Limnol. Oceanogr., 45(4), 2000, 972–981

The physical regime and the respective biogeochemical processes in the lower water mass of Lake Kinneret

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Abstract

Physical measurements made in Lake Kinneret, during the stratified period, indicate that the lower water mass (LWM) consists of two layers: a turbulent benthic boundary layer (BBL) and a hypolimnetic layer overlying the BBL. The water in the LWM moves in response to vertical mode one seiching of the metalimnion; this movement is accentuated near the perimeter of the metalimnion due to shoaling of the seiche and breaking of internal waves. The motion associated with this phenomena induce a well mixed benthic boundary layer (BBL) adjacent to the lake bottom. The BBL and hypolimnion were distinguished chemically because transport of solutes between these water bodies was very small. Compared to the hypolimnion, the BBL was characterized by more intensive biomineralisation processes as indicated by the faster depletion of DO and NO_3, by higher levels of NH_4, H_2S, and soluble reactive phosphorus (SRP) and by lower pH values. SRP levels in the hypolimnion were particularly low, suggesting that phosphorus was either preferentially removed by sedimentation from the hypolimnion, or it was not released from particles. As a result NH_4 over SRP ratios in the hypolimnion were significantly higher than in the BBL and diffusional fluxes of both nutrients from the LWM to the trophogenic epipelagic water, should therefore be characterized by relatively high N/P ratios.

Warm monomictic Lake Kinneret (LK) is thermally stratified between April and December. Following the onset of stratification the lower water mass (LWM), undergoes a sequence of redox changes as a result of the succession of microbially mediated processes, including oxygen consumption, denitrification (Cavari 1977), fermentation, and sulfate reduction (Hadas and Pinkas 1995*a*). Approximately 10% of the organic matter produced by photosynthesis undergo decomposition in the LWM during the stratified period (Nishri et al. 1998). Triggered by the supply, through sedimentation, of organic material from the photic zone the so-called anaerobiosis of the LWM lasts typically until June–July when sulfide becomes detectable throughout the LWM (Serruya 1978; Eckert and Trüpper 1993; Hadas and Pinkas 1995*b*). Summer and fall are characterized by the gradual accumulation of sulfide, concomitant with a steady increase in ammonium and soluble phosphorus in the LWM.

Long-term records of phosphorus levels in the LWM of LK reveal a prominent rise (Stone et al. 1993), starting in late 1970's. Several years later (in summer 1981) a steplike increase in summer phytoplankton biomass began and stabilized over the following decade (Berman et al. 1992). This raised the question of whether the increase in the P limited summer algae (Pollingher et al. 1988) was caused by an enhanced upward flux of P from the LWM.

The sediment-water interface is often considered as an important site of organic matter degradation in lakes. Part of the degradation process may occur in the benthic boundary layer (BBL). The occurrence of such layers in stratified lakes has been shown repeatedly (e.g., Imberger and Patterson 1989; Imberger and Ivey 1993; Gloor et al. 1994; Wüest 1994) and in the case of LK they were recently documented by Lemckert and Imberger (1998, in prep.). High-resolution profiles of vertical temperature gradients in the water column, obtained during the present experiment, confirmed the presence of such a BBL in LK.

The objective of the present study was to understand how the physical regime prevailing in the LWM affects

Acknowledgments

Ora Hadas is acknowledged for discussing this work. Efrat Ori and Rivka Hershcovitch are acknowledged for assisting in preparing this ms. This study was partially supported by G.I.F Research Grant I-416–026.08/95. The Centre for Environmental Fluid Dynamics of UWA provided financial support for the physical field programme. This paper forms the CWR contribution ED 1384 AN.

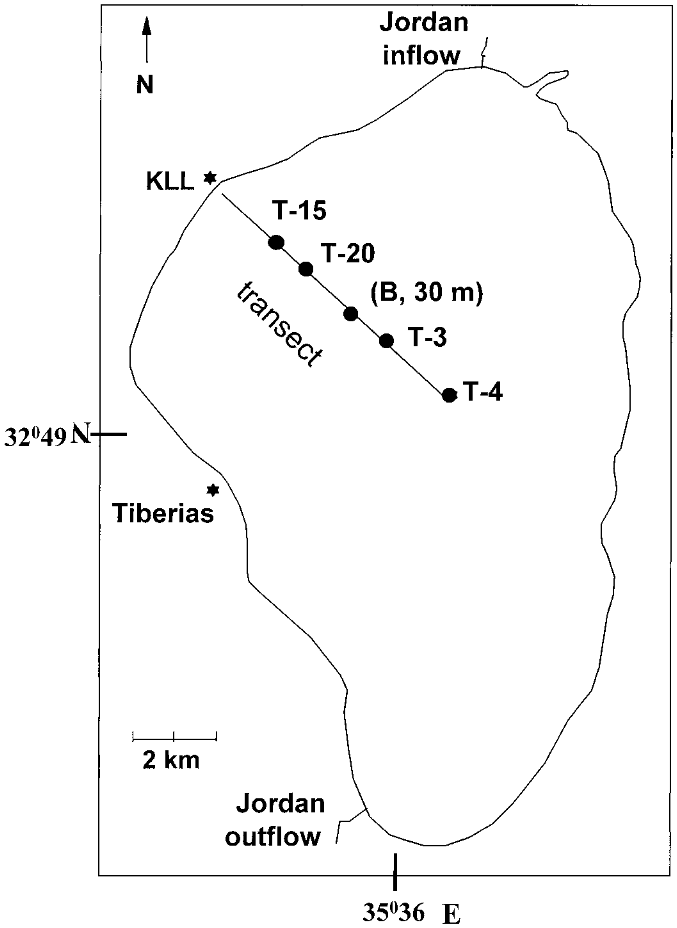

Fig. 1. Lake Kinneret location map and layout of transect performed on 30 June 1997.

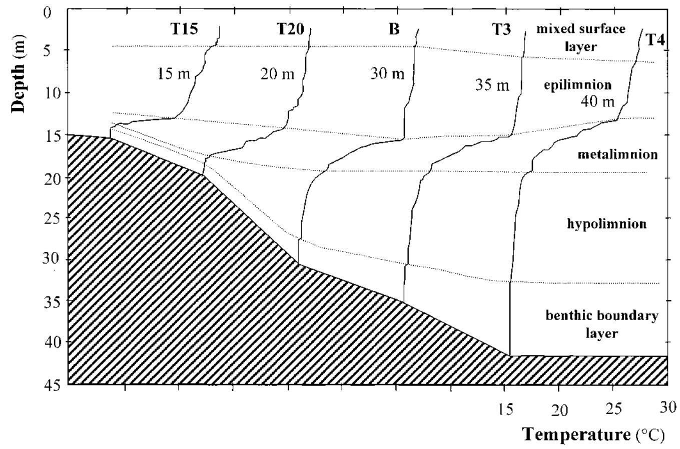

Fig. 2. The water layers in Lake Kinneret, according to Lemckert and Imberger (1998).

the resident, biogeochemical processes. These include resuspension of sediments from the lake floor, as indicated by turbidity, mineralisation processes and transport of solutes in the LWM. Chemical data collected during additional cruises, in summer 1997, as well as historical data were used to explain the observed seasonal evolution of the solutes in the LWM.

Study Site

Lake Kinneret, the Sea of Galilee, Israel, is a monomictic, calcareous freshwater lake, located at the northern edge of the Afro-Syrian Rift Valley. The lake is thermally stratified between April and December with epilimnetic water temperatures reaching a temperature of 30°C in the peak of summer. The water column temperature profile is characterized by a steep temperature gradient (3°C m^{-1}) that adds great stability to the water in the lake (Serruya 1978).

During the stratified period the temperature in the pelagic zone near the bottom of the lake remains close to the winter prestratification value of about 15°C rising only slightly (less than 0.6°C) throughout the summer. The water level of LK fluctuates both seasonally and annually, ranging from −213 m (m.s.l) at the end of the summer to −209 after the winter rains. The stratification commences in April, peaks at the end of June and begins to weaken by surface cooling in September. The summer is locally characterized by strong (up to 12 m s^{-1}) daily westerly winds, which typically last from noon until sunset. As a result of this regular wind pattern, intensive internal waves are generated in LK (Serruya 1975; Saggio and Imberger 1998; Imberger 1998).

Lake Kinneret is characterized by a spring bloom of the dinoflagellate *Peridinium gatunense* (sometimes reaching a biomass of over 200 g m^{-2}) (Berman et al. 1992), during which time the pH in the epilimnion may rise to 9.6; accompanied by massive sedimentation of authigenic $CaCO_3$. Following this, in summer and fall a predominance of nanoplankton algae is observed. These are green and blue-green algae with lower biomass (20–40 g m^{-2}) and lower epilimnetic pH levels (ca. 8.4).

The LWM becomes anoxic by June, about 1–3 months after the onset of the thermal stratification leading to anaerobic mineralisation processes and to the accumulation of CO_2. Bacterial sulfate reduction (Hadas and Pinkas 1995*a*) causes the accumulation of sulfide on the account of the SO_4 entrapped in this layer prior to the onset of stratification (Eckert and Trüpper 1993). In near bottom water approximately half (ca. 0.3 mM) of the SO_4 entrapped undergoes reduction to hydrogen sulfide. In the H_2S and CO_2 enriched LWM the pH varies between 7.0, at the sediment water interface, to ca. 7.8 at its upper part (Serruya 1978).

Sampling and analytical procedures

Most of the physical and hydrochemical data presented in this study were collected at four stations located along a transect from the central lake station (T4) to T15 (Fig. 1). The physical properties in the water column were documented using the portable flux profiler (PFP, Imberger and Head 1994). This device was equipped with microsensors for temperature, conductivity, and three components of velocity capable of measuring these properties with a resolution of a millimetre, allowing the turbulent properties to be quantified. The main parameter of interest for the present paper is the bottom shear velocity. This was calculated directly from the estimates of the Reynolds stresses as described in Lemckert et al. (in prep.). The height of the benthic boundary layer was obtained from the temperature gradient signal by checking the stationarity of the signal using the segmentation algorithm developed by Imberger and Ivey (1991). The top of the benthic boundary layer was taken at that point marked by the top of the stationary segment. This always corresponded to small, but definite, increase of temperature and the beginning of a weak temperature gradient.

Turbidity and redox intensity (**pe**) were measured at the same stations and in parallel to the physical measurements. In situ turbidity measurements were performed using an HYDROLAB Sonde-4 system. This measuring device was left at least a minute at each depth, collecting at least 12 readings. The in situ redox intensity was determined with a multiprobe system described in Eckert et al. (1990). In situ DO profiles were determined using a polarographic electrode.

Detailed (each 1 m interval) chemical concentration profiles of various solutes: NO_3, NH_4, total phosphorus (TP), total dissolved phosphorus (TDP), soluble reactive phosphorus (SRP) and pH were made at another central pelagic station, Sta. 108 (located ca. 500 m south of Sta. T4) on 1 June, 29 June, and 3 August 1997 as well as a year earlier, on 30 June 1996. At each time sampling was performed between 0800 h and 1000 h. Weekly concentrations of these solutes have been measured routinely, at 20 m, 30 m, and 40 m depth (Sta. T4) since 1970 and were taken from the Lake Kinneret database (LKDB).

The pH was measured in the laboratory, ca. 2 h after sampling in BOD bottles. NO_3, H_2S, NH_4, TP, TDP, and SRP were determined according to standard analytical procedures (APHA 1985). TDP was determined on filtered (0.45 μm) LK samples using the same procedure of digestion as for TP analysis. The detection limit for the determination of molibdate reactive phosphorus was 1.5 μg P L^{-1} and for NH_4 3.0 μg N L^{-1}.

Background: The physical regime in the Lower Water Mass

The wind acting on the surface of LK imparts both momentum and turbulent kinetic energy (TKE) to the water in the surface layer (Stevens and Imberger 1996). The TKE causes the momentum to be distributed downward initiating a general motion in the surface layer in the direction of the wind and inducing mostly a long internal wave heaving of the metalimnion (vertical mode one), but also bifurcating the metalimnion (modes two and three response; Imberger 1998). As the motion proceeds and the water velocity increases, the earth's rotation converts the response to Kelvin and Poincare waves. As the propagation proceeds the wave properties are modified by nonlinear wave steepening (Horn et al. 2000), shoaling, wave–wave interaction and dissipation (Michellet and Ivey 1999). Depending on the strength of the wind and the depth and strength of the stratification, these ultra degenerate in LK into a spectrum of waves with frequencies ranging from 24 h for the Kelvin waves to minutes (buoyancy frequency) for the free waves (Imberger 1998). In summary, the initiation of a wind stress thus leads to the establishment of a complete spectrum of internal waves, with the relative energy levels at different frequencies depending greatly on the phase of the wind and the strength of stratification (Imberger 1998).

Three consequences follow from the symphony of long internal waves propagating through the metalimnion in LK. First, the higher frequency waves have short horizontal wavelengths and so when they impinge on the sloping boundary of the lake they break and lose most of their energy and so form a turbulent benthic boundary layer (Ivey et al. 1995; De Silva et al. 1997; Ivey et al. 1998; Michallet and Ivey 1999). The turbulence so created may lead to resuspension of fine sediments. Second, the long period, basin scale (vertical mode one) waves seiche the LWM across the bottom boundary generating turbulence and further internal waves. The associated mixing forms a benthic boundary layer in the LWM which can be many meters thick (Lemckert and Imberger 1998). Third, direct flux measurements in the metalimnion of LK (Imberger 1998) have shown that the shear induced by the long freewaves propagating through the metalimnion is sufficient to cause considerable turbulence, but little mixing. During periods of strong internal wave activity the vertical average diffusion coefficient in the metalimnion and hypolimnion was close to molecular (Imberger and Ivey 1991; Saggio and Imberger in prep.).

Results and Discussion

The physical behavior of the BBL—The net result on the BBL of the sequence of processes described above is well illustrated by the transect of temperature microstructures profiles shown in Fig. 2. Clearly depicted is a BBL (marked with a dashed line) 8 m to 10 m thick at Sta. T4, but reduced to about 1 m at station T15 due to the presence of the strong thermal gradient associated with the immediately overlying metalimnion.

In this paper we shall focus only on the behavior of the BBL at the deep stations, T4, T3, and T25. For this region Lemckert et al. (in prep.) demonstrated that the turbulence was initiated at the lake bottom and then propagated upwards as the shear velocity increased during the seiche period. The rate of entertainment may be estimated from an integration of the turbulent kinetic energy equation across the BBL, as shown in Fischer et al. (1979). If u_* is the source of turbulent kinetic energy at the lake bottom, and we assume the water column has a linear density gradient with a buoyancy frequency **N** above the turbulent front of the BBL, then:

$$\frac{N^2h^2}{2}\frac{dh}{dt} = C_\kappa{}^* u_*{}^3, \qquad (1)$$

where **h** is the BBL thickness and $\mathbf{C}_\kappa{}^* = 0.23$ (Fischer et al. 1979).

If we assume that

$$u_* = u_{*m} \sin \omega t \qquad (2)$$

mimics the variation due to a simple Kelvin wave passing the site ($\omega = 7.3 \times 10^{-5}\ s^{-1}$) then the maximum thickness

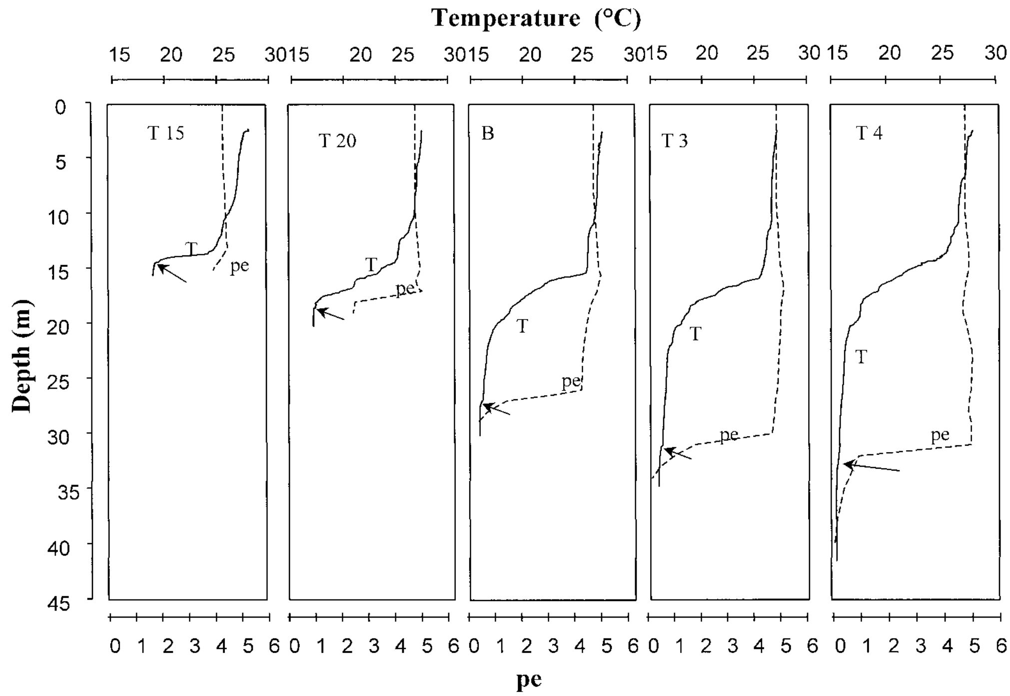

Fig. 3. Redox intensity and temperature profiles taken along the 30 June transect. Top of BBL at each station is marked by an arrow.

reached in one seiche period may be obtained by substituting (2) in (1) and integrating the resulting equation over one period to yield:

$$h_m = \frac{2C_\kappa{*}^{1/3}u_{*m}}{(\omega N^2)^{1/3}}. \quad (3)$$

Direct measurements of the shear velocity by Lemckert and Imberger (1998) showed the maximum shear velocity at the time of measurement was close to 4 mm s^{-1}. The buoyancy frequency N in the deep part of the lake (*see Fig. 2*) was very small. Fitting a straight line to the temperature profile at T4 shown in Fig. 2 yields a value of $N^2 = 1.5 \times 10^{-4}$. Substituting this value into (3) yields $h_m = 2.2$ m, which is less than the observed thickness of about 8 m (Fig. 2). This suggests that the observed BBL thickness (Fig. 2) is the result of entrainment over many seiche periods. The internal seiching causes an oscillatory u_* which in turn leads to a source turbulent kinetic energy proportional to u_*^3. This flux of TKE causes the water near the bottom to mix forming a well-mixed BBL. During slack periods u_* is close to zero and the TKE will decay rapidly leaving behind a stagnant well-mixed BBL. On the subsequent seiche u_* increases once again initiating a turbulent front at the sediment–water interface which moves upwards through the BBL, at a speed of 0.3 u_* (the rate of propagation into a homogenous water column). Once it reaches the top of the BBL, and provided the seiche is still active, the turbulence will erode the top of the BBL and penetrate into the hypolimnion, thickening the BBL, on each seiche until such time that the propagation of the turbulent front takes half of the seiche period. At that time the u_* is back to zero by the time the front reaches the top of the BBL. The observed BBL thickness is thus given not so much by (3), but rather by the entrainment rate through a homogenous water column acting over a 12-h period. Once again assuming a shear velocity variation given by (2) and a maximum shear velocity of 4 mm s^{-1} we arrive at a total benthic boundary layer thickness of about 33 m which is larger than the 8–10 m observed (Fig. 2). What therefore was observed was a progression towards this final step; a composite behavior of the front propagating through a homogenous water column until the turbulent front reached the top of the benthic boundary layer and then continued to erode the upper interface as expressed by (3) until the shear velocity had abated. Such a simple model was used to obtain the benthic boundary layer thickness as a function of time and this suggested, from the time of commencement, a depth of 8 m after 30 days and 10 m after 60 days. Given that the data in Fig. 2 were collected on Julian day 175 and stratification commenced on Julian day 120 this is a reasonable prediction. It must however, be remembered that during the intervening period the bottom buoyancy frequency, the seiche induced shear velocity and seiche period would have been continuously changing, all affecting the predictions obtained from this simple model.

Turbidity in the BBL

Turbidity measurements performed in parallel to the physical parameters are presented in Table 1. In most stations there were significantly higher levels of turbidity in the BBL, as compared to the hypolimnion. At Sta. B and T3 average hypolimnetic levels were 0.46 and 0.53 NTU as compared to BBL values of 1.3 and 1.75 NTU, respectively. Turbidity levels in the BBL increase toward shallower stations consis-

Table 1. Average turbidity levels of measurements performed on 30 June along a transect in Lake Kinneret. Data, in NTU units, represents averages of over 10 samplings performed at the same depth. Measurements taken in the BBL of the LWM are italicized.

Station	Sampling depth (m)	Turbidity (NTU) average	SD of turbidity
Sta. B	26	0.46	0.10
	28.5	*1.78*	*0.88*
	29	*1.73*	*0.65*
T3	30.5	0.53	0.16
	34.5	*1.30*	*0.33*
T4 (Sta. A)	30	0.25	0.13
	36	*0.38*	*0.05*
	38.7	*0.38*	*0.05*
	40.6	*0.34*	*0.05*

tent with the observed increase in u_* and decrease in the BBL thickness.

The BBL in the central lake station (T4) is characterized by relatively low turbidity (0.34 ± 0.06 NTU), which is only slightly higher than the value in the hypolimnion. Turbidity levels monitored in LK during the last 30 years approach a minimum level of 0.30 ± 0.06 NTU. We therefore refer to this minimum as some sort of a background level typical of this lake. It is thus assumed that in the BBL only turbidity levels, which are in excess (i.e., significantly higher) of this background, may result from resuspension of the underlying lake floor. The absence of detectable excess turbidity in station T4 may well be explained by the low u_* values estimated for this station. It may therefore be concluded that at this station the kinetic energy introduced to the system was large enough to develop a BBL with a thickness of 8–9 m, but it was too small to cause significant resuspension from the organic rich cohesive sediment surface layer of the lake floor.

It should be mentioned that the uppermost layer of pelagic and sublittoral bed sediments of LK is enriched with organic matter (Serruya 1978; Koren 1993; Ostrovsky et al. 1997). Hence resuspension of these sediments into the BBL may lead to heterotrophic microbial activity in this water layer.

Chemical stratification in the LWM

Detailed profiles of redox intensity (**pe**), DO, and H_2S concentration, taken in May–June 1987–1988 by Eckert and Trüpper (1993), were a preliminary indication that the evolution of anoxic conditions and accumulation of H_2S follows sublayering within the LWM and that DO depletion and H_2S accumulation occurred earlier in near bottom layers. In the absence of DO and NO_3 in the LWM of LK, these authors obtained a linear correlation between **pe** and H_2S values.

Redox intensity profiles taken on 30 June 1997 along the transect reveal a sharp redox gradients at the top of the BBL (Fig. 3). Oxygen measurements taken with a polarographic electrode at T4 (Fig. 4) shows, (1) relatively high levels of DO in the surface water, as expected due to photosynthetic activity and air–lake gas exchange; (2) complete depletion of DO in the metalimnion, below the seasonal thermocline;

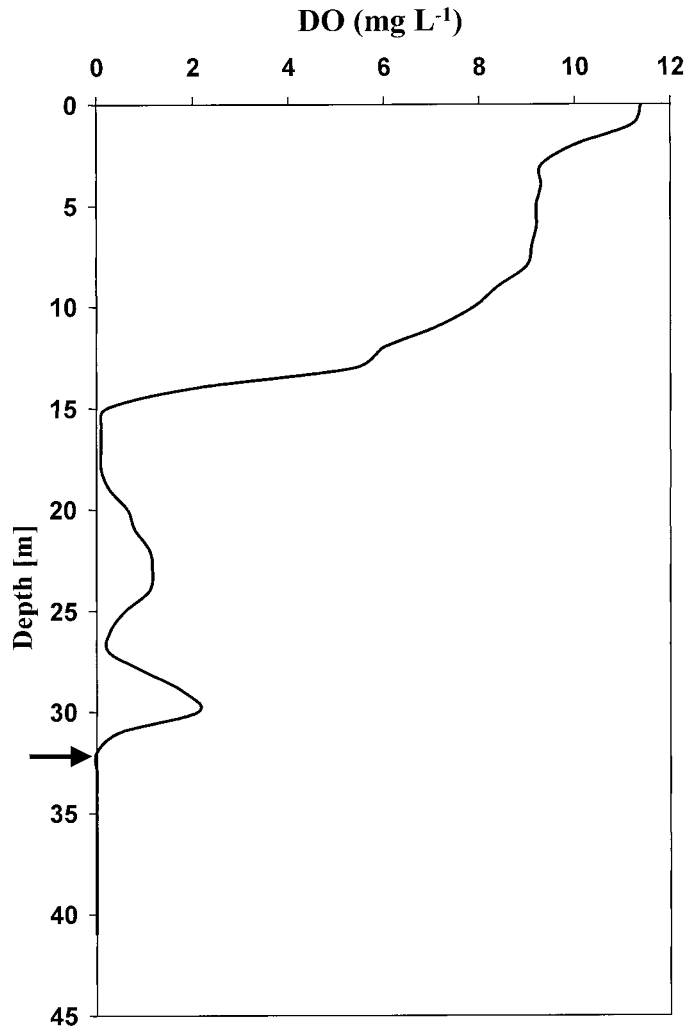

Fig. 4. Dissolved oxygen profile at station T4 (30 June 1997). Top of BBL at Sta. T4 is marked by an arrow.

(3) low concentration of DO in the hypolimnion; and (4) an oxygen depleted BBL layer (below 32.4 m depth). Measurements taken a day earlier revealed the presence of H_2S in the BBL. It is therefore concluded that chemical layering is affected by the physical layering and that redox processes, including DO depletion and H_2S accumulation, occur faster in the BBL than in the hypolimnion.

The extent of mineralization in the LWM and its response to layering in the LWM was also investigated. A sequence of profiles for pH and for different solutes was taken at the pelagic station T4 during the summer of 1997.

In surface water pH values (Fig. 5) decreased during the summer, concomitant with the decline in primary productivity (LKDB data, not shown). In the LWM (from 15 m depth to bottom) during most of the stratified period pH levels usually decrease. A pH profile taken on 31 August revealed (data not shown) a further decrease to pH 7.61 ± 0.05 in the BBL and to 7.77 ± 0.06 in the hypolimnion. As the carbonate system constitutes the major pH buffer in LK water (Serruya 1978), the steady decrease of pH with depth

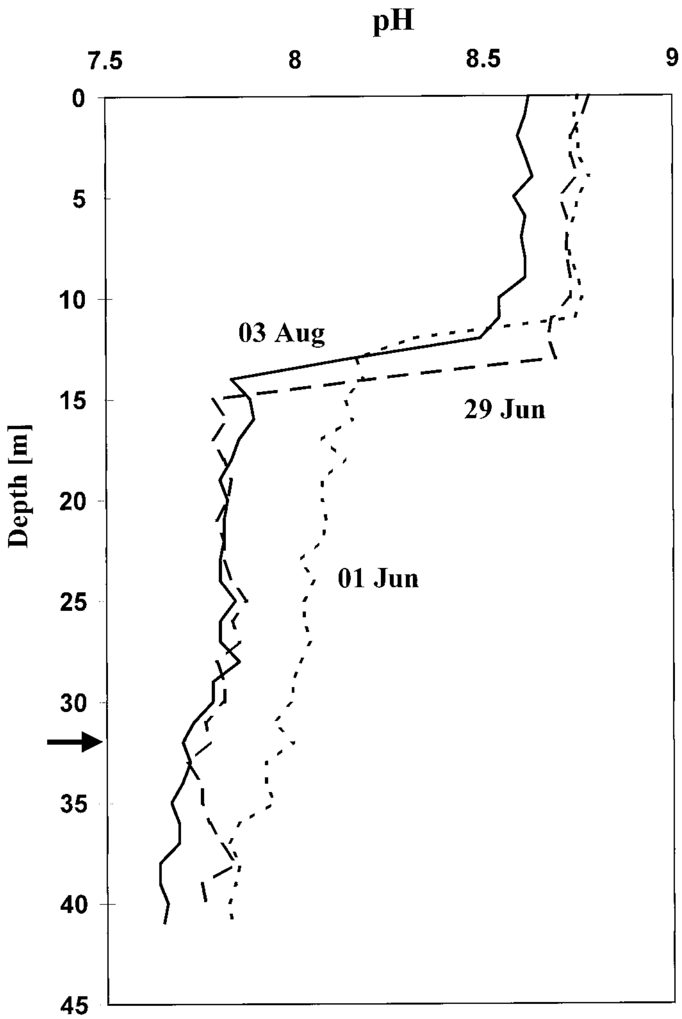

Fig. 5. pH profiles recorded during summer 1997 at Sta. 108. Top of BBL in T4 on 30 June 1997 is marked by an arrow.

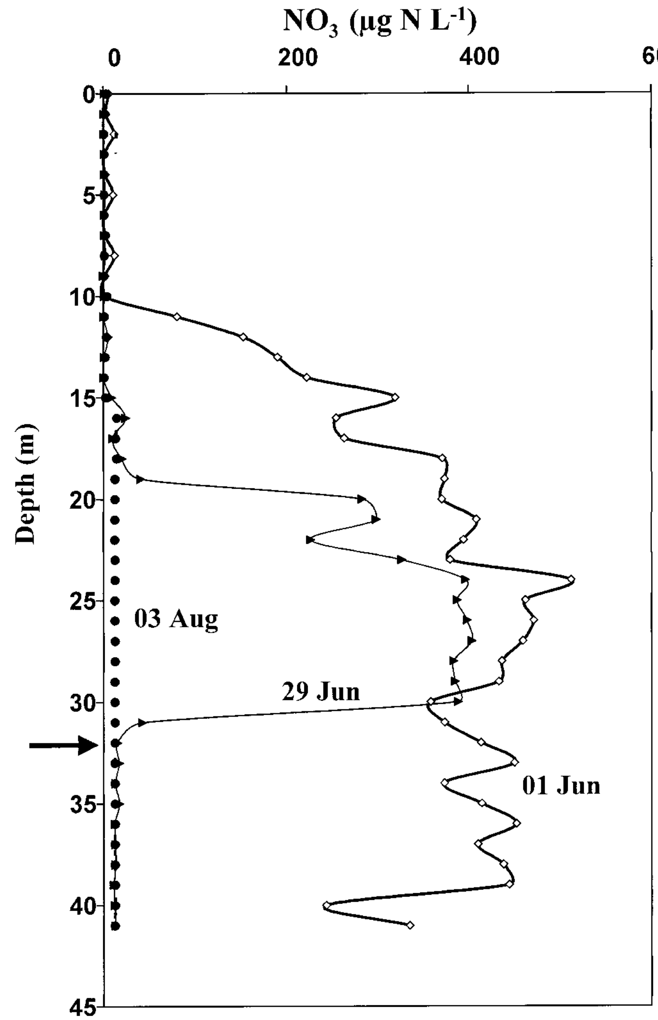

Fig. 6. Nitrate (NO_3) concentration profiles taken at Sta. 108 on 1 June (open diamonds indicate sampling depths); 29 June (filled triangles); and 3 August 1997 (filled circles). Top of BBL in T4 on 30 June 1997 is marked by an arrow on the 29 June Sta. 108 profile.

(Fig. 5) is an expected result of more intensive respiratory processes in the BBL, leading to elevated CO_2 levels.

On 1 June 1997 surface water NO_3 concentrations were only a few microgram per liter (Fig. 6) whereas along most of the LWM levels were similar to those prevailing there at the onset of stratification in mid-April (ca. 450 μg L^{-1}). The profile of NO_3 concentration, taken on 29 June 1997, reflects the layering in the LWM. While lowest NO_3 levels ($<$20 μg L^{-1}) were found in the epilimnion, slightly higher NO_3 levels, of 20–30 μg L^{-1}, were recorded in the BBL and the highest levels (380 μg L^{-1}) remained in the hypolimnion. Cavari et al. (1977) suggested that NO_3 removal from LK LWM during the stratified period is due to denitrification. Hence, the slightly decreased levels in the hypolimnion and low levels in the BBL are therefore attributed to weak denitrification in the hypolimnion and relatively active denitrification in the BBL. About a month later, on 3 August, NO_3 was depleted in all of the LWM.

Concentration profiles of ammonium during summer 1997 also reflect the BBL separation in the LWM (Fig. 7). On 1 June 1997, NH_4 levels in the entire water column were relatively low (0–30 μg L^{-1}). A month later, on 29 June, increased levels of NH_4 were observed only in the BBL (ca. 110 μg $L^{-1)}$ whereas in the rest of the water column they remained at lower levels. On August 3, NH_4 concentration had increased in both the BBL (ca. 420 μg L^{-1}) and the hypolimnion (ca. 140 μg L^{-1}) but the increase was much stronger in the BBL.

During the summer the profiles of TDP and SRP (Fig. 8 and Fig. 9, respectively) are also affected by the BBL separation. The concentration of TDP in the LWM was about 10% higher than SRP. In early June slightly higher levels of TDP (and SRP) were noticed in the BBL (5–10 μg L^{-1}) as compared to the rest of the water column (2 μg $L^{-1)}$. By the end of June TDP levels in the BBL increased to 14 μg L^{-1} and in August to 44 μg L^{-1}. The respective increase in hypolimnetic TDP levels was from about 5 to ~7μg L^{-1}. Comparison of total phosphorus levels (Fig. 10) to TDP levels shows that in the BBL, TDP accounts for about 90% of TP. In the hypolimnion it accounts for only about 50%, sug-

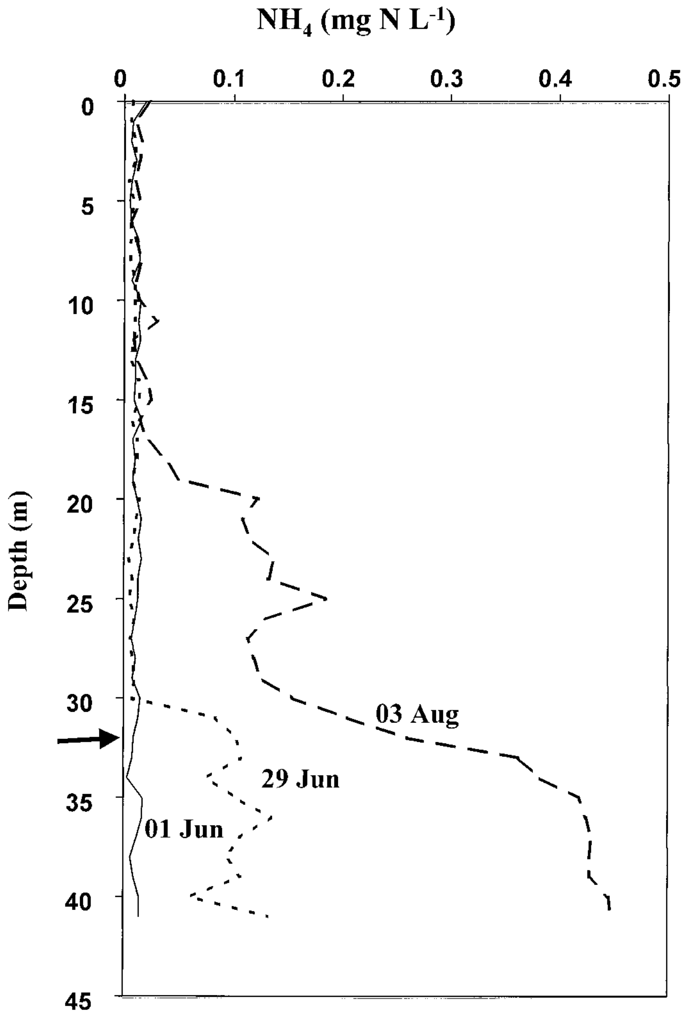

Fig. 7. Ammonium (NH_4) concentration profiles taken at station 108 on 1 June, 29 June, and 3 August 1997. Top of BBL in T4 on 30 June 1997 is marked by an arrow.

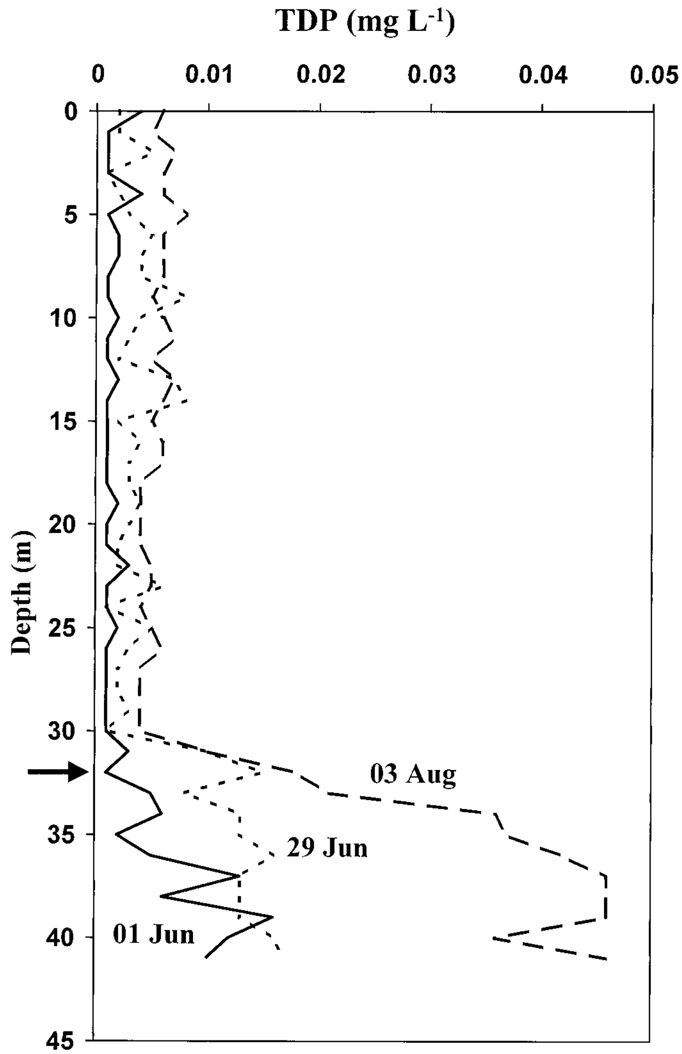

Fig. 8. Total dissolved phosphorus (TDP) concentration profiles taken at Sta. 108 on 1 June, 30 June, and 3 August 1997. Top of BBL in T4 on 30 June 1997 is marked by an arrow.

gesting that the levels of particulate P (PP = TP − TDP) as well as the ratio of PP over TP are higher in the hypolimnion than in the BBL.

Comparison between solute profiles in summer 1997 and in 30 June 1996 (not shown) indicates that in both periods the thickness of the BBL, as indicated from the NH_4 and TDP profiles, was similar, from about 32 m depth to the bottom.

The variation of the parameters shown in Figs. 5–10 precludes the possibility that vertical turbulent diffusion contributed to the observed changes; the variations were in general, not from a high concentration to a low concentration except for NH_4 (Fig. 7). This conclusion also follows naturally if it is remembered that the vertical diffusion coefficients are too small to allow for comparable fluxes.

However, particles in the water column do settle taking with them certain attributes. Preferential removal of NH_4 and H_2S from the hypolimnion by sedimentation of particles can be ruled out as a possible explanation for the variations between the concentrations of these solutes in the two LWM layers. In the LWM during the summer, the molar concentration of dissolved sulfide plus that of SO_4 was shown (Hadas and Pinkas 1995*a,b*) to be equal to the concentration of SO_4 in this water strata prior to stratification. This means that most of the sulfide formed in the LWM originates from the reduction of dissolved sulfate, entrapped in this strata at the onset of stratification, so that during the summer there is no significant removal, of sulfur [i.e., as FeS_x], by sedimentation. In addition, historical data (1988 to 1996), analyzed here show significant correlations between sulfide and NH_4 concentrations ($R^2 = 0.9$, $P < 0.0001$] suggesting that during the summer NH_4 is also not removed from the LWM (i.e., by incorporation to bacteria, followed by sedimentation). It is therefore concluded that the differences in the solute concentrations between LWM layers reflect the magnitude of the mineralisation processes in each layer.

In order to examine the continuity of the mineralisation processes in the BBL we have plotted the concentration of NH_4 (measured weekly) at 40 m depth (at T4) during June–September 1997 against time (Fig. 11). Continuous stirring

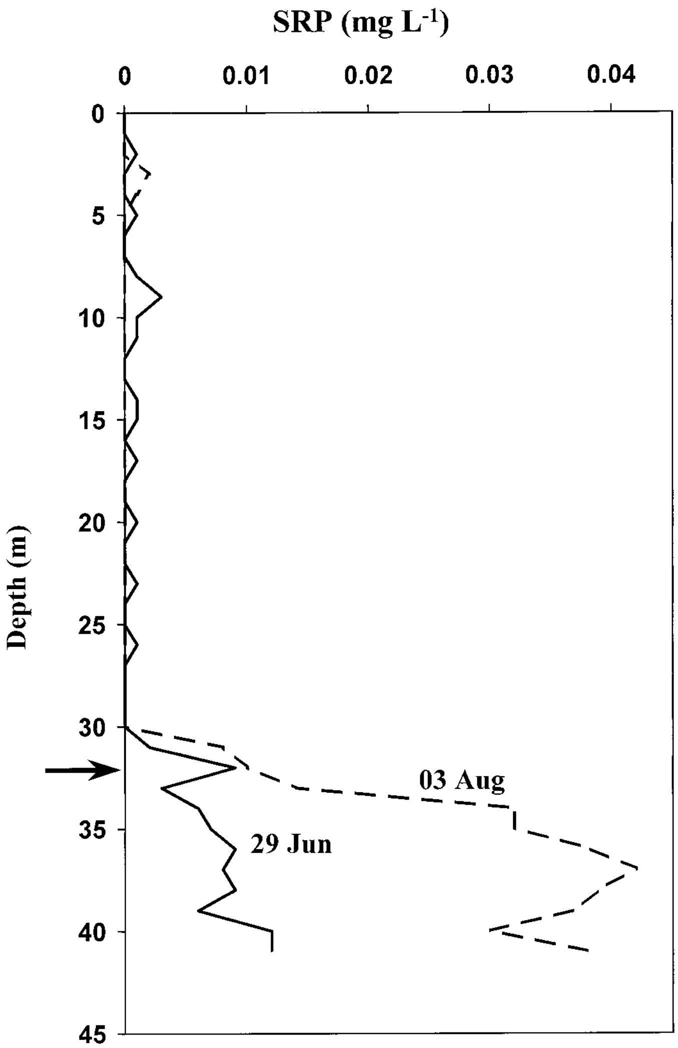

Fig. 9. Soluble reactive phosphorus (SRP) concentration profiles taken at Sta. 108 on 1 June, 30 June, and 3 August 1997. Top of BBL in T4 on 30 June 1997 is marked by an arrow.

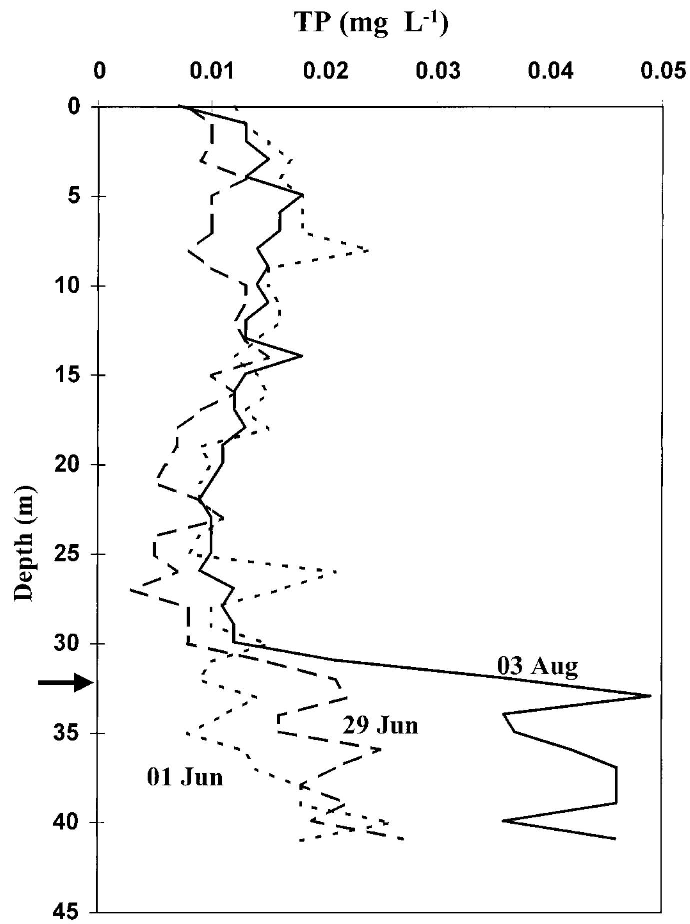

Fig. 10. Total phosphorus (TP) concentration profiles taken at Sta. 108 on 1 June, 30 June, and 3 August 1997. Top of BBL in T4 on 30 June 1997 is marked by an arrow.

in the BBL suggests that the relation between NH_4 concentration and time be described by a gradual increase. In general this plot shows continuous accumulation of NH_4 and in only a few cases was there a leveling off in the rise of the concentrations (but not a decline) in consecutive weeks. This temporary decrease in the rate of accumulation of NH_4 may also result from slower mineralisation rates. It may therefore be concluded that the dilution due to the net entrainment of the BBL into the hypolimnion is slower than the rate of production of NH_4 due to mineralisation.

In summer, NH_4 and H_2S can be regarded as inert with respect to sedimentation, the selective depletion of SRP (or TDP) in the hypolimnion, as compared to the BBL, suggests the existence of a P removal process and/or that very little soluble P is released from particles within the hypolimnion. The data presented above on particulate P levels in the hypolimnion support both mechanisms. A possible mechanism for the removal of SRP by sedimentation from the upper hypolimnion could be adsorption onto settling particles. Since during the stratified period H_2S accumulates in the hypolimnion, adsorption of phosphorus onto iron oxy-hydroxide particles is unlikely to take place, whereas sorption onto clay minerals can not be ruled out.

Some of the above suppositions were also examined through a statistical analysis of long term (1974–1995) summer–fall, monthly mean concentrations of SRP and NH_4. The routine monitoring program in the LWM included only the 20 m, 30 m, and 40 m depth layers (at T4) and these are assumed to represent the upper hypolimnion, lower hypolimnion, and BBL, respectively. Trend analysis shows that NH_4, SRP, and H_2S accumulate at the 30 and 40 m depth layers during the summer–fall and that NH_4 and H_2S, but not SRP, accumulate at the 20 m depth layer. Due to the restricted transport between the LWM and the overlying epipelagic water it is expected to have positive correlations between these solutes both within each LWM layer and between these layers. An even better correlation is expected since the most probable direct (for NH_4 and SRP) and indirect (SO_4) source of these solutes is the mineralisation of organic matter. However the extent to which these parameters are correlated may also be affected by additional factors. The data shown in Table 2 reveals that R^2 values obtained between NH_4 levels (as well as for H_2S, $R^2 = 0.89$, $P <$

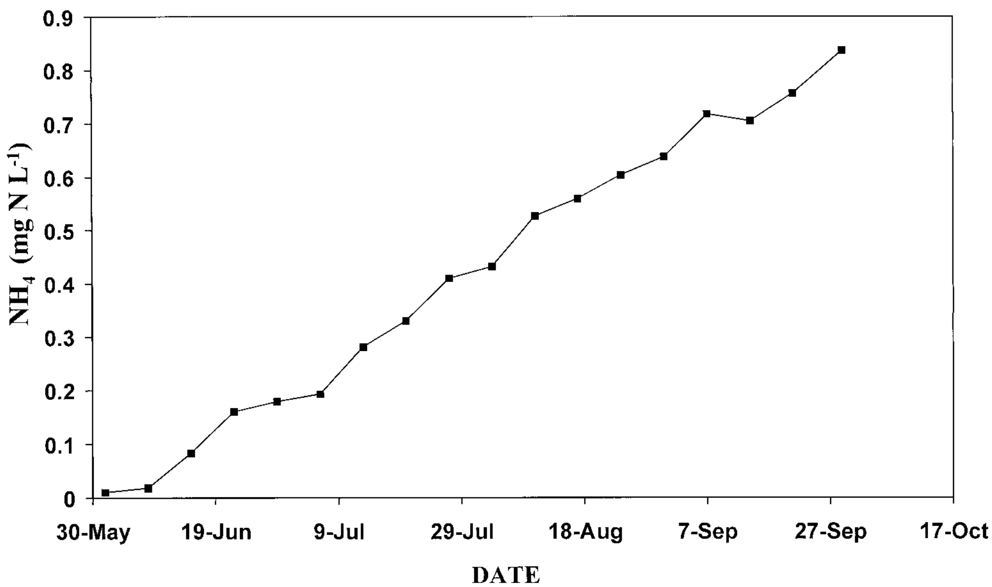

Fig. 11. Ammonium weekly concentration at 40 m depth (T4) during May–October 1997.

0.0001, not presented) at 30 m and 40 m depth are higher than the respective R^2 values for SRP levels. Also the correlation between NH_4 at 30 m to 20 m is significant whereas no correlation was found between SRP in the respective depths and moreover SRP and NH_4 at 20 m depth are not correlated. Again, these findings suggest that SRP is removed by its incorporation in particulates and/or that soluble P is not released from particulates and that these processes result with relative low SRP levels particularly in the upper hypolimnion.

Historical data (1974–1995), monitored at Sta. T4, indicates that NH_4, H_2S, and SRP tend to accumulate in the BBL, rather than in the hypolimnion, but that this tendency is stronger for SRP. Assuming that the hypolimnion is represented by the average between 20 m and 30 m depth layers and that the BBL is represented by the 40 m depth layer it was calculated that the average concentration (for June–August) ratios for H_2S, NH_4 and SRP between the BBL and the hypolimnion are 1.90 ($\pm$0.06), 1.88 ($\pm$0.06), and 4.17 ($\pm$0.14), respectively. The preferential accumulation of SRP in the BBL, as compared to NH_4 and H_2S leads to a high N/P ratio in the nutrients transported by diffusion across the seasonal thermocline during the stratified period, from the LWM to the trophogenic epipelagic zone. The higher N/P ratio may be even more significant toward the end of the stratified period, while the thermocline deepens more rapidly, and relatively large volumes of hypolimnetic water are entrained in surface waters.

Table 2. Correlation matrix between the concentrations of SRP and NH_4 at different depths in the lower water mass during 1969–1991. The 20-, 30-, and 40-m depth layers are assumed to represent the upper hypolimnion, the lower hypolimnion and the BBL, respectively. This table includes data representing the period between May and September.

Type of correlation	Value of R^2	Probability (P)
SRP 20 m vs. SRP 30 m depth	*0.03**	*(P = 0.18)*
SRP 30 m vs. SRP 40 m depth	0.74	($P < 0.0001$)
NH_4 20 m vs. NH_4 30 m depth	0.79	($P < 0.0001$)
NH_4 30 m vs. NH_4 40 m depth	0.91	($P < 0.0001$)
SRP 20 m vs. NH_4 20 m depth	*0.04**	*(P = 0.14)**
SRP 30 m vs. NH_4 30 m depth	0.50	($P < 0.0001$)
SRP 40 m vs. NH_4 40 m depth	0.61	($P < 0.0001$)

* Insignificant correlations.

Conclusions

The occurrence of two layers in the LWM of Lake Kinneret, a well-mixed intermittently turbulent BBL and a laminar hypolimnion, has significant consequences on the timing and site of biogeochemical processes. During the stratified period anoxia occurs earlier and the biodegradation processes are more intensive in the BBL than in the hypolimnion.

As suggested previously (Nishri et al. 1996) the rate that sulfate reducing bacteria degrade organic matter may be controlled by the availability of SO_4. Sulfate is absent in the pore waters, but is always present in the overlying BBL (even towards the end of the stratified period $[SO_4] > 0.2$ mM). Thus, the well-mixed BBL may also serve as a catalyst for organic matter degradation, leading to enhanced accumulation of dissolved nutrients.

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Received: 28 April 1998
Accepted: 7 January 2000
Amended: 22 February 2000