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First assessment of the ecological status of Karaoun Reservoir, Lebanon

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Abstract

Many reservoirs have been constructed throughout the world in the 20th century which often suffers from eutrophication. This worldwide problem increases phytoplankton biomass in reservoirs and impairs their uses. Except for Lake Kinneret, the environmental status of lakes and reservoirs in the Middle East is poorly documented. Karaoun Reservoir, also known as Qaroun, Qaraoun or Qarun, the largest water body in Lebanon, was built for irrigation and hydropower production. In this article, we provide a brief monograph about the reservoir characteristics, uses, water quality and phytoplankton succession, in order to assess the environmental status of the reservoir, based on the few previous publications. Since 2004, 39 years after its construction, the reservoir was found to be hypereutrophic, with low phytoplankton biodiversity and regular blooms of toxic cyanobacteria. The nutrient and trace metals concentrations would not prevent drinking water production for Beirut as is planned, but not all micropollutants are not documented. We compare Karaoun Reservoir to other monitored lakes and reservoirs around the Mediterranean Sea. They share annual toxic cyanobacterial blooms of *Aphanizomenon ovalisporum* and of *Microcystis aeruginosa*. The phytoplankton composition and succession of Karaoun Reservoir matches more with El Gergal Reservoir, Spain, than with closer natural lakes like Lake Kinneret, Israel and Lake Trichonis, Greece. Phytoplankton diversity in Karaoun Reservoir was the lowest, due to higher nutrient concentrations and a larger decrease in water level in the dry season. Karaoun Reservoir presents an interesting example of what would be the response of the phytoplankton community in other lakes and reservoirs during the drought periods expected from global climate change.

Keywords: eutrophication, Litani River, Middle East, phytoplankton diversity, water level, water quality.

1. Introduction

Over 45 000 large dams had been constructed in more than 140 countries by the end of the 20th century. An ongoing increase in the construction of reservoirs is expected in the future (Seitzinger et al., 2010). These artificial water bodies meet human needs for drinking water production, agricultural irrigation, power generation, industrial and cooling water supply, commercial fishing and recreation (Jørgensen et al., 2005).

Fertilizers and untreated sewage in their catchments often increase nutrient loads and concentrations in these ecosystems and cause their eutrophication (Smith and Schindler, 2009). Eutrophication threatens freshwater bodies as it promotes the development and persistence of harmful algal blooms in warm conditions (Heisler et al., 2008; Salmaso et al., 2012; Søndergaard and Jeppesen, 2007; Xavier et al., 2007). Many lakes and reservoirs throughout the world suffer from toxic phytoplankton blooms (Messineo et al., 2009; Oberholster et al. 2006; Okello and Kurmayer, 2011; Rejmánková et al., 2011). These harmful photosynthetic species are mostly cyanobacteria; they reduce ecosystem biodiversity and produce toxins (neurotoxins, hepatotoxins, cytotoxins, dermotoxins and endotoxins).

The assessment of the environmental status of aquatic ecosystems is achieved by studying their hydro-morphology, physico-chemical and biodiversity conditions (Piha and Zampoukas, 2011). This assessment is poorly documented for many lakes and reservoirs in the Middle East, except for Lake Kinneret in Israel. Karaoun Reservoir, the main reservoir in Lebanon, suffers from annual blooms of potentially toxic cyanobacteria, as reported since 2009 (Atoui et al., 2013). Documents about the hydrology, the water quality and the phytoplankton of Karaoun Reservoir are scarce. In this paper, we analyse this bibliographic basis to perform the first assessment of the environmental status of the reservoir and compare it to the environmental status of other lakes and reservoirs around the Mediterranean Sea.

After presenting the geological and hydrological characteristics and the current and future uses of Karaoun Reservoir, we analyse the available data about its water quality and phytoplankton succession, in order to assess the environmental status of the reservoir. We then compare Karaoun Reservoir to other monitored lakes and reservoirs around the Mediterranean Sea.

2. Material and methods

2.1. Geology and hydrology of Karaoun Reservoir

Karaoun Reservoir (33.34° N, 35.41° E), constructed in 1965, is the largest reservoir in Lebanon. It is located in the Bekaa valley on the Litani River at an elevation of 800 m, 86 km upstream from the mouth of the Litani River into the Mediterranean Sea (Figure 1).

The Litani River, the longest and largest perennial river in Lebanon, with a length of 170 km, flows between the Mount Lebanon Mountains in the West and the Anti-Lebanon Mountains in the East (Doummar et al., 2009). It rises from Olleiq village (altitude 1800m) and drops a total of 1000 m down to the Karaoun Dam. This upper part of the watershed (Figure 1) constitutes the Karaoun Reservoir catchment and has a surface area of 1600 km^2. The reservoir is located before the steepest descent of the river between Karaoun and Khardali, where the river drops 600 m in about 30 km. In its final stretch, the Litani River flows rather gently and drops a total of 300 m over a distance of 50 km from Khardali to the Mediterranean Sea (Figure 1).

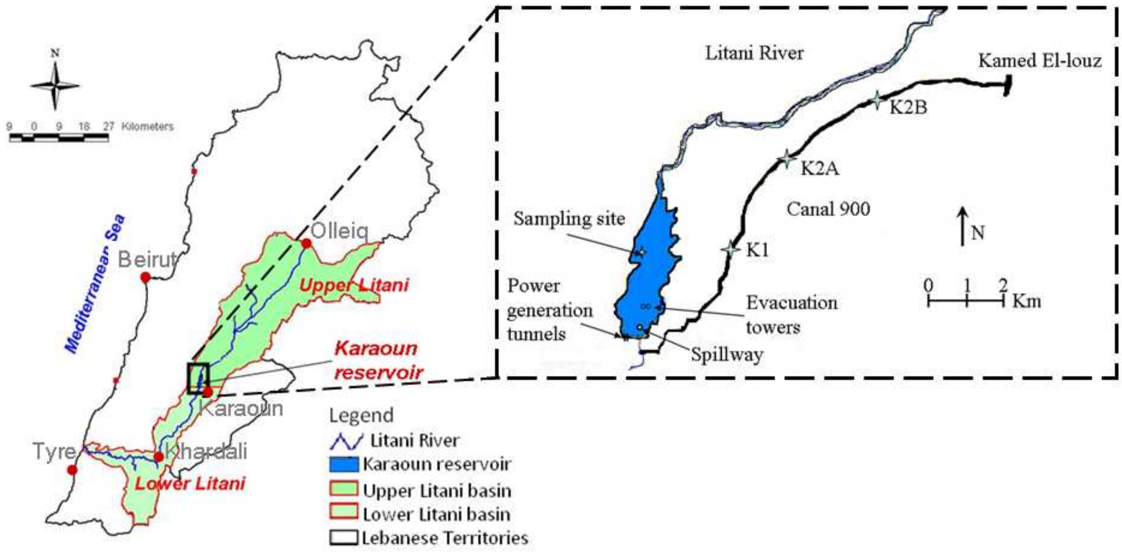

Figure 1 Location of Karaoun Reservoir with reservoir outlets, sampling sites in the reservoir (Atoui, et al. 2013) and in canal 900 (K1, K2A, K2B ; unpublished results), maps adapted from USAID (2003).

Karaoun Reservoir has a surface area of 12 km^2 at full capacity, a maximum depth of 60 m, mean depth of 19 m, total capacity is 224.10^6 m^3, and water residence time of 0.77 year (Table 1).

The climate in the vicinity of Karaoun Reservoir is semiarid, characterized by moderately cold winters (the normal mean temperature is 13°C in January and February) and dry, hot summers (the normal mean temperature varies between 25 and 27°C from July to September). The average annual precipitation in the reservoir catchment is about 700 mm (Amery, 2000). The heaviest rainfall period spreads from November to April. There is little or no precipitation between June and August (Sene et al., 1999).

Table 1 Comparison of the physical and hydrological characteristics of Karaoun Reservoir and other freshwater bodies around the Mediterranean Sea. (-): data not found

	Karaoun Reservoir	Lake Kinneret	Lake Trichonis	Lake Lisimachia	El Gergal Reservoir	Lake Vela
Mean depth (m)	19	24	30	4	15.7	1.1
Max depth (m)	60	43	58	9	37.5	2.1
Area (km^2)	12	167	97	13.2	2.5	0.7
Catchment area (km^2)	1600	2730	250	246	-	-
Volume (x 10^{6}m^3)	224	4000	2600	53	35	0.8

Altitude at max. level (m)	860	-210	18	16	63.5	50
Annual level fluctuations (m)	23	5	2	-	8.5	-
Water residence time (years)	0.77	5.1	9.4	-	-	-

Both the Litani River and Karaoun Reservoir are water resources managed by the Litani River Authority (LRA). This authority, which works under the patronage of the Ministry of Energy and Water, was established to develop the Litani River Basin domestic, irrigation and hydropower water schemes, as well as the national power grid (Yamout and Jamali, 2007). The authority was also given the technical and financial power for operating all projects related to the Litani River Basin.

2.1.1. Reservoir geology

Most of the soils in the Karaoun Reservoir catchment exhibit high permeability and are subject to erosion, which makes them a source of minerals like calcium, carbonate, magnesium and iron. Two active faults are present in the Bekaa area; namely, the Yammouneh Fault along the western edge of the Bekaa and the Serghaya Fault along its eastern edge (Figure 2a). The formations at the Karaoun Reservoir site are Cretaceous limestone (C4, C5, C6 on Figure 2b), Eocene limestone (E1, E2) and marly limestone. The Cretaceous Cenomanian limestone (C4), which is composed partly of dolomite, covers the upper portion of the reservoir catchment. It draws an anticline, oriented from the North to the South-West and filled with quaternary alluvial deposits. To the East, the reservoir area is covered by Senonian marls on the western slope of Mount Jabal al-Arabi. To the West, the upper part of the reservoir contacts the Neocene marls and its lower part the Lower Cretaceous limestone. Finally, to the South of the reservoir, we have the Eocene limestone. On the upper part of this last region there are basalt rocks composed of magnesium and iron (Dubertret, 1955).

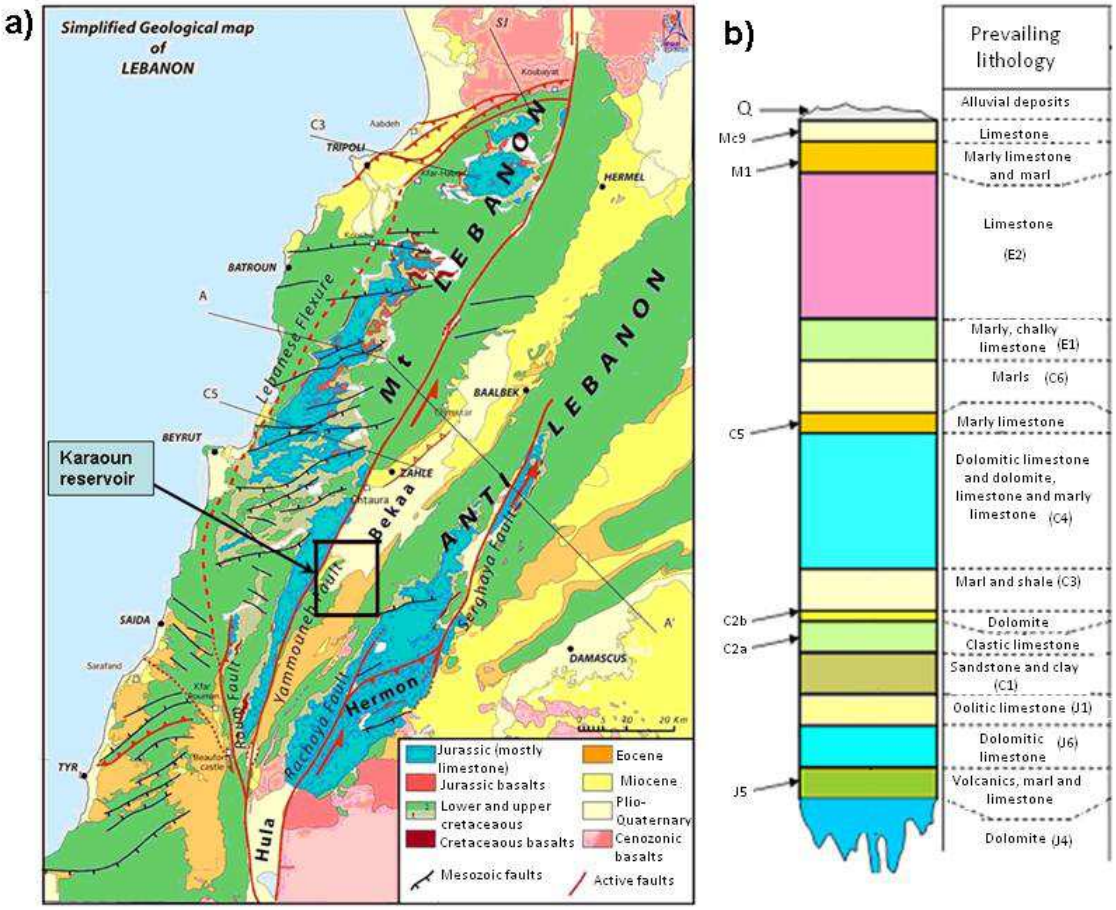

Figure 2 a) Simplified tectonic and geologic map of Lebanon, adapted from Dubertret (1955) by UNDP (1970); b) Stratigraphic section of Karaoun Reservoir adapted from UNDP (1970) by Cadham (2007).

2.1.2. Reservoir hydrology

The main inflow to Karaoun Reservoir is the Litani River. Based on Litani River Authority estimates, the current annual discharge rate into the reservoir averaged between 2009 and 2011 amounts to 9.2 m^3/s, *i.e.* 290 × 10^6 m^3/year (Table 2).

Table 2 Inflow - outflow water balance in Karaoun Reservoir between 2009 and 2011

Year	2009	2010	2011	3 years average
Litani inflow (m^3/s)	9.08	9.18	9.24	9.2
Withdrawal for hydropower (m^3/s)	6.43	10.61	8.45	8.5
Withdrawal for irrigation (m^3/s)	0.5	0.25	0.25	0.3
Evacuation using tunnels (m^3/s)	0	0	0.1	0.03

Springs also discharge along the reservoir. Their contribution to the Litani River was not negligible before the dam construction (UNDP, 1970). A flow rate of 0.7 m^3/s was measured from one of these springs in summer 1952.

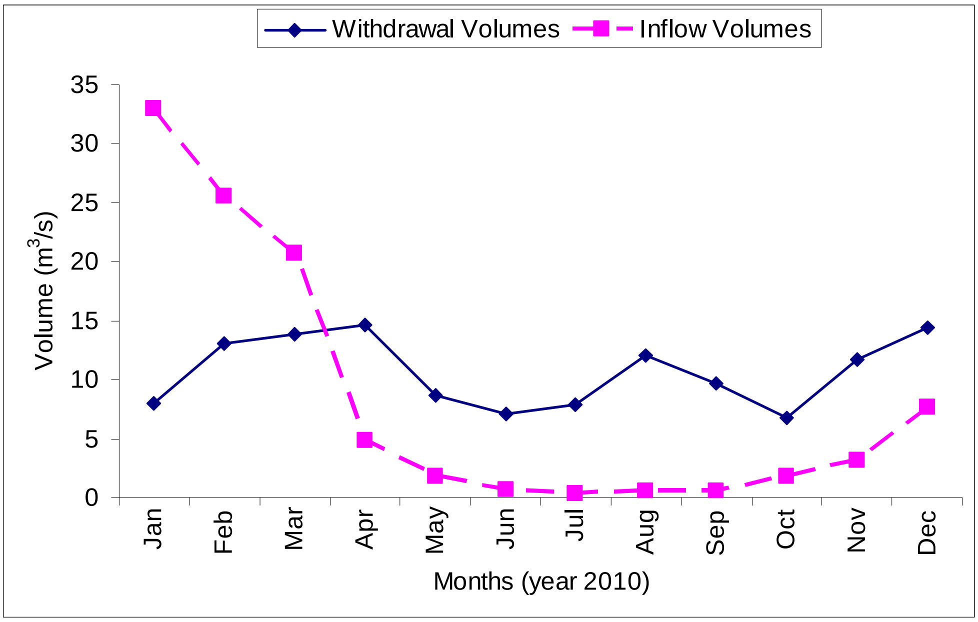

Figure 3 Monthly average withdrawal and inflow volumes at Karaoun Reservoir in the year 2010 (LRA data).

Karaoun Reservoir has three main outputs: 1) the power generation tunnels which are loc Figure 1); 2) two discharge towers originally used to empty the reservoir, with a total capacity of 21 m^3/s (personal communication), and currently used to supply Canal 900, an irrigation canal, through a pumping station; and 3) the bell-mouth spillway, located near the dam at an elevation of 859m, used to convey the overflow into the Litani River at the bottom of the dam, thereby avoiding the water overtopping, damaging or even destroying the dam. About 280×10^6 m^3 are withdrawn annually for the different uses which will be detailed in the next section (personal communication). Withdrawal volumes are regular in the year, contrary to inflow volumes (Figure 3), which causes a large decrease in the water level during the dry season. A volume of about 30×10^6 m^3 is kept in the reservoir as dead storage before rain resumes in late autumn (Figure 4).

Part of the stored volume is lost by evaporation, seepage through the dam and infiltration. Losses by evaporation, amounted to about 0.21 m^3/s in summer 2012. Losses by seepage and infiltration vary between 0.01 and 0.03 m^3/s, depending on the water level in the reservoir (personal communication). The losses are small compared to the withdrawals.

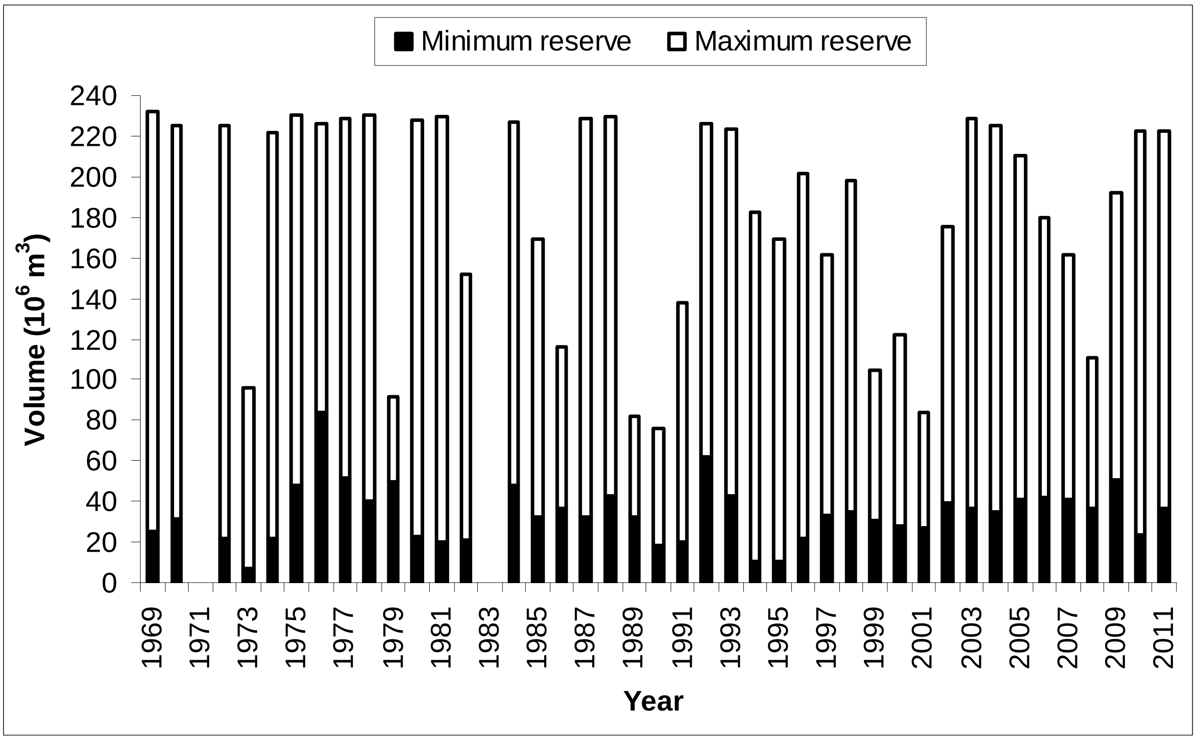

Figure 4 Minimum and maximum reserves in Karaoun Reservoir between 1969 and 2011 (source: LRA).

2.2. Current and anticipated uses of Karaoun Reservoir

Karaoun Reservoir was built for hydropower production and irrigation, but professional fishing is also practiced in the reservoir. A major drinking water supply for Beirut, the capital of Lebanon, is also planned, the Awali-Beirut Project.

2.2.1. Hydropower production

The power generation tunnels diverted an average volume of 268×10^6 m^3 (8.5 m^3/s) between 2009 and 2012 (Table 2). This water was used to generate energy at three hydroelectric power stations; namely, the Paul Arcache power plant located at Markaba (34 MW installed capacity), the Charles Helou power plant at Awali (108 MW) and the Abdel-Aal power plant at Joun (48 MW). The total yearly power production is estimated to around 600 GW.h, which makes up about 8 % of the total power production in Lebanon.

2.2.2. Future water supply to Beirut

The Awali-Beirut Project was planned as soon as the 1950s to improve to the drinking water supply of Beirut (Watson, 1998). In 2012, the decision was made to start the construction. The project is designed for the transfer and the treatment of about 6 m^3/s and is expected to solve the water deficit of Greater Beirut and its 1.7 million inhabitants (Watson, 1998; Yamout and Jamali, 2007). The water will come from Karaoun Reservoir only during the dry season, complemented by the Awali River and springs during the wet season (Figure 5). Little is said about the potential impact of this project on the water balance of Karaoun Reservoir.

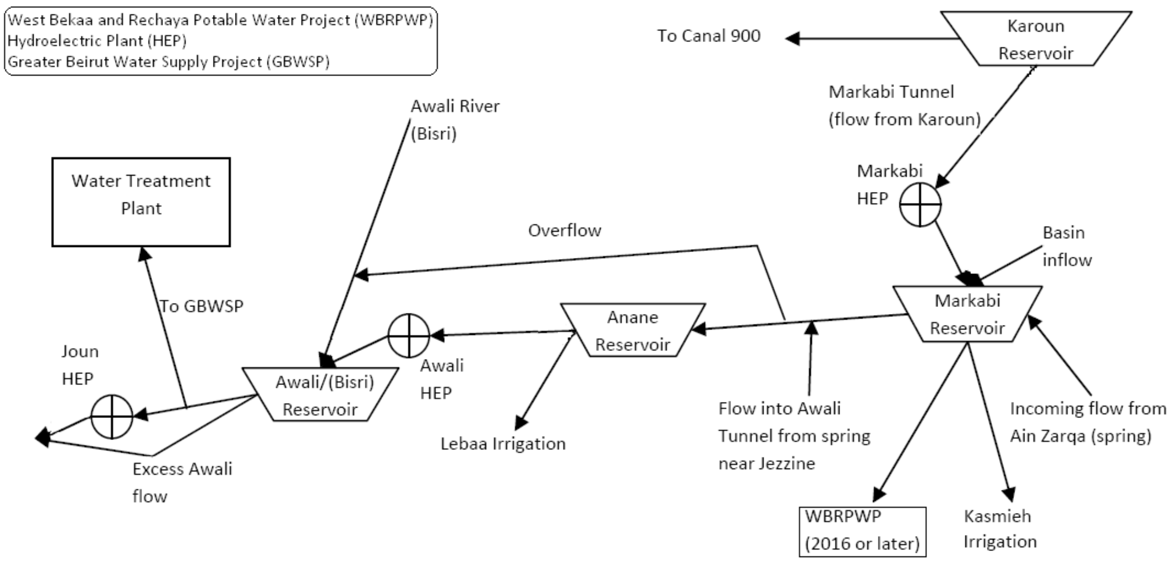

Figure 5 Sketch of the Awali-Beirut Project (ABP), adapted from Bartram and LoBuglio (2011).

2.2.3. Irrigation through Canal 900

In order to provide water for the irrigation of the upper Litani basin, Canal 900 was built in the early 1970s to transfer up to 4.8 m^3/s of water from Karaoun Reservoir and from groundwater and springs in the upper Litani basin (Figure 1). Canal 900, an open-surface channel of approximately 18.5 km length, irrigates an area of about 190 km^2 (USAID, 2005-a). It was named Canal 900 because it irrigates several villages situated around 900 m above sea level, higher than the reservoir base elevation.

2.2.4. Future Canal 800

Since irrigation needs are increasing, another canal has been planned, and is known as Canal 800. It is intended to deliver both irrigation and drinking water through a combination of open channels and tunnels from Karaoun Reservoir to Chaqra village, located 45 km to the south of the reservoir (USAID, 2005-a). It will provide 90×10^6 m^3/year to irrigate 150 km^2 in villages located between 400 m and 800 m altitude, in the South Lebanon and Nabatiyeh districts (Bichara et al., 2003; USAID, 2003). Again, little is said in these reports about the potential impact of this project on the water balance of Karaoun Reservoir.

2.2.5. Professional fishing

Freshwater fishing is very limited in Lebanon. However, Karaoun Reservoir seems to produce significant quantities of fish compared to sporadic catches in rivers like the Litani and Ibrahim rivers (MOE, 2001). About 30 fishermen practice net fishing on Karaoun Reservoir, with a fleet of about 15 traditional boats, producing about 150 tons per year. This catch is comprised mainly of carp (*Cyprinus carpio*) and common trout (*Oncorhynchus mykiss*) (MOE, 2009).

2.3. Assessment of the environmental status

2.3.1. Water quality and trophic state

Karaoun water quality affects present and future uses. To assess the reservoir trophic state and compatible uses, we analysed previous research studies and technical reports which document chemical characteristics of the reservoir, including major elements, nutrients and trace metals. To assess the trophic state of a freshwater body, the total phosphorus concentration is compared to thresholds in Vollenweider's classification (Vollenweider and Kerekes, 1982). Here we use the phosphate concentration. In the wet season, it is close to the total phosphorus concentration, since the phytoplankton biomass is low and the reservoir fully mixed by low air temperatures and strong winds.
We also compared the water quality of the reservoir to the World Health Organization's standard values for raw water for drinking water production (WHO, 2008).

2.3.2. Phytoplankton analyses

Harmful algal blooms result from eutrophication, can reduce ecosystem biodiversity and produce toxin. These harmful blooms are mostly cyanobacterial; they produce cyanotoxins (neurotoxins, hepatotoxins, cytotoxins, dermotoxins, anatoxins and endotoxins). These toxins cause skin irritation upon contact, and illness and death to livestock, pets, and wildlife that ingest water contaminated with toxic cyanobacterial cells or toxins released from decaying cyanobacterial cells (Azevedo et al., 2002; Codd et al., 1999; Codd et al., 2005). In addition, other nuisances are attributable to bloom-forming cyanobacteria. They include: 1) a decrease in water transparency; 2) a reduction in the dissolved oxygen concentration in the hypolimnion; 3) decreases in the abundance and diversity of hypolimnetic and benthic animal species like fish, due to hypoxia and cyanotoxins; 4) bad smell and scum production; and 5) and several negative economic impacts such as preventing the recreational use of the water bodies, clogging irrigation pumps and disturbing hydropower equipment (Smith, 2003).
We analysed the phytoplankton composition and diversity in Karaoun Reservoir from previous research studies. We calculated the total biovolumes of each phytoplankton species by multiplying the number of cells per millilitre by the average biovolume of a cell of that species and size category, according to the most suitable geometric models (Sun and Liu, 2003). We used Shannon's diversity index, which characterizes species diversity in a community (Shannon, 1948). It accounts for both abundance and evenness of the species. We computed it for each sampling date, according to the equation:

$$H' = -\sum_{i=1}^{n} (P_i \ln P_i)$$

where P_i is the relative biovolume of species i in the total biovolume and n the total number of species.

3. Results: environmental status of Karaoun Reservoir

3.1. Water quality and trophic state

3.1.1. Nutrient concentrations and trophic state

Subsurface nutrient concentrations, phosphate expressed in milligram phosphorus per litre ($P\text{-}PO_4$), nitrate and ammonium expressed in milligram nitrogen per litre ($N\text{-}NO_3$ and $N\text{-}NH_4$), were measured during the wet and dry seasons in 2005 and 2010 (Jurdi et al., 2011). Nutrient concentrations dropped between the years 2005 and 2010, phosphate concentration by a factor of 16, nitrate by 7, and ammonium by 2 (Figure 6). The dissolved inorganic phosphorus and dissolved inorganic nitrogen concentrations were always higher in the wet season than in the dry season, due to the lower consumption by phytoplankton in the wet season.

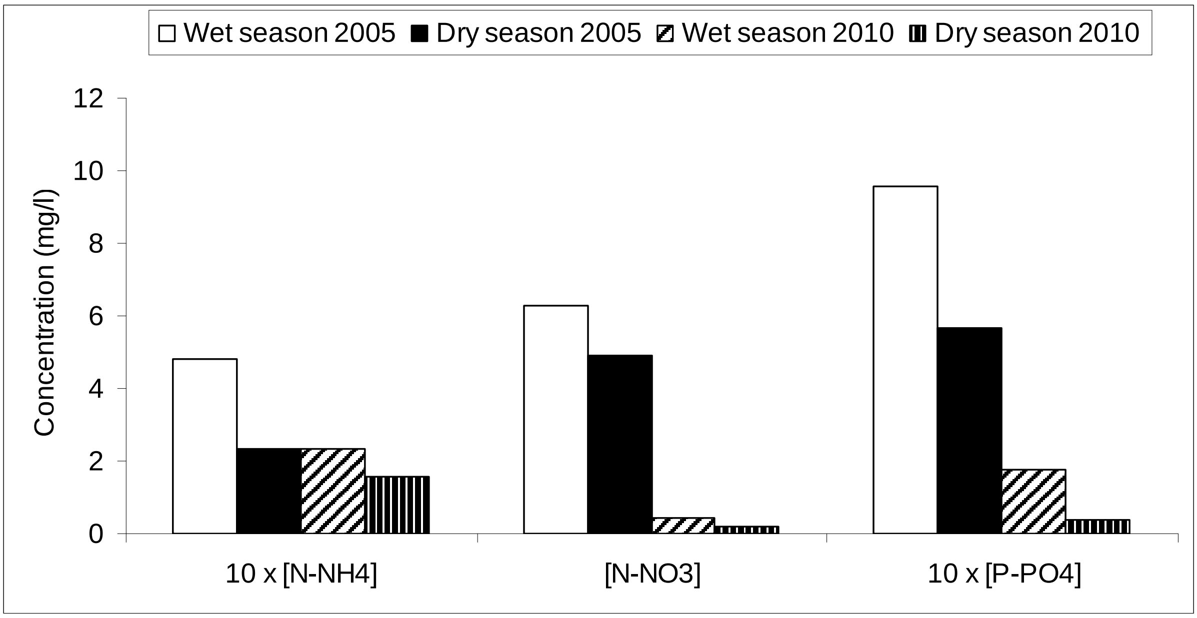

Figure 6 Comparison of subsurface nutrient concentrations in different seasons at Karaoun Reservoir (Jurdi et al., 2011).

Although the phosphate concentrations decreased from about 1 mg/L in 2005 to 0.2 mg/L in 2010, the values of this first study remained above 80 µg/L, threshold for the hypereutrophic trophic state in Vollenweider's classification. This classifies Karaoun Reservoir as hypereutrophic.

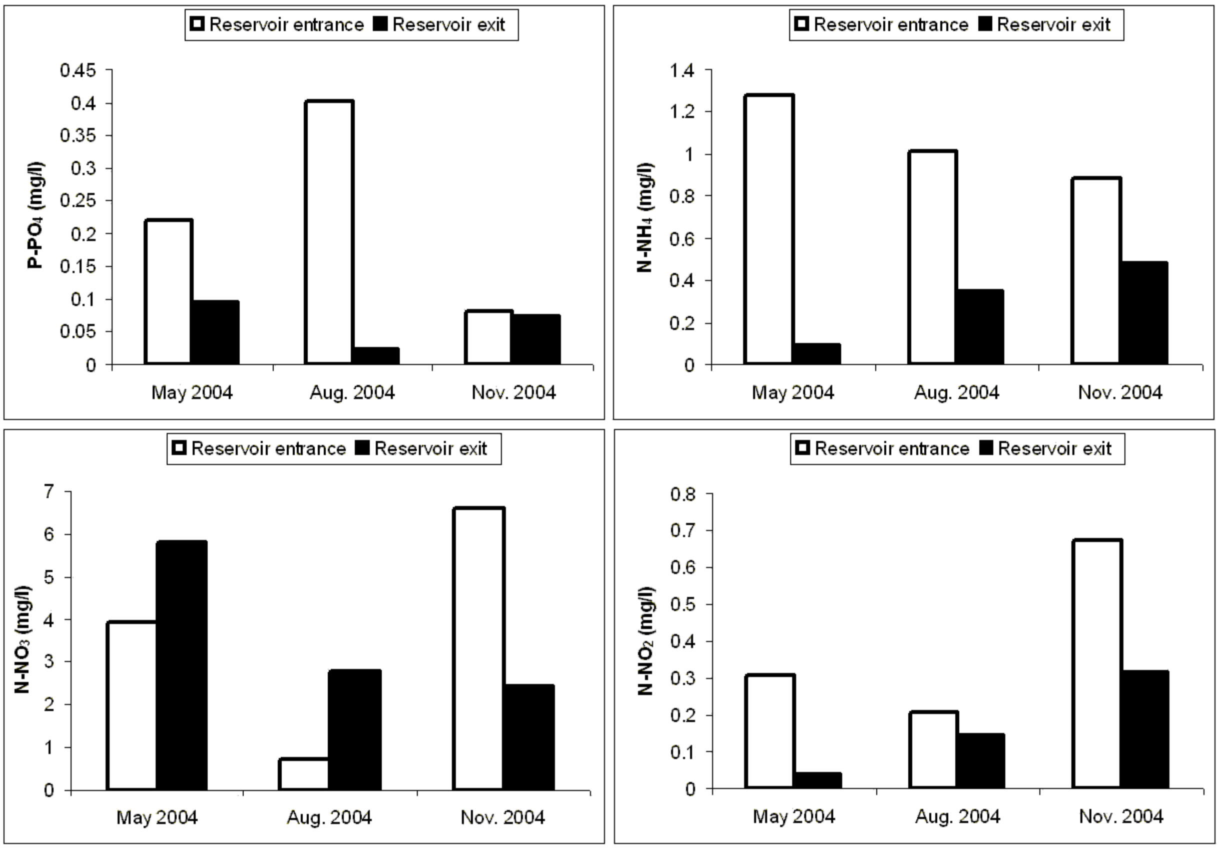

Figure 7 Comparison of nutrient concentrations at the output and input of Karaoun Reservoir (Cadham, 2007)

To compare the nutrient concentrations upstream and downstream of Karaoun Reservoir phosphate, nitrate, nitrite and ammonium concentrations were analysed in May, August and November 2004 (Cadham, 2007). Water samples were taken from two sites: at the inlet of the Litani River into the reservoir at an unprecised depth, and at the outlet of one of the power generation tunnels downstream the dam. Phosphate, ammonium and nitrite concentrations always decreased after passing through the reservoir (Figure 7). Only nitrate concentrations exhibited a seasonal pattern: they decreased in November but increased in May and August 2004. The authors explained the reduction of phosphate and ammonium concentrations by the presence of nutrient consumers like phytoplankton and microbial activity in the reservoir. The increase in the nitrate concentrations while passing through the reservoir was not interpreted. We think the high concentrations of nitrate in May and August 2004, coinciding with low concentrations of nitrite and ammonium suggest the nitrification of ammonium and nitrite into nitrate.

The lower phosphate concentrations in the wet season in this second study (80 to 90 µg/L) would again classify the reservoir as hypereutrophic. From both studies, we conclude that the reservoir is hypereutrophic.

3.1.2. Metal concentrations in water and in fish

We compared the oncentrations measured in Karaoun Reservoir to the World Health Organization's standard values for raw water for drinking water production. The monitoring of metals in Karaoun Reservoir has been conducted since 1995 (Jurdi et al., 2002; Korfali and Davies, 2005; Korfali and Jurdi, 2010; Korfali et al., 2006). The main objective of this monitoring was to assess the suitability of the water for its possible use in different sectors, including recreation, irrigation, domestic use, fishing, and hydropower generation. The authors used the same sampling, collection and analysis methods (APHA-AWWA-WPCF, 1992) for the dry season campaigns in 1995 (13 July, 2 August, 26 September and 6 October) and 2008 (unprecised dates) (Jurdi, Korfali et al. 2002; Korfali and Jurdi 2010). An automatic sampler was used to collect water from mid depth along various transects (19 points in 1995 and 15 points in 2008), ranging from the river inlet to a point located 800 m upstream from the dam. Total metal concentrations (Fe, Cr, Ni, Zn, Cu, Pb, and Cd) were determined by flame atomic absorption spectrometry. A titration procedure was used for Ca and Mg analyses.

We compare these results for both 1995 and 2008 in Figure 8. No significant variation in the concentrations of Ca, Mg, Na and Cu was observed. Zn concentration decreased by a half between 1995 and 2008, Cr concentration decreased by a factor of 7 and Fe concentration increased by a factor of 10. Korfali and Jurdi (2010) revealed that 60 % of the iron in Karaoun Reservoir is lithogenic. We have mentioned the presence of basaltic rocks in the Karaoun Reservoir catchment in subsection 2.1. The erosion of these rocks can result in a high iron influx to the reservoir.

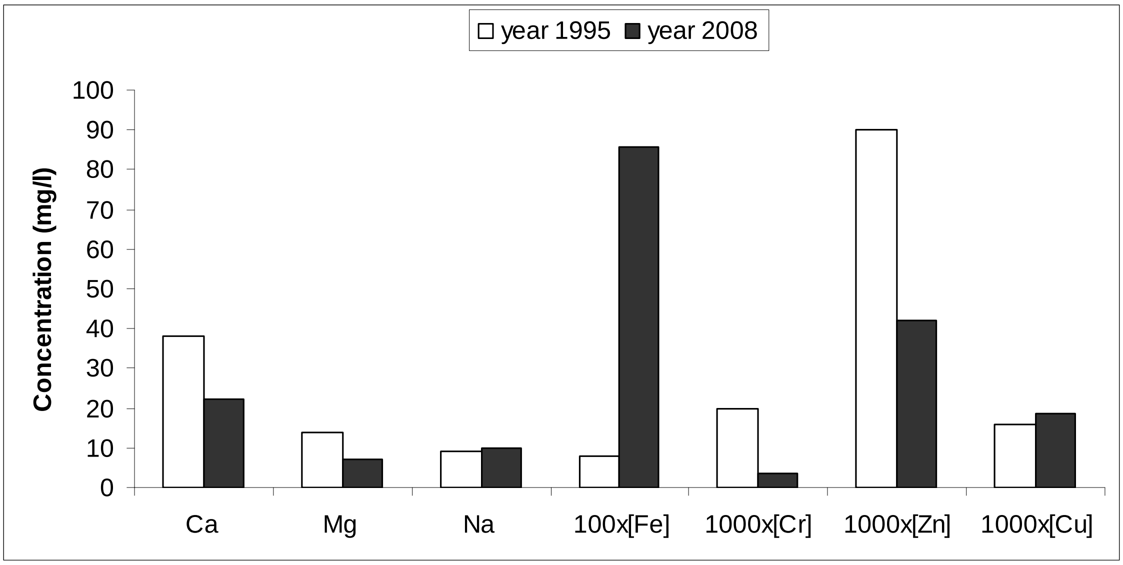

Figure 8 Comparison of average metal and cation concentrations in the years 1995 and 2008 (Jurdi et al. 2002; Korfali and Jurdi 2010).

The metal concentrations measured in the Karaoun Reservoir were compared (Table 3) to the standard values prescribed for raw water for drinking water production (WHO, 2008). Na, Cr, Zn and Cu concentrations were below the standard values for these metals in raw water supplies. Only the Fe concentration reached 3 times its standard value in 2008.

Table 3 Comparison between the maximum total metal concentrations recorded in 1995 and 2008 in Karaoun Reservoirs and WHO standard values for drinking water (WHO, 2008)

Metals	Na	Fe	Cr	Zn	Cu
WHO standard value (mg/l)	200	0.3	0.05	3	2
Maximum concentration in Karaoun (mg/l)	10	0.85	0.02	0.09	0.019

Trace metals were quantified in 7 fish samples in 2005 (USAID, 2005-b). The test was conducted in accordance with the US Environment Protection Agency 200.8 method that uses inductively coupled plasma–mass spectrometry (USAID, 2005-b). The results were compared to the US Food and Drug Administration (FDA) levels for toxic elements in fish, 12 mg/kg for chromium (Cr), 3 mg/kg for Cadmium (Cd), and 1.5 mg/kg for lead (Pb). The results obtained by the LRA showed that Cr levels in the sampled fishes were significantly below the FDA levels. However, Cd and Pb levels exceed the FDA guidelines in two samples and one sample respectively. This may indicate the degree of bioaccumulation and biomagnification of trace metals (Ebrahimpour et al., 2011; Vinikour et al., 1980) since the heavy metal concentrations remain low in Karaoun Reservoir.

3.2. Phytoplankton proliferation

3.2.1. Algal succession in Karaoun Reservoir

Different phytoplankton populations have dominated Karaoun Reservoir in the last few years. Before 2009 there were scarce reports concerning the aquatic flora of Karaoun Reservoir, based on relatively few subsurface samples (Saad et al., 2005; Slim, 1996). From the beginning of 2009 to the end of 2011, phytoplankton samples were collected five times per year in spring, summer and autumn, between 9:00 and 13:00, at 0.5 m beneath the water surface and fixed with 5 % formaldehyde, on the north-western bank of the reservoir (Atoui et al., 2013).

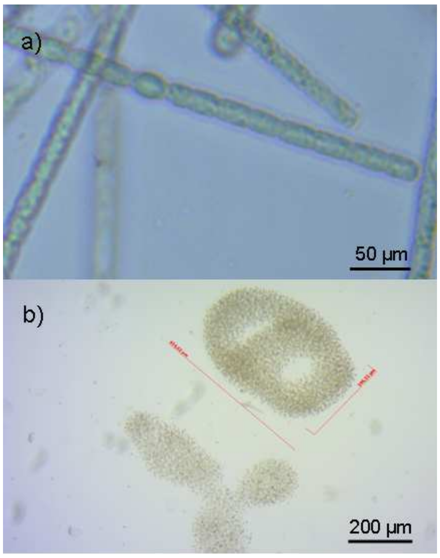

Figure 9 a) *Aphanizomenon ovalisporum* b) *Microcystis aeruginosa* (photos by A. Fadel, photographed from Karaoun Reservoir samples in 2011).

Before 1996, the phytoplankton of Karaoun Reservoir was dominated by diatoms which represented about 80% of the total phytoplankton count (Slim, 1996). The phytoplankton biodiversity in 2000-2001 was rich, but a biodiversity index cannot be calculated due to the absence of biomass data. At that period, 98 species were reported, among which about 60 species of planktonic diatoms dominated by *Aulacoseira granulata*, and a high concentration of dinoflagellate *Ceratium hirundinella* (Slim et al., 2012).

Between 2002 and 2003, filamentous green algae dominated (*Spirogyra lambertiana*, *Cladophora glomerata*, *Oedogonium sp.* and *Ulothrix zonata*) and the diversity was low.

A decrease in phytoplankton diversity and regular blooms of cyanobacteria *Aphanizomenon ovalisporum* and *Microcystis aeruginosa* has been reported since May 2009 (Figure 9). Table 4 shows the succession of phytoplankton species during years 2009, 2010, 2011 and their biovolumes. These biovolumes were computed from cell density measurements published by Atoui et al., (2013). *Aphanizomenon ovalisporum* was mostly observed at the beginning of spring and autumn while *Microcystis aeruginosa* was observed in summer. In spring 2010, other phytoplankton species coexisted with cyanobacteria. However, they appeared in low concentrations and for short periods before the bloom of *Microcystis aeruginosa* in summer. The general succession pattern in the year 2011 was comparable to that in the year 2010 insofar as *Aphanizomenon ovalisporum* and *Microcystis aeruginosa* were the main bloom-forming cyanobacteria and coexisted with green algae (Table 4).

Table 4 Phytoplankton species composition, biovolumes (× 10^{-3} mm^3/L), and Shannon's diversity index at the surface of Karaoun Reservoir from 2009 to 2011; (-): not detected.

	May 2009	Sep. 2009	Dec. 2009	Mar. 2010	May 2010	Sep. 2010	Mar. 2011	Apr. 2011	May 2011	Jun 2011	Nov. 2011
Cyanobacteria											
Aphanizomenon ovalisporum	5336	-	-	-	5104	-	-	-	5336	-	4872
Microcystis aeruginosa	-	990	28	-	-	990	-	-	-	924	132
Microcystis wesenbergii	-	3	-	-	-	-	-	-	-	-	-
Oscillatoria tenuis	-	-	5	-	-	-	-	-	-	-	-
Diatoms											
Aulacoseira granulata	-	-	-	-	-	-	1336	-	-	-	-
Fragilaria ulna	-	-	162	-	-	-	-	-	-	-	-
Melosira varians	-	-	329	-	-	-	-	-	-	-	-
Green algae											
Closterium acutum	-	103	-	206	-	-	-	386	-	-	-
Coelastrum microporum	-	-	-	53	70	-	-	26	-	-	-
Micrasterias radiata	-	-	-	4968	8280	-	-	-	-	-	-
Pediastrum boryanum	-	-	-	3146	5505	-	-	-	-	-	-
Pediastrum duplex	-	-	-	5899	5899	-	-	-	-	-	-
Staurastrum sebaldi	-	-	-	1729 0	24055	-	-	4322	-	-	-
Volvox aureus	-		-	-	-	-	-	-	-	1178	-
Dinoflagellates											
Ceratium hirundinella	-	-	2574 3	-	-	1800	3780 4	-	-	-	-
Peridinium gatunense	-	-	-	-	-	-	5600	-	-	-	-
Shannon's diversity index	0	0.4	0.1	1.2	1.4	0.7	0.4	0.3	0	0.7	0.1

Between 2009 and 2011, Shannon's diversity index ranged between 0 and 1.4 in Karaoun Reservoir (Table 4). The lowest values of the diversity index (0 or 0.1) occurred when a single species like *Ceratium hirundinella*, *Aphanizomenon ovalisporum* and/or *Microcystis aeruginosa* counted for more than 95% of the phytoplankton biomass. The highest value, *H'*=1.4 was recorded in March and May

2010, when 6 species coexisted, but it remains a low value, compared to the usual values of Shannon's diversity index that range between 1.5 and 4.

3.2.2. Eutrophication of Canal 900

Filamentous green algae (*Cladophora sp.*) that was previously observed in Karaoun Reservoir in 2002 and 2003, planktonic green algae (*Scenedesmus sp.*) and planktonic cyanobacteria (*Planktothrix agardhii*) were reported as dominant species in Canal 900 (Figure 1) during summer 2005 (USAID, 2005-a). These algae take advantage of intense light, high temperatures, and low turbidity accompanied with alternative periods of slow flows and standing water (USAID, 2005-a; USAID, 2003).
In September 2011, microscopic identifications on samples taken from K1, K2A, and K2B sites at canal 900 (Figure 1), showed the presence of cyanobacterium *Microcystis aeruginosa* and four filamentous algal species in all samples: *Cladophora glomerata, Spirogyra glomerata, Vaucheria sp.* and *Hydrodictyon reticulatum* (unpublished results).

In addition to their economic damage arising from the interruption of irrigation due to canal clogging, these filamentous algae have negative health consequences associated with toxic cyanobacteria proliferation. An allelopathic relationship exists between filamentous algae and cyanobacteria species. Allelopathy covers chemical interactions between bacteria and/or plants, including both stimulatory and inhibitory activities (Rice, 1984). In Egypt, bloom formation and toxin production by cyanobacterium *Planktothrix agardhii*, a toxic cyanobacterium, were favoured in irrigation canals containing filamentous green algae *Spirogyra sp.* (Mohamed, 2002). Furthermore, filamentous green algae can also promote bacterial development, including the development of pathogens, posing an additional threat to public health (Ishii et al., 2006).

To resolve the clogging problems created by these filamentous algae, the LRA used copper sulphate as they found it inexpensive, safe for workers, safe for drinking, bathing and irrigation, and easy to use. Its toxicity to fish was not regarded as an issue as no fish farm takes water from the canal. The amount of copper sulphate added to the canal in June and July was tapered to a dose of 0.1mg/L until middle July, the algal biomass decreased by 75 to 90 % from its initial state. Significant amounts of algae were then noted in the first week of August. As a result, the dosing target was increased to 1 mg/L for the month of August. The problem of screen clogging was solved and the volume of water delivered to the farmers increased. However, time has proven the inefficiency of copper sulphate treatments. It only temporarily inhibits the growth of filamentous algae, but also kills cyanobacteria which release their toxins. These toxins may cause worse problems than the filamentous algae: the toxins can be absorbed by the irrigated crops and the planters suffer from irritation by contact with contaminated water. After stopping the treatment, the algal proliferation recurred (Van Hullebusch et al., 2002).

As an alternative to this treatment, research performed on barley straw as an algal inhibitor proved its efficiency in suppressing filamentous green algae *Cladophora glomerata* in canals (Caffrey and Monahan, 1999; Welch et al., 1990). But barley straw clogged canal pump screens. Titanium dioxide (TiO_2), a non-toxic photocatalyst shown to break down the chloroplast pigments and successfully inhibit the growth of problematic filamentous algae like *Cladophora,* in the presence of sunlight (Peller et al., 2007), is being considered.

3.3. Environmental status of Karaoun Reservoir

The above presented results are not sufficient to give a complete evaluation of the environmental status of Karaoun Reservoir, but they reveal that Karaoun Reservoir is hypereutrophic with low phytoplankton biodiversity. Chlorophyll-a measurement were not performed but nutrient concentrations have decreased between 2005 and 2010 suggesting a decrease in eutrophication level. The phytoplankton biodiversity was high in the 1990s (98 species), but was low in recent years (less than 16 species), marked by toxic cyanobacterial blooms.

With regard to the Awali Beirut Project, the presented metal concentrations are insufficient to determine whether the water of Karaoun Reservoir is suitable for drinking water production, because many other parameters like the concentrations of organic micropollutants need to be measured.

4. Discussion: comparison with other Mediterranean lakes and reservoirs

Monitored freshwater bodies are rare in the geographic neighbourhood of the Karaoun Reservoir, except the closest natural lake, Lake Kinneret (Sea of Galilee, Israel). Among other lakes and reservoirs around the Mediterranean Sea, comparable phytoplankton succession is documented in Lakes Trichonis and Lisimachia in Greece, El Gergal Reservoir in Spain and Lake Vela in Portugal (Table 1). This section compares the morphological and hydrological characteristics, the eutrophication level, the phytoplankton diversity and the bloom-forming cyanobacteria of Karaoun Reservoir to those of these lakes and reservoirs.

4.1. Morphological and hydrological characteristics

Lake Kinneret located 85 km to the South of Karaoun Reservoir has been intensively studied. Lake Kinneret is a medium-sized (170 km^2) warm monomictic lake located in northern Israel at an elevation of -210 m below mean sea level (Serruya, 1978). It has a total water volume of 4×10^9 m^3, a maximum depth of 43 m, a mean depth of 24 m , and a water residence time of 5.1 years (Table 1). Lake Kinneret is used for power generation and domestic water usages. About 12% of the maximum lake volume is pumped annually into the National Water Carrier system (Zohary, 2004). Annual fluctuations of the water level in Lake Kinneret reach 5 m, with maximum water level (-208,8 m) and minimum observed level (-214,9 m in November 2001) (Zohary, 2004).

Lake Trichonis, the largest natural lake in Greece, is a deep warm monomictic lake situated in Aetoloakarnania Province (central western Greece) with a maximum depth of 58 m, a surface area of 97 km^2, an approximate volume of 2.6×10^9 m^3 and a residence time of 9.4 years (Zotos et al., 2006). Annual water level fluctuations in Lake Trichonis reach 2 m (Dimitriou and Moussoulis 2010). Lake Lisimachia is located 2.8 km to the west of Lake Trichonis, with a surface area of 13.2 km^2, and a maximum depth of 9 m, (Tafas and Economou-Amilli, 1991).

El Gergal Reservoir, located in the south-west of Spain, is the last in a chain of reservoirs (Aracena, Zufre, La Minilla and El Gergal Reservoirs) on the Rivera de Huelva. El Gergal Reservoir is a medium-sized canyon-type reservoir with a surface area of 2.5 km^2, a volume of 35×10^6 m^3, a maximum depth of 37.5 m, a mean depth of 15.7 m and an elevation of 26 m above sea level (Moreno-Ostos et al., 2008). Large seasonal and inter-annual volume variations are due to irregular inflows (Cruz-Pizarro et al., 2005). In 2007, the water level fluctuation was 8.5 m, with a maximum elevation of 63.5 m (full capacity) recorded in March and a minimum elevation of 55 m recorded in August (Rigosi and Rueda 2012).

Lake Vela is a shallow eutrophic freshwater body located in Quiaios, Figueira da Foz Province (Western Central Portugal). It has a surface area of 0.7 km^2 and a maximum depth of 2 m (Pereira et al., 2005).

The previously presented lakes and reservoir present much lower water level fluctuations than Karaoun Reservoir, less than 10 m (Table 1). Large volumes are withdrawn from Karaoun Reservoir between May and October during a drought period with low inflows. This often reduces its volume to 30 % of its capacity at the end of each year (Figure 4), and results in a 23 m decrease of its water level.

4.2. Eutrophication level and integrated water management

Karaoun Reservoir is more eutrophic than the natural lakes to which we compare it, and has nutrient concentrations comparable to El Gergal Reservoir (Table 5). In 2005, P-PO_4 reached up to 0.95 mg/l, N-NO_3 6.3 mg/l and N-NH_4 0.48 mg/l in Karaoun Reservoir. The nutrient concentrations in the top 10 m of Lake Kinneret were always below 2×10^{-3} mg/l for P-PO_4, 0.16 mg/l for N-NO_3 and 0.23 mg/l for N-NH_4, during the period between 1997 and 2003 (Gal et al., 2009). In El Gergal Reservoir, between 1979 and 2003, nutrient concentrations reached up to 2.92 mg/l for P-PO_4, 5.28 mg/l for N-NO_3 and 7.39 mg/l for N-NH_4 (Moreno-Ostos et al., 2007). In Lake Vela, between 2004 and 2005, nutrient concentrations reached up to 1.30 mg/l for P-PO_4, 2.8 mg/l for N-NO_3, and 0.76 mg/l for N-NH_4 (Abrantes et al., 2009). There are no recent studies about the nutrient concentrations in Lake Trichonis, but it has been considered as an oligotrophic lake with P-PO_4 always below 0.014 mg/l, and N-NO_3 below 0.147 mg/l (Skoulikidis et al., 1998). During the same studied period, nutrient concentrations in the Karaoun Reservoir were comparable to that of El Gergal Reservoir, and much higher than in the natural lakes except for P-PO_4 concentration that was lower than in Lake Vela.

In the catchment of Karaoun Reservoir, there are 1.06 million habitant, 570 km^2 of cultivated farmland and several industries, mostly food, paper, tanning, plastic, cosmetic and detergent industries (Arif, 2013). This deteriorates the water quality of Karaoun Reservoir through agricultural effluents (pesticides and fertilizers), untreated industrial and municipal wastewaters, and solid and liquid wastes dumped into the Litani River (ELARD, 2011). These contamination sources along the Litani River and its tributaries are the main causes of the high nutrient concentrations in Karaoun Reservoir leading to algal blooms.

Table 5 Comparison between maximum nutrient concentrations measured in Karaoun Reservoir and other freshwater bodies around the Mediterranean Sea. (-): data not found

Maximum concentrations (mg/L)	Karaoun Reservoir (2005)	Lake Kinneret (1997-2003)	Lake Trichonis (before 1998)	El Gergal Reservoir (1979-2003)	Lake Vela (2004-2005)
P-PO4	0.95	0.002	0.014	2.92	1.30
N-NO3	6.3	0.16	0.147	5.28	2.8
N-NH4	0.48	0.23	-	7.39	0.76

The Awali-Beirut project which will supply Beirut with water mostly from Karaoun Reservoir is expected to start soon. However, questions of water quality arise because this water supply is intended for domestic use and drinking water production. Cyanobacteria *Aphanizomenon ovalisporum* and *Microcystis aeruginosa*, both present in Karaoun Reservoir, produce lethal toxins. To avoid public health problems caused by toxic cyanobacterial blooms, we should reduce the nutrient loading and prevent eutrophication by treating wastewater effluents from municipalities and industries in the reservoir catchment area before its arrival to Karaoun Reservoir.

4.3. Phytoplankton diversity

Between 2009 and 2011, Shannon’s diversity index for Karaoun Reservoir phytoplankton was always below 1.5 (Table 4).This index was not computed for the other mentioned lakes and reservoirs, except Lake Kinneret, where the diversity index ranged between 1 and 3 and was higher than in Karaoun Reservoir most of the time (Ostrovsky, et al. 2012). The phytoplankton flora of Karaoun reservoir (13 genus, Table 4) is not as rich as in Lake Kinneret (74 genus) (Roelke et al., 2007), Lake Trichonis (46 genus found in the species list of Tafas and Economou-Amilli (1997)) and El Gergal Reservoir (24 genus found in the species list of Hoyer et al. (2009).
Intensive precipitations and seasonal climatic oscillations in total radiation and water temperature are known to increase the ecosystem diversity (Figueredo and Giani, 2001). We believe that in Karaoun Reservoir, low or no precipitations between May and October, simultaneous with a large water level decrease (Table 1), thermal stratification (Slim et al., 2013) and high nutrient concentrations (Table 5) result in a low biodiversity. El Gergal Reservoir presents comparable high nutrient influx and ecological behaviour: surface algal blooms occur during calm and dry periods and limit the reservoir phytoplankton biodiversity (Cruz-Pizarro et al., 2005).

Amongst the presented lakes and reservoir, the general trend of phytoplankton succession in Karaoun Reservoir agrees best with the typical succession observed in El Gergal Reservoir (Hoyer et al., 2009): diatoms, green algae, cyanobacteria, and finally dinoflagellates. Karaoun Reservoir and El Gergal Reservoir share no less than 11 genus (Table 4): diatoms (*Aulacoseira, Fragilaria, Melosira*), green algae (*Coelastrum, Pediastrum, Volvox, Staurastrum*), cyanobacteria (*Aphanizomenon, Microcystis, Oscillatoria*), and dinoflagellates (*Ceratium*) (Hoyer et al., 2009).

The hydrological functioning of Karaoun and El Gergal Reservoirs has more in common than that of the presented Mediterranean natural lakes. This explains why the phytoplankton composition and succession in Karaoun Reservoir match more with those of El Gergal Reservoir.

4.4. Toxic cyanobacterial succession

In spite of different altitudes, hydraulic management and nutrient concentrations, Karaoun Reservoir and the presented Mediterranean lakes and reservoir share annual toxic cyanobacterial blooms of *Aphanizomenon* sp. and *Microcystis aeruginosa.*

Between 2009 and 2011, these cyanobacteria dominated the algal population of Karaoun Reservoir in warm and nutrient-rich conditions. Cyanobacterial blooms are a new phenomenon in Karaoun Reservoir compared to the near Lake Kinneret, and yet Lake Kinneret is less eutrophic than Karaoun Reservoir. As early as the late 1960s, winter and spring blooms of cyanobacterium *Microcystis* sp. were reported in Lake Kinneret (Pollingher, 1986), while nitrogen-fixing cyanobacteria *Aphanizomenon ovalisporum* and *Cylindrospermopsis raciborskii* were first detected in September 1994 and summer 1998, respectively (Berman and Shteinman, 1998; Pollingher et al., 1998).

Aphanizomenon ovalisporum and *Microcystis aeruginosa* were found to occur not only in Lake Kinneret but also in other Mediterranean freshwater bodies. *Aphanizomenon ovalisporum* but not *Microcystis aeruginosa* was reported for the first time in July 1999, in the warm monomictic lakes Lisimachia and Trichonis in Greece (Gkelis et al., 2005). In Lake Vela (Central Portugal), blooms of *Aphanizomenon* sp. occurred early in May 2010 and were then followed by blooms of *Microcystis aeruginosa* in June 2010 (Figueiredo et al., 2006).

In Lake Vela and in Karaoun Reservoir, *Aphanizomenon* sp. blooms occurred in late spring and were always followed by *Microcystis aeruginosa* blooms in summer. We think that the competition between *Aphanizomenon* sp. and *Microcystis aeruginosa* is mainly driven by water temperature. In Karaoun Reservoir, *Aphanizomenon ovalisporum* blooms occurred both in spring (mainly in May) at surface water temperature of 20 – 22 °C and autumn at 18 – 20 °C, while a *Microcystis aeruginosa* bloom occurred in summer at 25 - 27 °C. In Lake Vela, a massive cyanobacterial bloom of *Aphanizomenon flos-aquae*, a species with similar traits to *Aphanizomenon ovalisporum*, occurred early in May at a surface water temperatures of 17.5 °C, and was then followed by a *Microcystis aeruginosa* bloom in June at higher water temperatures ranging from 23.4 to 29.4 °C. This succession can be explained by the fact that the growth of *Microcystis* sp. stops below 15 °C and is optimal at a water temperatures ranging from 27.5 to 32 °C (Imai et al., 2009; Robarts and Zohary, 1987). In contrast, *Aphanizomenon* sp. has an optimal growth temperature ranging from 15 to 28 °C (Robarts and Zohary, 1987) and is able to outgrow *Microcystis* sp. at lower temperatures (Miller et al., 2013).

5. Conclusions

On the local scale, this review provides important background data for the Lebanese water management authorities who aim to use high volumes from this reservoir for drinking water production and irrigation. The reservoir was found to be eutrophic to hypereutrophic, with low phytoplankton biodiversity and regular blooms of toxic cyanobacteria. The nutrient and metal concentrations would not prevent drinking water production for Beirut as is planned, but other micropollutants like organic micropollutants are not documented.
Except for Lake Kinneret, little or no studies were performed on other lakes and reservoirs in the Middle East region. In this study we compared the environmental study of Karaoun Reservoir to other lakes and reservoirs around the Mediterranean Sea. The environmental status of Karaoun Reservoir matched more with El Gergal Reservoir in Spain than with natural lakes like Lakes Kinneret in Israel and Trichonis in Greece. Comparing Karaoun Reservoir to other Mediterranean freshwater bodies revealed that this reservoir suffers from a lower phytoplankton biodiversity and higher nutrient concentrations, and shares with them toxic cyanobacterial blooms of *Aphanizomenon ovalisporum* occurring in spring and autumn, and *Microcystis aeruginosa* in summer. Unlike in these other lakes and reservoirs, the yearly water level fluctuations are very large in Karaoun Reservoir. The large decrease in water level in the dry season with others factors like a high nutrient influx, the absence of rain and thermal stratification result in a very poor phytoplankton diversity. This makes Karaoun Reservoir a very interesting example of what would be the response of the phytoplankton community to decreases in water levels due to drought periods in other lakes and reservoirs in a Mediterranean climate.

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References

Abrantes, N., Pereira, R., de Figueiredo, D.R., Marques, C.R., Pereira, M.J., Gonçalves, F., 2009. A whole sample toxicity assessment to evaluate the sub-lethal toxicity of water and sediment elutriates from a lake exposed to diffuse pollution. Environmental Toxicology **24**, 259-270.

Amery, H., 2000. Assessing Lebanon`s water balance, in: Brooks, D., Mehmet, O. (Eds.), Water balances in the eastern Mediterranean. International Development Research Centre, Canada, pp. 13-28.

APHA-AWWA-WPCF, 1992. Standard methods for the examination of water and waste water, 18th ed., American Public Health Association Publications, Washington, D.C.

Arif, S., 2013. Cost of Water Reseources Degradation (CAWRD) of the Litani Basin. *National consultation workshop on the cost of the environmental degradation and remediation of the Litani River Basin (Lebanon)*, December 12, 2013, Beirut, Lebanon.

Atoui, A., Hafez, H., Slim, K., 2013. Occurrence of toxic cyanobacterial blooms for the first time in Lake Karaoun, Lebanon. Water and Environment Journal **27**, 42-49.

Azevedo, S., Carmichael, W., Jochimsen, E., Rinehart, K., 2002. Human intoxication by microcystins during renal dialysis treatment in Caruara-Brazil. Toxicology **181**, 441-446.

Bartram, J., LoBuglio, J., 2011. Greater Beirut water supply project: independent technical review of source water quality, The World Bank, Washington, DC.

Berman, T., Shteinman, B., 1998. Phytoplankton development and turbulent mixing in Lake Kinneret (1992-1996). Journal of Plankton Research **20**, 709-726.

Bichara, A., Nemer, R., Fuleihan, J., Al-Salihi, N., Hajjar, Z., 2003. , Republic of Lebanon - Policy note on irrigation sector sustainability. World Bank

Cadham, J.S., 2007. Towards an ecosystem approach to the sustainable management of the Litani watershed - Lebanon: final technical report to IDRC. IDRC research results, Cadham Hayes Systems Ottawa, Canada

Caffrey, J.M., Monahan, C., 1999. Filamentous algal control using barley straw. Hydrobiologia **415**, 315-318.

Codd, G., Bell, S., Kaya, K., Ward, C., Beattie, K., Metcalf, J., 1999. Cyanobacterial toxins, exposure routes and human health. European Journal of Phycology **34**, 405-415.

Codd, G.A., Morrison, L.F., Metcalf, J.S., 2005. Cyanobacterial toxins: risk management for health protection. Toxicology and Applied Pharmacology **203**, 264-272.

Cruz-Pizarro, L., A. Basanta, C. Escot, E. Moreno-Ostos, and D. George, 2005, Temporal and spatial variations in the water quality of El Gergal reservoir, Seville, Spain. : Freshwat Forum **23**, 62–77.

Dimitriou, E., Moussoulis, E., 2010. Hydrological and nitrogen distributed catchment modeling to assess the impact of future climate change at Trichonis Lake, western Greece. Hydrogeology Journal **18**, 441-454.

Doummar, J., Massoud, M., Khoury, R., Khawlie, M., 2009. Optimal Water Resources Management: Case of Lower Litani River, Lebanon. Water Resources Management **23**, 2343-2360.

Dubertret, L., 1955. Carte géologique de la Syrie et du Liban au 1/200000$^{\text{ème}}$. 21 feuilles avec notices explicatrices. Ministère des Travaux Publics. L'imprimerie Catholique, Beyrouth, 74p.

ELARD (Earth Link and Advanced Resources Development), 2011. Business plan for combating pollution of the Qaraoun Lake, UNDP ed., Beirut, Lebanon.

Ebrahimpour, M., Pourkhabbaz, A., Baramaki, R., Babaei, H., Rezaei, M., 2011. Bioaccumulation of heavy metals in freshwater fish species, Anzali, Iran. Bulletin of environmental contamination and toxicology **87**, 386-392.

Figueiredo, D., Reboleira, A.S.P., Antunes, S., Abrantes, N., Azeiteiro, U., Gonçalves, F., Pereira, M.r., 2006. The effect of environmental parameters and cyanobacterial blooms on phytoplankton dynamics of a Portuguese temperate Lake. Hydrobiologia **568**, 145-157.

Figueredo, C. C., and A. Giani, 2001, Seasonal variation in the diversity and species richness of phytoplankton in a tropical eutrophic reservoir: Hydrobiologia, **445**, 165-174.

Gal, G., Hipsey, M.R., Parparov, A., Wagner, U., Makler, V., Zohary, T., 2009. Implementation of ecological modeling as an effective management and investigation tool: Lake Kinneret as a case study. Ecological Modelling **220**, 1697-1718.

Gkelis, S., M. Moustaka-Gouni, K. Sivonen, and T. Lanaras, 2005. First report of the cyanobacterium *Aphanizomenon ovalisporum* Forti in two Greek lakes and cyanotoxin occurrence: Journal of Plankton Research, **27**, 1295-1300.

Heisler, J., Glibert, P.M., Burkholder, J.M. et al., 2008. Eutrophication and harmful algal blooms: A scientific consensus. Harmful Algae **8**, 3-13.

Hoyer, A. B., E. Moreno-Ostos, J. Vidal, J. M. Blanco, R. L. Palomino-Torres, A. Basanta, C. Escot, and F. J. Rueda, 2009, The influence of external perturbations on the functional composition of phytoplankton in a Mediterranean reservoir. Hydrobiologia, **636**, 49-64.

Imai, H., Chang, K.H., Kusaba, M., Nakano, S., 2009. Temperature-dependent dominance of *Microcystis* (Cyanophyceae) species: *M. aeruginosa* and *M. wesenbergii*. Journal of Plankton Research **31**, 171-178.

Ishii, S., Yan, T., Shively, D.A., Byappanahalli, M.N., Whitman, R.L., Sadowsky, M.J., 2006. *Cladophora* (Chlorophyta) *spp.* Harbor Human Bacterial Pathogens in Nearshore Water of Lake Michigan. Applied and Environmental Microbiology **72**, 4545-4553.

Jørgensen, S.E., Löffler, H., Rast, W., Straškraba, M., 2005. Lake and reservoir water uses and abuses. In: Lake and Reservoir Management. pp. 43-106. Elsevier, Amsterdam

Jurdi, M., Korfali, S., El Rez, M., Karahagopian, Y., Kreidieh, K., 2011. Wet Season Water Quality Survey of the Litani River Basin Project, USAID, Lebanon.

Jurdi, M., Korfali, S., Karahagopian, Y., Davies, B.E., 2002. Evaluation of Water Quality of the Qaraaoun Reservoir, Lebanon: Suitability for Multipurpose Usage. Environmental Monitoring and Assessment **77**, 11-30.

Korfali, S., Davies, B., 2005. Seasonal Variations of Trace Metal Chemical Forms in Bed Sediments of a Karstic River in Lebanon: Implications for Self-purification. Environmental Geochemistry and Health **27**, 385-395.

Korfali, S., Jurdi, M., 2010. Speciation of metals in bed sediments and water of Qaraaoun Reservoir, Lebanon. Environmental Monitoring and Assessment **178**, 563-579.

Korfali, S., Jurdi, M., Davies, B., 2006. Variation of Metals in Bed Sediments of Qaraaoun Reservoir, Lebanon. Environmental Monitoring and Assessment **115**, 307-319.

Messineo, V., Bogialli, S., Melchiorre, S. et al., 2009. Cyanobacterial toxins in Italian freshwaters. Limnologica **39**, 95-106.

Miller, T.R., Beversdorf, L., Chaston, S.D., McMahon, K.D., 2013, Spatiotemporal Molecular Analysis of Cyanobacteria Blooms Reveals *Microcystis-Aphanizomenon* Interactions. PLoS ONE **8**(9): e74933.

MOE (Ministry of Environment), 2001. State of the Environment Report. Beirut, Lebanon.

MOE (Ministry of Environment), 2009. Fourth National Report of Lebanon to the Convention on Biological Diversity, Lebanon.

Mohamed, Z.A., 2002. Allelopathic activity of *Spirogyra sp.*: stimulating bloom formation and toxin production by *Oscillatoria agardhii* in some irrigation canals, Egypt. Journal of Plankton Research **24**, 137-141.

Moreno-Ostos, E., J. A. Elliott, L. Cruz-Pizarro, C. Escot, A. Basanta, and D. G. George, 2007, Using a numerical model (PROTECH) to examine the impact of water transfers on phytoplankton dynamics in a Mediterranean reservoir.: Limnetica, **26**, 1-11.

Moreno-Ostos, E., L. Cruz-Pizarro, A. Basanta, and D. G. George, 2008, The spatial distribution of different phytoplankton functional groups in a Mediterranean reservoir: Aquatic Ecology, **42**, 115-128.

Oberholster, P.J., Botha, A.M., Cloete, T.E., 2006. Toxic cyanobacterial blooms in a shallow, artificially mixed urban lake in Colorado, USA. Lakes & Reservoirs: Research & Management **11**, 111-123.

Okello, W., Kurmayer, R., 2011. Seasonal development of cyanobacteria and microcystin production in Ugandan freshwater lakes. Lakes & Reservoirs: Research & Management **16**, 123-135.

Ostrovsky, I., Rimmer, A., Yacobi, Y.Z., Nishri, A., Sukenik, A., Hadas, O., Zohary, T., 2012. Long-Term Changes in the Lake Kinneret Ecosystem: The Effects of Climate Change and Anthropogenic Factors. In: Climatic Change and Global Warming of Inland Waters. (eds. Goldman, C.R., Kumagai M., Robarts R.D.) pp. 271-293. John Wiley & Sons, Ltd.

Peller, J.R., Whitman, R.L., Griffith, S., Harris, P., Peller, C., Scalzitti, J., 2007. TiO2 as a photocatalyst for control of the aquatic invasive alga, *Cladophora*, under natural and artificial light. Journal of Photochemistry and Photobiology A: Chemistry **186**, 212-217.

Pereira, R., A. Soares, R. Ribeiro, and F. Goncalves, 2005, Public attitudes towards the restoration and management of Lake Vela (Central Portugal): Fresenius Environmental Bulletin, **14**, 273-281.

Piha, H, Zampoukas, N., 2011. Review of Methodological Standards Related to the Marine Strategy Framework Directive Criteria on Good Environmental Status. Publications Office of the European Union, Luxembourg. doi:10.2788/60512

Pollingher, U., 1986. Phytoplankton periodicity in a subtropical lake (Lake Kinneret, Israel). Hydrobiologia **138**, 127-138.

Pollingher, U., Hadas, O., Yacobi, Y.Z., Zohary, T., Berman, T., 1998. *Aphanizomenon ovalisporum* (Forti) in Lake Kinneret, Israel. Journal of Plankton Research **20**, 1321-1339.

Rejmánková, E., Komárek, J., Dix, M., Rejmánková, J., Girón, N., 2011. Cyanobacterial blooms in Lake Atitlan, Guatemala. Limnologica. **41**, 296-302.

Rice, E.L., 1984. Allelopathy. 2nd Edn., FL, pp: 422, Academic Press Inc., Orlando.

Rigosi, A., Rueda, F.J., 2012. Hydraulic control of short-term successional changes in the phytoplankton assemblage in stratified reservoirs. Ecological Engineering **44**, 216-226.

Roelke, D.L., Zohary, T., Hambright, K.D., Montoya, J.V., 2007. Alternative states in the phytoplankton of Lake Kinneret, Israel (Sea of Galilee). Freshwater Biology **52**, 399-411.

Robarts, R.D., Zohary, T., 1987. Temperature effects on photosynthetic capacity, respiration, and growth rates of bloom-forming cyanobacteria. New Zealand Journal of Marine and Freshwater Research **21**, 391 - 399.

Saad, Z., Slim, K., Elzein, G., Elsamad, O., 2005. Evaluation of the water quality of Karaoun Reservoir (Lebanon). Bulletin de la Société Neuchâteloise des Sciences Naturelles **128**, 71-80.

Salmaso, N., Buzzi, F., Garibaldi, L., Morabito, G., Simona, M., 2012. Effects of nutrient availability and temperature on phytoplankton development: a case study from large lakes south of the Alps. Aquatic Sciences. **74**, 555-570.

Seitzinger, S.P., Mayorga, E., Bouwman, A.F. et al., 2010. Global river nutrient export: A scenario analysis of past and future trends. Global Biogeochemical Cycles **24**, 1-16.

Sene, K.J., March, T.J., Hachache, A., 1999. An assessment of the difficulties in quantifying the surface water resources of Lebanon. Hydrological Science Journal **44**, 79-96.

Serruya, C., 1978. Lake Kinneret, Monographiae Biologicae. 32, Junk Publishers, The Hague. 502 p.

Shannon, C. E. (1948) A mathematical theory of communication. The Bell System Technical Journal, 27, 379–423 and 623–656.

Skoulikidis, N.T., Bertahas, I., Koussouris, T., 1998. The environmental state of freshwater resources in Greece (rivers and lakes). Environmental Geology **36**, 1-17.

Slim, K., 1996. Contribution to the study of the flora of the basin of the Litani basin. Lebanese Scientific Research Reports **1**, 65-73.

Slim, K., Atoui, A., Elzein, G., Temsah, M., 2012. Effets des facteurs environnementaux sur la qualité de l'eau et la prolifération toxique des cyanobactéries du lac Karaoun (Liban). Larhyss Journal **10**, 29-43.

Slim, K., Fadel, A., Atoui, A., Lemaire, B.J., Vinçon-Leite, B., Tassin, B., 2013. Global warming as a driving factor for cyanobacterial blooms in Lake Karaoun, Lebanon. Desalination and Water Treatment, **52:10-12**, 2094-2101

Smith, V., 2003. Eutrophication of freshwater and coastal marine ecosystems a global problem. Environmental Science and Pollution Research **10**, 126-139.

Smith, V.H., Schindler, D.W., 2009. Eutrophication science: where do we go from here? Trends in Ecology & Evolution **24**, 201-207.

Søndergaard, M., Jeppesen, E., 2007. Anthropogenic impacts on lake and stream ecosystems, and approaches to restoration. Journal of Applied Ecology **44**, 1089-1094.

Sun, J., and D. Liu, (2003). Geometric models for calculating cell biovolume and surface area for phytoplankton. Journal of Plankton Research 25 (11), 1331-1346.

Tafas, T. P., and A. Economou-Amilli, 1991, Evaluation of phytoplankton variation in lake Trichonis (Greece) by means of multivariate analysis. : Mem. Ist. ital. Idrobiol., **48**, 99-112.

Tafas, T. P., and A. Economou-Amilli,, 1997. Limnological survey of the warm monomictic lake Trichonis (central western Greece). II. Seasonal phytoplankton periodicity – a community approach. Hydrobiologia, **344**: 141-153.

UNDP (United Nations Development Program) 1970. Liban: Etude des eaux souterraines. DP/SF/UN 44, UNDP, New York, 185p.

USAID (United States Agency for International Development) 2003. Water quality assessment of the upper Litani River basin and Lake Qaraoun, Lebanon. FORWARD Program - Integrated Water and Coastal Resources Management.

USAID (United States Agency for International Development), 2005-a. Canal 900 Algae Control: Testing and Validation. BAMAS - Litani water quality management project.

USAID (United States Agency for International Development) 2005-b. Technical survey report on the Litani water quality management. BAMAS - Litani water quality management project.

Van Hullebusch E., Deluchat V., Chazal P. M., Baudu M., 2002. “Environmental impact of two successive chemical treatments in a small shallow eutrophied lake: Part 2. Case of copper sulfate.” Environmental Pollution **120**: 627-634.

Vinikour, W.S., Goldstein, R.M., Anderson, R.V., 1980. Bioconcentration patterns of zinc, copper, cadmium and lead in selected fish species from the Fox river, Illinois. Bulletin of environmental contamination and toxicology **24**, 727-734.

Vollenweider, R.A., and Kerekes, J. 1982. Eutrophication of waters. Monitoring, assessment and control. OECD Cooperative programme on monitoring of inland waters (Eutrophication control), Environment Directorate, OECD, Paris. 154 p.

Watson, M., 1998. Phase I interim environmental impact assessment for the Awali-Beirut water conveyor. Project No. 1026. Contract No. 6682. CDR, Council for Development and Reconstruction., Lebanon.

Welch, I., Barrett, P., Gibson, M., Ridge, I., 1990. Barley straw as an inhibitor of algal growth I: studies in the Chesterfield Canal. Journal of Applied Phycology **2**, 231-239.

WHO (World Health Organization), 2008. Guidelines for drinking-water quality, Geneva.

Xavier, L., Vale, M., Vasconcelos, V.M., 2007. Eutrophication, phytoplankton dynamics and nutrient removal in two man-made urban lakes (Palácio de Cristal and Serralves), Porto, Portugal. Lakes & Reservoirs: Research & Management **12**, 209-214.

Yamout, G., Jamali, D., 2007. A critical assessment of a proposed public private partnership (PPP) for the management of water services in Lebanon. Water Resources Management **21**, 611-634.

Zohary, T., 2004, Changes to the phytoplankton assemblage of Lake Kinneret after decades of a predictable, repetitive pattern: Freshwater Biology, **49**, 1355-1371.

Zotos, A., T. Raus, and P. Dimopoulos, 2006, New floristic reports from the lakes Trichonis and Lisimachia (W Greece): Willdenowia, **36**, 731-739.