Vertical boundary mixing events during stratification govern heat and nutrient dynamics in windy tropical lakes with high water-level fluctuations: a long-term (2001-2018) study.

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Abstract: Physical processes play important roles in controlling eutrophication and oligotrophication. In stratified lakes, internal waves (IW) can cause vertical transport of heat and nutrients without breaking the stratification, through boundary mixing (BM) events. Such is the case in tropical Valle de Bravo (VB) lake, where strong diurnal winds drive IW, BM and hypolimnetic warming during stratification periods. We monitored VB during 18 years (2001-2018) when important water-level fluctuations (WLF) occurred, affecting mixing and nutrient flux. Mean hypolimnetic temperature increase (0.06–1.04°C month^{-1}) occurred in all the stratifications monitored. We analyzed temperature distributions and modeled the hypolimnion heat budget to assess vertical mixing between layers (26,618–140,526 m^{-3}h^{-1}), vertical diffusivity coefficient K_z (6.2x10^{-7}–3.3x10^{-6} m^{2}s^{-1}) and vertical nutrient entrainment to epilimnion on monthly scale. Stability also varied as a function of WLF. Nutrient flux to the epilimnion ranged 0.36–5.99 mg m^{-2}d^{-1} for soluble reactive phosphorus (SRP) and 5.8–97.1 mg m^{-2}d^{-1} for dissolved inorganic nitrogen (DIN). During low water-level years, vertical nutrient fluxes increase and can account for up to >40% of the total external nutrients load to the lake. Vertical mixing changes with WLF affect nutrient recycling, their flux to sediments, metabolic balance and planktonic composition of VB.

Keywords: eutrophication; water management; hypolimnetic warming; boundary mixing; mixing events; internal waves; long-term series; Valle de Bravo; biogeochemistry; nutrient flux

1. Introduction

Understanding mechanisms that control eutrophication and oligotrophication is an issue that involves fascinating theoretical and applied possibilities. The vertical exchange between the warm surface layer (epilimnion) and the colder hypolimnion below the thermocline boundary in stratified lakes is an understudied critical process that may affect the nutrient dynamics and, consequently, therefore their trophic condition [1]. In lakes characterized by stable stratification, vertical transport of dissolved materials is generally restricted by the metalimnetic barrier. Therefore, in stratified eutrophic lakes, primary producers inhabiting the epilimnion are often limited by the low availability of dissolved nutrients, while in the hypolimnion, concentrations of these elements can be much higher due to the microbial decomposition of settling organic material and to their release from the bottom sediments [e.g. 2]. Thus, any physical mechanism responsible for significant cross-metalimnetic upward mass transport will be important in controlling lake productivity and the trophic condition of the lake.

External loading and deep-water entrainment are usually the two dominant sources of nutrients to lakes at an annual time scale, yet their relative importance during the period of stratification and low nutrient availability is under discussion [3]. Because crossing the metalimnetic density barrier requires energy, entrainment –the transport of nutrients from the deep water– has been considered low or negligible during strong stratification [4]. Recent work, however, suggests that the vertical flux of nutrients across the thermocline may be an important driver of epilimnetic metabolism in some stratified lakes [5]. In these cases, the energy required has often been shown to come from processes such as wind mixing and shear production within boundary layers of the lake [6]. Intense periodical winds can drive internal waves (IW), which can cause increased dissipation of turbulent kinetic energy both at the periphery and the center of the lake [7]. Recently, [8] found that the synchronization of IW can even provoke enhanced shear in the hypolimnion and vertical diffusivity (Kz) reaching up to 10^{-4} m^2 s^{-1}. Nevertheless, processes driving the enhancement of boundary mixing (BM) events and hypolimnetic entrainment are still understudied, and even more seldom approached in tropical lakes [9,10]

This kind of processes are likely to occur in Valle de Bravo (VB), a deep monomictic tropical lake in Central Mexico, which is daily swept by strong (7.4-16.5 m s^{-1}) diurnal (12:00–19:00 h) winds [11]. These periodical winds drive IW in VB that cause important vertical diurnal displacements of the thermocline at the extremes of the lake [12]. As a result of the interaction of the thermocline with the bottom and margins of the lake, these IW drive daily BM events in VB. Although these events do not break the stratification, its cumulative effect drives a gradual increase of the hypolimnetic temperature during the stratification periods in VB [11,13,14]. Additionally, it has been found that these mixing processes, and their effects on the metabolic balance of the lake, may be intensified by water level fluctuations (WLF) occurring in VB [13,14].

Mixing processes and their variability can significantly affect multiple aspects of water bodies, including nutrient availability and budgets [11, 15], as well as plankton composition and dominance [13, 16]. Additionally, there are important management issues in VB -such as toxic cyanobacterial blooms– that challenge its value and use as a touristic hot spot [11], and are probably affected by these mixing processes and their variability associated to WLF. Indeed, this has been outlined as a broadly found issue by [9], who stressed that the response of aquatic ecosystems, particularly deep lakes, to WLF is an under-studied field of crucial importance to the management of water resources.

Because important WLF have been occurring in VB in the past two decades, its study to long-term may contribute to understanding this response and to better manage deep monomictic lakes and reservoirs to cope with eutrophication. We have been monitoring this lake system during 18 years, and here we report on the variability of temperature distributions in the water column of the lake with a strong diurnal wind regime, and use the hypolimnetic temperature increase rates observed during all the stratification periods to calculate the water mass mixing between layers during each stratification cycle

throughout time series. These calculations yield estimates of the magnitude of vertical mixing, the coefficient of vertical eddy diffusivity (Kz) and the vertical nutrient entrainment into the epilimnetic zone. The temporal variability of these fluxes is analyzed to assess the effects of water level fluctuations (WLF) and other factors, such as nutrient loads, on the intensity of this water mixing and nutrient entrainment, which in turn have important ecological effects and implications for the adequate management of tropical lakes.

2. Materials and Methods

2.1. Study Area

Valle de Bravo (VB) is the biggest of seven reservoirs that form the Cutzamala System, which provides 30% of the drinking water supply to the Mexico City Metropolitan Area and other cities. Nevertheless, because of its depth, VB behaves as a monomictic lake [11]. This high-altitude (1,830 m a.s.l. at its maximum water level) tropical lake in Central Mexico (19°21′30′N; 100°11′00″W), receives water from a watershed of 547 km² through 4 rivers (Amanalco, Molino, González y Carrizal) and three sewage outlets, including the Tizates, a former river [16]. The lake′s surface is 18.6 km², its mean depth 21.1 m, and its maximum depth is 38.6 m. As previously mentioned, this deep lake is characterized by strong diurnal winds that blow along its two arms, of which the longer has a 6.9 km length (Figure 1). The wind at VB exhibits a regular diurnal pattern (12:00-19:00 h) blowing from the reservoir's dam (WNW) into the valley arms (SSE). Wind speed averages 5.5 m s⁻¹ and frequently reaches over 10 m s⁻¹ [11].

VB exhibits a warm-monomictic thermal regime, similar to other water bodies of the Mexican tropical highlands, except for the occurrence of a continuous increase of its hypolimnetic temperature during the stratification period [11]. In contrast, no hypolimnetic temperature increase has been observed in any other water bodies of the Mexican tropical highlands [17].
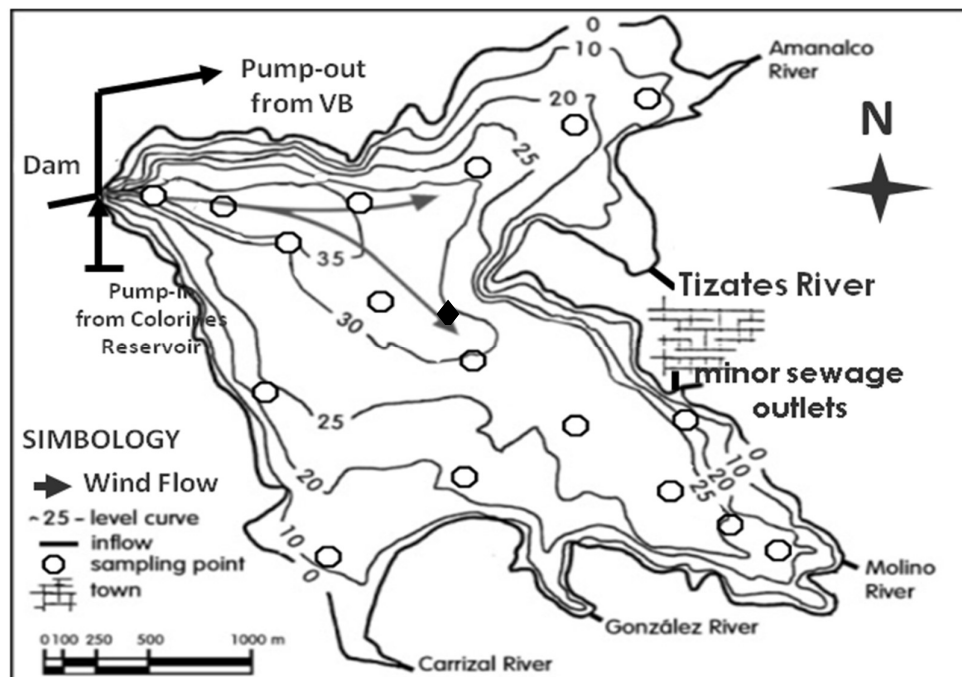
Figure 1. Bathymetric map of Valle de Bravo lake (after Ramírez-Zierold et al. 2010) showing sampling stations, main inputs (rivers and sewages) and water withdrawal route. Central station sampled throughout the studied period indicated by ♦. Depth contours in m below the maximum level of the lake. Daily wind pathways over both arms are also indicated (➡).

2.2. Long-term monitoring of VB

VB monitoring was performed monthly at up to seventeen sampling stations distributed throughout the water body and along the wind axis (Figure 1). During the initial years of the monitoring (2001-2003), all the stations shown in Figure 1 were sampled, to identify and include any spatial variations. However, as horizontal homogeneity was confirmed [11,18], the number of stations was reduced, initially to 5 stations, and from September 2007 on, to a single sampling station at the center of the lake, to allow for the long-term monitoring that has proceeded since then. The water level for each sampling date was taken from the government official reports, and the area of the lake basin at different depths was obtained from the bathymetry reported by [11].

Temperature and dissolved oxygen (DO) were measured at 1 m vertical intervals using a Hydrolab DS4/SVR4 (From February 2001-September 2004) or a Yellow Spring Instruments (YSI) field probe (October 2004-January 2019), which were previously intercalibrated. Water samples were collected with a 1.5 l Uwitec sampler at regular vertical intervals (0, 1, 2, 4, 8, 12, 16, 20, 24, 28 and 32 m, when possible) down to the bottom. Subsamples for nutrients [dissolved inorganic nitrogen (DIN) = [NH_4^+ + NO_2^- + NO_3^-], and soluble reactive phosphorus (SRP)] analysis were held in polypropylene containers after filtration with 0.45 and 0.22 μm (Millipore™ type HA) nitrocellulose membranes, and kept frozen until their analysis (within 24 to 48 h) in a Skalar segmented-flow continuous auto-analyzer; using the methods and circuits suggested by [19].

2.3. Vertical mixing model and calculations

Our approach is based on the increasing evidence [6,20–22] that turbulence generated by IW breaking in BM events can transport nutrients and gases vertically through the metalimnion in systems where a source of external energy, such as wind, drives these processes, which are summarized in Figure 2.
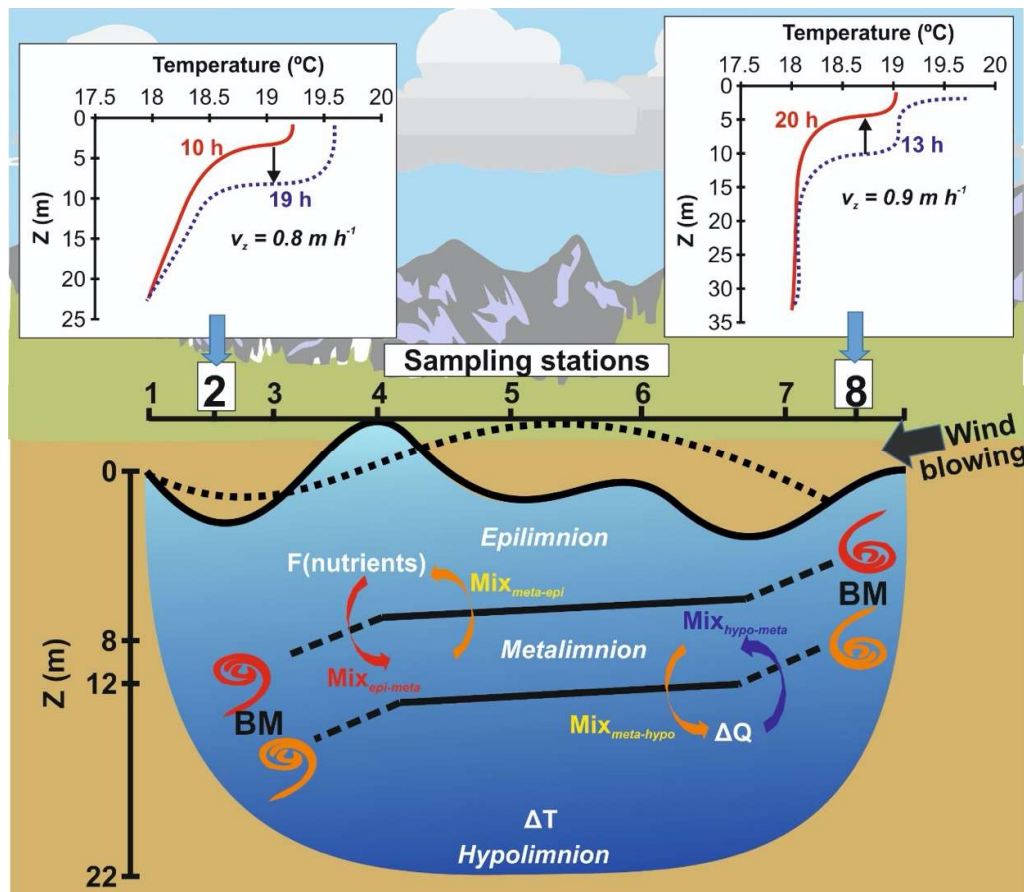
Figure 2. Observed daily thermocline oscillation driven by diurnal wind forcing in VB (top diagrams, taken from [12]), and conceptual mixing model processes considered (see section 2.4 for explanation)..

2.4. Calculation of vertical water mixing

As in VB there are no additional heat sources that could warm the hypolimnion [11], its thermal increase was entirely attributed to vertical mixing. We used the simplest model possible, considering the three distinct water layers in a monomictic lake: the warm epilimnion, metalimnion or thermocline layer, and the colder hypolimnion (Figure 2). Because, in spite of hypolimnetic warming, the lake remained stratified during the spring to autumn months, and the thermal structure did not change notoriously between samplings, we assumed a steady-state model to calculate vertical mixing, in which vertical water exchange between the epilimnion and the metalimnion was equal to vertical water exchange between this thermocline layer and the hypolimnion (Figure 2). Therefore, the rate of epilimnetic water mixed into the metalimnion ($Mix_{epi-meta}$) is assumed approximately equal to the rate of metalimnetic water mixed into the hypolimnion ($Mix_{meta-hypo}$), as well as to the rate of hypolimnetic water mixed back into the metalimnion ($Mix_{hypo-meta}$) and to the rate of metalimnetic water mixed back into the epilimnion ($Mix_{meta-epi}$):

$$Mix_{epi-meta} \simeq Mix_{meta-hypo} \simeq Mix_{hypo-meta} \simeq Mix_{meta-epi} \tag{1}$$

$Mix_{epi-meta}$, $Mix_{hypo-meta}$, and $Mix_{meta-epi}$ are difficult to assess as their thermal traces are easily altered by solar heat input through the surface of the lake. As there are no known direct inputs of heat to the hypolimnion of VB [1], $Mix_{meta-hypo}$ can, fortunately, be traced back from the observed hypolimnetic temperature increases. This was done through a heat balance of the hypolimnion (2), taking into account both the heat exchange due to:

a) vertical mixing of water ($\Delta Qhypo_{mix}$, cal h^{-1}) and b) thermal conductivity flux ($\Delta Qhypo_{cond}$, cal h^{-1}), as:

$$\Delta Qhypo_{tot} = \Delta Qhypo_{mix} + \Delta Qhypo_{cond} \tag{2}$$

Total heating of the hypolimnion, $\Delta Qhypo_{tot}$, was calculated for each period between samplings (Δt, days), using the observed temperature increase (ΔT_{hypo}, ºC), the calorific capacity of water, (c, cal g^{-1} ºC^{-1}), the volume of the hypolimnion (V_{hypo}, m^3) and the mean hypolimnetic density (ρ_{hypo}, g cm^{-3}),   as:

$$\Delta Qhypo_{tot} = (\Delta T_{hypo} \, c \, / \, \Delta t \,)^* \, V_{hypo} * \rho_{hypo} \tag{3}$$

The conductivity heat flux, $\Delta Qhypo_{cond}$, was calculated from the vertical temperature gradient ($\Delta T_{epi-hypo}$) at the metalimnion-hypolimnion frontier and the water thermal conductivity. Then, the mixing heat exchange was calculated by subtracting the thermal conductivity flux from the total heat exchange (equation 2). In turn, from the obtained heat exchange due to mixing ($\Delta Qhypo_{mix}$), the volume of water exchanged (V_{hypo}) was calculated as:

$$Mix_{meta-hypo} = \Delta Qhypo_{mix} / \rho_{hypo} \, c \, (T_{epi} - T_{hypo}) \tag{4}$$

Where $Mix_{meta-hypo}$ (m^3 h^{-1}), $\Delta Qhypo_{mix}$ (heat exchange due to water mixing; cal h^{-1}), ρ_{hypo} (mean hypolimnetic density, g cm^{-3}), c (calorific capacity of water, cal g^{-1} ºC^{-1}), T_{meta} (mean metalimnetic temperature, °C) and T_{hypo} (mean hypolimnetic temperature, °C).

The vertical diffusivity coefficient, K_z (m^2 s^{-1}) (*sensu* [6,8] was calculated dividing the vertical water flow ($Mix_{meta-hypo}$) by the exchange area at the depth of the base of the metalimnion and the top of the hypolimnion, which we estimated at $1.2 * 10^6$ m^2.

The stability of stratification (S) was also calculated for each sampling date through the Schmidt index [23], integrating from the surface to the maximum depth:

$$S = g/A_o \, \Sigma \, (\rho_z - \rho_m) \, (z - z_g) \, A_z \Delta z \tag{5}$$

$$\rho_m = 1/V \int A_z \rho_z dz \tag{6}$$

Stability is expressed in work units per surface lake area because it represents the amount of work that would be required to mix the lake into an isothermal state. It describes how much the center of mass of the lake has been lowered by the stratification process.

3.5. Calculation of vertical nutrient fluxes

Since, under steady-state conditions, we assumed $Mix_{meta-hypo} = Mix_{meta-epi}$ (equation 1), we used the calculated $Mix_{meta-hypo}$ to estimate $Mix_{meta-epi}$, the vertical water flux responsible for transporting nutrients to the epilimnion. The nutrient entrainment, or flux to the epilimnion (F (nutrients)), for each period between samplings was calculated as the product of mean nutrient concentration in each layer times $Mix_{meta-hypo}$.

$$F \text{ (nutrients)} = Mix_{meta-hypo}. * [\text{nutrients}] \tag{7}$$

Where F (nutrients) is the ascending nutrient flux (kg h^{-1}); $Mix_{meta-hypo}$ the exchange of water between layers (m^3 h^{-1}) and [nutrients] is the mean hypo or metalimnetic concentration of DIN or SRP (kg m^{-3}).

3. Results

3.1. Water Level Fluctuations (WLF) in VB during 2001–2018

The water level in the VB lake varied seasonally during the full study period (Fig. 3a) following the seasonal rain variations for the region, where the rainy season is from June to October. These seasonal water level variations were normally of only 4 to 6 meters,

between the lake's maximum level (1830 m a.s.l.) at the end of the rainy season and a minimum of 1824 to 1826 m a.s.l. by the end of the dry season (Fig. 3a). However, the level of the lake decreased much more dramatically during 2005–2013, apparently as a result of its use for the supply of drinking water to the Mexico City Metropolitan Area and other surrounding cities. During 2005–2013, the water level decreased up to 12 m below its maximum and remained below the maximum for most of the years except for 2010 (Fig. 3a). Three extraordinary minimum water levels were reached in the summers of 2006 (1819.7 m a.s.l.), 2009 (1817.9 m a.s.l.) and 2013 (1818.3 m a.s.l.).
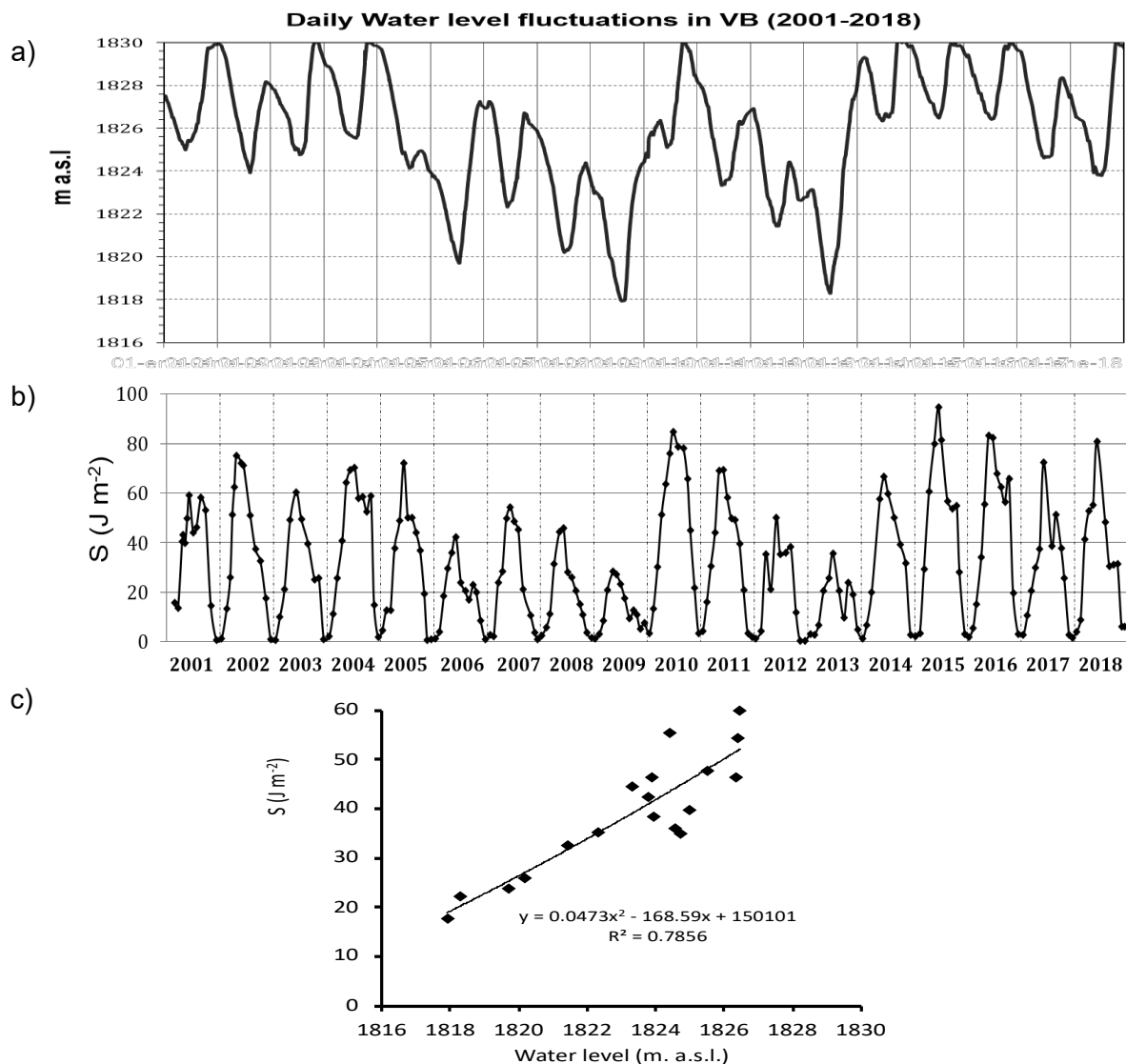
Figure 3. Temporal variations during 2001–2018 in VB of (a) water level, (b) stability of stratification (S), and (c) relationship between mean S and mean water level over the stratification periods.

3.2. Thermal regime and stratification

During 2001-2008, VB behaved every year as a warm monomictic lake with a mean stratification period of 241.4 ± 30.1 days. A similar seasonal pattern occurred in the reservoir during the 18 years studied: the maximum surface temperature was reached in June, with slight variations (23.0–23.9 C) among years. Circulation began in November and the water column remained homogeneous every winter, at least from December

through January. This was reflected in the stability of the water column, which decreased to zero every year during the mixing months, but raised again above at least 20.0 J m^{-2} during all the stratification periods (Fig. 3b). This seasonal pattern (Fig. 3b) shows that stratification was never broken during any of the stratification periods the full 2001–2018 period. Nevertheless, the stability during the stratification periods diminished siggnificantly as the water level decreased (Fig. 3c).

3.3. Hypolimnetic warming

During each and every stratification period, the mean temperature of the hypolimnion of VB increased from one sampling to the next for the 18 years here reported (Fig. 4a). The rates of temperature increase between consecutive samplings ranged overall 0.0003–0.04°C d^{-1} , while the mean rates for each entire stratification period, as estimated by linear regressions in Figure 4a ranged from 0.009–0.022°C d^{-1}, and the maximum mean increases ocurred during the stratifications of 2009 (0.022°C d-1), 2013 (0.020°C d-1) and 2006 (0.019°C d-1). Although linear fits yielded quite high correlation coefficients for all the stratification periods (R^2 ranging from 0.965 to 0.999) some of the stratifications showed a sigmoidal trend (e.g. 2016, 2012, 2018, 2005), that could be related to the transitions between stratification and circulation periods.
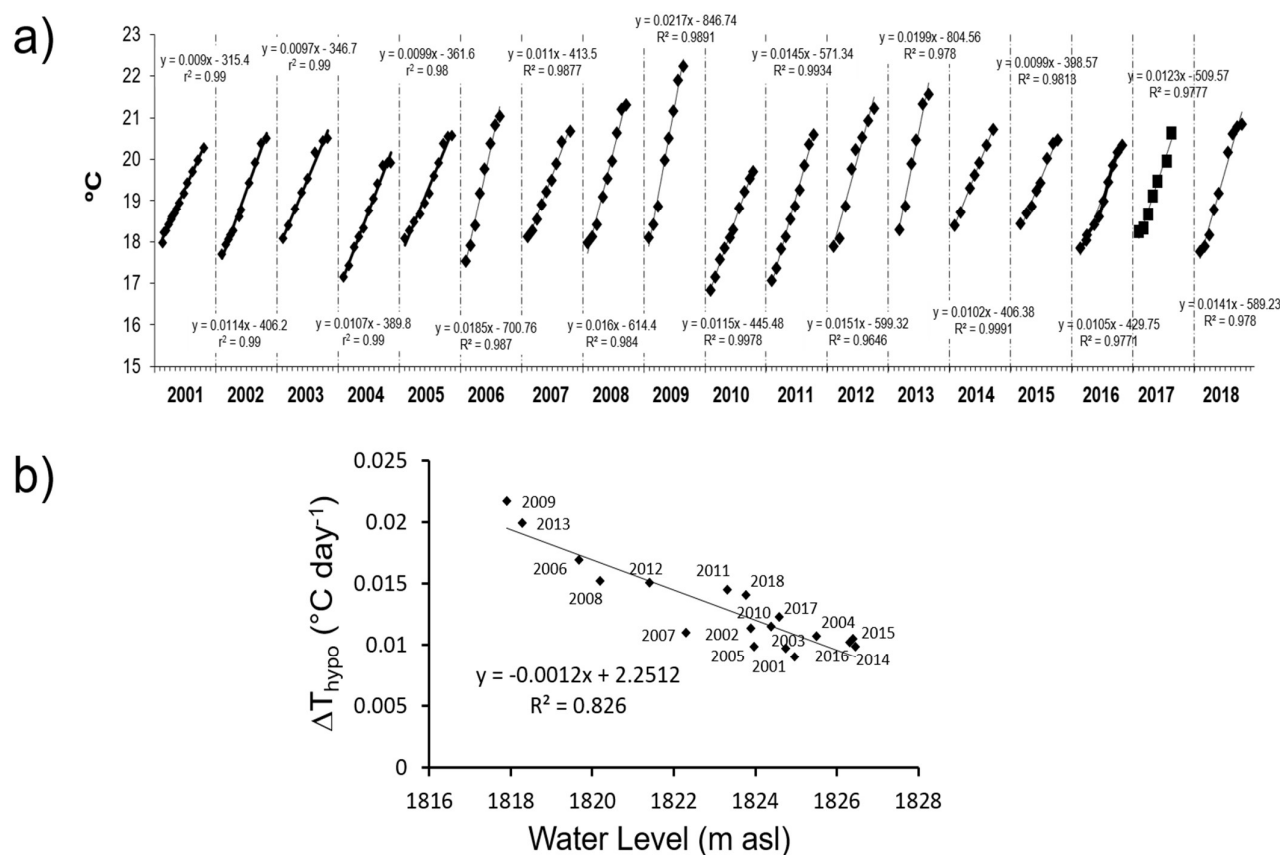
Figure 4. Hypolimnetic water warming and water level relationship in VB: (a) Hypolimnetic temperature variation during each stratification period sampled from 2001 to 2018 [the slopes of the regressions were used to assess the mean warming rate for each of the stratifications] and (b) mean hypolimnetic temperature increase rate during each annual stratification period plotted against the mean water level throughout 2001-2018..

Among years, the mean thermal increase during the stratification period showed a strong inverse correlation with the mean water level for that year (R^2= 0.826): the lower the level of the lake, the higher the rate of hypolimnetic warming (Fig. 4b).

3.3. $Mix_{meta-hypo}$, Kz and nutrient fluxes

The rate of vertical water mixing ($Mix_{meta-hypo}$) ranged from 26,618 m^3 h^{-1} to 140,526 m^3 h^{-1} among the stratifications, being lowest in 2015 and highest in 2009 (Table 1). $Mix_{meta-hypo}$ showed an inverse relationship with the mean water level for each year, with a good fit (R^2= 0.826) through a polynomial regression (Fig. 5). The mean calculated vertical diffusivity coefficients (Kz) followed a similar pattern among years, ranging from 6.2 x 10^{-7} m^2 s^{-1} in 2015 to 3.3 x 10^{-6} m^2 s^{-1} in 2009 (Table 1). On the monthly scale, Kz values as low as 4.0 x 10^{-8} m^2 s^{-1} and as high as 1.2 x 10^{-5} m^2 s^{-1} were obtained through our calculations.

Table 1. Mean vertical water mixing rates (m^3 h^{-1}) and mean vertical diffusivity coefficients, Kz (m^2 s^{-1}), estimated for VB.

Stratification Period	$Mix_{meta-hypo}$ (m^3 h^{-1})	Kz (m^2 s^{-1})
2001	35,862	8.3x10^{-7}
2002	38,480	8.9x10^{-7}
2003	44,035	1.0x10^{-6}
2004	36,652	8.5x10^{-7}
2005	43,567	1.0x10^{-6}
2006	70,465	1.6x10^{-6}
2007	53,254	1.2x10^{-6}
2008	81,774	1.9x10^{-6}
2009	140,526	3.3x10^{-6}
2010	59,942	1.4x10^{-6}
2011	52,963	1.2x10^{-6}
2012	60,262	1.4x10^{-6}
2013	97,856	2.3x10^{-6}
2014	34,656	8.0x10^{-7}
2015	26,618	6.2x10^{-7}
2016	29,678	6.9x10^{-7}
2017	53,998	1.2x10^{-6}
2018	49,170	1.1x10^{-6}
Mean	**56,098**	**1.3x10^{-6}**

Figure 5. Mean vertical mixing rate ($Mix_{meta-hypo}$) plotted against the annual mean water level of VB.

Vertical nutrient fluxes towards the epilimnion followed a similar pattern to that of $Mix_{meta-hypo}$ and Kz, relating inversely with the lake water level, but exhibited higher variability, as shown in Figure 6 and by their lower correlation coefficients(R^2= 0.684 for SRP and R^2= 0.563 for DIN). SRP vertical flux to the epilimnion ranged from 0.56 to 5.99 mg SRP m^{-2} d^{-1} among the different stratification periods and averaged 1.97 mg SRP m^{-2} d^{-1} for all the 18 years studied. DIN vertical flux to the epilimnion ranged from 5.79 to 97.12 mg DIN m^{-2} d^{-1} among the different stratifications and averaged 30.45 mg DIN m^{-2} d^{-1} for the 18 years studied.
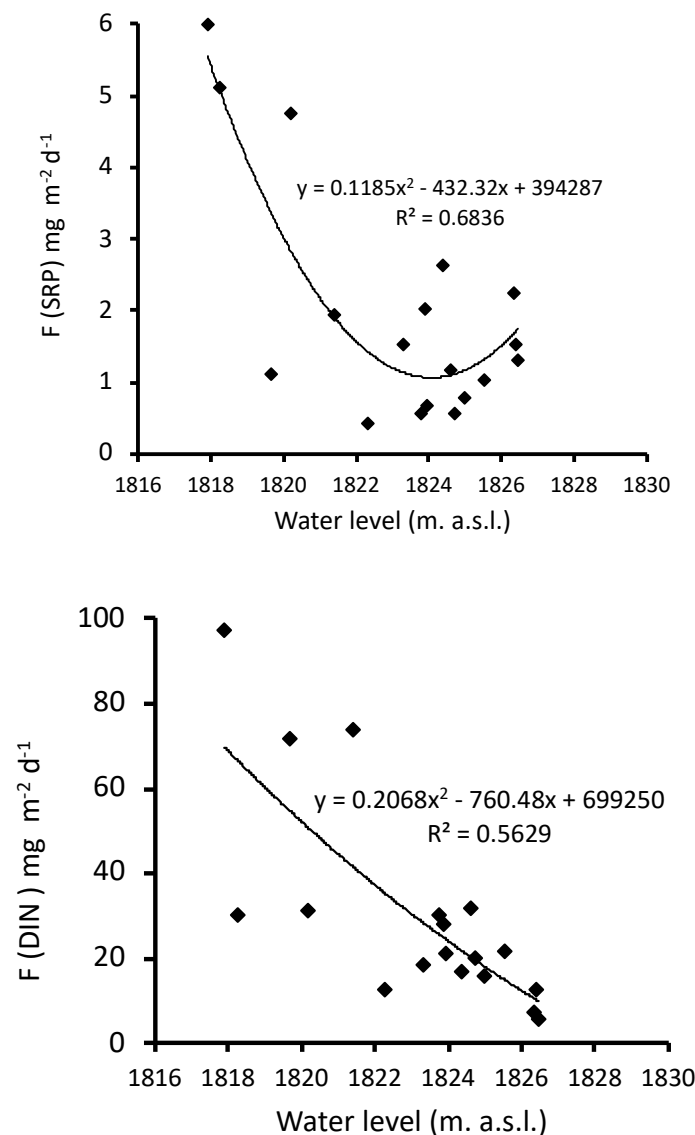
Figure 5. Mean rates of nutrient vertical flux (F) of: a) SRP and b) DIN, plotted against the annual mean water level of VB.

4. Discussion

The approach here presented derived from long-term observation throughout two decades of monthly monitoring at VB, where strong winds, eutrophication, and water extraction for the Mexico City interplay in a system where explosive phytoplankton blooms are frequent [11,15]. In such a complex system, the assessment of the vertical exchange of water and nutrients and its variations can help to reveal the mixing and nutrient environment that plankton perceives. From this understanding, insight and prediction of the processes involved could be derived, and eventually become useful tools for the management of the lake in the global change scenarios to come.

Despite of the high WLF recorded in VB during this 18 years, our observations demonstrated that the lake behaves regularly as a monomictic tropical lake, exhibiting a single stable stratification summer period and water circulation during the winter [10,11,14,16]. Water-level in VB regularly presents small seasonal changes as a function of

seasonal rainfall in its basin, but higher WLF are a result of longer term climatic variability and management decisions that consider requirements of water for human consumption and water availability within the Cutzamala system as a whole, so they occur on longer time scales . Therefore, a long-term series, as the one here reported, is needed to include enough WLF variability to allow the identification of patterns and the effects of these variations in tropical deep lakes, like VB. The magnitude of WLF in VB during this period was so high that a level decrease of up to 12 m was registered, which is more than half of the mean depth of the lake when it is at its maximum level. However, VB remained stratified during the warm months (March to November) of the year, every year.

Our results demonstrated that the hypolimnion warmed regularly during every stratification in VB throughout the entire observation period, although the warming rate varied from year to year. We attribute this warming to vertical mixing events, that are likely driven by IW caused by the wind pattern in VB, which has a very regular diurnal oscillation [11]. This is in agreement with the findings of [6,20–22] in similar systems, where IW have been proposed to drive BM and generate vertical nutrient transport. Indirect evidence also supports this phenomenon in VB. The vertical distribution of dissolved oxygen through the water column reported by [13] supports the occurrence of frequent (≈daily) events of BM in stratification. They found, within the anoxic hypolimnion of VB, occasional patches of slightly oxygenated water which last only between a few hours to days. Additionally, [14] found that WLF strongly influenced gross primary production and respiratory rates in VB, which could be attributed to vertical mixing processes occurring during the stratification periods. In accordance, the variations in phytoplankton composition related to WFL found by [15] as well as the changes in zooplankton community identified in VB by [13,24] would also be reflecting the effects of vertical mixing.

The vertical water exchange rates here calculated (Table 1) imply that 5–11% of the total volume of the lake is being exchanged monthly between layers during the stratification period of the years when the water level is relatively high. But during the lowest water level years, it can reach up to 26% (e.g. 2009) of the lake′s volume in a single month. On an annual scale, for the full stratification period, these volumes of water represent 40-83% of the total lake′s volume being exchanged between layers, and can reach up to 131 % in the low level and stronger mixing years, as in 2009. This magnitudes suggest that vertical transport can be much higher than what would be expected from the traditional paradigm of stratification and metalimnetic barrier [2], and could also provide a physical mechanism to explain the sustained heterotrophic behavior found for VB even under stratification conditions [14].

Table 2 shows our vertical diffusion coefficients, Kz, along with those found for other lakes. Our calculated coefficients (4.0×10^{-8} m^2 s^{-1} to 1.2×10^{-5} m^2 s^{-1}) fall within the range of values reported in specific studies of vertical diffusivity (10^{-8} m^2 s^{-1} to 10^{-3} m^2 s^{-1}, Table 2), but they are rather on the lower part of the range. This could mean that this normally undetected vertical mixing could be occurring on many of the systems included in the table.

However, it should be born in mind that our estimates assess the intensity of vertical mixing averaged over a full month –i.e. between two consecutive sampling dates– while direct diffusivity measurements (such as those pooled together in Table 2) are made on much smaller time scales, and likely register the peak values that occur during mixing events. In contrast, our estimates are smoothed values over the full period between samplings, and are likely more representative of the actual mixing rates. For instance, at Lake Kinneret, where mixing process are amongst the most well-known, [25] outline the variability that might affect the representativity of short term measurements: "most of the time the vertical flux through the metalimnion was negligible, but, at times, the eddy diffusivity did reach values as high as 10^{-2} m^2 s^{-1} ". We believe that, by integrating the effect of these relevant vertical mixing pulses, our results likely better represent actual mixing rates at the near monthly scale. Nevertheless, to fully verify this in upcoming research we will be exploring the mixing intensity at short-time scales.

Table 2. Comparison of vertical diffusion coefficients, Kz, reported here and in other studies. Measurements are ordered from higher to lower maximum Kz approximately

Kz ($m^2\ s^{-1}$)			Location	Reference
Mean	**Min**	**Max**		
1.30×10^{-6}	6.2×10^{-7}	3.3×10^{-6}	VB (annual mean)	This paper
	4.0×10^{-8}	1.2×10^{-5}	VB (monthly integrated)	This paper
	1.0×10^{-5}	1.0×10^{-3}	North Lake Australia	[26] MacIntyre 1993
	8.0×10^{-5}	1.3×10^{-4}	Lake Rotowhero, New Zealand	[27] Brookes et al. 2013
1.0×10^{-6}	1.0×10^{-8}	1.0×10^{-4}	Mono Lake, California	[6] MacIntyre et al. 1999
	1.0×10^{-6}	1.0×10^{-4}	Lake Biwa, Japan	[8] Auger et al. 2014
2.2×10^{-6}	3.0×10^{-6}	8.0×10^{-5}	Lake Alpnach (central Switzerland)	[28] Goudsmith et al. 1997
	6.0×10^{-6}	5.0×10^{-5}	Lake McIlwaine, Rhodesia	[29] Robarts & Ward 1978
3.4×10^{-6}	Molecular (10^{-7})	2.6×10^{-5}	Mono Lake, California	[30] Jellison & Melack 1993
		1.0×10^{-7}	Molecular conductivity	[6] MacIntyre et al. 1999

From a biogeochemical point of view, our results for vertical nutrient flux demonstrate that vertical mixing can transport a significant amount of nutrients to the epilimnion during the stratification in lakes exposed to events of BM as VB, which has important implications for internal nutrient recycling and metabolism. Our vertical diffusion coefficient estimates are, on average, similar to the those that have been calculated for other lakes (Table 3), such as Kivu [31], Mendota [3], McIlwaine [29] and Malawi [32] when the higher level years are considered. However, for the years with the low water levels, our Kz values are higher than all of those in Table 3. This clearly indicates that the vertical nutrient flux in VB from the hypolimnion can increase by an order of magnitude when the water-level drops sharply ($\approx$ 12 m), which has never been considered an important factor in water reservoir management until now.

Table 3. Nutrient fluxes ($mg\ m^{-2}\ d^{-1}$) obtained for VB and in the few lakes where they have been estimated. In the case of nitrogen, we only found data for ammonia, so we included our ammonia flux calculations together with the DIN values (in parenthesis).

SRP	Ammonia (DIN)	Lake	Reference
1.97	12.3 (30.5)	VB (mean)	This paper
5.99	63.1 (97.1)	VB (low water level)	This paper
2.71		Lake Kivu, Africa	[31] Pasche et al. 2009
2.59		Lake Mendota, Wisconsin, USA	[3] Kamaraimen et al. 2009
1.60	6.1	Lake McIlwaine, Rhodesia, Africa	[29] Robarts and Ward 1978
$\backsim$ 3.0	$\backsim$ 20.0	Lake Malwi/Nyasa, Africa	[32] Hamblin et al. 2003

When compared with the mean external phosphorus load to VB (16.9 ± 8.7 mg TP m^{-2} d^{-1}, [16]), nutrient vertical entrainment to the euphotic zone represents, on average, about 12% of the phosphorus annually entering the reservoir through its main tributaries. Nevertheless, this proportion can increase up to > 35% when the level decreases 12 m or more. Thus, the water level can alter significantly the amount of nutrients available in the euphotic zone of the lake during stratification and therefore its primary production and functional eutrophication level, as identified by [14]. This means that nutrients will be recycled more intensively in VB when the water level is low, while N and P fluxes to the sediments through sedimentation will likely be higher when the water level is higher and vertical transport decreases. In fact, the changes in metabolism found in VB [13] which are presumably associated to the variation of vertical mixing, alter both the metabolic balance and the role of the lake as a source or sink of carbon to the atmosphere [14], and all this depends a lot on the variation of WLF. Changes in water level and therefore mixing events can also drive changes in the planktonic composition, both for phytoplankton [15]

and zooplankton [24]. Increased mixing can favor diatoms and decrease cyanobacterial blooms. The associated changes in zooplankton composition can favor fisheries availability. Finally, the possible effects of WLF on the littoral communities will likely also be important. (see [16]).

Altogether, the multiple consequences of WLF in systems as VB can alter both the ecology of the lake and its suitability for a sustained water exploitation by the main users. The effects we have here identified should be accounted for by water managers, who could outweigh them against the particular needs of water distribution that may require affecting the water level of VB.

5. Conclusions

Vertical mixing calculated from hypolimnetic warming in VB through a heat balance shows that there is a significant vertical exchange in this lake during the stratification months. The intensity of this vertical mixing increases as the level of the lake decreases, likely because of the enhancement of BM events as IW intensify their interaction with the lake´s bottom and margins, as found for other lakes that have a similar wind forcing. Vertical diffusivity coefficients are within the range found in this kind of lakes but are comparatively low, likely because they integrate the average vertical mixing occurring over monthly to annual scales, while most direct measurements reported for other water bodies address peak mixing pulses.

The vertical nutrient transport derived from this water exchange in VB would be enough to overcome the stratification barrier during the stratification periods and sustain the observed eutrophic conditions during stratification. This is consistent with the fact that VB is more productive during stratification than during circulation months when nutrients would not be segregated to the hypolimnion. The estimated vertical nutrient entrainment to the epilimnion in VB is similar to other systems on average, but seems to become much higher during years with low water levels. These vertical mixing and associated nutrient flux affect significantly the planktonic communities, the metabolic balance of the lake, and likely the recycling of the external nutrient loading to the lake and the fraction that may be accumulated at the bottom of VB.

Our model allows for the prediction of vertical mixing and nutrient entrainment as a function of the water level in the lake, providing an additional tool for water authorities and lake users to improve their management strategies of this and similar lakes.

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