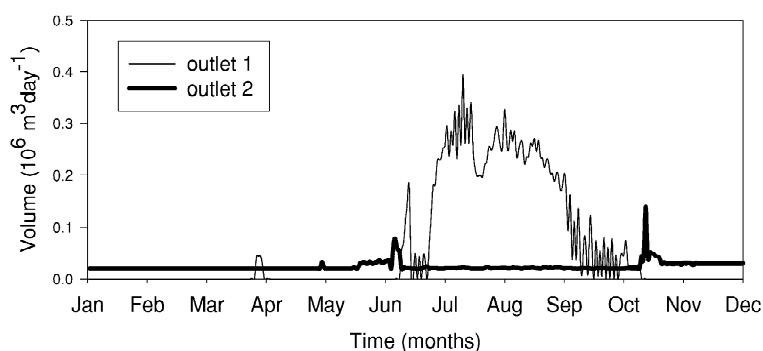


Figure 2. Volume of water withdrawn during the year 2000 through outlets 1 and 2 in Boadella reservoir.

Study site

Boadella Reservoir (Fig. 1) is located 106 m above sea level in the north-east of Spain in the eastern pre-Pyrenees ($42^{\circ} 20' 15''$ N, $2^{\circ} 21' 07''$ E). It has a maximum capacity of $6.2 \cdot 10^7$ m³, with a maximum surface area of 364 Ha. The yearly average total net inflow in the reservoir is $6.9 \cdot 10^7$ Hm³. One of the main characteristics of the Mediterranean climate is its variability; dry and wet years combine with hot or cool ones to produce many different types of seasonal patterns. Because of this, the reservoir's hydrological regime mainly depends on the seasonal nature of rainfall events, which commonly occur in the form of concentrated storm-fronts in spring and fall, and relatively low rainfall in summer and winter.

Water inflows occur through two main tributaries: the Muga and the Arnera. It has been estimated that the Muga contributes 65%, while Arnera contributes 35% to the total inflow. Outlet spills are located 7 m (Outlet 1), and 18 m (Outlet 2) from its base. A percentage of the outflow water is released to the river as 'ecological flow'. The remaining outflow water is used to supply drinking water to Figueres and other small towns downstream, and to sustain a hydroelectric plant. After leaving the turbines, the water of the hydroelectric plant is used for field irrigation (Table 1). The volume of outflow water used for field irrigation is highest in summer. In summer 2000, for example (Table 1), 61% of the total withdrawn water was used for this purpose, and was withdrawn through outlet 1 (Fig. 2).

The nutrient input in the reservoir is not very high, with average values of $3.2 \mu\text{g N l}^{-1}$ for nitrates and $0.2 \mu\text{g P l}^{-1}$ for total phosphorus (APHA, 1989), although the small ratio N:P causes the appearance of cyanobacteria blooms (Baserba, 1999). The chlorophyll-

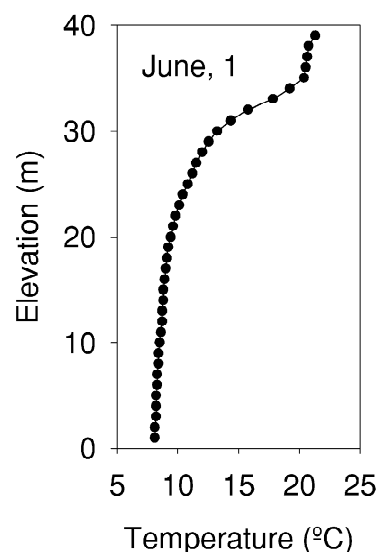


Figure 3. Measured temperature profile in 1 June, 2000. This is the initial profile for the simulations carried out in this paper.

a concentration (Jeffrey & Humphrey, 1975) values can be as high as $27.8 \mu\text{g l}^{-1}$ with a mean value of $5 \mu\text{g l}^{-1}$ and because of this the reservoir can be considered eutrophic. Cyanobacteria, diatoms and green algae dominate the composition of plankton. During the stratification period, the hypolimnion of the reservoir is anoxic, with ammonium, sulfides and other fermentation products that contribute to the reduction of the redox potential and to the re-dissolution of the phosphorus from the sediments (Baserba, 1999).

The model

The lake model used is DLM, a one-dimensional simulation model of the vertical distribution of temperature

Table 1. Monthly average of the total volume of the reservoir, the% of the total Maximum Volume, total inflow (TI), total outflow (TO). This outflow is composed of the ecological flow (EF), the drinking water (DW) and the hydroelectric plant and field irrigation flows (HP-FI)

	Volume 10^6 m^3	% Volume	TI	TO	EF $10^6 \text{ m}^3 \text{ day}^{-1}$	DW	HP-FI
Jan	31.272	50.47	0.030	0.021	0.009	0.012	0.000
Feb	31.357	50.61	0.025	0.022	0.009	0.013	0.000
Mar	31.250	50.44	0.023	0.026	0.009	0.013	0.004
Apr	32.900	53.10	0.077	0.022	0.009	0.012	0.000
May	33.905	54.72	0.060	0.027	0.010	0.016	0.001
Jun	32.047	51.72	0.066	0.127	0.012	0.025	0.091
Jul	23.793	38.40	0.022	0.288	0.012	0.033	0.244
Aug	16.556	26.72	0.005	0.239	0.012	0.037	0.190
Sep	14.903	24.05	0.012	0.067	0.012	0.025	0.030
Oct	15.892	25.65	0.072	0.040	0.012	0.019	0.009
Nov	15.948	25.74	0.030	0.028	0.012	0.017	0.000
Dec	40.878	65.98	0.832	0.028	0.012	0.016	0.000
Average	26.725	43.133	0.104	0.078	0.011	0.020	0.047

and salinity for small and medium lakes and reservoirs. This model has been described previously in the literature (Imberger & Patterson, 1981; Casamitjana & Schladow, 1993; Casamitjana et al., 1993; Han et al., 2000) and so only a brief description will be included here. The vertical profile of the lake is represented as a set of up to 100 Lagrangian layers that are free to move vertically, contract and expand in response to river inflows and outflows and to surface mass fluxes. The model uses measured, daily-average meteorological data and total daily inflow and outflow data. The surface fluxes of momentum, sensible heat, and latent heat are computed from bulk aerodynamic formulae. Surface layer dynamics is based on an integral turbulent kinetic energy model. The turbulent kinetic energy budget is partitioned in four discrete processes: wind stirring, convective overturn, interfacial shear production, and Kelvin-Helmoltz billowing (Sherman et al., 1978).

River inflow is modeled in three stages as a quasi two-dimensional process. As the stream enters a reservoir, it pushes stagnant lake water ahead of itself until buoyancy forces, due to the difference in density between reservoir and stream water, arrest the flow. At this point, the stream either flows over the reservoir surface, if the stream density is less, or plunges beneath the surface, if the stream density is greater. Once submerged, the stream will flow down the drowned river valley, entraining ambient water, until reaching the level at which its density equals that of the reser-

voir. At its level of neutral buoyancy, the combined stream and entrained flow intrudes horizontally in a narrow distribution governed by either a gravitational-inertial or a gravitational-viscous balance depending on a Grashof number and Froude number criterion.

Where outflow from a lake occurs from submerged oftakes (as it typically would be for water-supply purposes), most of the water withdrawn typically comes from a narrow layer approximately centered at the oftake level. The thickness of the layer is determined by the stratification and the discharge, and the nature of the oftake (line or point sink), and is governed by the same Grashof and Froude number relationships as for intrusions. Hypolimnetic mixing is modeled by a turbulent diffusivity coefficient, the value of which depends directly on the dissipation of the turbulent kinetic energy and inversely on the stratification.

The simulations shown were each commenced using measured profile data from 1 June, 2000 (Fig. 3), for a period of 150 days. The input meteorological data were from measurements taken at Agullana meteorological station, which is the nearest one to the reservoir, situated 6-km to the north. As there were no direct measurements of the water inflow, these were deduced from the level of the reservoir and the outflow volumes. The total inflow measurement was distributed between the two tributaries using the percentages indicated above. Also, as there were no temperature inflow measurements, we also used the mean air tem-

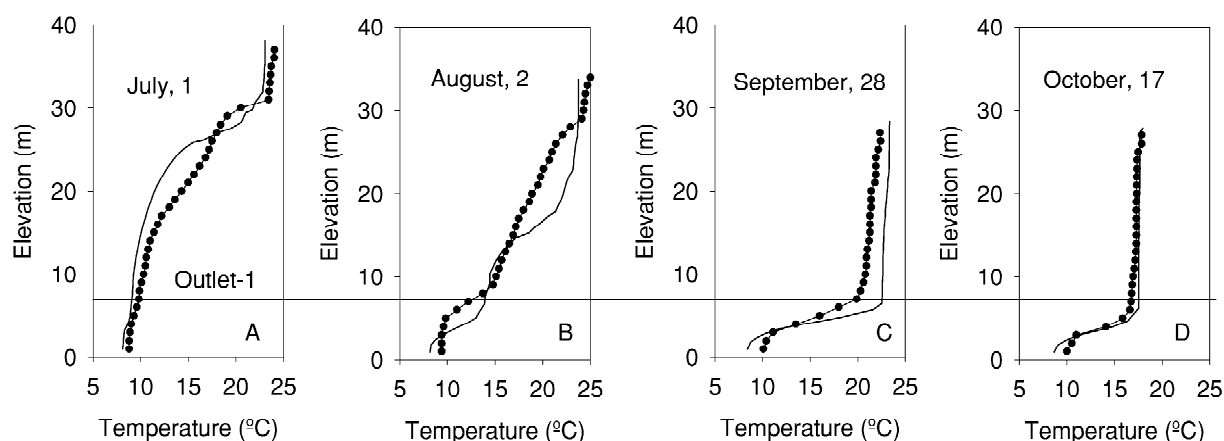


Figure 4. Measured (circles) and predicted (straight line) temperature profiles for Boadella reservoir. The straight line shows the location of outlet-1 (at 7 m elevation).

perature during the last four days as the value of the temperature inflow (Armengol et al., 1999).

Model results

In Figure 4, results from the model are compared with temperature measurements performed monthly. A decrease in the water level from 37 m on July 1 (Fig. 4A), to 27 m on October 17 (Fig. 4D) can be seen. This is due to water withdrawal, mostly occurring at outlet-1 (Fig. 2). On the 1st of July (Fig. 4A), the predicted temperature distribution profile shows a three-layered vertical stratification pattern, with a typical epilimnion-metalimnion-hypolimnion layered column, which is in accordance with the experimental vertical temperature profile. In the July 1 profile, the formation of a seasonal mixed layer of ~ 7 m depth is clear. The August 2 profile shows a continuously stratified pattern (Fig. 4B). The formation of a thermocline can be appreciated at elevation of 7 m, coinciding with the level of outlet-1. During all the withdrawal period, a layer of cold water below the outlet-1 can be appreciated. In September and October, the water column above outlet-1 was completely mixed (Fig. 4C,D) and a three-layered column, with the thermocline situated at the outlet-1 depth, again occurs. Although the use of a one-dimensional model for a longitudinal shaped reservoir, such as Boadella (Fig. 1) may be debatable, the predicted temperatures follow the basic trend of the experimental ones. Obviously there are 2 dimensional processes that are not taken into account in the model that might cause some of the observed mismatches at the mid depths of the reservoir (see for

example Fig. 4 B). All in all, the model gives a good prediction of the formation of the thermocline at the depth of outlet-1.

Given the reasonable agreement between the measured and the simulated data, we can use the model to simulate other possible scenarios. As an example, it is instructive to compare the measured profiles with a hypothetical situation where no inflow and water withdrawal has taken place (Fig. 5). The simulated profiles are classical lake-profiles with a surface mixed layer that has deepened with time. This simulation shows that the continuous stratification occurring in the August 2 profile (Fig. 5B) is clearly induced by the water withdrawal and that the thermocline occurring at the outlet-1 (Fig. 5C,D) is induced by this water outflow. The overall simulated temperature of the reservoir is lower than the experimental one, because in this case there is not withdrawal of the colder hypolimnetic water.

Figure 6 compares the measured and the simulated values if the entire water withdrawal had taken place through outlet 2. In July, the temperature profile does not differ much from that obtained experimentally and corresponds to the case where the outflow is through outlet-1 (Fig. 6A). In contrast, when the stratification is completely developed (Fig. 6B), the thermocline reaches the level of the outlet-2 and stays at this depth until the end of the stratified period (Fig. 6C,D). It is therefore clear that the depth of the outlet determines the final location for the thermocline. This behaviour can be expected in many Mediterranean reservoirs which, especially in the summer period, are subject to very severe levels of water withdrawal. At present, the

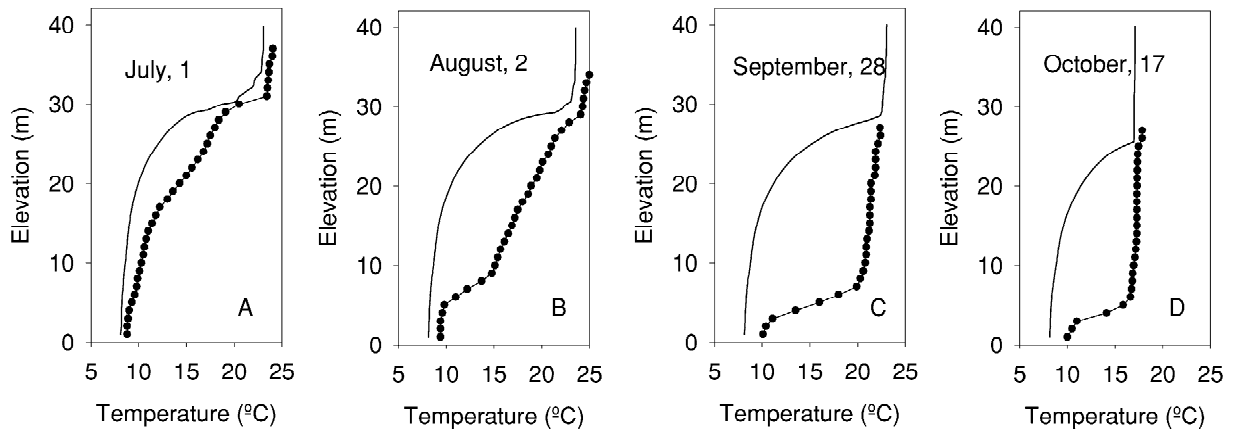


Figure 5. Measured (circles) and predicted (straight line) temperature profiles for Boadella reservoir, assuming that there was no water inflow and withdrawal.

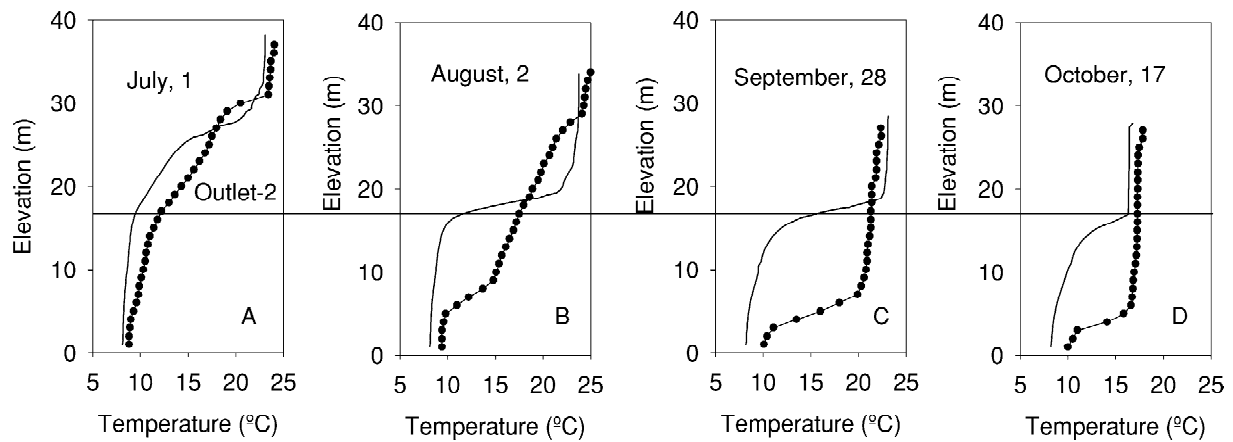


Figure 6. Measured (circles) and predicted (straight line) temperature profiles for Boadella reservoir, assuming that water was withdrawn through by outlet-2. The straight line shows the location of outlet-2 (at 18 m elevation).

amount of water withdrawn during summer represents in Boadella Reservoir 47% of the total amount of the reservoir at the beginning of the season.

Another possible scenario for water withdrawal could be the combinative extraction of the water from both outlets. For example, water can be withdrawn alternatively at weekly intervals from outlets 1 and 2. Simulated temperature profiles for this week-interval case were compared to the other two cases studied above (Fig. 7) for August and October. It can be seen that in the week-interval case, the thermocline is weakened. This fact can be quantified by calculating the Brunt-Väisälä frequency at the center of the thermocline, which changes from $N \approx 3.2 \text{ s}^{-1}$ when the water is withdrawn either through outlet-1 or outlet-2 to $N \approx 1.7 \text{ s}^{-1}$ for the for the week-interval withdrawal scenario.

Discussion

In summer, the inflow rates of Boadella Reservoir are very low ($\approx 10\,000 \text{ m}^3/\text{day}$; see Table 1), especially when compared to water withdrawals (Fig. 2). Because of this, the dynamics of the reservoir, as have been shown from the model results, is mainly determined by the water withdrawal. Selective withdrawal structures allow water to be released from various strata of the reservoir. Different strategies can be adopted depending on the water quality parameters considered. For example, Fontane et al. (1981) present a methodology that combines simulation and optimization techniques for selective withdrawal structures in order to maintain a desirable downstream temperature. Barbiero et al. (1997) employed selective withdrawal to reduce phytoplankton populations by strengthening

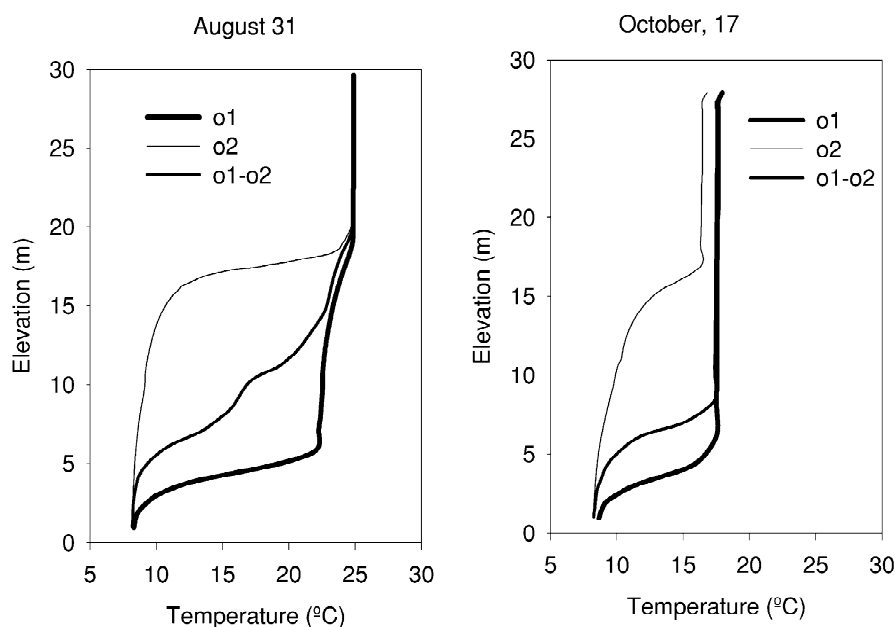


Figure 7. Simulated temperature profiles on August 31 and October 17, 2000 considering that water was withdrawn by outlet-1 (o1), that water was withdrawn through outlet- 2 (o2), or that the water was taken at weekly intervals through both outlets (o1–o2).

thermal stability, thereby decreasing vertical entrainment of hypolimnetic phosphorus and by increasing the epilimnetic flushing rate and discharge of algae.

Due to the water high demand during summer, the volume of Boadella reservoir has considerably decreased at the end of the season (see Fig. 5). The present politics of the water withdrawal, mainly through outlet-1 (Fig. 2), contributes to reducing the volume of hypolimnetic water to the very small value of approx. $6 \cdot 10^5 \text{ m}^3$. The hypolimnion is therefore confined to the deepest part of the reservoir (Fig. 1), and much of the bottom of the reservoir is in direct contact with the epilimnetic water. As a result, re-suspension of the compounds of the sediment to the epilimnetic waters, and therefore an increase in its organic matter contents, can be expected. As the water in the epilimnion is oxygenated the re-dissolution of the sediment nutrients would be small, and therefore the contribution of this process to the eutrophia would be small.

However, if water withdrawal were changed to outlet-2, the depth of the thermocline would decrease and therefore the volume of the hypolimnion would increase ($V \approx 5.2 \cdot 10^6 \text{ m}^3$) (Fig. 6). The hypolimnion would be expected to be highly reduced and the thermocline would act as a strong barrier to the diffusion of the sediment products. Most of the bottom of the reservoir would also be isolated from the

epilimnion, in direct contact with the hypolimnion, and with important loads of soluble reactive phosphorus obtained after sediment redissolution favoured by the highly reduced conditions of the hypolimnion. These conditions would promote the denitrification processes and the release of the nitrogen to the atmosphere. Furthermore, there is a potentially higher negative effect in this change. At the end of summer, the photic zone extended from the surface of the reservoir until the elevation of 14 m. (Baserba, personal communication). If the extraction were through outlet-2, the photic zone would reach the hypolimnion of the reservoir in September (Fig. 6C). Given the foreseeable presence of nutrients in this layer, a possible phytoplankton bloom could be expected under these physico-chemical conditions. Moreover, the low N:P ratios characteristic of this reservoir could be favourable to the development of cyanobacteria, with the known negative effects on the water quality of the reservoir and the outlet switch might therefore be a wrong management option.

All in all, stratification plays a crucial role in determining the reservoir's water quality. The prediction of the reservoir's thermal evolution is therefore essential for lake management. The DLM model has been found to correctly predict the basic trends in the thermal stratification of the reservoir and it can also be used to predict the stratification pattern in other

water withdrawal scenarios. It has been shown that the thermocline occurred at the depth where water was withdrawn. The extension of the present hydrodynamic model to a water quality model, previously calibrated, may give us a better understanding of the possible consequences of the effect of the change in operations.

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