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Effects of Historical Lake Level and Land Use on Sediment and Phosphorus Accumulation Rates in Lake Kinneret

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Current paradigms of reservoir ontogeny suggest that water-level fluctuations may increase sedimentary nutrient release, causing long-term eutrophication of water bodies formed by dryland flooding. Less is known of the changes in nutrient status following conversion of natural lakes into reservoirs. Here, we use historical hydrological and limnological data and paleolimnological records of sedimentary P accumulation to evaluate changes in nutrient storage in Lake Kinneret, Israel since ~1860. Impoundment in 1932 increased water level fluctuations and altered seasonal hydrologic patterns in the lake. Geochemical analysis of sediment deposits indicated that bulk sediment and P accumulation rates in the central lake increased >600% following dam installation (1930s), draining of Lake Hula wetlands (1951–1957), and diversion of surface water outflow (1964 to present). Further, comparison of sedimentary P stratigraphies with long-term chemical records showed that the period of maximum P deposition corresponds to observed increases in whole-lake and in hypolimnetic P content, as well as epilimnetic biological changes indicative of ongoing eutrophication. Together, these patterns suggest that hydrologic management of natural lakes can increase sedimentary nutrient flux under circumstances where lake volume and water levels become more variable.

Introduction

Seasonal water-level fluctuations are important components of reservoir ecosystems, affecting nutrient dynamics, underwater light climate, plankton dynamics, and littoral development (*1*, *2*). Nutrient flux to pelagic habitats often increases following de novo reservoir formation due to both leaching of nutrients from flooded soils and to decomposition of inundated vegetation (*3*), whereas littoral zone erosion may increase mass transport to deep waters where additional decomposition and hypolimnetic deoxygenation can increase internal nutrient supply (*4*, *5*). Less is known of the biogeochemical response of natural lakes to impoundment (*6*), possibly because fluctuations in lake volume, water levels, and productivity may actually decrease following impoundment (*7*). This situation is particularly complex in semi-arid environments where strong seasonality in precipitation and evaporation lead to naturally variable lake chemistry and water levels (*8*). Improved understanding of lake response to water-level regulation is essential for the formation of effective management strategies in such regions (*9*).

Lake Kinneret, Israel, is typical for many low-latitude lakes that are exposed to highly seasonal precipitation and nutrient fluxes. Lake Kinneret has been subjected to extensive water-level regulation since 1932, and during the past two decades, the combined effects of drought and water use may have altered the abundance and species composition of littoral fish and macrophyte assemblages (*10*, *11*); hypolimnetic oxygen depletion rates (*12*); hypolimnetic concentrations of ammonia, sulfide, and phosphorus (*13*); and even epilimnetic phytoplankton biomass and production (*13*, *14*). In addition, several lines of evidence demonstrate that the water column P content of Lake Kinneret increased by ~60% (30 t of P) during 1969–1985 (*15*), mainly as a result of 3-fold increases in hypolimnetic, but not epilimnetic, P concentrations since 1969 (*16*). As yet, little is known of the relationship between such observed water-column changes and the changes in water level that preceded intensive limnological investigations.

We hypothesize that changes in Lake Kinneret P dynamics may have resulted from anthropogenic modification of lake hydrology during the last century. Unfortunately, scientific study of Lake Kinneret only began routinely in 1969 with the establishment of the Kinneret Limnological Laboratory (KLL) (*17*), so repercussions of earlier perturbations have gone largely unstudied (but see Stiller, ref *18*). Nevertheless, recent analyses suggest that part of the observed increase in lake P content could stem from increased internal P loading accompanying water level reductions during the past three decades (*13*). Alternately, changes in lake nutrient status may have resulted from increased sediment and nutrient loading following the draining of Lake Hula (1951–1957) in Lake Kinneret's northern catchment and increased human activity in the lake's catchment (*19*, *20*). In this paper, we use historical and paleolimnological data to further examine the possible effects of past environmental perturbations on P dynamics in Lake Kinneret and to evaluate the relative importance of water-level regulation and watershed disturbance as controls of sediment and P accumulation on the lake bottom.

Materials and Methods

Study Site and Background. Lake Kinneret is a moderately large (surface area = 168 km^2; volume = 4000 million m^3) natural freshwater lake (Figure 1) with an extensive history of hydrologic modification and water-level variability. The distinctive alternations between rainy winters and dry summers characteristic of the local Mediterranean climate produce seasonal fluctuations in water levels that have probably been an integral feature of the Kinneret ecosystem since the lake formed approximately 20 000 years ago (*17*). In addition, humans have altered lake hydrology since at least 1932, producing four distinct periods of water-level variation: two of natural or seminatural water level fluctua-

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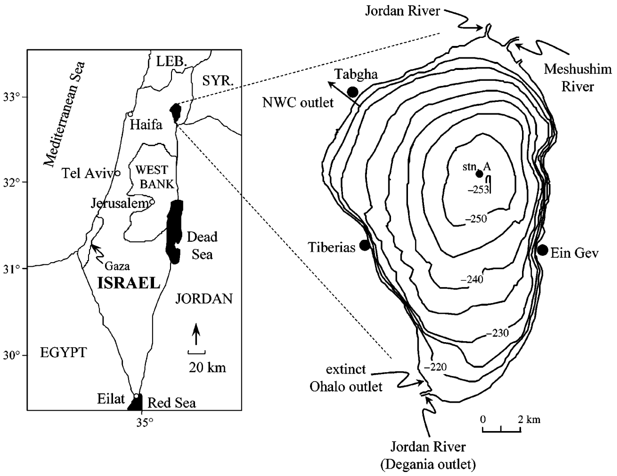

FIGURE 1. Schematic of Lake Kinneret. Depth in meters altitude. Cores were taken within a 25 m^2 area near station A.

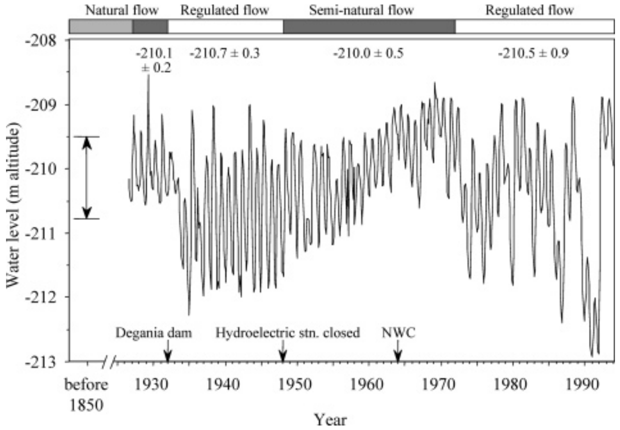

FIGURE 2. Mean monthly water levels in Lake Kinneret during 1926−1993. Range of water levels prior to 1850 was estimated from archeological evidence (*21*).

tions (pre-1932, 1948−1972) and two highly regulated eras characterized by increased hydrologic variability (1932−1948, 1973 to present).

On the basis of archeological evidence, Nun (*21*) concluded that water levels in Lake Kinneret fluctuated naturally over a range of 1.3 m (between −209.5 and −210.8 m altitude) between 1100 and the mid-1800s (Figure 2). Nun (*21*) also suggested that this amplitude of fluctuation, as well as the relatively low maximum water level (−209.5 m), was apparently maintained by the presence of two outlets at the southern end of the lake: a narrow (30−40 m), relatively deep outlet near Degania through which small floods were released, and a wider (150 m) but shallower outlet near Ohalo (see Figure 1), through which large volumes of water were flushed when the lake level rose due to heavy floods. Over time, the Ohalo outlet gradually filled in with sediments, and by the mid-1800s, closed completely. With only the Degania outlet, the maximum water levels in the lake increased by approximately 0.5 m, although, with the exception of the unusual flood years of 1919 and 1929, the overall amplitude of annual fluctuations remained below 1.5 m until the 1930s (*21*).

The second distinct hydrologic period began with the construction of a hydroelectric power station south of the lake in 1932. At that time, the Degania outlet was deepened from its natural level of −211 m to −214.5 m altitude, and a regulatory dam was constructed to ensure a constant supply of water to the hydroelectric station throughout the year. Subsequently, the amplitude of water level fluctuations in Lake Kinneret increased from an annual average (±SD) of 1.1 m (±0.5 m) prior to 1932 to 2.1 m (±0.6 m) for the period 1932−1948, with a maximum fluctuation of >3 m. The range of water levels recorded for this period was −209 to −212.3 m altitude. An era of seminatural water-level fluctuations began in 1948, when the hydroelectric station was closed. Nevertheless, the Degania dam continued to operate through the early 1960s, supplying water for irrigation in the Jordan Valley south of the lake (*17*). During this period (1948−1964), water-level fluctuations were gradually reduced to below 1.5 m, while the average annual water level was gradually raised to above −210 m altitude. Finally, the fourth hydrologic period commenced in 1964 when Lake Kinneret became the primary storage reservoir for the National Water Carrier (NWC). With full operation of the NWC system in 1973, Lake Kinneret water-level fluctuations again increased to greater than 3 m. Although the hydroelectric station and NWC both created high amplitude water-level fluctuations, maximal amplitudes remained below 3.3 m until the minimum legal level of the lake was reduced from −212 to −213 m altitude in 1981. This change eventually led to the record fluctuation of 4.1 m during 1991−92 following two consecutive drought years and a century-flood year. Further droughts and continued pumping into the NWC during the late 1990s and early 2000s resulted in consecutive record low water levels, reaching −214.87 m in November 2001.

P Export. Mean monthly P export was estimated for three hydrologic periods (natural water level fluctuations prior to 1932; regulated water level fluctuations 1932−1948 and 1973−1995) as a product of mean epilimnetic total P (TP) concentrations and total water outflows. Because of lack of data prior to 1970, we assumed that the annual pattern in mean monthly epilimnetic TP concentrations (averaged for 0−10 m) during 1970−1990 was representative of epilimnetic P content for all three periods. Mean outflows (Out_n) for each month (n) were calculated as

$$\mathrm{Out}_n = \mathrm{InTot}_n - \mathrm{Evap}_n - (\mathrm{Vol}_{n+1} - \mathrm{Vol}_n)$$

where mean monthly total water inflows (InTot_n) and evaporation (Evap_n) calculated from the period 1970−1995 were assumed representative for all three periods, and mean monthly lake volumes (Vol) were calculated from the measured water levels (shown in Figure 2) and known basin morphometry (*17*). For this simple model, annual inflows, evaporation, and outflows for all three periods were 780, 280, and 500 million m^3, respectively (i.e., the means for 1970−1995). Basically, this exercise allows one to estimate the effects on P export from the lake due to hydrology changes alone without the confounding effects of changes in P pools and nonhydrological fluxes.

Annual P export was also estimated directly from available data for the recent NWC period (1973−1995), as a product of monthly epilimnetic TP concentration and total water outflows.

Sedimentary P Accumulation. Historical changes in net P deposition (sedimentation−release) were quantified by paleolimnological analysis of P accumulation rates in Lake Kinneret sediments. In March 1995, eight 5 cm diameter intact sediment cores were collected within a small area (∼25 m^2) from the central region of Lake Kinneret (Station A). The cores were stored vertically at 4 °C and extruded and sliced into 1 cm increments within 1 day of collection. The 36 individual slices from each core were combined into 36 composite samples (*22*). This procedure was chosen to provide sufficient dry material for radiometric dating. Further, although Stiller and Imboden (*23*) have demonstrated high variability in sediment accumulation rates lake-wide, especially in relation to distance from the Jordan River inlet, variability in sediment accumulation within a given 25 m^2

area is likely minor. Thus, most variability between cores would be expected to be due to the coring and slicing procedures, and although not explicitly quantified, this variability is included in our analysis. After centrifugation (20 min; 26890*g*), the volume of pore water was recorded, while sediment pellets were weighed, dried at 100 °C for 24 h, and reweighed for wet and dry weight determinations. The difference between wet and dry weights was added to the volume of decanted water following centrifugation and recorded as total water content. Fixed-volume subsamples of the dried sediment samples were digested by persulfate oxidation, and total phosphorus content was measured colorimetrically using the molybdate assay (*24*). Replicate analyses following open reflux digestion in a mixture of nitric, sulfuric, and perchloric acids revealed consistent P recovery (mean ± SE; 96.6 ± 2.8%, $N = 65$) by the persulfate method (*24*).

The core chronology was determined principally by analysis of ^{210}Pb using γ-spectroscopy (A. Bollhöfer, Radiometrische Altersbestimmung von Wasser und Sedimenten, Heidelberger Akademie der Wissenschaften, Germany) following Bollhöfer et al. (*25*). ^{210}Pb is a natural radioisotope produced by the decay of ^{226}Ra. In lake sediments, ^{210}Pb is derived from in situ decay of ^{226}Ra (supported ^{210}Pb) and from secondary decay of ^{226}Rn in the atmosphere to unsupported or excess ^{210}Pb (*26*), which then falls to the lake directly or is washed in via riverine inflows. In Lake Kinneret, most excess ^{210}Pb originates from the atmosphere (0.15 dpm cm^{-2} yr^{-1}) and watershed (0.34 dpm cm^{-2} yr^{-1}), whereas a further 20% (0.12 dpm cm^{-2} yr^{-1}) arises from seepage via Ra-rich saline springs; ca. 10% (0.06 dpm cm^{-2} yr^{-1}) leaves the lake by outflow or decay before sedimentation (*23*). Excess ^{210}Pb was determined as the difference between activities of ^{210}Pb and ^{214}Bi (*25*).

We estimated sediment ages using the constant rate of supply (CRS) model (*27*) according to Appleby and Oldfield (*26*) that allows calculation of ^{210}Pb dates under varying sediment accumulation rates. We attempted to verify the ^{210}Pb-based chronology using bomb-derived and Chernobyl-derived ^{137}Cs markers also detectable by γ-spectroscopy (*25*), but these efforts proved unsuccessful (see Results). Instead, sedimentary patterns of diatom and dinoflagellate accumulation rates were compared with long-term estimates of annual algal biomass (*Aulocoseira*; Berman et al. (*34*)) or plankton sedimentation rates (*Peridinium*; Zohary et al. (*33*)).

Results

P Export. Construction of the Degania dam, and consequently the start of outflow volume regulation, resulted in a shift in the timing of maximal water levels and outflows from the lake (Figure 3a). Prior to impoundment, maximal water levels occurred concurrently with maximal inflows (February to March), whereas since 1932, maxima were achieved two months later (May). On average, post-impoundment water levels were consistently 0.5−1 m lower than they had been prior to 1932 (see also Figure 2). Prior to construction of the Degania dam, water discharge from Lake Kinneret varied only as a function of inflows, water levels, and evaporation; therefore, maximal water discharge should have occurred during April (Figure 3b,c). In contrast, maximal water discharge following impoundment occurred during the late summer and fall months (hydroelectric station period) or was distributed more evenly throughout the year (NWC period).

Rates of P export in Lake Kinneret were greatest in the period prior to construction of the Degania dam (Figure 3e), particularly during winter and spring seasons. In contrast, P export was lower during eras of regulated flow (1932−1948, 1969−1995), mainly because a large portion of the annual discharge occurred during months with lower epilimnetic P concentrations (Figure 3d). Annual P export was ~2 t lower during a typical year of regulated discharge than during a year of natural outflow.

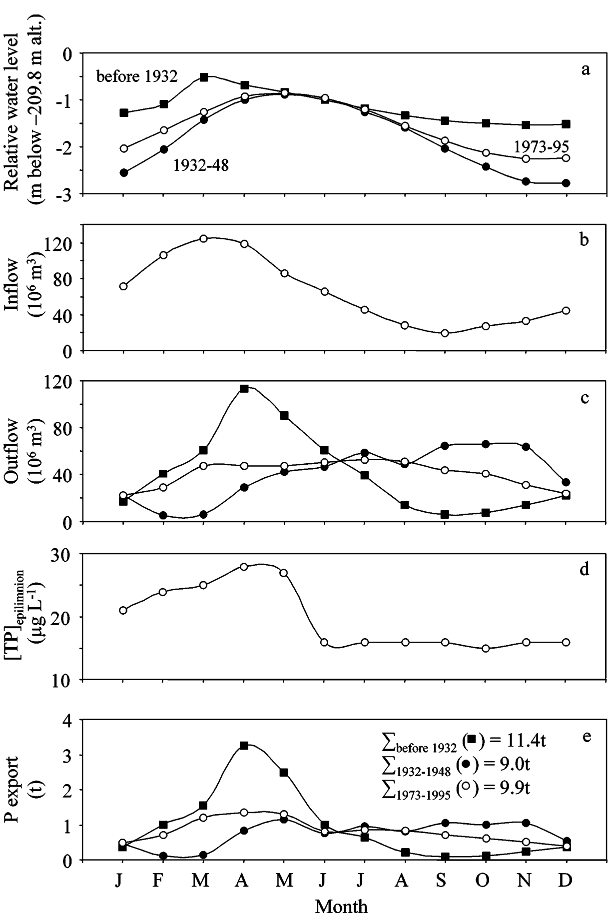

FIGURE 3. Mean monthly (a) water levels, (b) inflows, (c) outflows, (d) epilimnetic P concentrations, and (e) P export estimated for Lake Kinneret during the period of natural water level fluctuations (prior to 1932) and periods of regulated water level fluctuations (1932−1948, operation of the hydroelectric station; 1973−1995, operation of the NWC).

During the recent NWC period, both water outflows and P export varied significantly ($P < 0.0001$) with mean water level (Figure 4). Years during which water levels were lower had reduced P export.

Core Chronology. The specific activity of excess ^{210}Pb was low as compared with that typical to north temperate lakes (*28*) and declined from ~6−8 dpm g^{-1} in the upper sediment layers to a minimum of ~2 dpm g^{-1} below 25 cm (Figure 5a). The nonmonotonic decline indicated substantial variation in sediment accumulation rates throughout the period encompassed by the core. Application of the CRS model indicated that the core represents sediments deposited since the 1860s. Verification of the chronology using ^{137}Cs was not possible because ^{137}Cs peaks exhibited substantial dislocation relative to known temporal patterns in fallout (Figure 5b). For example, although activity profiles revealed the two peaks expected to correspond to peak bomb fallout (~1963) and the Chernobyl accident (1986), activity maxima occurred in sediments too young (shallow) according to ^{210}Pb analyses. Similarly, considerable ^{137}Cs activity occurred well below ^{210}Pb depths corresponding to the first Northern Hemispheric peak in atmospheric ^{137}Cs (1954), as well as the date of its first detection in the atmosphere (1945 (*30*)).

Because of the low specific activity of excess ^{210}Pb, the apparent dislocation of the ^{137}Cs peaks, and recent publication of an alternate chronology (*31*), we determined the chronol-

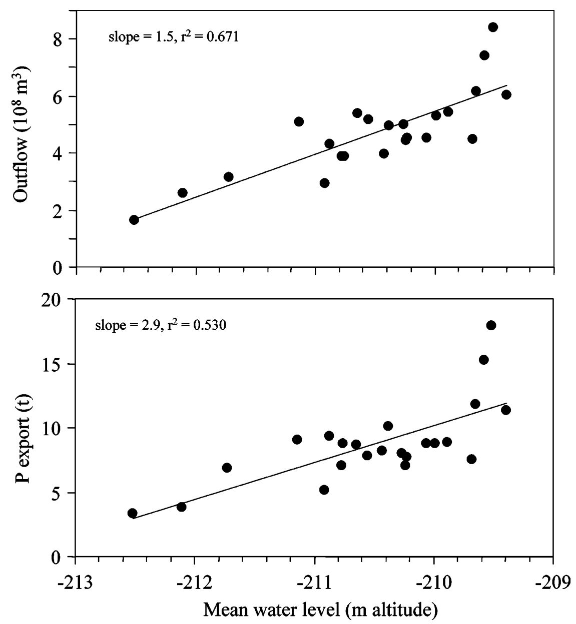

FIGURE 4. Relationships of (a) water outflows and (b) P export with mean lake water levels during the NWC period (1973–1995).

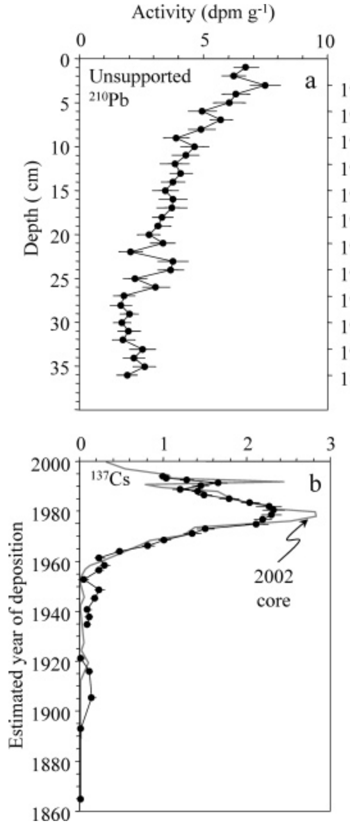

FIGURE 5. (a) Unsupported ^{210}Pb activity (±1 SD) of sediment cores taken from Lake Kinneret as a function of depth showing chronology (right-hand axis) based on the CRS model according to Appleby and Oldfield (*26*)) and (b) activity of ^{137}Cs (±1 SD) plotted against the ^{210}Pb-derived chronology showing dislocation from known temporal peaks in fallout (e.g., 1986–Chernobyl). Standard deviations were calculated according to Binford (*29*). Note that chronologies for the two panels are indicated on different scales.

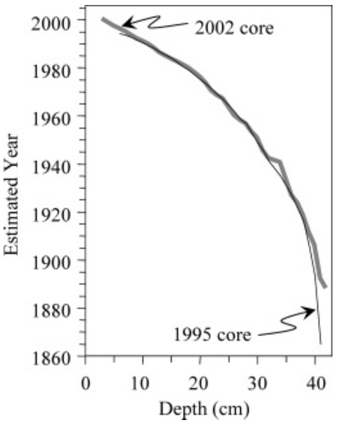

FIGURE 6. Comparison of core chronology with independent chronology established from a separate core taken from the same are of Lake Kinneret in April 2002 and analyzed for ^{210}Pb using gamma spectroscopy at the University of Florida. For both cores, the uncertainty associated with the ^{210}Pb-derived ages (calculated according to Binford (*29*)) increases with depth from <±2 yr at the top of the cores to <±20 yr at the bottom of the cores.

ogy in a new (April 2002) single core taken from the same area of the lake using ^{210}Pb (γ-spectroscopy, University of Florida) following Schelske et al. (*32*). The specific activity of excess ^{210}Pb was slightly lower than in the 1995 core (5.8–6.1 dpm g^{-1} in the upper layers; <1 dpm g^{-1} in the lower levels), but the estimated chronology (1995 and before) was similar (Figure 6). Moreover, the ^{137}Cs peaks exhibited the same dislocation with respect to known fallout patterns and the ^{210}Pb chronology (Figure 5b).

In addition to radioisotopes, we used several sedimentary markers to independently validate depths corresponding to 1991, 1988, and 1957, based on the ^{210}Pb-derived chronology. First, we note that sedimentation of the dinoflagellate *Peridinium* peaked in 1991 in both historical data collected by sedimentation traps (*33*) and in microscopic analyses of algal remains from our core material (Figure 7a). Preliminary analysis of *Aulocoseira* frustules in our sediments also reveals that maximum accumulation rates occurred in 1988, the same year as standing crops reached their historical maximum in the 1969–95 record of Lake Kinneret (*34*) (Figure 7b). The third verification mark is in the form of a massive sediment influx to the lake that occurred during draining of Lake Hula (~12 km²) and its surrounding wetland (~60 km²) in the northern catchment of Lake Kinneret during the mid 1950s (Figure 8a,b). An estimated 13 million m³ of rock and sediments was excavated during the draining process (*17*, *18*), much of which flowed downstream into Lake Kinneret, especially in 1957, when 30 million m³ of water, sediments, and debris was released downstream in the final stage of draining (*19*). In a sediment core taken nearer the Jordan River inflow, Stiller (*18*) found large deposits of ancient organic material sandwiched between much younger materials, which corresponded to the draining of Lake Hula.

Sedimentary P Accumulation. Sediment accumulation rates generally increased throughout the last 130 years, from <0.25 kg m^{-2} yr^{-1} in the late 19th century to ~1.5 kg m^{-2} yr^{-1} for material deposited since 1990 (Figure 8a). Increased mass deposition was observed coincident with both periods of enhanced water level fluctuations including both dam construction and operation in the 1930s and the outflow diversion and operation of the NWC since the mid-1960s. As noted previously, sediment accumulation peaked in 1957 due to the draining of Lake Hula.

Patterns of phosphorus accumulation were similar to those of bulk sediment flux and generally increased from <0.25 g m^{-2} yr^{-1} in the late 1800s to ~1.4 g m^{-2} yr^{-1} since 1990 (Figure 8b). As with sediment accumulation rates, marked increases in P accumulation rates occurred concomitant with both periods of increased water-level fluctuations and with the draining of Lake Hula. In contrast to the

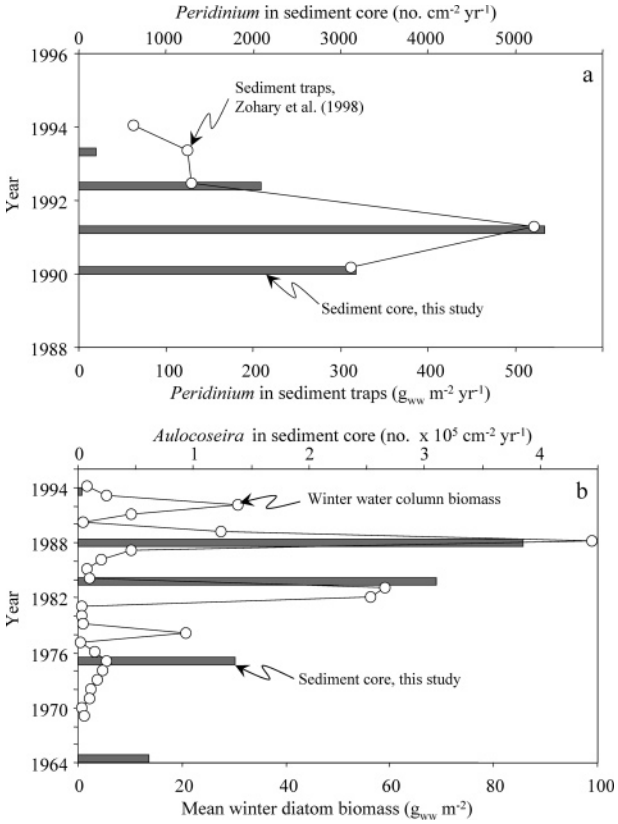

FIGURE 7. (a) Comparison of accumulation rates of *Peridinium* in sediment cores with accumulation rates of *Peridinium* in sediment traps suspended in mid-hypolimnion (*33*) and (b) accumulation rates of *Aulocoseira* in sediment cores with winter means of integrated water column diatom biomass in Lake Kinneret (*34*). *Peridinium* (usually intact cell membranes only) and *Aulocoseira* remains were counted on subsamples of Lugol's-preserved bulk material on an inverted microscope. Winter diatom biomass in Lake Kinneret is comprised of >90% *Aulocoseira* when diatom biomass exceeds 5 g_{ww} m^{-2} (T. Zohary, personal communication).

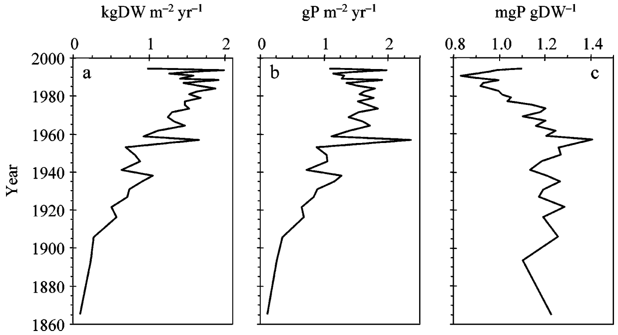

FIGURE 8. (a) Sediment and (b) P accumulation rates and (c) relative P content in cores taken from Lake Kinneret.

sediment and phosphorus accumulation rates, sedimentary P concentrations (i.e., mg P per g_{DW} sediments) were similar (~0.12%) from the 1860s to the 1960s but declined to nearly 0.08% during 1970−1990, before rising to ~0.1% thereafter (Figure 8c).

Discussion

Phosphorus is the main nutrient limiting phytoplankton growth in Lake Kinneret (*35*) (but see ref *34*), and improved understanding of P dynamics is required for effective lake management and acceptable water quality. In particular, recent changes in algal biomass, composition, and production (including first-ever blooms of N_2-fixing cyanobacteria and recurrent failures of the typical spring *Peridinium* bloom) (*36*, *37*), unstable secondary zooplankton production (*38*), and loss of an economically important bleak fishery (*39*) suggest a destabilization of the food web of Lake Kinneret. Here, we argue provocatively that these changes may have resulted from long-term and ongoing hydrologic and drainage-basin management strategies.

The records of sediment and P accumulation rates contained in the upper 36 cm of Lake Kinneret sediments indicate that both bulk sediment and P accumulation rates have increased >600% since 1900. Assuming a summer hypolimnion area of 82 km^2 (= mean for 1969−1991 (*16*)), mass accumulation rates have increased from <20 kt_{DW} yr^{-1} (<20 t of P yr^{-1}) in the late 1800s to >120 kt_{DW} yr^{-1} (>120 t of P yr^{-1}) during 1970−1995. Further, our results suggest that P accumulation rates have been greater during the periods of water-level regulation than during natural eras prior, mainly as a result of engineering activities within the lake's catchment. For example, sediment and P accumulation rates increased by a factor of 5 (to >1 kg_{DW} m^{-2} yr^{-1}; 1 g P m^{-2} yr^{-1}) shortly following construction of the Degania dam. Similarly, the period of maximal sediment and P accumulation coincided with the diversion of the Lake Kinneret outflow into the NWC. During this period, sediment and P accumulation rates approached 2 kg_{DW} m^{-2} yr^{-1} and 2 g P m^{-2} yr^{-1}, respectively. The average value of 1.5 kg_{DW} m^{-2} yr^{-1} sediment accumulation rate during the 1990s is very similar to the mean sedimentation rates measured in the central lake during 1989−95 with sediment traps suspended in the mid hypolimnion (~1.5 kg_{DW} m^{-2} yr^{-1}) (*40*). Together, these patterns suggest that management strategies designed to increase water supply may have inadvertently reduced water quality by altering the basic supply and retention of growth-limiting nutrients, especially P.

Several mechanisms could link observed changes in accumulation rates to modifications of water-level fluctuations. First, changes in natural hydrologic regimes would be expected to reduce P export in the lake outflows, resulting in increased nutrient retention within the lake. For example, during the two periods of water-level regulation, relatively more water was discharged from the lake during the summer and autumn months when TP concentrations in the upper water column are typically lowest (see Figure 3d). Results from our P export analyses indicate that this altered discharge regime could increase P retention in the lake on average by ~2 t annually. Given that typical P loading during the 1970s and 1980s was ~120 t annually and that the mean water column P content was ~50 t (*15*), the additional retention of 2 t of P annually could easily account for the observed 30 ton increase in lake P inventory in the 1970s and 80s (*15*). However, while important, this increased retention is inadequate to also account for increases in sedimentary P accumulation rates noted in our core during much of the past 3 decades (~75 t to >120 t). Instead, additional nutrient sources are required to balance P influx to the deep sediments. Further, we suggest that a more detailed model incorporating actual monthly P values (rather than means across an entire period), and more realistic estimates of historical water inflows and P concentrations are required to better estimate the absolute magnitude of nutrient retention within the lake. For example, given that our sedimentary P results suggest increased lake P content since the early 1900s, our assumption of similar epilimnetic P content during the three hydrologic periods is liberal, as epilimnetic P content during the early 1900s may have been considerably lower than in the more recent hydrologic period. Nevertheless, in relative terms, our model still indicates that the amount of P exported during spring mixis in years prior to 1970 would still have amounted to a greater export of total lake P (relative to import and storage) as compared to more recent years when little P export occurs during spring. Thus, while the present model is a reasonable first approximation of relative changes in nutrient retention during the past 75 years, model output is sensitive to assumptions about change in the absolute nutrient content of inflowing and epilimnetic waters and therefore requires further modification to better estimate absolute export during the periods prior to 1970.

Second, P sedimentation and accumulation rates may have been affected by changes in resuspension and transport of littoral materials arising from lake-level regulation. For example, Nishri et al. (*41*) used a numerical model to demonstrate that near-bottom turbulence and resuspension of fine sediments increased lateral mass transport during low lake levels because of reduced hypolimnion thickness and increased transmission of wave energy to the lake bottom. Similarly, although they did not address possible implications of low water levels, Ostrovsky et al. (*42*) and Ostrovsky and Yacobi (*43*) demonstrated that resuspension of settled particles by internal seiches can redistribute littoral sediments to the profundal zone of Lake Kinneret during summer and fall amixis. In particular, they identified an active belt of resuspension (washing zone) within the metalimnion (15−25 m) that was devoid of freshly settled particles. We hypothesize that above-normal fluctuations in lake water levels could yield higher seiche-driven resuspension and transport by effectively increasing the size of this washing zone. Because the epilimnion thickness is independent of water level (*13*, *41*), this zone of disturbance should move downward as water is withdrawn, thereby increasing the depth to which resuspension processes operate. This hypothesis is consistent with recent modeling efforts of Håkanson et al. (*44*) that suggest reductions in Lake Kinneret water levels could lower water quality (as indicated by increased concentrations of suspended particulate matter) through, in part, changes in the area of active erosion and transport in the littoral zone. Similarly, because the active washing zone is also covered alternately by oxic and anoxic waters (see below), Wetzel (*45*) suggests that the relatively large size of the washing zone in reservoirs is one of the primary mechanisms leading to higher trophic status in reservoirs as compared with similar-size natural lakes.

Third, there is growing evidence that the magnitude of P release from the bottom sediments may have been altered by recent changes in lake management policy associated with the NWC. In particular, P release is hypothesized to have increased as a result of enhanced reducing conditions in the hypolimnion and because of an inverse relationship between lake water levels and hypolimnion volume (*13*). Historically, P release from Lake Kinneret sediments was considered to be dominated by pH-dependent dissolution of Ca-associated P complexes, a process that is relatively independent of redox conditions (*17*, *46*). However, recent work demonstrates that redox-dependent P release may also occur (*47*), possibly reflecting increased algal production or organic matter degradation. These recent increases in internal loading are also recorded by changes in sedimentary P content. Prior to the 1970s, the P concentration (mg P g_{DW}^{-1}) of Lake Kinneret sediments was relatively constant at ~0.12%. However, after 1970, P content declined ~30% either because of dilution of deposits with P-poor bulk sediments or because of increased P release from sedimentary deposits. We favor the latter explanation because long-term limnological records demonstrate that hypolimnetic TP concentrations have increased 2−3-fold since 1969, whereas epilimnetic concentrations remained constant (*16*, *48*). Additionally, estimates of the increase in P release calculated as the difference between the actual P measured in the core during 1973−1983 and the theoretical amount that would be present if the P concentration remained at 0.12% as in deeper sediments amount to ~30 t yr^{-1} (Figure 9), a value that corresponds closely to observed increases in whole-lake P inventory noted by Smith et al. (*15*) for the same period.

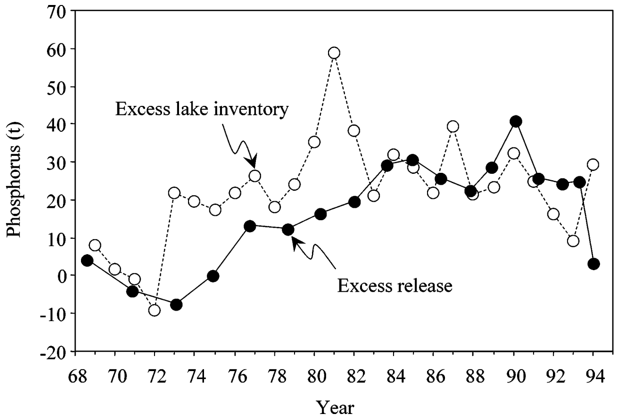

FIGURE 9. Comparison of excess P inventory (calculated as total P content of Lake Kinneret (t of P) standardized to the mean inventory during 1969−1972) and excess sedimentary P release (t of P) (calculated as the difference between the actual amount of P in lake sediments and the theoretical amount that would be present if the P concentration remained at 0.12% as in deep sediments) in Lake Kinneret during 1969−1994.

Finally, draining of Lake Hula and its surrounding swamps also may have impacted sediment and P accumulation in Lake Kinneret during the last three decades. Prior to removal of Lake Hula, 65−111 $kt_{DW}\ yr^{-1}$ of allochthonous material was deposited in wetlands before reaching Lake Kinneret (*18*). However, following the loss of upstream depositional regions, most of this material would be expected to be deposited in Lake Kinneret, a mechanism that is consistent with our estimates of increased mass deposition from 53 to 87 $kt_{DW}\ yr^{-1}$ just after impoundment to 106−164 $kt_{DW}\ yr^{-1}$ during the NWC period. Thus, while it is difficult to estimate the precise contribution of hydrologic variability and wetlands loss as controls of nutrient flux to Lake Kinneret, it appears that both management strategies have combined to increase P retention and internal nutrient cycling within Lake Kinneret. Further, we propose that this altered nutrient regime is at the root of ongoing lake eutrophication and ecosystem destabilization.

Our conclusions regarding the impacts of hydrology changes on sediment and P accumulation rates in Lake Kinneret depend, in part, on the validity of the ^{210}Pb-based chronology. In general, inventories of unsupported ^{210}Pb for the 130 yr core period (31.5 dpm cm^{-2}; 0.98 dpm $cm^{-2}\ yr^{-1}$) were greater than recent estimates of decay-corrected flux at the sediment-water interface (17.6 dpm cm^{-2}; 0.55 dpm $cm^{-2}\ yr^{-1}$; Stiller and Imboden (*23*)). However, given that atmospheric inputs account for only 25% of the unsupported ^{210}Pb supply to Lake Kinneret (*49*), and that influx of allochthonous ^{210}Pb-bearing mass have increased substantially during the past century (Figure 8), radioisotope inventories are consistent with requirements of the CRS model. Significant inputs of radioisotopes from terrestrial sources are also indicated by the observation that peak ^{137}Cs activities due to bomb fallout (~1963) and Chernobyl (1986) were substantially delayed, while total activities were much lower than expected. It is well-known that erosion inputs of ^{137}Cs to lakes can produce a delay in both peak and total input of ^{137}Cs reaching the lake sediments relative to production and fallout and that migration of ^{137}Cs both upward and downward can be substantial (*28*, *50*, *51*). Neither our ^{210}Pb-based chronology established using the CRS approach, nor a recently published independent chronology established using the ^{210}Pb and the CIC approach (*31*) are corroborated by ^{137}Cs profiles. Fortunately, the presence of three independent chronological markers for 1991 (*Peridinium*), 1988 (*Aulocoseira*), and 1957 (Lake Hula mass flux) add considerable confidence to the ^{210}Pb-derived chronology, especially since ~1950. Moreover, our established chronology and the dislocation of the ^{137}Cs peaks was verified independently using a separate core taken in 2002 and analyzed by another institution.

Lake Kinneret has recently exhibited a series of events suggestive of ecosystem destabilization (*14*). While the causes of these events are undoubtedly complex, many are symptoms of eutrophication and are consistent with elevated nutrient availability following creation of reservoir-like hydrology (*3*). Unlike other impounded lakes in semi-arid environments (*7*), conversion of Lake Kinneret to a reservoir was marked by overall increases in water-level fluctuations. Our study suggests that these water-level fluctuations may be an important factor contributing to the accelerated eutrophication of the lake, and if continued, may be expected to result in reduced water quality in the future.

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