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ORIGINAL RESEARCH

# Long-Term Impacts of Draining a Watershed Wetland on a Downstream Lake, Lake Kinneret, Israel

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**Abstract:** During the 1950s, the shallow Lake Hula and its adjacent marshes, located in the watershed of Lake Kinneret (LK), were drained in order to increase arable land. The drainage resulted in increasing loads of nutrients in the Jordan River and in oxidative degradation of the underlying peat, followed by Aeolian (mostly) and riverine transport to LK. Peat had been accumulating in LK bed sediments since the 1950s, with peak deposits recorded in the mid-1970s. The routine monitoring of Norg and Corg, associated with the peat, in the watershed streams and in LK water (initiated in 1970) also showed the highest levels in the mid-1970s. During the 1980s, a succession of dense natural vegetation inhibited soil surface erosion and a decline in Aeolian transport of peat to LK was recorded. Inversed temporal patterns appear for oxygen and pH, and this is suggested to result from the dependence of these parameters on the magnitude of respiratory process, induced by peat availability. During the 1970s allochthonous peat resources supported about half of the zooplankton activity in LK and therefore the decline in peat availability during the 1980s was accompanied by a two-fold decline in zooplankton biomass. The subsequent lessening of grazing pressure together with the elevated inflows of bio-available P resulted in a significant rise in LK phytoplankton biomass. The 1980s decline in Norg associated with the peat led to lower N/P ratios in the external sources of nutrients to LK. These conditions may have favored the appearance of $N_2$ fixing cyanobacteria noted in the lake since 1994.

**Keywords:** Wetland drainage, Peat degradation, Aeolian transport, Allochthonous loads to lake, Sediment cores

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## Introduction

Lake Kinneret (LK; The Sea of Galilee, Fig. 1) is a monomictic freshwater lake located at the north of Israel. LK serves as a source of freshwater to Israel and to the Hashemite Kingdom of Jordan. The lake covers an area of 165 $Km^2$, a maximum depth of 42 m, a volume of 4000 (±300) × $10^6$ $m^3$ and has a water residence time between. 6 to 9 years.[1] The lake is stratified for about 9 months a year (March-December) during which time the hypolimnion becomes anoxic and $H_2S$ enriched. In most seasons, phosphorus is considered the nutrient limiting the growth of algae in LK except for the summer when epilimnetic dissolved inorganic nitrogen (DIN) levels drop below ~ 1 μM and nitrogen may then be the limiting nutrient.[2]

A major anthropogenic perturbation in the watershed was the drainage of the Hula wetlands in the 1950s. Routine monitoring of biological and chemical parameters in LK and in its watershed began in 1970, more than a decade later and this monitoring program revealed a two-fold decrease in the biomass of zooplankton, particularly of Copepods and Cladocerans,[3,4] between 1970 to 1990. A significant raise in phytoplankton abundance in winter[5] and summer[2] was noted in the early 1980s. Since 1994 LK has been characterized by occasional blooms of cyanobacteria[6] as well by changes in the phytoplankton assemblage after decades of predictable repetitive pattern.[5] The concomitant chemical data, presented below, reveals the occurrence of major changes in many parameters both in the watershed and in LK. A new synthesis of available limnological data and re-evaluation of long-term biological and chemical data was successfully used to identify and quantify major ecological perturbations governing in-lake processes since the 1950s.

## Metods

### Site description

Lake Kinneret watershed is characterized by a typical Mediterranean climate of hot dry summers (June–October) and cool rainy winters (Nov.–March). The watershed (area of ~2600 $Km^2$) extends mostly to

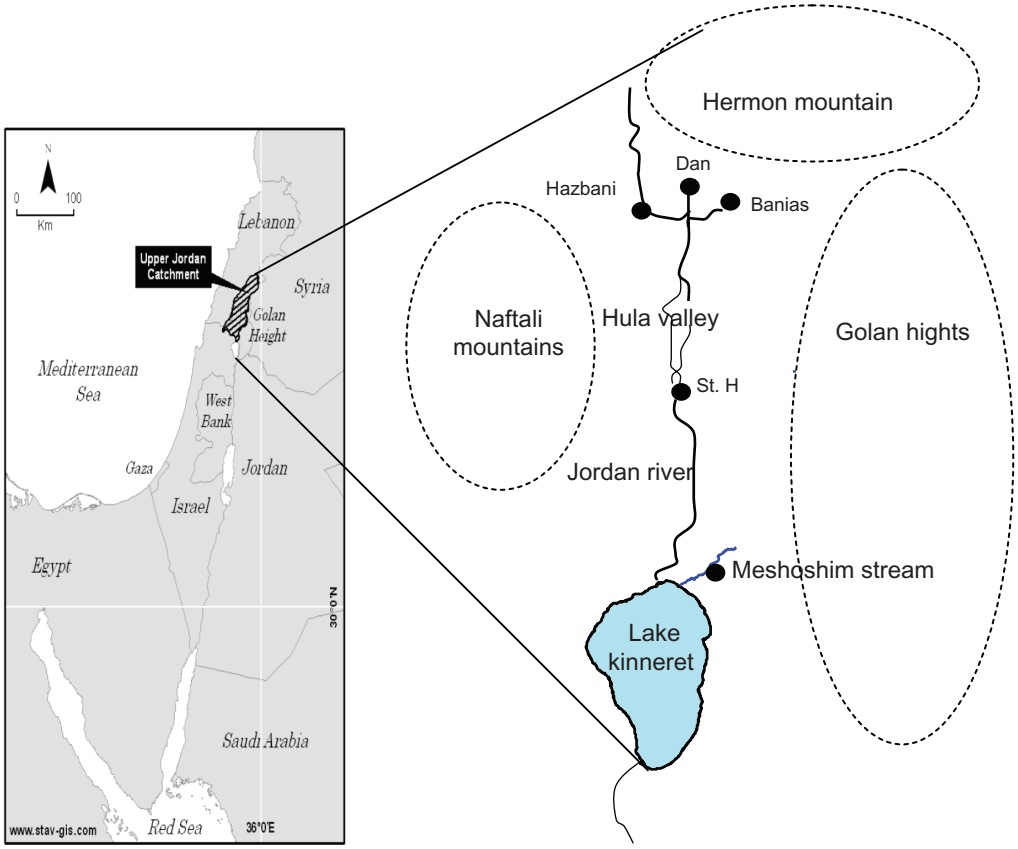



**Figure 1.** Lake Kinneret watershed location map (left) and schematic view (right) of the watershed.



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the north of the lake, up to the Hermon Mountains, with the Hula Valley at its center (Fig. 1). A major source of water for LK is the northern branch of the Jordan River, which supplies ca. $450 \times 10^6$ m$^3$ year$^{-1}$. Three tributaries feed this river; Dan (~$235 \times 10^6$ m$^3$ y$^{-1}$), Banias (~$120 \times 10^6$ m$^3$ y$^{-1}$) which emerge from springs located at the southern margins of the Hermon mountainous area and the Hatsbani (~$70 \times 10^6$ m$^3$ y$^{-1}$) which emerges from springs located west of this mount. The three tributaries converge at the northern part of the Hula Valley to form the Jordan River. Additional water sources to this lake include direct rain (~$70 \times 10^6$ m$^3$ y$^{-1}$), smaller streams not within the Jordan River catchment and saline water springs. The Meshoshim stream (Fig. 1) is an example of a small perennial stream (~$25 \times 10^6$ m$^3$ y$^{-1}$) that drains 160 Km$^2$ of basaltic terrain in the Golan Heights[7] and flows into the lake from the north-eastern side.

## Anthrophogenic preturbations in the watershed

Until the early 1950s, the southern and central parts of the Hula Valley were covered by the shallow Lake Hula and adjacent marshes (Fig. 2). These water bodies served as a wetland for Lake Kinneret, which is located further downstream, retaining some of the nutrients that originated in the northern part of the watershed. In the 1950s, Lake Hula was drained requiring the removal of $1.5 \times 10^6$ ton peat from the bed sediments of the marshes,[8] and later scattering this over parts of the valley.

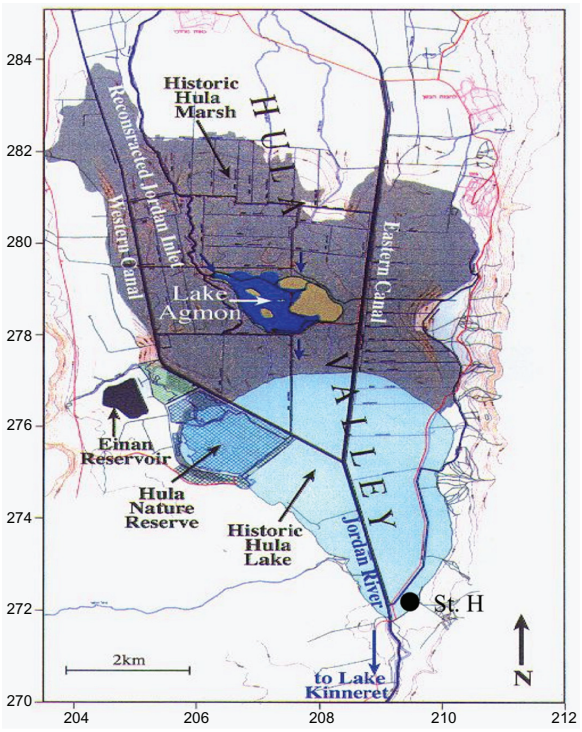



**Figure 2.** The Hula Valley with historic Lake Hula (light blue) & Marshes (dark grey).

The drainage of the Hula was performed in order to increase arable land, to eradicate malaria and to reduce evaporation losses.[9,10] The soils exposed were mostly peat (~26 Km$^2$) underlying the marshes[11–13] and mineral soils (mostly marl) underlying the historical lake (~14 Km$^2$:.[14]

Until the early 1970s these farm land were irrigated by sub-surface flooding, thus maintaining soil-water levels at more or less the depth of the vegetation root zone. Fertlizers introduction to the soils, particularly phosphorus, was increased during he early 1970s.

The drainage of the Hula valley, and the subsequent agro-engineering activities resulted in exposure of the peat to atmospheric oxygen thereby accelerating its biodegradation.[15] Cotton was grown over most of the valley (an area of up to 60 Km$^2$), as a mono-culture leaving the ploughed soils denuded of vegetation for ~5–6 months of the year (October through March). The combination of both degradation of peat and exposure of surface soils resulted in extensive erosion and heavy dust storms. As long as the groundwater table was maintained at the depth of the vegetation root zone (some 30–50 cm) this degradation was restricted to the top soil layer. Surveys made after drainage showed that the soils contained gypsum ($CaSO_4$*$2H_20$; 10%–20% of the dry weight) and an abundance of iron oxides which are products of processes associated with the aerobic decomposition of the peat.[16–18]

Toward the end of the 1970s, the combined effect of the decreasing cotton prices with the poor quality of the soils, made cultivation of part of the peat soils no longer profitable and local farmers gradually abandoned them. In the 1980s these soils were covered by a succession of dense natural vegetation, including *phragmites* reeds and as a result, the frequency and strength of dust storms declined.

## Monitoring stations, sampling and analytical procedures

Lake Kinneret (LK) data was collected at St.A, the central deepest part of the lake. The four monitoring stations



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in the Jordan River catchment are located on the main river (at the Huri Bridge: St. H.) and on the three tributaries of the river, the Dan, the Banias and the Hatsbani. Another station was located away from this catchment, and on the Meshoshim stream, which flows directly from the Golan Heights to LK (Fig. 1). St. H was sampled daily, whereas the other stations were sampled, weekly.

The analytical techniques common for both databases used here are summarized in Table 1. Some differences between the sampling procedures in each monitoring program were noted. LK samples were collected with a Rhode sampler, stored in 1 L plastic bottles and brought back to the lab within 2–3 hours. Oxygen was fixed on board (Winkler reagents I+II) in a BOD bottle and samples for pH measurements were taken in chilled opaque BOD bottles. Both parameters were measured within 2–3 hours of sampling. Upon arrival in the lab, sub-samples were filtered (0.45 μm and GFF for soluble species and for suspended matter, respectively) and stored at ~4 °C until further analysis. The analysis of Soluble Reactive Phosphorus (SRP) and $NH_4$ was performed within 5 hours of sampling while $NO_3$, organic nitrogen (total and dissolved), total N and total phosphorus, were determined on the following day.

Sampling of the watershed was performed manually, with a bucket lowered from a nearby bridge into the middle of the stream (at about 1 m depth). Water samples were stored in closed and cooled 1 L plastic bottles. pH measurements were performed in the lab in sub-samples drawn from the original 1 L bottles several hours after sampling. The remaining samples were stored at 4 °C for further analysis, within 48 hours of sampling.

Sediment samples taken from a pelagic core were analyzed for total sulfur ($S_T$), total iron ($Fe_T$) as well as for few additional trace metals using ICP-AES, (Geological survey, Jerusalem) after solubilization of the sediment in a sodium peroxide sinter.

Monthly average data presented for chemical parameters measured in the epilimnion of LK represent an average of 16 water samples taken weekly at 1,3,5 and 10 m depth.

## Results

Two databases were used here; that of the watershed, which includes chemical and hydrological parameters collected by the Mekorot Water Company (MWC); and that of LK, collected by the Kinneret Limnological Laboratory, which includes biological, chemical and physical data (LKDB).

**Table 1.** Lake Kinneret Database (LKDB) and Mekorot Water Company parameters used in this study.

| Variable | Units** | Method and reference | Period measured |
|---|---|---|---|
| Suspended matter (SM) | mg L⁻1 | Filtration through GFC, drying 105 °C for 24 h, weighing pre and post. | 1970–1999 |
| Total organic nitrogen ($N_{ORG}$) | mg N $L^{-1}$ | K-persulphate oxidation. | 1970–1999 |
| Soluble $N_{ORG}$ | mg N $L^{-1}$ | Filtration (0.45 μm) followed by K-persulphate oxidation.* | 1970–1999 |
| Organic carbon ($C_{ORG}$) | mg C $L^{-1}$ | Potentiometric titration after dichromate oxidation.[39] | 1978–1999 and June 1974 |
| Soluble reactive phosphorus-SRP | μg $L^{-1}$ | Molybdate blue complexion. | 1974–1999 |
| Total phosphorus-TP | μg $L^{-1}$ | K persulfate oxidation followed by molybdate blue complexion. | 1970–1999 |
| Total dissolved phosphorus-TDP | μg $L^{-1}$ | K persulfate oxidation followed by molybdate blue complexion of a filtered (0.45 μ) water sample | 1974–1999 |
| Particulate phosphorus-PP | μg $L^{-1}$ | Obtained by calculation: PP = TP-TDP | 1974–1999 |
| pH | | Opaque BOD bottles-cooled. In-Lab meas. within 3–5 hours. | 1970–1999 |
| Dissolved oxygen (DO) | mg $L^{-1}$ | On board fixation, Winkler titration in the lab, within 3–5 hours. | 1970–1999 |
| Sulfate ( $SO_4$) | mg $L^{-1}$ | Turbidimetric, addition of $BaCl_2$. | 1970–1999 |
| Fe—total | mg $L^{-1}$ | Phenanthroline method* | 1970–1999 |

**Note:** (*) APHA (1971).



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## Monitoring of the watershed

Station H is a major monitoring station for the LK watershed as it is located on the Jordan River at the southern end of the Hula Valley (Fig. 2) and thus represents the combined contribution from most of the streams in the watershed. In the 1970s, the monthly average concentration of Norg at St.H (~1.3 mgN/L, Fig. 3A) was higher than that measured during the 1980s and 1990s (~0.4 mgN/L). The long-term pattern of pH is a mirror image (Fig. 3A) to that of $N_{ORG}$, characterized by lower levels (ave. 7.95) in the 1970s with higher levels (ave. 8.25) in the following decades.

At St.H, long-term trends for the concentrations of other parameters such as suspended matter (SM), particulate phosphorus (PP), total iron and total organic carbon ($C_{ORG}$) (Table 2) were similar to those of $N_{ORG}$. The multi annual average concentration of SM, PP and Fe dropped from 75, 0.17, 0.08 mg/L during the 1970s to 40, 0.1, 0.02 mg/L, respectively, during the 1980s. However, SRP showed a different temporal pattern, characterized by a gradual increase during the 1970s and a leveling off during the 1980s.[19]

The major tributary of the Jordan River is the Dan stream, which flows north of the Hula Valley (Fig. 1). However, the long-term patterns of $N_{ORG}$, pH and $C_{ORG}$ in this stream (Fig. 3, bottom and Table 2) were similar to those at St.H (Fig. 3, top). ie, higher $N_{ORG}$ and $C_{ORG}$ and lower pH levels in the 1970s, compared to the ensuing decades. Again, both organic constituents and pH showed mirror image profiles, suggesting a general tendency that when $N_{ORG}$ (or $C_{ORG}$) increases, the pH decreases and vice versa. Similar long-term patterns have been observed in the Banias and the Hatsbani streams (Table 2), during the transition from the 1970s to the 1980s. The pH rise observed in the Hatsbani was somewhat smaller than in the other two streams. In each decade, however, the concentration of $N_{ORG}$ (and of $C_{ORG}$) at St.H has been much larger than that in the northern tributaries (Table 2). This suggests that most of the organic constituents detected in St.H, were acquired by processes occurring within the Hula Valley (Fig. 1).

The Meshoshim stream (Fig. 1) drains 160 $Km^2$ of basaltic terrain in the Golan Heights[7] and is not included within the Jordan River catchment. Nevertheless, the long-term pattern of $N_{ORG}$ in this stream (Fig. 4) was similar to the Jordan River catchment streams (Table 2 and Fig. 3). In addition, the Meshoshim stream exhibited a phenomenon that had not been apparent in the catchment streams, sulfate concentrations were three fold higher during the 1970s than in the following decades;(~9 and ~3 mg $SO_4$ $L^{-1}$), respectively (Fig. 4).

## Monitoring of LK

The running average (±36 weeks) of weekly epilimnetic data (depths; 1, 3, 5 and 10 m) for $N_{ORG}$ species in Lake Kinneret (LK) is shown in Fig. 5. Total $N_{ORG}$ revealed a long-term pattern similar to that of the watershed streams, with about 0.8 mgN/l in the 1970s compared to 0.4 mgN/l in the ensuing decades. In the lake both total and soluble $N_{ORG}$ were measured, while articulate $N_{ORG}$ concentration was calculated by subtracting the soluble form from the total. It thus became possible to distinguish between long-term trends of both species. The long-term pattern of soluble Norg resembled that of total Norg while particulate $N_{ORG}$ did not show such a long-term pattern.

During the 1970s, soluble $N_{ORG}$ was two fold larger than particulate $N_{ORG}$, ~0.52 and ~0.26 mgN/l, respectively). In the mid-1980s, with the drop in the level of total $N_{ORG}$, this difference became less apparent. However, there were distinct short-term seasonal peaks in the concentration of the particulate form (week or two a year) that appeared mostly in April, during the spring bloom.

Routine measurements of $C_{ORG}$ in LK begun in 1978. The long-term profile of $C_{ORG}$ showed somewhat higher levels in 1978 and 1979 (~5 mg/L) compared to the following decades (Table 2). Similar to the streams, also LK epilimnion reveals lower pH levels in the 1970s, as compared to the1980s.[20] In the case of LK where dissolved oxygen was also monitored, lower epilimnetic DO levels were also recorded in the 1970s (Fig. 6) as compared to the 1980s and 1990s.

## Discussion

The results indicate that during the 1970s, all of the water bodies in the LK catchment basin, irrespective of their location or size, showed similar long-term patterns of higher levels of organic constituents and suspended matter (SM), particulate phosphorus (PP) and particulate iron and lower pH levels, compared



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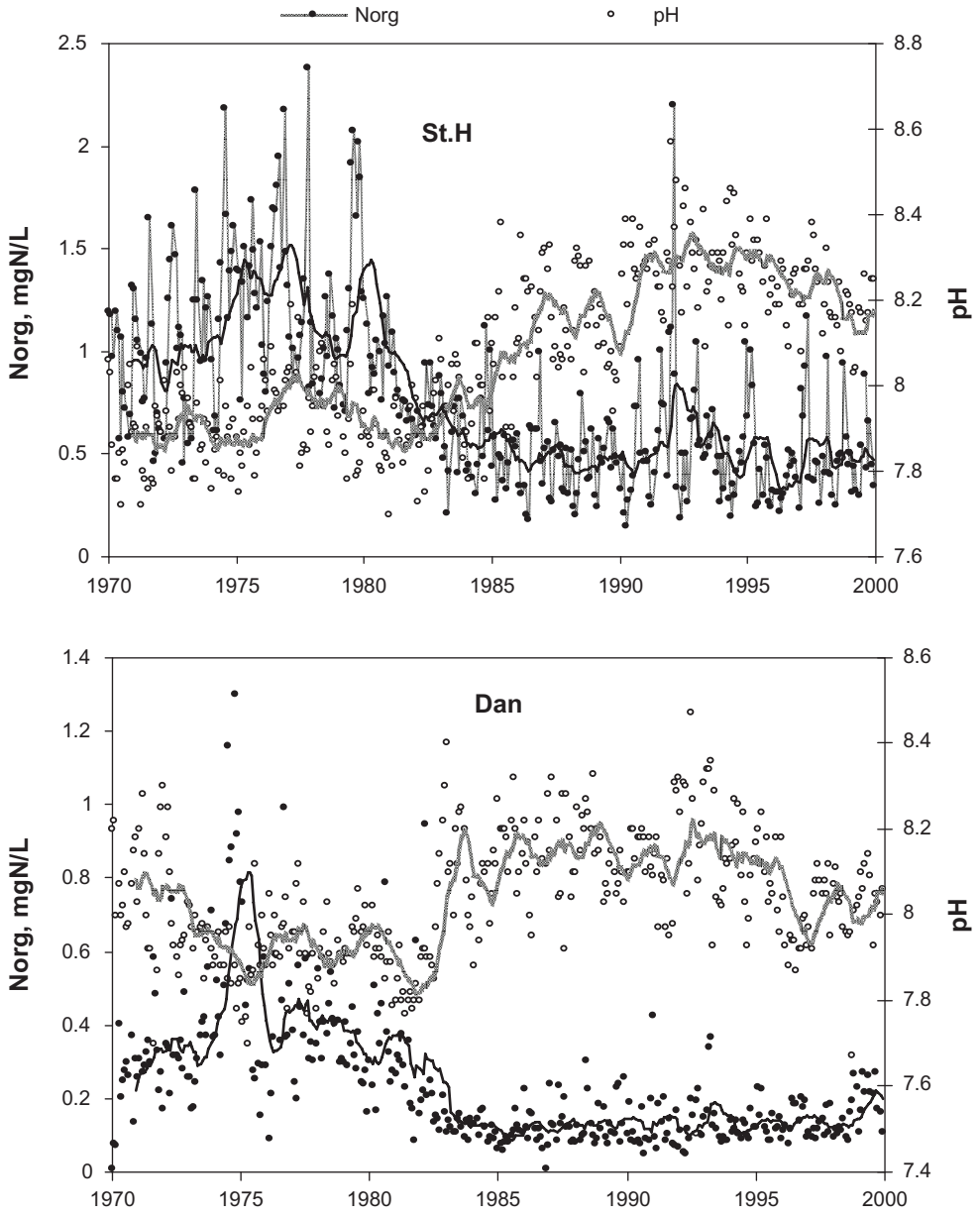



**Figure 3.** Total organic nitrogen, Norg (filled circles) and pH (empty circles), monthly average concentrations in the River Jordan St.H (top) and in the Dan stream (bottom), between 1970 and 1999. Running averages, (lines) represent ±12 months.

to the following decades. This suggests the presence of a common source of particulate material with high organic content that affected the entire basin and then later declined. This observation is supported by evidence given by Hula farmers regarding to heavy dust storms that had been a common phenomenon during the 1970s and declined afterwards. A combination of unusual dust storms and extreme levels of organic constituents in the watershed and in LK during 1974 offered an opportunity to follow these processes.

## The spring-summer 1974 event

The seasonal dynamics of $N_{ORG}$ in LK epilimnion during the 1980s can be best represented by the 1987 profile (Fig. 7, top). It indicates relatively high winter-spring levels, approaching ~1 mgN $L^{-1}$, while the crash of the spring bloom had been followed by a decline to relatively low levels of ~0.25 mgN $L^{-1}$, in both particulate and soluble forms. The respective profile for 1974 (Fig. 7, bottom) is however different for the summer in which an abrupt rise from ~0.7 mgN-$N_{ORG}^{-1}$ to ~1.3 mg $L^{-1}$ is shown in June,



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**Table 2.** General information on monitored parameters and typical decadal values in mg/L. Watershed parameters taken from MEK data base (Y.Geifman), LK parameters from LKDB.

| Water-body | Parameter | Starting month | Database used | Mid 1970s typical value | End of 1980s typical value |
|---|---|---|---|---|---|
| LK (St.A) | $N_{ORG}$ | Jan.70* | LKDB | 0.8 | 0.4 |
| LK (St.A) | $C_{ORG}$ | Oct.78** | LKDB | | 3.0 |
| LK (St.A) | DO | Jan.70 | LKDB | 8.0 | 9.4 |
| LK (St.A) | pH | Jan.70 | LKDB | 8.4 | 8.7 |
| St.H (Jordan R) | SM | Jan.70 | MEK | 75 | 40 |
| St.H (Jordan R) | $N_{ORG}$ | Jan.70 | MEK | 1.3 | 0.4 |
| St.H (Jordan R) | PP | Jan.70 | MEK | 0.17 | 0.1 |
| St.H (Jordan R) | pH | Jan.70 | MEK | 7.95 | 8.22 |
| St.H (Jordan R) | $C_{ORG}$ | June.75 | MEK | 1.5 | 0.5 |
| St.H (Jordan R) | Fe | Jan.73 | MEK | 0.013 | 0.005 |
| Dan stream | $N_{ORG}$ | Jan.70 | MEK | 0.4 | 0.1 |
| Dan stream | $C_{ORG}$ | Oct.75 | MEK | 1.5 | 0.7 |
| Dan stream | pH | Jan.70 | MEK | 7.9 | 8.15 |
| Banias stream | $N_{ORG}$ | Oct.72 | MEK | 0.45 | 0.1 |
| Banias stream | pH | Oct.72 | MEK | 7.65 | 7.90 |
| Hatsbani stream | $N_{ORG}$ | Jan.70 | MEK | 0.4 | 0.1 |
| Hatsbani stream | pH | Jan.70 | MEK | 8.20 | 8.25 |
| Meshoshim*** | $N_{ORG}$ | Oct.70 | MEK | 0.9 | 0.4 |
| Meshoshim*** | $SO_4$ | Jan.70 | MEK | 9 | 3 |

**Notes:** *Total Norg measured since Jan. 1970, DON measured since Jan. 1972. **Sampling and analysis also performed also on June 16 and June 23, 1974. ***A stream draining the Golan Heights.

particularly in the soluble form. This steep summer rise is equivalent to an increase in the overall lake inventory of approximately 2400 ton N, which cannot be accounted for by the concomitant one order of magnitude smaller riverine inflows. The summer of 1974 was also characterized by a noticeable rise in the turbidity (not shown) and in Corg concentrations in LK. Special profiles taken on the 16th and the 23rd of June 1974 revealed extremely high concentrations

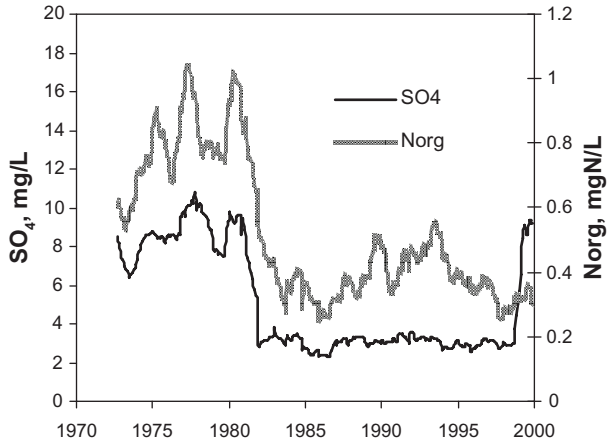



**Figure 4.** Monthly average concentration of Norg and $SO_4$ (Runing average ±12 months) in the Meshoshim stream during 1971–1999.

of Corg all along the water column, with an average of 23.4 ± 2.2 mg $C_{ORG}$ $L^{-1}$. This was a seven-fold higher concentration than the typical mid 1980's levels of 3 mg $L^{-1}$. Consequently, in June 1974, the amount of $C_{ORG}$ in the lake was estimated at about 92.000 tons as compared to typical inventories in the 1980s and 1990s of only 12,000 tons, suggesting an unexplained $C_{ORG}$ excess of 80,000 tons. Again, judging by the levels of Corg in the Jordan river (St.H) this huge reservoir of Corg in LK cannot be attributed to riverine inflows. The size of this reservoir was comparable to the annual primary production estimated for LK in the 1970s, which was in the order of magnitude of 100,000 tons carbon.[21]

As riverine inflows are ruled out dust is the only other possible source of organic constituents to the streams and to LK. In the Hula Valley 25 kilometers to the north of LK, the last week of March 1974 was characterized by an extreme dust storm, induced by a strong easterly wind, which lifted up a 5 cm thick layer of the local peat soils. A significant rise in Norg was noticed right after the storm in St.H, located on the Jordan River at the southern part of this valley (Figs. 1 and 2). About three months later, in June–July,



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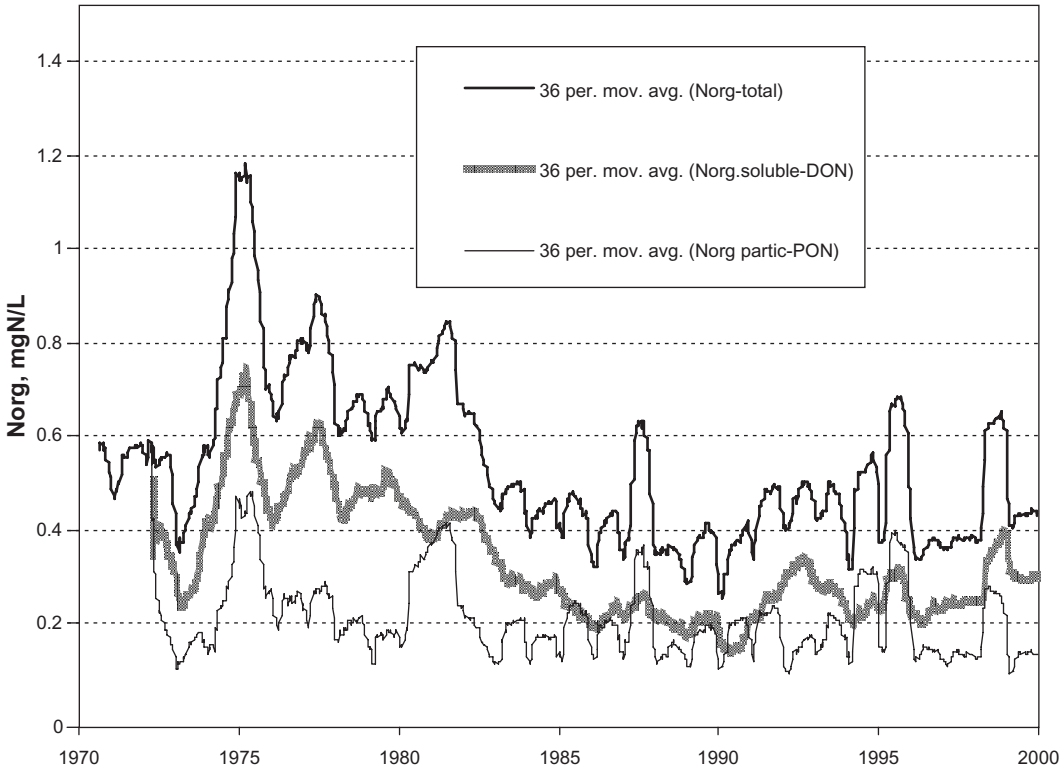



**Figure 5.** Lake Kinneret surface water (1 m depth) running averages, ±36 weeks, of total Norg (solid line: 1970–1999), DON (dashed line, 1972–1999) and PON (thin line, 1972–1999).

there was a significant rise in Norg in the northern tributaries (Fig. 3B and Table 2) and in LK (Fig. 5).

The prevailing directions and timing of wind events in the LK drainage basin may well be suited for the distribution of dust formed in the Hula Valley. In spring and fall, easterly and southerly winds predominate in the region. The easterly wind prevailing in March 1974 probably carried peat dust toward the Naftali Mountains range, bordering the west of the Hula Valley (Fig. 1). The southerly winds that followed may have carried the dust northward. In summer and fall, the predominant regional wind is from the north-west may have carried the dust directly to LK and to the Meshoshim watershed. Thus, the prevailing wind directions may also support the dust supposition.

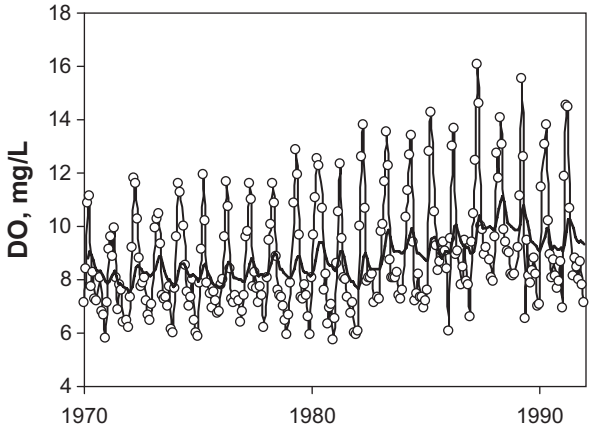



**Figure 6.** Monthly average concentration of DO measured in the 1 m depth layer of Lake Kinneret during 1970–1992. Solid line represent running average of ±12 months.

The long-term record of $SO_4$ in the Meshoshim stream provides an additional support to the dust supposition. During the 1970s (Fig. 4) $SO_4$ levels were three fold higher (~9 vs. ~3 mg $SO_4$/L, respectively) than in the subsequent decades. A most probable source for the additional $SO_4$ in this freshwater stream was the dissolution of Aeolian gypsum particles, which are a major constituent of Hula peat.[18] The reason why a similar affect had not been documented in the larger northern tributaries of Banias and Dan was perhaps their much higher and seasonally variable background $SO_4$ levels, ranging between 10 and 50 mg/l in the Banias tributary, and therefore masking the smaller contribution from the dissolution of gypsum.



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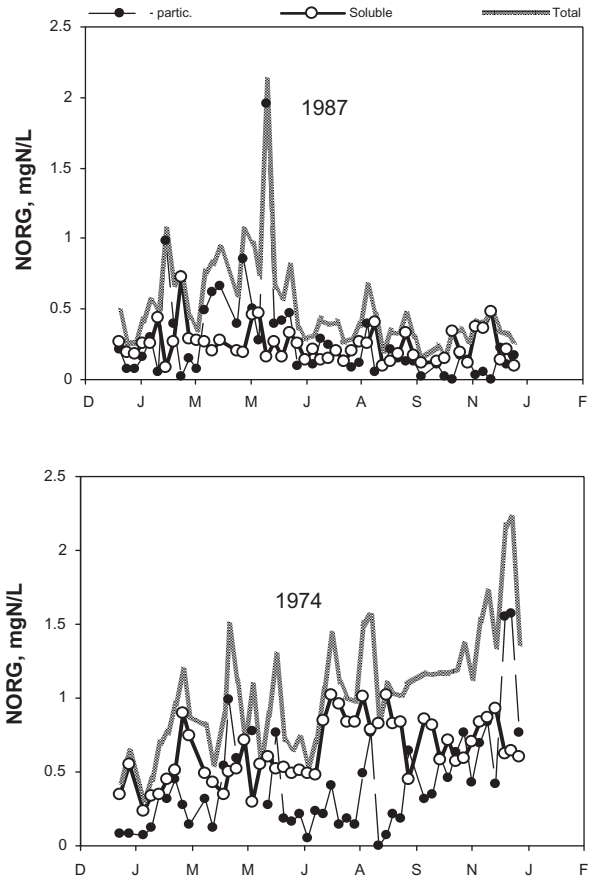



**Figure 7.** Weekly Norg species concentrations in LK surface water (1 m depth) during 1987 (top) and during 1974 (bottom).

According to Brenner et al[13] dry peat in Hula Valley (soil surface layer) contains between 15% to 29% $C_{ORG}$ and between 0.8% to 1.2% $N_{ORG}$, with average ratios (w/w) of 4.5 and 21 for dry peat/$C_{ORG}$ and C/N, respectively. Thus, the excess Corg inventory estimated in LK is equivalent to 330,000 tons of dry peat.

Most of the excessive $N_{ORG}$ detected in LK water during the 1970s appeared in the "soluble" form. This suggests that within several after the deposition of the peat dust on the lake surface, the particles would disintegrate to sizes small enough to pass the 0.45 μm filter used to distinguish between particulate and soluble phases. It should be noted that loads of DIN (mostly $NO_3$ and less $NH_4$) in the watershed did not show any significant long-term trends between 1970 and 1990.

## Relationship between organic material, pH and DO levels

The inverse temporal relationship detected between the concentrations of organic constituents and pH, and in the case of LK, also of DO, may be given a straightforward qualitative explanation. The general form of the photosynthesis (Pr) and Respiration (Re) equation[22] is given by:

$$CO_2 + H_2O \underset{\leftarrow Re}{\overset{Pr\rightarrow}{\longleftrightarrow}} (CH_2O) + O_2 \qquad (1)$$

Sources of organic matter may be both autochthonous and allochtanous. Upon the introduction of allochtonous biodegradable organic matter to an aquatic system Re is expected to increase and consequently DO is expected to decrease. In a carbonate buffered system, such as that of LK and the streams,[1] the pH is expected to decrease due to the $CO_2$ released during respiration. LK shows considerable daily, and seasonal variations in both DO, and pH levels in response shifts in balance between production and respiration. As an example of daily variations, the pH in LK surface water during the peak spring bloom may vary between ~8.8 during the night to ~9.6 at noon, while the respective DO levels vary between 120 to 200% saturation (LKDB-Russ profiler data).

Despite the apparent rise in winter and summer algal biomass in the early 1980s,[5,23] primary productivity in LK ($^{14}C$ uptake) did not show a parallel rise.[2] In fact, Pr, which has been measured continuously since 1970, does not show distinct long-term trends at all.[24] It is therefore concluded that the rise in DO and pH which was recorded during the 1980s resulted from smaller respiratory fluxes as compared to the previous decade. In other words the decline in inflow loads of allochthanous organics was sufficiently large to lead to the higher levels of both pH and DO in LK epilimnion.

## Evidence for peat deposited in LK bed sediments

Evidence for the occurrence of massive peat erosion in the Hula Valley during the 1970s is not only suggested from summer peaks in levels of $N_{ORG}$ in LK in 1974, 1976, 1977 and 1981 (Fig. 5) as well as through elevated levels during the 1970s in the streams (Figs. 3 and 4). The indication we have for peat transport to LK, prior to the initiation of the routine monitoring in the 1970s, is obtained from a pelagic sediment core, that was sampled in November 1993. Sub samples from this core were processed by Dubowski[8]



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who dated ($^{210}$Pb) and measured Corg concentrations (Corg-m; shown here in Fig. 8), and $\delta^{13}$C-Corg values in this core. Another set of sub-samples was used here to analyze the respective profiles of sulfur and iron (Figs. 8 and 9). The dating of this core was therefore adapted from Dubowski et al[25] but with one additional date attributed here to a layer deposited in 1982. A "green" lamina containing an abundance of chlorophyll preserved within diatom cells (*Melosira aulccelera*) was identified between 10.2 and 10.4 cm depth. This lamina is assumed to represent sedimentation in 1982 because the only large bloom of this alga in LK between 1969 and 1988 was documented in winter 1982.[2]

Apparently, there is a large difference between the $\delta^{13}$C ($C_{ORG}$) values in the upper layers of the Hula peat of –18‰[16] and of autochthonous $C_{ORG}$ from LK, of –28 and –29‰.[26] Duboswki et al[25] had shown that the 25 cm depth layer in this core represented sedimentation in the early 1950s and that $\delta^{13}$C ($C_{ORG}$) levels below this depth were ~–28‰ while above this depth the respective levels were in-between these two end members. The upper layer is hence assumed to represent mixtures of Corg from both sources. As an example, in the 13 cm depth layer, which was deposited in the mid 1970s, $C_{ORG}$ concentration was 4.3% (Fig. 8) and $\delta^{13}$C ($C_{ORG}$) equal to –24‰. Transferring the $\delta^{13}$C notation into relative concentrations of $^{13}$C and $^{12}$C, and considering the $\delta^{13}$C values of the above two end members, it is estimated that 32% of the $C_{ORG}$ in this layer, ie, 1.38% of the sediment dry weight, originated from the deposition of un-altered Hula peat ($C_{ORG-p}$), while the remainder 2.94% of the Corg represents autochthonous sources. Applying the same procedure all along this core (Fig. 8) suggests that in LK $C_{ORG-p}$ first appeared during the drainage of the Hula and that later its concentration gradually increased, with peak levels in the mid 1970s followed by a decline to lower levels during the 1980s. The temporal pattern of $C_{ORG-p}$ after 1970 thus resembles the respective pattern of $N_{ORG}$ in LK water and in the watershed, presented above for the period between 1970 and 1993 (Figs. 3, 4 and 7). Notice that the concentration of $C_{ORG-p}$ in the surface sediment layer (Fig. 8), which represents sedimentation in 1993, is estimated at 0.93%, hence significantly higher than that of the pre-1950s level of 0.65%. This suggests that even in 1993 peat derived $C_{ORG}$ was still accumulating in LK pelagic bed sediments

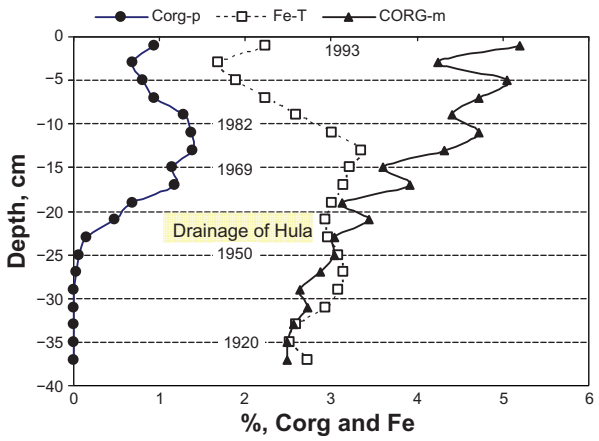



**Figure 8.** Corg and Fe concentrations (dw) in core St.A, Lake Kinneret pelagic zone. $Corg_p$:Corg of unaltered peat calculated from measured Corg and $\delta^{13}$C data (Dubowski et al 2003). $Fe_T$ – measured by AES after Na-peroxide sinter dissolution, Corg-m measured Corg. Sediment deposition time adapted from Dubowski et al (2003).

Following the seasonal oxygen depletion, the degradation of organic mater in LK hypolimnion is mostly through bacterial sulfate reduction (SRB:.[27,28] As indicated from the activity of sulfate reducing bacteria,[27,29] from sedimentary profiles of sulfide in pore-water[30] and from the sulfur content of the pelagic bed sediments.[28] $SO_4$ reduction occurs not only in the hypolimnion but also in the upper ~5 cm layer of the bed sediments. The source of the sulfur is $SO_4$ diffusing from the overlying lake water. Sulfide formed is entrapped in the bed sediments through pyritization, initially as mackinawite, $FeS_{0.9}$, which later converts to pyrite, $FeS_2$ in the LK pelagic zone.[30] The sedimentary profile of sulfur may therefore supply additional information on the past deposition flux of Corg.

Total sulfur ($S_T$) concentration in subsamples taken here from the core varied considerably. Below 25 cm depth (Fig. 9), ie, before the Hula drainage, it was relatively low and stable, at 0.65 ± 0.03%. The layer above showed a steep raise in $S_T$ to a maximum of 2.25% at 13 cm depth, which represents the mid-1970s and marks a peak in Corg-p (Fig. 8). The uppermost layers were characterized by a decrease in $S_T$, approaching c. 0.96% in the sediment surface layer.

Sulfur in the bed sediments of LK is assumed to have two potential sources; sulfur accumulated due to activity of sulfate reducing bacteria (SRB), associated with the decomposition of either autochthonous or allochthonous organic matter followed by pyritization, $S\text{-}_{SRB}$, and sulfur bound to un-altered Hula peat, $S_p$.



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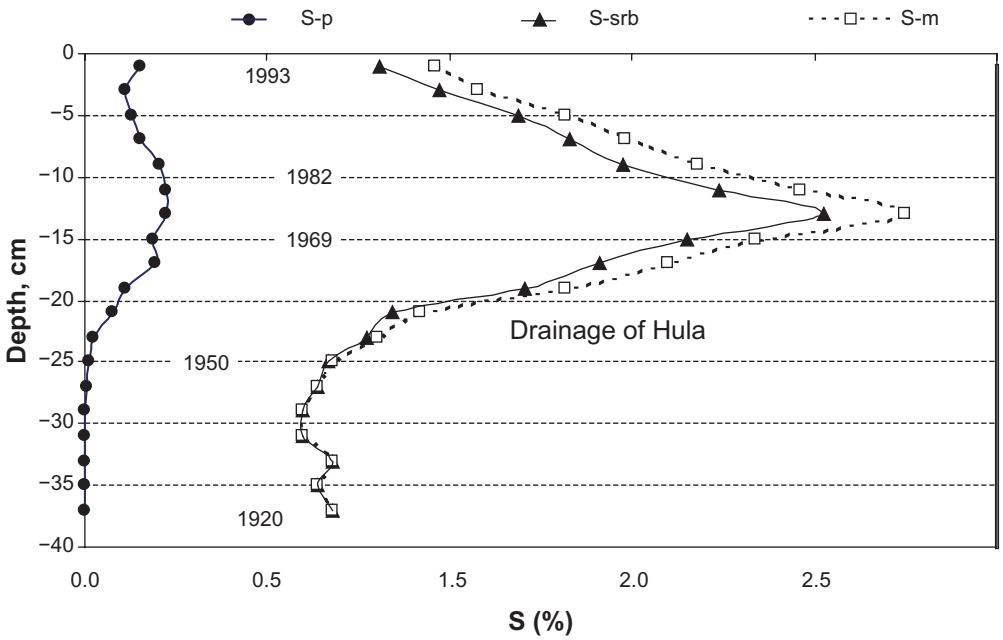



**Figure 9.** Core St.A, LK, Sedimentary profiles of total sulfur (in percentage dry weight), $S_T$ (squares), formed in-situ through SRB, $S_{-SRB}$ (triangles) and S associated with un-altered peat, $S_p$ (filled circles). The analytical error for the determination of $S_T$ is estimated at ±5%. The dating of layers deposition adapted from Dubowski et al (2003).

Hula peat is enriched with biogenic sulfur, with S concentrations several fold that of the precursor vegetation of phragmites, having an average C/S ratio of 6.15 (w/w).[13,17] Using this ratio for the peat deposited on the LK floor the $S_p$ profile in this sediment core was estimated from the respective $C_{ORG-p}$ data. $S_{-SRB}$, was then calculated by subtracting $S_p$ from $S_T$ (Fig. 9).

The expected Corg/S molar ratio in SRB is 2:1.[22] Hence organic carbon that had been removed from the sediment column through SRB activity followed by pyritization, $C_{ORG-S}$, can be estimated from $S_{-SRB}$ data. However, $C_{ORG-S}$ may not represent all of the sulfur formed due to SRB activity because it takes into account only S entrapped as $FeS_x$ while some of the S may have migrated through $H_2S$ diffusion to the overlying lake water. Another mechanism that may cause the removal of Corg buried in LK bed sediments and is not accounted for in $C_{ORG-S}$ is through methanogenesis.[28] Accordingly, the sum of Corg-m and Corg-s should be smaller than the original flux of Corg buried in the bed sediments.

Pyritization in the sediments may proceed as long as there is a sufficient amount of sedimentary iron oxi-hydroxides to interact with the sulfide formed through SRB and to trap it. In the case of LK pelagic sediments, the concentration profile of total iron, $Fe_T$ (Fig. 8), in the aforementioned core increases from 2.9 at 22 cm to a maximum of 3.4% at 13 cm and it then decreases to1.6% at 3 cm depth. ie, in layers deposited after the Hula drainage and until mid 1970s it increased but decreased later during the 1980s. In the upper 13 cm layer a significant positive correlation was found between Corg-p and $Fe_T$ ($R^2 = 0.92$, $P < 0.001$): $Fe_T = 2$ x Corg-P + 0.28. Considering the abundance of Fe-oxides in the Hula peat soils[18,31] and the long-term reduction in $Fe_T$ levels in St.H (Table 2) it is suggested that the decline in LK sedimentary $Fe_T$ also resulted from the reduced loads of particles originating in the Hula valley.

In the upper 13 cm sedimentary layer $S_{SRB}$ correlates with $Fe_T$ ($R^2 = 0.78$, $P < 0.001$: $Fe_T = 1.24$ $S_{SRB} + 0.78$, both in % dw). In the molar scale the slope obtained here is equal to 2.15, close to the expected stochiometry of $FeS_2$. Assuming that $FeS_2$ is the solid phase which represents the highest possible ratio of $S_{SRB}$/Fe, this slope suggests that iron oxide resources controls $S_{SRB}$ accumulation in LK bed sediments. The long-term decline in Fe sources to LK therefore allowed for a larger portion of the $H_2S$ formed in the bed sediments through SRB activity, to release to the overlying lake water during the 1980s. The long-term increase in the hypolimnetic inventory of $H_2S$ between 1970 and 1992[20] that can not be attributed to increased sedimentation of organic matter to the



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hypolimnion because there was no concomitant rise in primary productivity,[24] may support this hypothesis.

## Synthesis and implications

The drainage of the Hula wetlands in the 1950s led to two direct consequences. Firstly, it removed the shallow water bodies (volume approx. $50 \times 10^6$ $m^3$) that previously restricted downstream transport to LK of nutrients that originated in the northern part of the watershed. This is shown from the abundance of vegetation and peat that characterized those marshes prior to drainage. Overall, these shallow Hula water bodies may have been more efficient as traps for nutrients during the summer, which is characterized by much smaller river discharge. Secondly, the drainage of these wetlands resulted in the formation of new arable, heavily cultivated and fertilized land, which contributed to bioavailable phosphorus loads to LK.[32] These observations probably form the basis for Dubowski's general claim that the drainage of the Hula basin greatly increased primary production in LK:[8] in abstract).

As indicated from the $C_{ORG}$-p concentration profile, the LK pelagic sediments, peat erosion began concomitantly with the drainage of the Hula. Two decades later, erosion increased considerably due to unsuitable agricultural practices including the growth of cotton as a monoculture and the poor management of the groundwater table. from the conclusions drawn for 1974, the predominant transport mechanism of the eroded peat was by dust, which was efficiently scattered all over the drainage basin, including LK itself. Peat decomposition in the oxidized water bodies resulted in the decline of DO and pH levels of the ambient water. When peat supply became restricted, as in the 1980s, both pH and DO levels raised back close to what might have been the steady state levels prevailing in these water bodies prior to the Hula drainage.

The 1970s to 1990s witnessed a twofold decline in zooplankton biomass in LK[3,4] resembling the respective temporal pattern of Norg, and suggesting the possibility of a link between both. During these two decades phytoplankton composition reminded relatively, stable with Peridinium predominance in spring and green algae predominance in summer-fall. Hence, the long-term decline in zooplankton can not be attributed to a change from more eatable to less eatable algae. The decline in zooplankton can neither be attributed to to a parallel decline in the primary production in LK because no such decline was recorded.[24] Zooplankton respiration in LK between 1970 and 1990 was calculated[20] by considering the biomass (LKDB), average epilimnetic water temperature (LKDB) and taxon-specific rates, based on published information.[33,34] It showed that the mean decadal oxygen respiratory consumption by zooplankton during the 1970s was ~40% of oxygen production through photosynthesis, while the respective respiratory mean for the 1980s was only 20%. The later is similar to the average of 17.5 ± 5% between 2001 and 2007 estimated by Berman et al.[35] A most probable explanation for the decadal drop of 20% in zooplankton respiration is therefore that during the 1970s about half of the zooplankton activity was supported by allochthonous peat resources.

The decline in particulate phosphorus (PP) associated with the reduction in peat resources toward the 1980s (Table 2) would have had a minor effect on bio-available P inflows to LK because most of the PP in the Hula peat appears as some form of hydroxy or fluoro-apatite.[31] In the Jordan River, soluble P (SRP) accounts for almost half of total P (MEK database) and is considered the major source of bioavailable P to LK.[36] The 1970s gradual rise in SRP loads in the Jordan River[19] was suggested to trigger the increase, of algal biomass in LK during the early 1980s.[21,23] It is hypothesized here that not only the long-term rise in SRP but also the decline in zooplankton, that led to reduced grazing pressure, affected the 1980s algal growth.

Another possible factor in controlling long-term algal activity in LK is related to the available nitrogen sources. During the 1970s and 1980s the mean annual inflow loads of DIN to LK were relatively stable while the corresponding loads of $N_{ORG}$ declined from ~570 tons during the 1970s to ca. 200 tons, during the 1980s.[20] The respective drop in decadal mean inventories of Norg in LK was from 3000 ± 500 to 1400 ± 400 tons (LKDB). Owing to the reduced inflows monitored after the 1970s, part of the drop in LK may have been due to a shift in balance between Norg removal, through water pumping, and the inflows. An additional cause for the removal of Norg from LK could be that which is related to the biodegradation of the



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allochthonous peat, suggested from the inverse relationship between DO and pH vs. allochthanous Norg. However such mechanism of mineralization of organic matter is expected also to lead to a parallel long-term decline in $NH_4$ (and for $NO_3$ through nitrification), but no such trends were recorded. A possible explanation may be that the biodegradation of the allochthanous Norg occurred through some sort of a bypass over the $NH_4$ pathway, where by a portion of this Norg was directly consumed by bcateria[37] and zooplankton.

The long-term decline in aeolian transport of peat resulted in a general decrease in the N/P ratio in the inflows to LK. A concomitant decline in the ratio between PON to PP in the LK epilmnion was suggested[38] to have triggered blooms of the $N_2$ fixing blue-green cyanobacteria *Aphanizomenon Ovalisporum* since 1994.[6]

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## Disclosure

This manuscript has been read and approved by the author. This paper is unique and is not under consideration by any other publication and has not been published elsewhere. The author and peer reviewers of this paper report no conflicts of interest. The author confirms that they have permission to reproduce any copyrighted material.

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