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Water quality assessment of a recently refilled reservoir: The case of Bütgenbach Reservoir, Belgium

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Abstract

Bütgenbach Reservoir is situated in the High Ardennes plateau in eastern Belgium (50°25′N; 6°13′E). It is used principally for flood control and for production of hydroelectric energy. It has been subjected to a previous series of studies because of its eutrophication problems and their impacts on the local economy. Bütgenbach Reservoir was emptied during spring 2004 for dam restoration, being refilled in mid-September of the same year. Selected physicochemical and biological parameters (temperature, dissolved oxygen, pH, inorganic and organic nutrients, chlorophyll-*a*) were measured fortnightly during the lake's productive season (mid-April to mid-October 2005) at three sampling sites throughout the water column. The water quality conditions after refilling of the lake were compared to previous studies accomplished at the same sampling sites (prior to emptying the lake). The actual trophic status was mesotrophic to eutrophic, based on the combination of total phosphorous and chlorophyll-*a* concentrations, as well as water transparency. Bütgenbach Reservoir generally exhibits good water quality, based on the French water quality system SEQ-eau. A longitudinal decrease in water quality was observed from upstream to downstream, because mainly of the differences in lake bottom morphology and water residence time, and their impacts on nutrient distribution in the lake.

Key words

Belgium, Bütgenbach Reservoir, eutrophication, nutrients, reservoir refilling, trophic status, water quality.

INTRODUCTION

Artificial lakes (reservoirs) are considered to be environmental hybrids of lotic and lentic systems (Mergen 2002). About 500 000 still waterbodies with surface areas of >1 ha exist only in Europe (EEA 1999), representing a remarkable number compared to the estimated 8.3×10^6 lakes worldwide (Pourriot & Meybeck 1995). Thus, they are essential components of the hydrological and biogeochemical cycles (http://www.ilec.or.jp/eg/index.html).

As an integral part of any ecosystem, reservoirs influence many aspects of ecology, economy and human welfare (Lehner & Döll 2004). However, reservoir dynamics is largely characterized by severe hydrological fluctuations, as a result of the changes from a riverine to a lacustrine status, water level fluctuations, discharges from external and internal nutrient sources, etc., which can have a dramatic impact on their fish communities (www.irn.org; Geraldes & Boavida 1999, 2003b, 2005; Nakasone & Kuroda 1999; Nogueira *et al.* 1999; Wetzel 2001; Jugnia *et al.* 2004). The short life time of many reservoirs (<100 years) is considered one of their handicaps, often ensuring their inevitable emptying. In some cases, laws can make their emptying obligatory (e.g. France) (EEA 1999; Wetzel 2001).

Being known as a pluvious country, Belgium is not devoid of water resources. Nevertheless, because its water repartition is not homogeneous in time and space, the Belgian government, as well as private societies, has constructed dams to regulate the hydrological cycle in the country. Furthermore, reservoirs in Belgium provide additional production of electricity, supply drinking water, and enhance recreational possibilities.

This study focuses on a 73-year-old dam (Bütgenbach Reservoir) subjected to several changes in 2004. Bütgenbach Reservoir, a dimictic, eutrophic, temperate artificial lake with a surface area of ≈120 ha, is situated in the Hautes-Fagnes/Eifel area of Belgium (http://www.butgenbach.be). Although this region is considered to be relatively removed from industrial sources, its water

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network was recently found contaminated by a range of pollutants, including chemical fertilizers and organic sewage (Marneffe *et al*. 1998).

By the spring of 2004, Bütgenbach Reservoir was emptied for the purpose of dam restoration, being refilled in mid-September of the same year. The lake bottom, although not extracted, was exposed to the atmosphere for 6 months, and the refilling phase commenced without vegetation clearing. The literature contains a variety of reservoir management techniques for such cases, all of which conclude or even imply that the refilling of a reservoir marks the establishment of a new ecosystem, prone to various alterations during its first years of existence (Nienhüsen & Braches 1998; Scharf 1998, 2002; Geraldes & Boavida 2005). One exception to this concept was a reservoir for which no significant deterioration was observed because a high turbidity and elevated nutrient concentrations were prevented by flushing a very large water volume through the reservoir; this was the case of a small tropical reservoir that was semi-emptied (Townsend 1999). The main trends normally reported after flooding the grown vegetation in a recently filled reservoir are deterioration of water quality, including depletion of dissolved oxygen (DO) and accumulation of phosphorus in the hypolimnion, as well in the occurrence of a 'trophic upsurge' in the water column during the first years after coming into existence (Nienhüsen & Braches 1998; Geraldes & Boavida 1999; Scharf 2002). This reflects the relatively high productivity related to phosphorus leaching from flooded soils into the water column, as well as phosphorus released from inundated decomposing vegetation and soil organic matter (Schallenberg & Burns 1997 and literature therein) (Seto *et al.* 1982). According to Masson and Tremblay (2003), the inundated soil could equally represent a potential risk for human health.

This study presents the results of the first year following the refilling of Bütgenbach Reservoir. Both the trophic status of the reservoir and its water quality trends are discussed. A comparison of the main trends observed during a previous study of the same reservoir, as well as comparison with other lakes, is presented.

METHODS

Site description

Bütgenbach Reservoir was created in 1932 and is located on the High Ardennes plateau of eastern Belgium (50°25′N, 6°13′E) at 560 m a.s.l. It lies on the higher reaches of the Warche River, a major tributary of the upper Amblève. The lake has a surface area of 120 ha and its water volume reaches $11*10^6$ m^3 at full capacity. It has a water retention time of 4 months (Marneffe 2003). The maximum depth is ≈20 m in the proximity of the dam, whereas the mean depth of the lake is ≈9 m. The natural catchment area covers 72 km^2, being mainly agricultural (including ≈80% pastures), with minor industrial and sewage treatment point sources. It has significant surface inflows, based on its catchment to lake area ratio of 60. Flood control, recreation, and hydropower production are the principal uses of the lake. The latter provokes annual water level fluctuations of ≈6 m. The reservoir also serves as an indirect source of potable water, and drains to Robertville Reservoir, the second reservoir in a row of artificial lakes of Warche located upstream of Bütgenbach. The lake has been subjected to a series of eutrophication-related studies (Marneffe *et al*. 1998; Gielen 2000; Marneffe 2003) or fish-stocking concerns (DGRNE 1998; Tigny 2000; Mergen 2002)

Field measurements and sample collection

Monitoring of physicochemical and biological variables of the lake was carried out between mid-April and mid-October 2005, in order to examine the main trends in this 'new' ecosystem. The sampling sites are identified in Figure 1.

Sampling site A is situated in the eastern part of Bütgenbach Reservoir, and represents the riverine zone. With a maximum depth of 5 m, it is located at the proximity of the confluence of the Warche and Holzwarche Rivers. During the sampling period, intense vegetation was observed growing from the bottom to the surface in this area of the lake. Because of the shallowness of this lake, site A represents a well-mixed area, easily disturbed by the wind.

Sampling site B is located on the central part of the lake, at the sports centre of Worriken, near the influx of Hartbach and Herresbach (two minor effluents). With a maximum depth of 9 m, this area represents the transitional zone of the lake. Throughout the sampling season, decomposing inundated vegetation was clearly observed when lifting the boat anchor at this sampling point.

Sampling site C, with a maximum depth of 18 m, is located in the proximity of the dam, and receives the waters of a small stream (Berg). This area constitutes a typical lacustrine zone, having the characteristics of a dimictic temperate lake.

Water samples were collected biweekly during the productive season (mid-April to mid-October). Temperature, percentage of oxygen saturation, conductivity, and pH were measured *in situ* at 1-m depth intervals, using a multiparametric probe (Hydrolab Datasonde® 4, Austin, TX, USA). Water samples for nutrient analyses (nitrate, nitrite, ammonium, phosphate, total phosphorus, silicon)

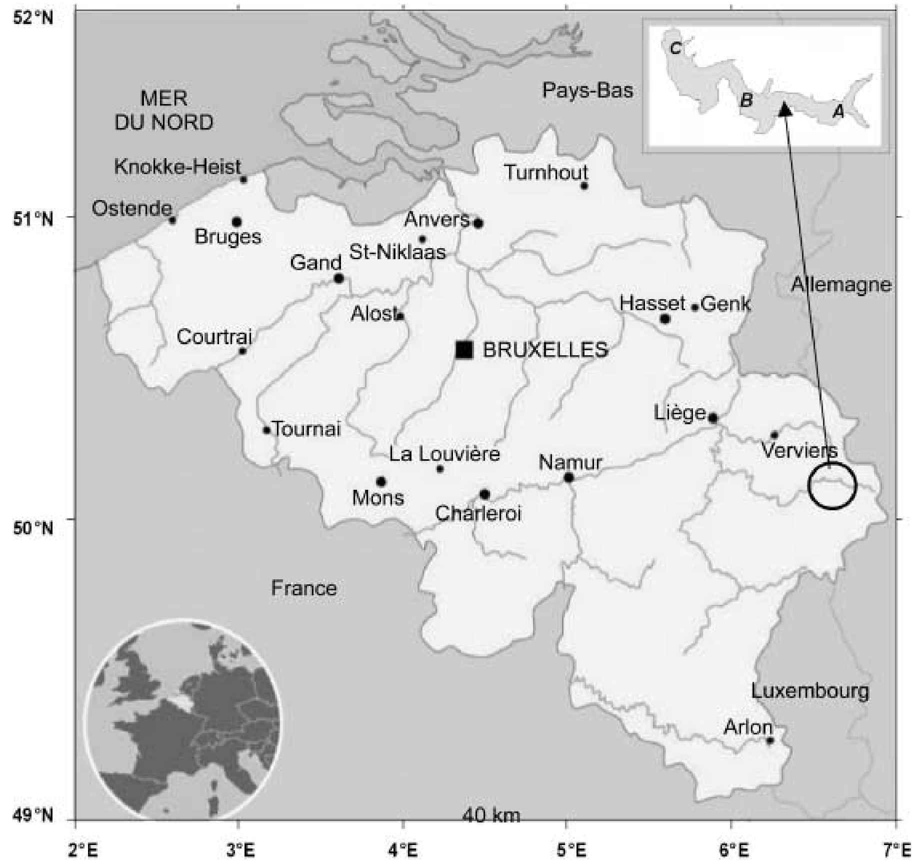


Fig. 1. Location of Bütgenbach Reservoir and its sampling points in Belgium.

and chlorophyll-*a* (Chla) content were collected with a 5-L Van Dorn bottle (Hydro Bios Apparatebau GmbH, Kiel-Holtenau, Germany) at specific depths (site A: 1, 3, 5 m; site B: 1, 3, 5, 8 m; site C: 1, 3, 5, 10 and 15 m), depending on the sampling point and water level. Unfiltered water was transferred into polyethylene bottles (for nutrient analyses, with the exception of phosphorus, for which glass bottles were used) or into dark bottles for phytoplankton analyses. Water transparency was measured with a 20-cm diameter black and white Secchi disk.

Nutrient analysis

Samples for nutrient analysis were filtered at the time of sample collection, using Glass Microfibre GF/C Whatman filters (1.2 μm) (Whatman International Ltd, Kent, UK). Glass-free filters were used for silicon samples. The filtered samples were put in acid-rinsed bottles, transported to the laboratory in a cold container, and stored at 4°C in the dark until analysis (maximum storage time of 24 h).

Nitrate, nitrite, ammonium, phosphate and silicon concentrations were determined using standard photometric methods with a SQ 118 photometer and Spectroquant® kits (Merck, Darmstadt, Germany). Nitrate was assayed in the form of a red nitro compound, after reaction with concentrated sulphuric acid and nitrospectal (a benzoic acid derivative) at 515 nm. Nitrites, as a red-violet azo dye form, were measured at 525 nm, using sulfanilic acid and 1-naphthylamine (Griess reaction – Bratton *et al.* 1939). Ammonium, as a blue indophenol derivative, was analysed at 690 nm (Bolleter *et al.* 1961; American Public Health Association 1971). Silicates were reduced to silicomolybdenum blue, with their absorbance measured at 665 nm. After being reduced to phosphomolybdenum blue, orthophosphate was determined photometrically at 712 nm (Rodier 1965). Total phosphorus (representing organic phosphorus and polyphosphate ions found in *raw* water) was assayed as phosphates, after having been hydrolysed by potassium persulphate and autoclaved (120°C for 35 min at 1.2 bar, according to the method of Wetzel & Likens 1979).

Chlorophyll analysis

Chlorophyll-*a* samples were obtained from 0.5 to 1.5 L of water filtered through a Whatman GF/F filter (0.7 μm) within 2 h after sample collection. Chlorophyll-*a* concentrations were determined spectrophotometrically, after extraction at 65°C for 2 min, using a 5 : 1 mixture of acetone 90% and methanol, according to the method of Pechar (1987).

Data treatment

The maps presented herein, which represent the temporal evolution of measured variables as a function of depth, were created using the SURFER program (Golden Software, Golden, CO, USA), by interpolating values measured in the field. The trophic status of the lake was calculated according to the methods of Carlson (1977) and OECD (1982). Based on interpretation of the results of selected variables, the actual water quality is assessed and compared to values obtained in previous years, using the limits of a quality evaluation system developed in France for superficial waters (SEQ-eau). It is based on the assessment of certain alterations susceptible to disturbing the function of streams, as well as human use. These alterations, expressed as quality indices, are presented on a 0–100 scale, which is further subdivided into five classes. In terms of quality, a blue colour represents a superior condition, while a green, yellow and orange colour represent a good, tolerable, and bad water quality, respectively. A red colour equals inaptitude.

RESULTS

Temporal evolution of examined paremeters

The water temperature varied between 5.70 and 22.88°C during the study period (Table 1; Figs 2a, 3a and 4a). As with many temperate lakes, high atmospheric temperatures observed during the late Spring led to thermal stratification of the water column at the deeper lake points. In late July, the temperature reached its maximum values, gradually decreasing thereafter. By the end of summer, with needs for hydropower-generated electricity being greater, a water release downstream from the dam bottom led to a gradual decrease in the lake water level. This latter phenomenon disturbed the water column and, combined with the onset of winter mixing, a homogenous water column profile was observed in mid-October

The mean specific conductivity was 100.18 ± 14.73 μS cm^{-1}, fluctuating during the study period between 76.60 and 223.00 μS cm^{-1}, with only minor vertical variations. It was slightly greater next to the lake bottom. An average conductivity value of 100 μS cm^{-1} is characteristic of the Warche watershed, which drains slightly mineralized waters (Tigny 2000; Mergen 2002). The opposite trends were observed for pH, which exhibited a remarkable variation from the surface to bottom waters in the lake, with the former exhibiting higher values (i.e. maximum value of 9.41 pH units), being controlled by photosynthesis. The pH maxima coincided with those for the Chla concentration (Fig. 2c,d), verifying the former statement.

The DO concentrations exhibited a vertical distribution closely related to the temperature pattern. The well-saturated water column observed in April was no longer seen in late May and, during the entire summer, the DO concentration in the bottom waters of the lake decreased to practically zero at sites B and C (Figs 2b and 3b). The autumn water holomixis, facilitated by the removal of lake bottom waters from the dam gates, improved the water quality, with the entire water column starting to exhibit the vernal well-oxygenated profile.

Table 1. Range of measured values, and integrated mean values and standard deviation (SD) for measured parameters in the ensemble of sampling sites in Bütgenbach Reservoir from April to October 2005

Parameter	Units	Range of values	Mean value ± SD
Temperature	°C	5.70–22.88	13.81 ± 3.95
Conductivity	μS cm^{-1}	76.60–223.00	100.18 ± 14.73
pH	–	4.01–9.41	7.22 ± 0.79
Dissolved oxygen	mg L^{-1}	0–17.6	7.13 ± 3.81
	% saturation	0–162	70.10 ± 37.49
Ammonium (NH_4^+)	mg $NH_4^+ L^{-1}$	0–0.48	0.10 ± 0.08
Nitrate (NO_3^-)	mg $NO_3^- L^{-1}$	3–18	10.84 ± 3.10
Nitrite (NO_2^-)	mg $NO_2^- L^{-1}$	0.02–0.31	0.093 ± 0.044
Phosphate (PO_4^{3-})	mg $PO_4^{3-} L^{-1}$	0–0.11	0.024 ± 0.020
Total phosphorus (Ptot)	μg P L^{-1}	13.05–97.90	31.52 ± 11.20
Silicon	mg Si L^{-1}	0.40–1.90	0.91 ± 0.33
Chlorophyll-*a* (Chla)	μg Chla L^{-1}	0–39.46	7.37 ± 5.99
Secchi disc transparency	m	1.40–6.00	2.89 ± 1.21

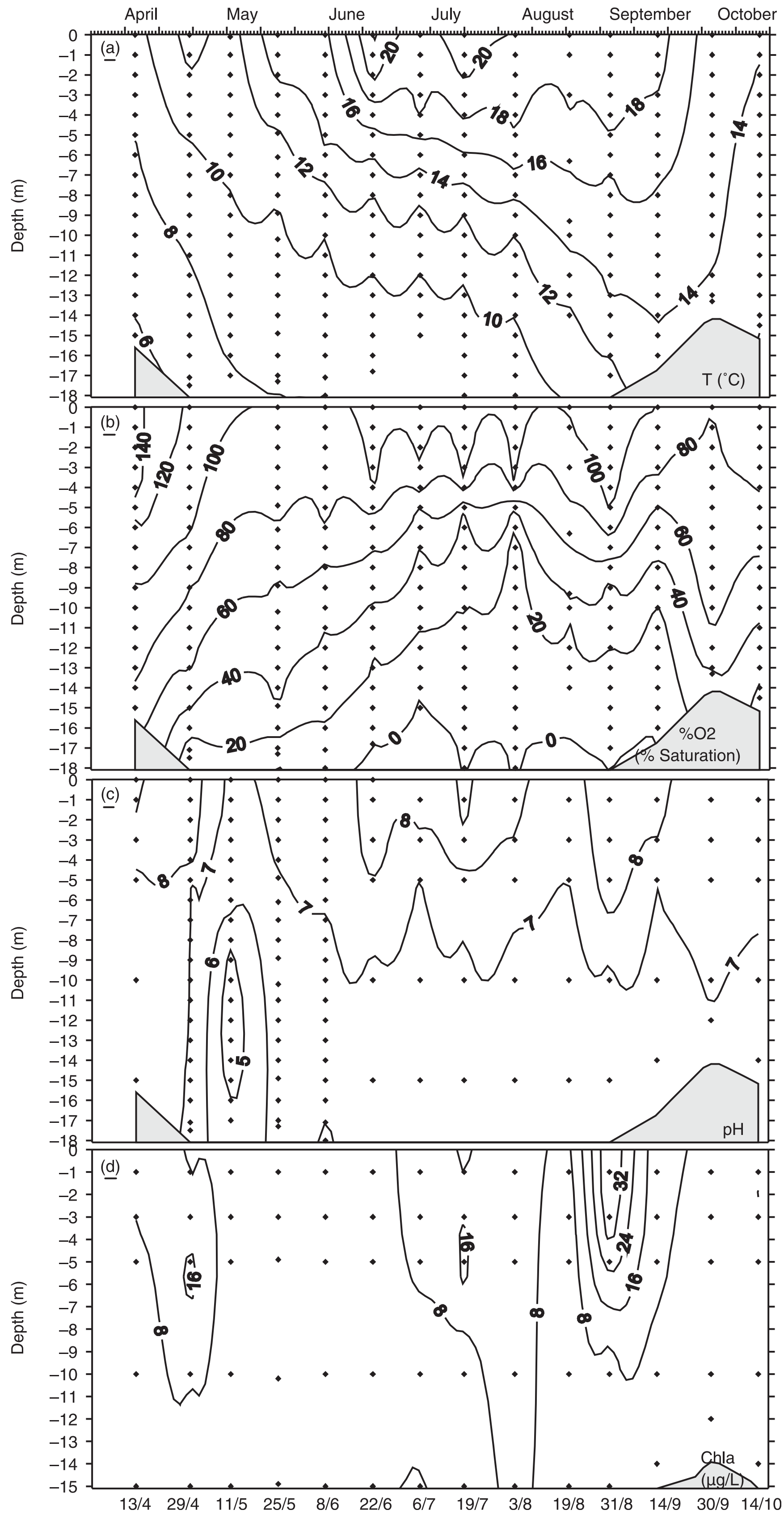


Fig. 2. Temporal evolution of (a) temperature, (b) oxygen, (c) pH and (d) chlorophyll-*a* in Point C of Bütgenbach Reservoir from mid-April to mid-October 2005.

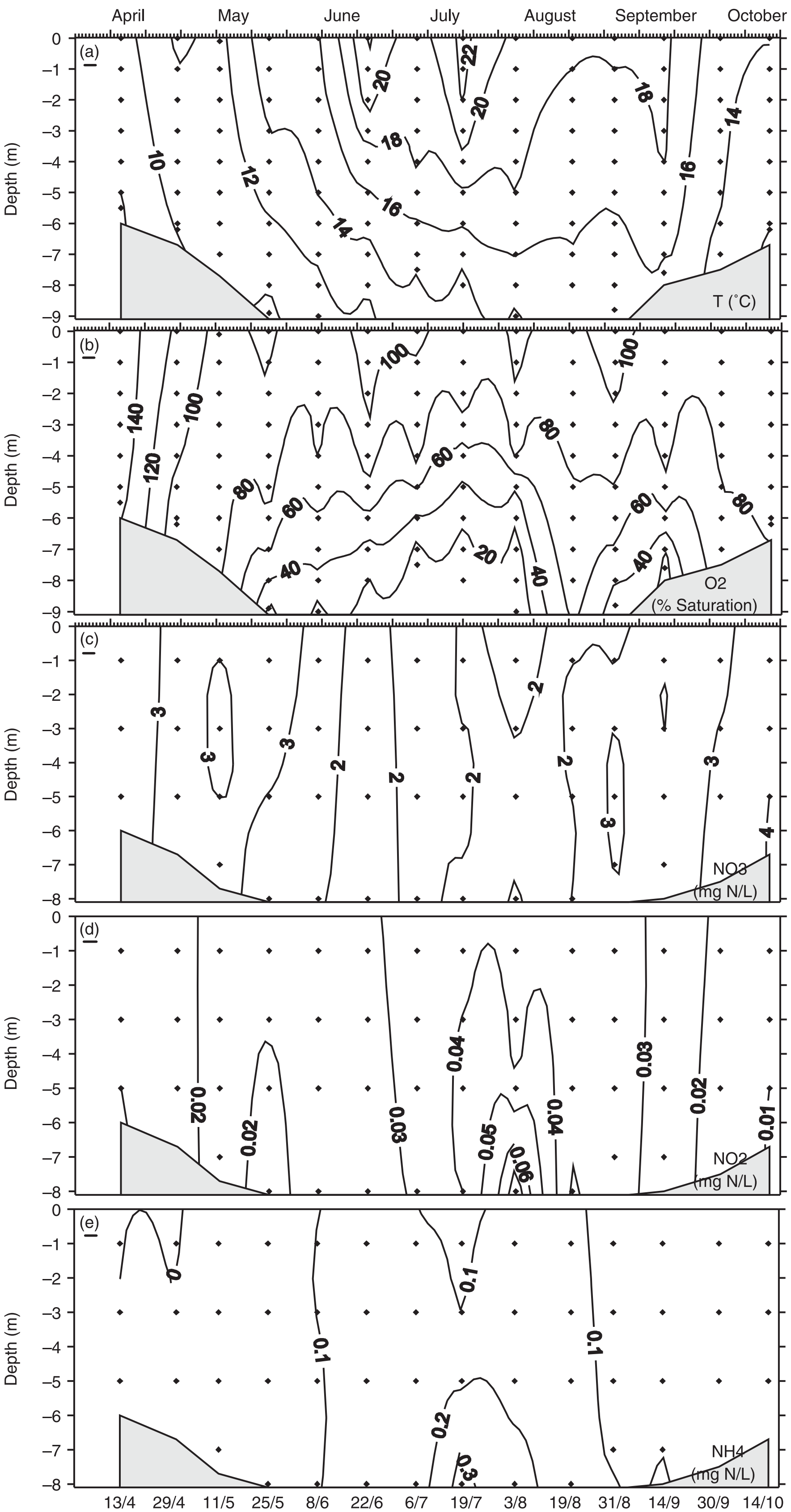


Fig. 3. Temporal evolution of (a) temperature, (b) oxygen, (c) nitrates, (d) nitrites and (e) ammonium in Point B of Bütgenbach Reservoir from mid-April to mid-October 2005.

The summer oxygen and temperature distribution influenced the profile of the concentration of phosphates and reduced forms of nitrogen. The maximal concentrations of phosphates (0.11 mg PO_4^{3-} L^{-1}), nitrites (0.31 mg NO_2^- L^{-1} or 0.09 mg N-NO_2 L^{-1}) and ammonium (0.48 mg NH_4^+ L^{-1} or 0.37 mg N-NH_4 L^{-1}) were measured in the bottom waters of the deeper sampling sites during summer (Fig. 3d,e).

The opposite trends were observed for nitrates, the most oxidized form of nitrogen. The mean measured concentration was of 10.84 ± 3.10 mg NO_3^- L^{-1}, while the minimum value observed was 3 mg NO_3^- L^{-1} (= 0.68 mg N-NO_3 L^{-1}) in the bottom waters of the lake during the summer (Fig. 3c).

Silicon, the nutrient most derived from natural sources, exhibited a variant seasonal distribution, showing a slight decrease during the summer. A marked accumulation was reported in the meta- to hypolimnion in spring and late summer, with a maximum value of 1.9 mg Si L^{-1}.

The total phosphorus concentration, which ranged between 13.05 and 97.90 µg P L^{-1}, followed the main seasonal trends of phosphates (Fig. 4c,d for site A). The Secchi depth varied between 1.40 and 6 m, while the Chla concentration fluctuated between 0 and 39.46 µg Chla L^{-1} (Table 1; Fig. 2d). For the ensemble of sampling sites, a pronounced ‘clear-water phase’ was observed during May and June; the Secchi depth and Chla concentration confirming it. Figure 5 illustrates the temporal evolution of these two parameters for sampling site C.

Spatial/longitudinal evolution of examined parameters

The transition from the riverine (site A) to the lacustrine zone (site C) is equally marked by changes in physico-chemical characteristics and biological dynamics in reservoirs (Wetzel 2001). Sampling site A generally exhibited higher temperatures (integrated mean value of 15.50°C, compared to 12.75°C at site C; Figs 4a and 2a) and

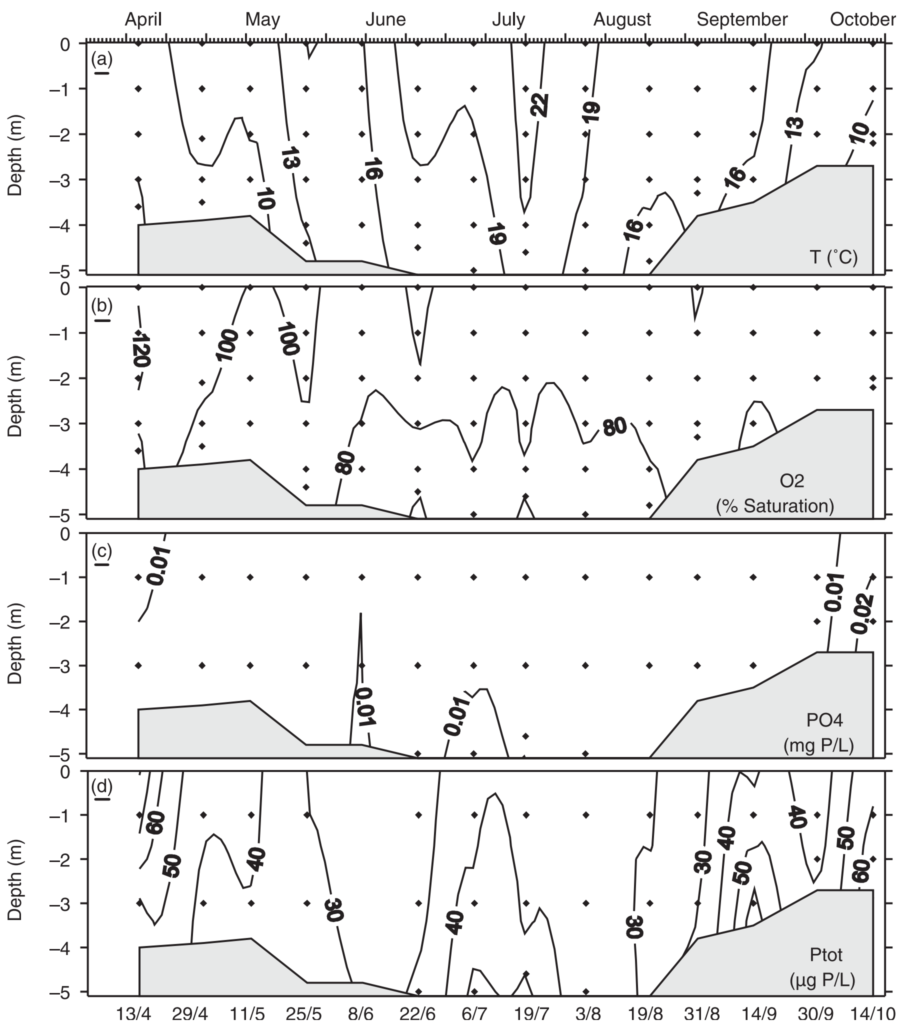


Fig. 4. Temporal evolution of (a) temperature, (b) oxygen, (c) phosphates and (d) total phosphorus in Point A of Bütgenbach Reservoir from mid-April to mid-October 2005.

DO concentrations (integrated mean value of 9.11 mg O_2 L^{-1}, compared to 6.03 mg O_2 L^{-1} at site C; Figs 4b and 2b). It also exhibited higher pH (integrated mean value of 7.48, compared to 7.08 at site C) and Chla concentrations (9.41 µg Chla L^{-1}, compared to 6.39 µg Chla L^{-1} at site C). The location of site A near the Warche tributary, with its susceptibility to allochthonous sources, explains the higher nutrient concentrations observed at the site, especially for total phosphorus, silicon and nitrites. No thermal stratification or particular nutrient vertical tendencies were observed at site A (Fig. 4a).

In contrast, site C has the characteristics of a typical dimictic temperate lake (Marneffe *et al.* 1998), experiencing thermal stratification that generated a well-marked vertical distribution of the examined parameters (Fig. 2a). Oxygen depletion was intensely observed in the bottom waters at site C during the summer. The accumulation of phosphates and the most reduced forms of nitrogen in the bottom waters was equally experienced. If only the epilimnetic zone (restricted to the first 5 m of the water column) was considered, a different conclusion would have been reached. It appears that epilimnetic waters in the proximity of the dam were warmer, therefore being more productive, with higher mean values of Chla, DO and pH being recorded (15.77°C, 10.12 µg Chla L^{-1}, 9.66 mg O_2 L^{-1}, and 7.81 pH units, respectively).

Trophic status and water quality of Bütgenbach Reservoir

Phosphorus is considered to be the algal growth-limiting factor in Bütgenbach Reservoir (Marneffe 2003). Based on the literature, the total phosphorus and Chla concentrations and Secchi disc transparency are usually correlated to estimate the trophic status of lakes and reservoirs (Carlson 1977; OECD 1982; EEA 1999; Geraldes & Boavida 1999, 2003a). The results from the application of two methods for evaluating trophic status are presented in Table 2, and are compared to the conditions that existed before the emptying of the lake (Marneffe 2003). The results obtained from both methods indicate a mesotrophic-to-eutrophic character for the Bütgenbach Reservoir. Similar trends were observed when comparing these results to those of previous studies of the lake, with the trophic status being only slightly better. Figure 6 presents the trophic longitudinal evolution for the sampling sites, with the upstream site A being more polluted than the site located near the dam.

The limits of a quality evaluation system developed in France for superficial waters (SEQ-eau 2003) also were used to obtain information about the water quality of Bütgenbach Reservoir, based on selected measured parameters. Figure 7 summarizes the results for (i) phosphates; (ii) total phosphorus; (iii) ammonium; (iv) Chla and

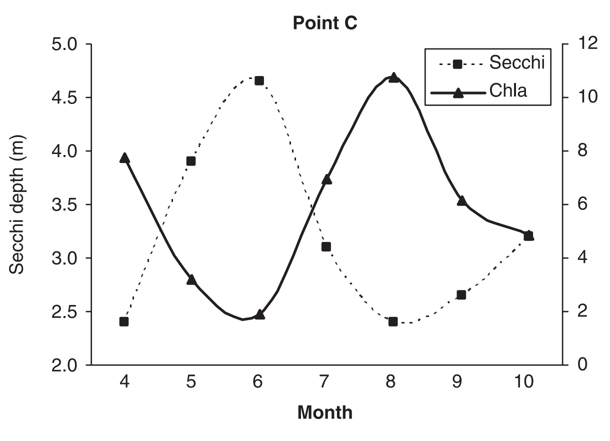


Fig. 5. Temporal evolution of Secchi disc transparency versus chlorophyll-a (integrated mean values) in Point C of Bütgenbach Reservoir in 2005.

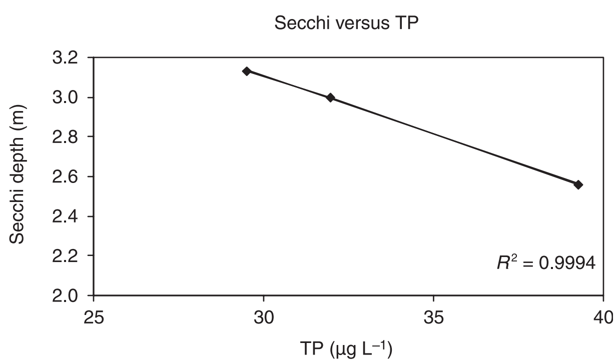
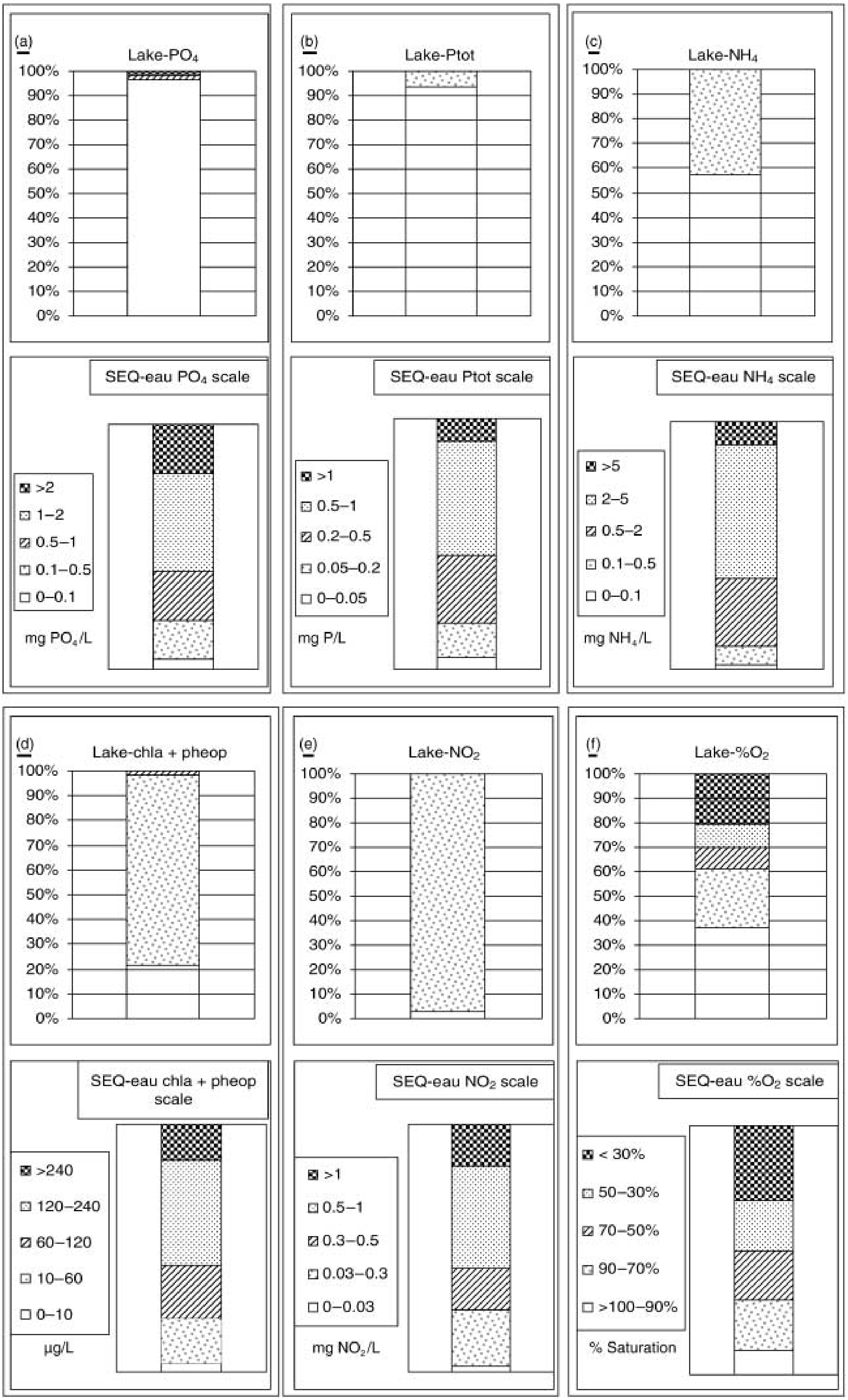


Fig. 6. Longitudinal evolution of Secchi disc transparency versus total phosphorus (integrated mean values) in Bütgenbach Reservoir in 2005.

Fig. 7. Water quality evaluation based on French SEQ-eau scales for (from higher to lower quality results): (a) phosphates, (b) total phosphorus, (c) ammonium, (d) chlorophyll-*a* and phaeopigments, (e) nitrites and (f) oxygen. Bottom columns: SEQ-eau scaling for each variable: from bottom to top we pass from very good to poor quality. Upper columns: in detail the percentage of data corresponding to each threshold area calculated for the entire water column and for the ensemble of sampling points; in parallel, the colour corresponding to 90% of values is the dominating colour for each variable according to SEQ-eau. Waters of Bütgenbach Reservoir were found to be within the 'green' threshold, according to SEQ-eau standards – taking into account the 90th percentile – interpreted as good water quality; the phosphorus (total and soluble) being of very good quality (white area), whereas oxygen displayed poor water quality (dark area).


(a)
Lake-PO4
SEQ-eau PO4 scale
>2
1–2
0.5–1
0.1–0.5
0–0.1
mg PO4/L
(b)
Lake-Ptot
SEQ-eau Ptot scale
>1
0.5–1
0.2–0.5
0.05–0.2
0–0.05
mg P/L
(c)
Lake-NH4
SEQ-eau NH4 scale
>5
2–5
0.5–2
0.1–0.5
0–0.1
mg NH4/L
(d)
Lake-chla + pheop
SEQ-eau chla + pheop scale
>240
120–240
60–120
10–60
0–10
µg/L
(e)
Lake-NO2
SEQ-eau NO2 scale
>1
0.5–1
0.3–0.5
0.03–0.3
0–0.03
mg NO2/L
(f)
Lake-%O2
SEQ-eau %O2 scale
< 30%
50–30%
70–50%
90–70%
>100–90%
% Saturation
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%

phaeopigments; (v) nitrites; and (vi) DO. For soluble and total phosphorus, and ammonium, the predominant colour is blue, which corresponds to a very good water quality. Based on SEQ-eau standards, however, the representative colour is that which corresponds to 90% of the measured values. Thus, the water quality of the lake is very good when considering both forms of phosphorus, whereas the representative colour (green) for ammonium corresponds to good water quality. The same trends as observed for ammonium also are seen for Chla and phaeopigments and nitrites. In contrast, the DO results indicated poor water quality (red colour). Comparing the actual quality trends with those obtained by interpreting the 1995 data, the same general tendencies are obtained for phosphates, nitrites and ammonium, whereas the DO exhibited a rather considerable deterioration, being in the green threshold in 1995.

DISCUSSION

Interannual comparison of main tendencies for Bütgenbach Reservoir

The main trends of the status of Bütgenbach Reservoir are compared to the results of previous studies completed before the emptying of the reservoir at the same sampling sites (Marneffe *et al*. 1998; Tigny 2000; Marneffe 2003). A detailed comparison between the results of 2005 and 1995 was carried out, as illustrated on the website: http://www.aquapole.ulg.ac.be/butgenbach/. The year 2005 (especially based on the spring data) appears to be warmer, as the thermal stratification was initiated earlier and lasted longer than the pre-emptying years. Recent studies on temperate lakes also reveal an earlier occurrence of thermal stratification that lasts for a longer period (Jacquet *et al*. 2005, based on a 20-year study of Lake Bourget). These latter authors attributed these tendencies to global warming.

The above-mentioned thermal fluctuations, which are representative of temperate regions, regulate the rates of chemical and biological processes that occur in reservoirs (Pourriot & Meybeck 1995; Wetzel 2001; Jugnia *et al*. 2004). More intense anaerobic conditions (even anoxia) were observed in the hypolimnion of the deepest sampling sites in the lake in 2005. The fact that the bottom vegetation was not removed during the restoration works partially explains this situation. Although anoxia is a common phenomenon in temperate stratified reservoirs (emptied or not) and lakes (Kleeberg *et al*. 2000; Lewis 2000; Mihopoulos *et al*. 2000; Zacharias *et al*. 2002), it is even more intense in tropical regions (Nogueira *et al*. 1999; Townsend 1999).

Table 2. Predicted trophic status for each sampling site and for the whole lake between April and October 2005

	Trophic state index (TSI) (Carlson 1977)			
Sampling site	TSI (Chla)	TSI (PT)	TSI (SD)	Mean TSI
Point A	52,60	57,08	46,45	52,04
Point B	51,61	54,10	44,17	49,96
Point C	48,76	52,95	43,55	48,42
Total for 2005	50,19	53,91	44,70	49,60
Total for 1998*	56,00	56,60	50,30	54,30

*data from *Marneffe*, 2003
(measured for the whole water column)

	OECD (1982)				
Sampling site	Mean Chla** ($\mu g\ L^{-1}$)	Max Chla** ($\mu g\ L^{-1}$)	PT ($\mu g\ L^{-1}$)	Mean SD (m)	Min SD (m)
Point A	9,41	22,85	39,27	2,56	1,4
Point B	9,37	21,92	31,95	3,00	1,8
Point C	10,12	39,46	29,49	3,13	1,5
Total	9,66	39,46	31,52	2,89	1,4

**measured in the epilimnion.

Chla, chlorophyll-*a*; Max Chla, maximum chlorophyll-*a*; Mean Chla, mean chlorophyll-*a*; PT, total phosphorus; SD, Secchi depth.

Based on the literature, the remobilization of nutrients from sediments into the water column under anoxic conditions is relatively common in stratified natural lakes and reservoirs (Pettersson 1998; Townsend 1999; Kleeberg *et al.* 2000; Wetzel 2001; Selig & Schlungbaum 2003). The seasonal distribution of these parameters exhibits similar patterns in spring and autumn (i.e. lower values throughout the water column before and after summer thermal stratification) compared to summer maxima following an increasing vertical profile. In 2005, a greater phosphate and nitrite accumulation in the bottom waters of the lake was observed, but was not the case for ammonium. Higher quantities of the reduced forms of nitrogen (i.e. nitrites, ammonium) were measured, however, while the nitrates were found to be reduced. This correlates with the observed reduced DO trends, especially during the summer temperature peak, when the reservoir is stratified and the water column more stagnant because of no hydropower electricity needs during this period). The Chla concentration trends appeared to be of the same magnitude, but exhibited shifted peaks.

The most significant changes observed on an interannual basis in Bütgenbach Reservoir were for oxygen, ammonium and nitrates. All three parameters were lower than in 1995 and 1998 (Table 1; Marneffe 2003).

The reduction in nitrates is consistent with the oxygen trends, and could be attributed largely to the renewal of the local water purification station. Moreover, recent results illustrated an amelioration of water quality in terms of nitrates that could be attributed either to a reduced use of fertilizers (implementation of nitrate Directive 91/676/EEC), or reduced atmospheric deposition in north-western Europe (Stoddard *et al.* 1999; Rekolainen *et al.* 2005).

Ammonia accumulation in the sediment–water interface typically accompanies anaerobic conditions in a lake. An exponential decrease in the ammonia concentration in sediment until the oxycline is usually observed, which indicates that sediment organic matter is the primary source of hypolimnetic ammonia (Townsend 1999). Ammonium accumulation in the bottom waters of the lake occurred during 2005 during thermal stratification, but was less intense at site C, compared to previous studies conducted in 1995 and 1998 (Marneffe *et al.* 1998; Marneffe 2003). This phenomenon could be attributed to several reasons. First, higher nitrite concentrations (the next most reduced form of nitrogen) were also observed in the bottom waters of the lake, while sediment NH_4^+ releases occur only when nitrates and nitrites are absent (Selig & Schlungbaum 2003). Furthermore, a significant part of nutrient removal is attributed to ammonia volatilization (Rodriguez-Gallego *et al.* 2004 and literature within). In addition, ammonium is the major fraction of total nitrogen in domestic sewage effluents, even stored in old sewer sediments (Dabrowski 2000; Settacharnwit *et al.* 2003 and literature therein). A sewage diversion plan was recently effectuated for Bütgenbach Reservoir, in order to improve its water quality. The ammonium decrease could eventually be attributed to this event, which is a good world example for a lake restoration (Arhonditsis *et al.* 2004 and related literature). Finally, there was no fish (which excrete ammonium) in the reservoir in 2005 that could contribute to the ammonium increase in the water column (Schindler & Eby 1997; Walsh *et al.* 2001). A study by Geraldes and Boavida (2004) also did not indicate any ammonium accumulation in the anaerobic lake bottom waters, while elevated values of total phosphorus and phosphates were observed.

The most preoccupant variable in the literature that is related to anoxia is phosphorus. The prementioned sewage diversion plan reduced the phosphorus load to the reservoir. The very good water quality in Bütgenbach Reservoir, in terms of SEQ-eau registered for phosphorus, however, does not represent the entire reservoir. In fact, considering the poor quality revealed for DO, in addition to the fact that phosphorus release from sediments occurs some time after the appearance of anoxic conditions (Townsend 1999), could possibly contribute to a considerable internal nutrient load, eventually resulting in significant algal blooms (Jann-Para *et al.* 2004). During the study period, however, the Chla concentrations exhibited the main trends found in temperate, thermally stratified lakes, in which phytoplankton concentrations typically peak in the spring, decrease in the early summer, and increase in autumn, before again decreasing in winter (Arhonditsis *et al.* 2004).

An irritating odour was observed during the bottom water sampling in the summer, probably because of hydrogen sulphide release from the anoxic lake bottom sediments (Scharf 2002; Rodriguez-Gallego *et al.* 2004). An analysis of sulphides and thiols was effectuated by the end of September, but indicated only low concentrations (<1 mg L^{-1}), which could be attributable to water column recirculation. The latter is consistent with the homogeneous nutrient distribution observed during the autumn sampling campaigns. Abrupt water release from the bottom dam gates could be the main reason for brown-coloured water observed downstream, presumably attributable to humic acids from the decomposition of inundated vegetation (Scharf 2002)

Overall, the trophic status of Bütgenbach Reservoir is representative of the majority of reservoirs situated in a wider area (Luxembourg, Belgium) and being principally eutrophic, based on abstracts of a workshop on comparative reservoir limnology and integrated basin management in the Ardennes-Eifel Region (CRP-Gabriel Lippmann 2005).

PERSPECTIVES

The water quality of Bütgenbach Reservoir was found within the green threshold, based on the French quality system. Combined with the meso-to-eutrophic status obtained in this study, a better situation than expected was observed in the refilled reservoir. Subsequent to it being refilled, no intense trophic upsurge in regard to nutrient enrichment can be reported, as there are no data available for the period just before the emptying of the lake. In addition, monitoring efforts after the refilling period lasted only 6.5 months, an insufficient period for determining major long-term tendencies. Although Bütgenbach Reservoir can exhibit massive blue-green algal blooms, the conditions in the summer of 2005 were not marked by previously noted blooms. Continued vigilance is nevertheless called for, given that this aquatic ecosystem underwent several changes over the past year.

A decade ago, the European Topic Centre on Inland Waters Lakes and Reservoirs Study aimed to provide an overview of environmental conditions in major lakes and reservoirs (all dams with dam heights >15 m) in Europe. The purpose was to create a sufficiently adequate data network, in order to develop integrated amelioration and remediation strategies. The country of Belgium, which apparently does not have a national database, did not respond to this call, thereby excluding its participation on a global scale (EEA 1999). With this study, which also represents an effort to narrow the Belgian data gap, we hope that other studies on private Belgian dams will be conducted and the results placed in a wider database.

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