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Ecological dynamics of a peri-urban lake: A multi-proxy paleolimnological study of Cultus Lake (British Columbia) over the past ~200 years --Manuscript Draft--

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Title: Ecological dynamics of a peri-urban lake: A multi-proxy paleolimnological study of
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Abstract

Peri-urban lakes offer many valued ecosystem services, but their vulnerability to climate change and anthropogenic disturbances increases with expanding human populations. As the effects and interactions of multiple stressors on lakes can lead to unexpected outcomes, affecting societal and ecological values, it is necessary to evaluate ecosystem trajectories and respective drivers in peri-urban lakes. Better management practices could thus be applied to preserve ecosystem services of peri-urban lakes. We conducted a multi-proxy paleolimnological study on Cultus Lake, British Columbia, a Canadian peri-urban lake experiencing cultural eutrophication, to reconstruct a comprehensive ecological trajectory of the lake over the past ~200 years. We also integrated historical data as well as historical archival information to identify the potential drivers of the changes. We identified ca. 1800-1900 CE as a reference period, reflected in muted variations across most paleo-indicators. Minor increases in sedimentary $\delta^{15}\text{N}$ ca. 1880-1940 CE coincided with the onset of anthropogenic modifications to the Cultus Lake watershed. Signs of early eutrophication were evident by ca. 1940 CE, as indicated by increases in all sedimentary pigments. By ca. 1970-1990 CE, elevated concentrations of sedimentary cyanobacterial pigments and changes in diatom species assemblages highlighted the potential interactive effects of multiple stressors, including cultural eutrophication, climate warming and declines in the endangered Cultus Lake sockeye salmon population. Recent (ca. 1990-2008 CE) declines in sedimentary pigments and increases in cladoceran fluxes suggested an increase in top-down control of the lake food web. From the collection of changes observed in the past ~200 years in our study, it is clear that Cultus Lake and its associated ecosystem services would benefit from abatement of nutrient loadings from terrestrial and atmospheric sources. Our study emphasizes the complexity and interactivity of drivers in peri-urban lake ecosystems and the necessity of

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59 **Keywords:** Anthropogenic drivers, Climate change, Eutrophication, Lake ecosystem,
60 Multiple indicators, Paleolimnology

Introduction

Peri-urban environments are experiencing increasing pressures from urban population growth as they are subjected to complex interactions between rural, urban and natural systems (Allen 2003), and rapid modifications of associated landscapes (Douglas 2008). Peri-urban lakes are particularly vulnerable to multiple anthropogenic stressors owing to residential development, recreation and agriculture within their watersheds as well as the deposition of atmospheric contaminants (Huang et al. 2007; Melymuk et al. 2011). Intensifying anthropogenic activities in urban centers and within peri-urban environments impose a suite of stresses that can degrade important habitats for aquatic species and critical ecosystem services (Chu et al. 2015). Climate change is concurrently modifying lake ecosystems (Adrian et al. 2009), and the potential interactive effects of multiple stressors can modify the ecological structure and functioning of affected ecosystems (Jackson et al. 2016). For instance, climate change can amplify lake ecological responses to cultural eutrophication, which is a pervasive stressor on freshwater ecosystems worldwide (Moss et al. 2011). The effect of multiple stressors on lakes can lead to unexpected ecological outcomes (Christensen et al. 2006), which may translate into unanticipated changes in ecosystem services that these lakes offer, such as water supplies, fishing and recreational activities (Vörösmarty et al. 2010; Waltham et al. 2014).

Evaluating the effects of multiple drivers on peri-urban lake ecosystems over centennial time scales provides an insightful perspective for understanding contemporary ecological conditions and developing effective lake and watershed management practices. With the expected global intensification of urbanization (United Nations et al. 2014), it is critical to conduct such studies, so that targeted management efforts can minimize further degradation of peri-urban lakes. Herein, we focus on a Canadian peri-urban lake, Cultus Lake, which is located ~50 km from the outer limit of the Greater Vancouver Regional District in British Columbia (BC; population of ~2.5 million; Province of BC 2018) and

~10 km from the city of Chilliwack (population of ~85,000; Province of BC 2018). Cultus Lake currently experiences strong recreational activities and residential development pressures (Shortreed 2007; Chiang et al. 2015; Sumka 2017). Recent limnological work at Cultus Lake has shown elevated metalimnetic phytoplankton biomass in summer and autumn relative to other regional lakes, as well as seasonal depletion of hypolimnetic oxygen (Shortreed 2007; Putt et al. 2019).

Effective lake and watershed management strategies are essential to halt or reverse the water quality degradation of Cultus Lake, which is a critical habitat for two species at risk, the endangered Cultus Lake sockeye salmon (*Onchorynchus nerka* Walbaum in Artedi; COSEWIC 2003) and the endemic, threatened Cultus pygmy sculpin (*Cottus aleuticus* Gilbert, Cultus Population; Rosenfield et al. 2007; COSEWIC 2010; Government of Canada 2011). Historically, the Cultus Lake sockeye salmon population has supported important indigenous, subsistence and commercial fisheries, but escapement has declined substantially over the past ~50 years (Cultus Sockeye Recovery Team 2005; Shortreed 2007). Fisheries management of Cultus Lake sockeye salmon for conservation objectives has been particularly challenging as it is part of the Fraser River sockeye salmon mixed-stock fishery and co-migrates with other abundant sub-populations of sockeye salmon (Fisheries and Oceans Canada 2017).

Despite historical fisheries assessment and limnological investigations on Cultus Lake (Ricker 1937, 1938; Shortreed 2007), we only have a fragmented perspective on the historical trajectory of ecosystem structure and functioning, as well as the principal drivers of lake change. Paleolimnology can be used to understand natural ecosystem variability over centennial scales and to identify the influences of more recent anthropogenically induced changes (Smol 2008; Battarbee 2010; Bennion et al. 2011). As such, our study combines a multi-proxy paleolimnological study with analyses of regional instrumental time series of

environmental change and a review of historical information (Moorhouse et al. 2014) to establish a history of lake ecology and potential drivers of changes. Our main objective was to evaluate the complexity of anthropogenic and climate drivers of ecological changes in a model Canadian peri-urban lake system using a long-term approach. Specifically, we aimed (1) to quantify the chemical and biological changes in Cultus Lake over the past ~200 years and (2) to relate these observed changes to suspected anthropogenic and climate drivers.

Site description

Cultus Lake has a surface area of 6.3 km², and mean and maximum depths of 31 m and 44 m, respectively (Shortreed 2007). Cultus Lake is currently a warm monomictic system, but there is sporadic historical evidence of ice cover (1937 from DFO archives; 1950 from Soutar 2005), as well as periodic dimixis in the past. The Cultus Lake watershed has an area of ~75 km² (Shortreed 2007) and contains two recreational parks (municipal and provincial), numerous campgrounds (~3 % of the watershed), areas of rural agriculture (~9 % of the watershed), and two residential developments (~2 % of the watershed; Fig. 1; Putt et al. 2019). Eleven primary tributaries channel surface runoff from ~60 % of the total watershed area, with the remainder of the water entering the lake by overland flows and groundwater influxes (Putt et al. 2019). The largest tributary to Cultus Lake, Frosst Creek, accounts for almost 50 % of the water flowing into the lake. Frosst Creek emerges directly from the Columbia Valley (Fig. 1), which is seasonally influenced by a large, unconstrained aquifer underlying principally agricultural lands and rural development (Putt et al. 2019).

The regional climate of the lower mainland of British Columbia is strongly influenced by quasi-periodic, inter-annual to inter-decadal variability associated with the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO), respectively (BC

Ministry of Environment 2016). In addition, this area has experienced significant directional warming since at least 1900 CE (BC Ministry of Environment 2016). While annual air temperatures have significantly increased (+ 0.8°C between 1900-2013 CE), the most pronounced warming has occurred in winter (+ 1.2°C; BC Ministry of Environment 2016). Regional air temperatures exhibited two periods of warming since the 1900s, with one from the beginning of the 1920s to the mid-1940s and another one since the 1970s (Fig. 2). Air temperatures greatly influence the upper water column temperatures (average from 0 to 5 m lake depth) in Cultus Lake as indicated by their linear regression of monthly data ($R^2 = 0.89$; p-value < 0.001, ESM1). In addition, the annual mean precipitation has increased ~14 % since the 1900s, with the most pronounced increases occurring in spring (BC Ministry of Environment 2016). Flood records, available for the past 100 years, show that the area is susceptible to large flooding event. Specifically, there was a substantial lake level rise associated with a major flooding event in the Fraser Valley in 1948 CE (Soutar 2005). A similar event also happened in 1950 CE after a very cold winter when the lake froze and, then water levels rose substantially the following spring (Soutar 2005).

Enumeration of sockeye salmon spawners (adults returning from the Pacific Ocean to spawn) and emigration of smolts to the Pacific Ocean has been conducted since 1925 CE (Foerster 1930, 1934, 1936; Shortreed 2007). The Cultus Lake sockeye salmon population has experienced a long-term decline since the 1970s in the off-cycle brood lines and pronounced declines across all brood lines occurring in the 1990s (Peterman et al. 2012).

History of anthropogenic and natural disturbances in the Cultus Lake region

Radiocarbon dating and indigenous oral history indicates modest use of the surrounding landscape of Cultus Lake by Coast Salish People (Stó:lō) for the past ~5000 years (Carlson

2001; Schaepe and Ts'elxwéyeqw Tribe 2017). Euro-American settlement was established in the Columbia Valley (south of Cultus Lake; Fig. 1) in the late 1880s and a road was built around Cultus Lake in the early 1900s, which facilitated logging activities within the watershed (Soutar 2005). Road access promoted a modest development of permanent lakeshore residences in the 1920s (Soutar 2005), which has greatly expanded in the subsequent period. Logging activities occurred between 1900 and ~1940 CE, with a peak in the 1920s (Cramer 2005). The area logged was primarily in the Columbia Valley and secondarily on Vedder Mountain (Cramer 2005). As logging declined, small-scale farming was established in the Columbia Valley (Cramer 2005). Clearing of land for agriculture with fire was prevalent, leading to several substantial forest fires (Cramer 2005). An extensive fire occurred in 1951 CE and burnt ~27 % of the watershed area (~20.4 km²; Province of BC 2013; ESM2). Much of the farming post-1940 CE focussed on dairy production, leading to further land clearing in the Columbia Valley (Cramer 2005). Post-1970s farming in the Columbia Valley has largely converged towards pastoral grazing, pork production, and more recently an extensive expansion of berry crops (Zubel et al. 2000; FVRD 2011).

Nutrient influxes to Cultus Lake are mainly derived from anthropogenic activities within its watershed as well as atmospheric deposition of regional pollutants (Putt et al. 2019). According to the steady-state water quality model developed for Cultus Lake by Putt et al. (2019), watershed runoff contributes to 53 % and 73 % of the total phosphorus (P) and nitrogen (N) loadings, respectively (Table 1). Substantial inputs of total N (41 %) and P (26 %) from the watershed to the lake arise from the Columbia Valley (Putt et al. 2019), which has been affected by agricultural activities (Zubel 2000; Putt et al. 2019). Further nutrient loadings to Cultus Lake include septic leachate (19 % of P and 9 % of N; Table 1) that largely arises from campgrounds and residential areas (Putt et al. 2019). Currently, residential and campground sewage collection systems mainly consist of individual or

communal septic tanks, which disperse waste via leaching fields (FVRD 2014). A sewer service was established in 1979, but it serves a limited number of people within the northern catchment (FVRD 2015). None of the existing sewage systems in the watershed carry waste to a treatment facility (FVRD 2014). Guano from migratory gulls has also been identified as a significant source of total P (22 %; Table 1) to Cultus Lake (Putt et al. 2019), as an expansion of the bird population has been occurring since at least the late 1970s (National Audubon Society, 2017). Finally, substantial nutrients loadings to the lake are attributable to atmospheric deposition from the nutrient-contaminated regional airshed. Direct atmospheric deposition on the lake surface contributed to 17 % and 5 % of the total N and P loadings to the lake, respectively (Table 1). Putt et al. (2019) estimated that ~66 % of N and ~70 % of P in the watershed runoff ultimately originated from atmospheric deposition. Thus, atmospheric deposition is considered the largest source of nutrient loadings to Cultus Lake with cumulative contributions of 42 % and 63 % of total N and P loaded to the lake, respectively. The Cultus Lake airshed is mainly influenced by emissions from agricultural and urban landscapes of the Greater Vancouver Regional District, Fraser Valley Regional District (total population of ~296,000; Province of BC 2018) and Whatcom County (population of ~221,000; U.S. Census Bureau 2018) in northwestern Washington State, USA (Metro Vancouver 2013).

Cultus Lake has been a popular recreational site since the beginning of the 1900s with two regional parks, the municipal Cultus Lake Park (established in 1924 CE; Chwk. Prog. Aug. 6, 1924) and the Cultus Lake Provincial Park (established in 1948 CE; BC Parks 2017). As early as 1960 CE, an estimated 500,000 people visited Cultus Lake Park during the summer months (Chwk. Prog. Aug. 2, 1960); these numbers increased to over 1 million in 1973 CE (Chwk. Prog. Oct 15, 1973). Today, it is estimated that 2 to 3 million people visit

Cultus Lake annually (FVRD 2011), largely during the summer for recreational activities, including camping, boating and fishing.

Major modifications to the littoral zone have occurred with the introduction of the invasive Eurasian milfoil (*Myriophyllum spicatum* (L.) Bonnier & Layens) after 1977 CE. By 1988 CE, *M. spicatum* covered ~60 % of the littoral zone to 6 m deep (Truelson 1988) expanding to 73 % littoral coverage by 2004 CE (Shortreed 2007). A detailed history on the anthropogenic development of Cultus Lake and its watershed are presented in ESM2.

Methods

Field and laboratory analyses

Limnological conditions of Cultus Lake have been monitored in 1923-1924, 1927-1929 and 1932-1936 CE (Ricker 1937, 1938) and from 2001 to 2003 CE (Shortreed 2007). Since 2009 CE, Cultus Lake has been monitored monthly by Fisheries and Oceans Canada (DFO Lakes Research Program, unpublished data). Only three limnological parameters (temperature, dissolved oxygen and Schmidt stability index) were comparable among the different sampling periods due to variation in methodology (ESM3). No major temporal changes were detected between the comparable limnological variables, except for a decline in hypolimnetic dissolved oxygen in the 2000s compared to the 1920s-1930s (Shortreed 2007; ESM3).

From July 2014 CE to June 2015 CE, a suite of physical, chemical, and biological limnological parameters were measured following the methods described in Shortreed (2007) and sediment traps were deployed monthly to assist in understanding seasonality in diatom species composition, which was also examined in the sediment core. Sediment traps were deployed at ~3 m above the sediment-water interface near the core collection site. The aspect

ratio (ratio of length to diameter) of the sediment traps was ~6 as suggested by Bloesch and Burns (1980), with a length of 61.0 cm and diameter of 10.2 cm. Diatom species assemblages were identified and enumerated from the sediment trap samples.

A 33-cm sediment core was collected in April 2008 CE from a deep depositional basin (N 49°03.45'; W 121°59.046') in Cultus Lake using a Glew Maxi Gravity Corer (diameter of 7.6 cm). The core was sectioned at 0.5 cm intervals from the surface to 2.5 cm and at 0.25 cm intervals thereafter. The samples were frozen (-20°C) until further analyses. Sediment samples were then lyophilized (~48 h, 0.01 Pa) prior to analyses for geochronology (²¹⁰Pb, ¹³⁷Cs activities), geochemistry (% dry mass carbon (C) and nitrogen (N); C and N stable isotopes $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$), algal abundance, and assemblage composition (sedimentary pigments, diatoms), and cladoceran zooplankton composition, sub-fossil size, and abundance.

The sediment core chronology was established by gamma spectroscopy of ²¹⁰Pb and ¹³⁷Cs activities on 18 sediment samples distributed across the core (one sample every ~1.5 cm) following the methods of Appleby (2001). A constant rate of supply (CRS) model was used to calculate the sediment age and mass accumulation rates ($\text{g cm}^{-1} \text{yr}^{-1}$) as well as the age error for each sediment interval (Binford 1990; ESM4).

At the Institute of Environmental Change and Society, University of Regina, a ThermoQuest (F-MAT) Delta ^{PLUS} XL isotope ratio mass spectrometer was used to determine bulk sediment C and N content (% dry mass) and stable isotope values for nitrogen ($\delta^{15}\text{N}$) and carbon ($\delta^{13}\text{C}$) following Savage et al. (2004). Isotopic values were expressed in conventional δ -notation relative to atmospheric N₂ and a local reference for the Vienna Pee Dee Belemnite standard, respectively. Sample reproducibility was ± 0.2 ‰. Elemental content and isotope values of bulk sediments were used to provide an indication of the source of organic matter (allochthonous, autochthonous, or admixture) to the sediments (Meyers and Teranes 2001).

Sedimentary pigments were extracted and purified following the standard procedures of Leavitt and Hodgson (2001). Pigments and their derivatives were isolated and quantified using an Agilent model 1100 high-performance liquid chromatography (HPLC) system, equipped with a photo-diode array and fluorescence detectors. The HPLC system was calibrated with authentic standards from DHI Lab (Denmark) prior to pigment quantification. Pigment concentrations were expressed as nmoles pigment g⁻¹ of dry sediment C. The pigments analysed through the HPLC system are indicative of all phototrophs (β -carotene, Chl *a* and its derivative pheophytin *a*), siliceous algae and some dinoflagellates (fucoxanthin, diatoxanthin), cryptophytes (alloxanthin), chlorophytes (chlorophyll *b*, pheophytin *b*), Nostocales cyanobacteria (canthaxanthin) and total cyanobacteria (echinenone) following Leavitt and Hodgson (2001). Two other pigments, lutein from chlorophytes and zeaxanthin from cyanobacteria were inseparable in this HPLC system and were presented together as lutein-zeaxanthin (Leavitt and Hodgson 2001). An index of UV radiation penetration into Cultus Lake (UV index) was estimated using standard procedures from photoprotective pigments as the ratio of UV-absorbing compound A to the sum of the carotenoid pigments alloxanthin, lutein+zeaxanthin and diatoxanthin (Leavitt et al. 1997). All pigments detected were used in our statistical analyses as they are known to be relatively stable once buried in lake sediments (Leavitt and Hodgson 2001).

Microfossil diatom slides were prepared following the standard methods of Battarbee et al. (2001). Identification and enumeration of diatom microfossils were performed at 1000X magnification under differential interference contrast (DIC) optics on a Leica DM4500 B microscope. Diatom microfossils were counted along parallel slide transects to reach a minimum sample size of at least 400 diatom valves and were expressed in relative abundance. The references used for diatom identification are presented in ESM5.

Cladoceran subfossil slides were also prepared according to standard procedures (Korhola and Rautio 2001). Briefly, the slides were counted using a Leica DM4500 B microscope under 200X and 400X magnification. The identification of bosminids (*Eubosmina* sp. and *Bosmina* sp.) and *Daphnia* spp. along with the sizes of their subfossil remains (carapace for bosminids and post-abdominal claws for *Daphnia* spp.) were quantified following Sweetman and Finney (2003) and Korosi et al. (2008, 2010). At least 50 individuals per interval were enumerated and the carapace of bosminids and the post-abdominal claws of *Daphnia* spp. were measured to infer relative size changes of cladoceran community through time. The abundance of individuals was integrated with our chronology to calculate sedimentary fluxes (number of individuals cm⁻² y⁻¹) to better infer changes in secondary production within Cultus Lake. The sedimentation rates used to calculate cladoceran fluxes were estimated from the age-depth model and the calculations for the cladoceran fluxes are presented in ESM4.

Data and statistical analyses

To identify different stratigraphic periods and detect temporal patterns that could indicate environmental changes in the lake, a constrained hierarchical clustering analysis, CONISS (constrained incremental sum-of-squares), followed by a broken-stick model (Birks 2012), was applied on chord-transformed data (Grimm 1987) using rioja package (Juggins 2017) in R software. This analysis was performed on four different datasets, which were sedimentary geochemistry (molar C:N ratios, $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$), pigments, diatom and cladoceran (*Daphnia* spp. and bosminid fluxes and remain sizes) data. Prior to the chord transformation, z-scores were calculated for the geochemical and cladoceran data because the units differed for each indicator within the datasets. To further identify the major changes in multivariate datasets

(pigments and diatoms), we applied a principal component analysis (PCA) to the data following a Hellinger-transformation (Legendre and Legendre 2012) using vegan package (Oksanen et al. 2018) in R software. The first principal component axis was then plotted against time to detect the major assemblage shifts over time. For the diatom community data, a total of 18 taxonomic groups were used in the statistical analyses. The rare species (< 1 % of relative abundance or taxa occurring only in 1 or 2 samples) were grouped and only the dominant species (> 1 % of relative abundance) were kept separate in our analyses (ESM5). All statistical analyses were performed using R statistical software v. 3.3.2 (R Foundation for Statistical Computing, Vienna, Austria).

Results

Modern limnology of Cultus Lake (2014-2015)

Contemporary limnological monitoring of Cultus Lake indicated clear seasonal differences in both physicochemical conditions and biological communities (Table 2, Fig. 3, ESM3). Chlorophyll *a* concentrations in Cultus Lake varied seasonally with epilimnetic concentrations averaging ~2 µg L⁻¹ throughout the year, reaching higher mean concentrations (~4 µg L⁻¹) in the metalimnion during the thermally-stratified period (Table 2). During thermal stratification, total phosphorus (TP) and total nitrogen (TN) reached maximal values in the metalimnion relative to the epilimnion (Table 2). The euphotic zone depth varied seasonally, with a shallower light penetration through the water column during the mixed period (Table 2). Given that it is unclear whether individual nitrogen fractions were bioavailable (e.g., dissolved organic N, DON), we have focussed on the dissolved inorganic nitrogen:total phosphorus mass ratio (DIN:TP) as an indicator of nutrient deficiencies

(Bergström 2010). Euphotic zone mass DIN:TP indicated potential P-deficient growth for most of the year (Fig. 3a, Table 2), with the exception of the summers 2014 and 2015 CE when mass DIN:TP were more suggestive of co-limitation of N and P. This co-limitation was largely coincident with larger biomasses of cyanobacteria and diatoms (Fig. 3b, c).

Diatom assemblages analyzed from our sediment traps indicated a strong seasonality in species dominance (Fig. 3d). From late autumn to early spring, the diatom community was composed principally of *Aulacoseira* species, mainly *A. subarctica* (Otto Müller) Haworth. *Lindavia intermedia* (Manguin ex Kociolek and Reviers) Nakov et al. ex Daniels et al. (previously *Cyclotella bodanica* var. *intermedia*) also exhibited elevated relative abundance for much of the year with the exception of the months of February and March 2015 CE (Fig. 3d). *Lindavia michiganiana* (Skvortzov) Nakov, Guillory, ML Julius, EC Ther. and AJ Alverson (previously *C. michiganiana*), a predominant species throughout most of the sediment record (Fig. 6), was low in relative abundance throughout the period of the sediment trap deployment. Another *Lindavia* species, *L. comensis* (Grunow) Nakov, Guillory, ML Julius, EC Ther. and AJ Alverson (previously *C. comensis*), was also present at a low relative abundance for the entire sediment trap deployment period. *Stephanodiscus* species, including *S. parvus* Stoermer & Håkansson, *S. minutulus* (Kützing) Cleve & Möller, *S. medius* H. Håkansson and *S. niagarae* Ehrenberg, were mostly present from February to June 2015 CE. The main *Stephanodiscus* taxon, *S. niagarae*, appears to have emerged in Cultus Lake since the collection of the sediment core in 2008 CE (Fig. 3d).

Sediment chronostratigraphy

Sedimentary ^{210}Pb unsupported activity showed a strong negative relationship to cumulative dry mass and reached background concentrations (supported ^{210}Pb) within the top 15 cm of

the sediment core (ESM4). Second and third order polynomial regressions were explored to develop age-depth models within the dated intervals (0-15 cm). The two polynomial regressions were mainly consistent in the period from 1900 to 2008 CE, an interval which includes most of the major changes identified by the broken-stick models. Although the third order polynomial model had a better fit based on Bayesian Information Criterion (BIC) values, the relationship seemed to rely substantially on the oldest data point. As such, we calculated the average age from the second and third order models to extrapolate the dates beyond the background of supported ^{210}Pb using a conservative approach (ESM4). This average age-depth model was then used to determine ages for all intervals of the core. The sediment chronological analyses also exhibited a ^{137}Cs peak at 12.25 cm indicating the date of 1963 CE (Appleby 2001), which corresponds well with the date of that level derived from the ^{210}Pb model (ESM4).

Sediment geochemistry

From the CONISS analysis, interpretable shifts in the geochemical data were identified at ca. 1858 / 1862, 1965 / 1966 and 1984 / 1985 CE (Fig. 4a, b). According to the constrained cluster analysis, the largest shift occurred in 1984 / 1985, followed by the one in 1858 / 1862 (ESM6). The first chronological break at ca. 1858 / 1862 CE detected very subtle changes in C:N and $\delta^{15}\text{N}$, which we have not over-interpreted (Fig. 4a, b). Sediment values of molar C:N generally followed an increasing trend prior to the mid-1940s, after which it briefly exhibited substantially higher values (Fig. 4a). Following this event, molar C:N decreased toward values lower than those prior to the mid-1940s, which was identified as a shift in ca. 1965 / 1966 CE by the CONISS analysis (Fig. 4a). Generally, $\delta^{15}\text{N}$ exhibited low values and only modest variation (± 1 ‰) prior to ca. 1900 CE, with the exception of a 2 ‰ drop ca.

1890 CE. Thereafter, $\delta^{15}\text{N}$ exhibited an increasing trend with a more pronounced increase since the shift identified in ca. 1984 / 1985 CE, coincident with the decreases in molar C:N (Fig. 4b).

Sedimentary pigments

CONISS analysis of the pigment data identified interpretable shifts ca. 1946 / 1950 and ca. 1992 / 1993 CE (Figs. 4c, 5). Prior to the shift in ca. 1946 / 1950 CE, sedimentary pigments remained at relatively low concentrations and were mostly stable, suggesting a low but consistent algal abundance in Cultus Lake (Fig. 5). All pigments increased markedly after the shift in ca. 1946 / 1950 CE, with most pigments reaching their highest total concentrations between the shifts in ca. 1946 / 1950 and ca. 1992 / 1993 CE. By contrast, echinenone (indicator for cyanobacteria) exhibited a more gradual increase after the shift in 1946 / 1950 relative to other sedimentary pigments, followed by an abrupt increase at the beginning of the ca. 1970s. Echinenone concentrations have increased during the recent period (1977-2008 CE; Fig. 5, ESM7), when temperatures were warmer, sockeye salmon escapements were lower, and nutrient run-off from the watershed was elevated relative to historical model hindcasts (Putt et al. 2019). From the shift in ca. 1992 / 1993 CE onwards, there was a general decline across all pigments (Fig. 5, ESM8). The UV index showed high variability during ca. 1806 to the shift in 1946 / 1950 CE (Fig. 5). The high variability in the UV index was followed by a decrease reflecting less UVR exposure (Leavitt et al. 1997), which coincided with higher sedimentary pigment concentrations. After the shift in ca. 1992 / 1993 CE, the UV index decreased further, exhibiting the lowest values of the entire sediment record (Fig. 5).

Sedimentary diatom assemblages

The first ~150 years of the sediment record (ca. 1824 to the shift in 1964 / 1973 CE) exhibited a relatively stable diatom assemblage predominated by *Aulacoseira ambigua* (Grunow) Simonsen and *L. michiganiana* (Fig. 6). No major taxonomic shifts in the diatom assemblages occurred until the shift in ca. 1964 / 1973 CE as shown by the first PCA axis (Fig. 4d) and CONISS analysis (Figs. 4d, 6). The transition in ca. 1964 / 1973 CE was marked by a shift in species composition from *A. ambigua* to *A. subarctica*, as well as a decrease in relative abundance of *L. michiganiana*. Two other centric species, *L. intermedia* and *L. comensis*, appeared in the sediment record following the shift in 1964 / 1973 increasing in relative abundance mainly after ca. 1980 CE (Fig. 6).

Sedimentary cladocerans

Both cladoceran groups showed limited variation and low fluxes to the sediments prior to the shift identified by CONISS in ca. 1973 / 1981 CE but increased in deposition thereafter (Fig. 4e). The broken-stick analysis following CONISS for both cladoceran fluxes and size measurements indicated only this one interpretable shift in ca. 1973 / 1981 CE. Fluxes of both cladocerans tended to exhibit increase in the most recent period (from the shift in 1973 / 1981 to 2008 CE; Fig. 4e, ESM7). The average length of bosminid remains showed a modest decline in size during the most recent periods, while *Daphnia* spp. claw length increased relative to earlier periods (Figs. 4f, g, ESM7).

Discussion

With the intensification of urbanization and climate change projected for the coming century, a wide range of ecosystem services offered by peri-urban lakes are likely to be compromised without proactive stewardship. As such, it is important to understand the complex interactions of human and natural drivers influencing ecological changes in these valued ecosystems. Our paleolimnological record from Cultus Lake indicates that it was a relatively nutrient poor ecosystem prior to Euro-American occupation in the 1900s, which is consistent with the pre-development conditions inferred from steady-state lake nutrient modeling (Putt et al. 2019). Following this period of relative stability, four major periods of change were identified within our sedimentary record and cultural eutrophication was identified as a major driver of the changes. Analysis of contemporary limnological data shows that Cultus Lake is currently oligo-mesotrophic (chl-*a* of $\sim 2.2 \mu\text{m L}^{-1} \pm 0.8$ and TP of $8.0 \mu\text{g L}^{-1} \pm 1.3$; Putt et al. 2019), and these values, considered in isolation, do not suggest substantial water quality degradation. However, our centennial scale study clearly shows how multiple environmental stressors can affect peri-urban lakes and provide context to frame management of the modern ecological conditions. Given the success of nutrient management strategies in similar fast-flushing temperate lakes (Jeppesen et al. 2005; Perga et al. 2010), we suggest that Cultus Lake could benefit from efforts to reduce nutrients from its water- and airshed (Putt et al. 2019).

Ecosystem stability in Cultus Lake (ca. 1800 to 1900 CE)

During the early to late 1800s, the Cultus Lake sediment record exhibited relatively low temporal variability across all sedimentary time series (Figs. 4, 5, 6), including the relatively low algal and cyanobacterial pigment concentrations and cladoceran fluxes characteristic of oligotrophic conditions. The source of organic matter during this period was inferred to be

principally autochthonous (molar C:N ~9-10) and fairly consistent, suggesting relative stability in the catchment and lake (Meyers and Teranes 2001; Selbie et al. 2009). Only a small change in molar C:N and $\delta^{15}\text{N}$ was identified by a break in ca. 1858 / 1862 CE by CONISS analysis and no apparent change was observed in the diatom assemblage. Thus, we consider ca. 1800-1900 CE to be a reference period for Cultus Lake, largely indicative of pre-disturbance conditions. Based on our analyses of the historical archives, anthropogenic influences within the Cultus Lake watershed were likely minimal prior to Euro-American settlement in the late 1800s (Soutar 2005; Schaepe and Ts'elxwéyeqw Tribe 2017), which is consistent with the ecological stability inferred from the sediment record.

Onset of Anthropogenic Watershed Changes (ca. 1900 to 1940 CE)

From the ca. 1900s to 1940s, sedimentary $\delta^{15}\text{N}$ increased slowly and consistently from the reference state (Fig. 4b) suggesting a change in N loading sources or cycling within Cultus Lake. While several within-lake processes (e.g. nitrification, denitrification, ammonia volatilization; Talbot 2002) and salmon carcass loading (Finney et al. 2000; Selbie et al. 2009) can increase $\delta^{15}\text{N}$ values within the sedimentary record, the changes in $\delta^{15}\text{N}$ observed from ca. 1900 to 1940 CE are most likely related to an increase in anthropogenic influences including wastewater from humans and livestock (Bunting et al. 2007, 2016; Botrel et al. 2014). Within the Cultus Lake catchment, we inferred that the enrichment in $\delta^{15}\text{N}$ was more consistent with the effects of increases in anthropogenic activities, such as agriculture and increases in human occupation (i.e., sewage; ESM2). The first European families settled in the Columbia Valley at the end of the 1800s and the population expanded in the area with the increase in logging, which reached a peak in the 1920s. Climate warming was observed from the 1920s to the mid-1940s, and was comparable in magnitude to that observed in 1977-2008

CE (Fig. 2b). Although some stressors (forest clearance and fires) could have influenced Cultus Lake during the period from the ca. 1880s to the ca. 1940s, our records indicate that it is not the most dynamic interval (i.e., slight increase in $\delta^{15}\text{N}$, no distinct changes in other proxies; Fig. 4) relative to other periods over the last ~200 years. These results are consistent with observations from other studies showing that effects of forest clearance and fires do not generally lead to persistent changes in sedimentary indicators (Paterson et al. 1998; Laird et al. 2001; Bredesen et al. 2002), although Scully et al. (2000) reported that forest clearcutting affected a lake's pigment record, likely caused by changes in lake mixing.

Early Eutrophication of Cultus Lake (ca. 1940 to 1970 CE)

The mid-1940s were marked by a brief increase of the molar C:N (Fig. 4a), which suggests a period of increased terrestrial organic matter delivery to the lake (Meyers and Teranes 2001; Selbie et al. 2009). The cumulative effect of two flooding events (1948 and 1950 CE) as well as a major forest fire (1951 CE) within the catchment (Soutar 2005) could have resulted in substantial allochthonous organic matter delivery to the lake. Following this period, greater concentrations of almost all sedimentary pigments were observed, a pattern suggesting increased influxes of nutrients to the lake from the watershed (Fig. 5). Increased nutrient delivery may have arisen from the dairy industry in the Columbia Valley and its associated spreading of manure as fertilizer on pasture lands, as well as the expansion of tourism, which intensified septic inputs within the watershed. As the septic systems were probably limited and localized during this period, the flooding events (Soutar 2005) and the forest fire (Province of BC 2013) may have also enhanced the delivery of nutrients to the lake from livestock and human waste. Molar C:N (ca. 1950 CE) subsequently decreased to values more

indicative of organic matter derived from aquatic production (Meyers and Teranes 2001; Selbie et al. 2009).

Atmospheric deposition of nutrients from the regional airshed influenced by urbanization, industry, transportation, and agricultural emissions, may have also contributed to nutrient loadings to Cultus Lake, as it is known to be a regional driver of aquatic enrichment (Putt et al. 2019). The sedimentary record of nearby Loon Lake, which in contrast to Cultus Lake has been protected from development within its watershed, has exhibited a significant decline in sedimentary $\delta^{15}\text{N}$ over the 1900s, tracking deposition of isotopically-depleted reactive nitrogen from the atmosphere (Holtgrieve et al. 2011). As atmospheric fluxes of nutrients to Cultus Lake were likely comparable during this period, the increase in sedimentary $\delta^{15}\text{N}$ and pigment concentrations in the Cultus Lake sediment record suggest early nutrient enrichment from locally-sourced, isotopically-enriched nutrient sources (i.e., cattle manure and human sewage), as observed elsewhere in agriculturally-dominated landscapes (Elliott and Brush 2006; Bunting et al. 2007, 2016; Botrel et al. 2014). Although increases in almost all sedimentary pigments were observed during this period, the diatom assemblages and cladoceran fluxes did not record any substantial changes in composition.

Multiple stressors underlying recent changes in Cultus Lake (ca. 1970 to 1990 CE)

Inferred changes in lake ecology from the ca. 1970s to 1990s were characterized by higher abundances of echinenone (a ubiquitous cyanobacterial pigment), reduced UV light penetration (based on pigment indicator), and an increase in cladoceran fluxes to the sediments. These changes coincided with measured declines in sockeye salmon escapement to the lake and the appearance of Eurasian watermilfoil in 1977 CE (Shortreed 2007). The decline in Cultus Lake sockeye salmon escapement certainly resulted in reduced in-lake

juvenile densities, thereby reducing planktivory on zooplankton, which could enhance grazing pressures and be recorded in the sediments with higher fluxes of large-bodied zooplankton and lower concentrations of sedimentary pigments (Hume et al. 1996; Kyle 1996). Moreover, a decrease in sedimentary molar C:N indicated coeval increases in autochthonous organic matter contributions to the sediments (Meyers and Teranes 2001; Leng et al. 2006; Selbie et al. 2009). Further enrichment in the sedimentary $\delta^{15}\text{N}$ signature at this time suggest an enhanced contribution of organic wastes to the lake (i.e., septic leachate, manure runoff, avian guano; Putt et al. 2019), supporting continued cultural eutrophication over this period.

A common symptom of cultural eutrophication in lakes is the development of greater cyanobacterial biomass and the appearance of surface bloom-forming species (Downing et al. 2001). The increase in total cyanobacteria (as echinenone) observed in our sediment record coincided with elevated nutrient loading from increases in residential development and an increase of recreational activities in the Cultus Lake watershed, which could have led to higher P export to the lake and N limitation. Modifications in limiting nutrient stoichiometry can result in a structural reorganization of the phytoplankton community (Dolman et al. 2012). Based upon the contemporary euphotic zone DIN:TP (Fig. 3a), Cultus Lake was generally P-limited, but exhibited the potential for co-limitation of N and P in summer, when cyanobacteria are more common. In addition, warmer water temperatures could favour cyanobacterial growth relative to other algal groups (Paerl et al. 2011) and warmer temperatures have been identified as a significant predictor explaining centennial-scale cyanobacterial trends in temperate and boreal lakes (Taranu et al. 2015). These inferred physical and biological changes may have, in turn, altered the depth of photosynthetic activity, and light penetration in the water column leading to changes in the inferred UV

index (Fig. 5). The growth of the contemporary observed metalimnetic phytoplankton community may have also altered underwater light conditions.

A diatom shift from *A. ambigua* to *A. subarctica* was observed following the 1970s, and could have been influenced, in part, by the development of a warmer thermal regime in Cultus Lake, particularly in winter. Our sediment trap data indicate that *A. subarctica* is most common during the winter and is largely absent during the summer months. *A. subarctica* can tolerate very low light environments (Foy and Gibson 1993; Kilham et al. 1996), which would make it highly competitive under the recent winter conditions in Cultus Lake including negligible winter ice cover, strong water column mixing, and shallow light penetration (Table 2). The observed pattern of *A. subarctica* is consistent with seasonal water column studies of other deep mixing lacustrine environments (Lund 1954; Stockner and Lund 1970; Horn et al. 2011), as well as other shallow lakes (Gibson et al. 2003) from the Northern Hemisphere. A similar pattern of increase in *A. subarctica* was also observed in a paleolimnological study, which was associated to a faster flushing rate as a consequence of increase in spring rainfall (Bennion et al. 2012). However, in the case of Cultus Lake, the diatom shift might have been the result of an interaction between human and climatic stressors. Whereas the magnitude of atmospheric warming after the 1970s was comparable to that recorded during the 1920s to the mid-1940s, water temperatures at 20-40 m have been warmer during the mixed season and DO concentrations have been lower at 30 m during both mixed and stratified seasons in recent years at Cultus Lake (compared to the 1920s and 1930s; ESM3). With the expansion of the human population and agriculture in the lower mainland of BC during the 1970s and the expected increase in nutrient loading to the lake (Putt et al. 2019), Cultus Lake could have been more vulnerable to climate warming during this recent period.

Additional variations in diatom species composition were observed in the recent sediment record, in particular the rise of two centric diatom taxa, *L. intermedia* and

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582 *L. comensis*, after ca. 1980 CE (Fig. 6). These two centric species were predominant in the
583 contemporary diatom communities from the sediment trap samples (especially *L. intermedia*)
584 between spring and autumn. The appearance of *L. intermedia* supports inferences of
585 increasing water column stability during the summer, as indicated by physical modeling of
586 Cultus Lake (Sumka 2017), as *Lindavia* sp. has been previously reported to benefit from its
587 positive buoyancy to persist in nutrient depleted and well-illuminated surface waters during
588 calm summer periods (Interlandi et al. 2003). Together, the combined inferences drawn from
589 the sedimentary pigments and diatom assemblages strongly suggest that the recent history of
590 Cultus Lake was subject to complex forcing resulting from cultural eutrophication and
591 climate warming (Fig. 2).

592
593 Recent lake conditions (ca. 1990 CE to present) and management strategies

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595 The Cultus Lake paleolimnological record following the 1990s was similar in trajectory to
596 that observed ca. 1970 to 1990 CE. Diatom assemblages did not exhibit additional changes
597 compared to the previous period (ca. 1970-1990 CE). However, the sedimentary record in the
598 1990s was marked by a sharp increase in $\delta^{15}\text{N}$, which could be associated with an increase of
599 recreational activities as well as residential development in the Cultus Lake watershed during
600 the recent period. A general decline in sedimentary pigment concentration was also observed,
601 likely as a result of an increase grazing pressure from zooplankton inferred from an increase
602 of cladoceran fluxes to the sediments.

603 Cladoceran fluxes continued to increase following ca. 1990 CE, while at the same
604 time an increase in *Daphnia* spp. body size and a decline in bosminid size was observed (Fig.
605 4, ESM7). The changes in cladoceran abundances could be a response to declines in sockeye
606 salmon abundances (Fig. 4h), as juvenile salmonids are key predators of cladocerans (Hume

et al. 1996; Kyle 1996). An inverse relation between cladoceran body sizes and temperature have been noted elsewhere (Havens et al. 2014), while changes in subfossil fluxes and modern *Daphnia* spp. size can be associated with variation in zooplankivory (Leavitt et al. 1989). Although the *Daphnia* spp. size increased in Cultus Lake following the decrease of sockeye salmon population, Mushet et al. (2019) have reported an increase of large bodied daphnids following the introduction of rainbow trout, which they explained with an increase of a deep, low oxygen refugia caused by the increase of nutrients and lake production. Given that multiple stressors influenced the changes in Cultus Lake during the recent periods, together with the limited taxonomic resolution of the cladoceran subfossils, it is difficult to disentangle all potential mechanisms. Interestingly, contemporary zooplankton collections (since 2009 CE) have shown an expansion of *Leptodora kindtii* Focke (DFO, unpublished data), a known predator on smaller-bodied cladocerans such as bosminids, and thus analyses of these water column time series could help advance our mechanistic understanding in the future. The overall increase in cladoceran fluxes during this period, suggests an inferred increase in herbivory that could have induced lower algal abundance, eliciting more pronounced grazing regulation of phytoplankton communities (Carpenter and Kitchell, 1993).

The recent ecological drivers acting upon Cultus Lake appear to involve interactions between excess nutrient loadings and a warming climate. Climate model predictions for the British Columbia's Fraser Valley indicate substantial warmer annual temperatures (+1.7 °C) by 2050 CE, with marked reductions in summer precipitation (-14 %; PCIC 2013). Such climatic changes will likely make Cultus Lake more prone to enhanced algal production, particularly if nutrient loading continues unabated (Moss et al. 2010). Land development and recreational use of the Cultus Lake watershed are rapidly expanding, as are intensive agriculture operations in the Columbia and Fraser valleys. Therefore, it is highly plausible that nutrient loadings to the lake will be sustained or increase without targeted intervention,

consistent with predictions and steady-state lake nutrient models for Cultus Lake (Putt et al. 2019). Our paleolimnological study indicates that Cultus Lake has already experienced cultural eutrophication since the beginning of the 1900s and that future degradation of water quality and habitat could negatively impact the persistence of two species at risk, the Cultus Lake sockeye salmon and the endemic Cultus pygmy sculpin, as well as the diverse services that this lake ecosystem offers. The current water quality in Cultus Lake, combined with the potentially rapid recovery of such fast-flushing coastal lakes in response to targeted nutrient management (Hampton et al. 2006), highlights that Cultus Lake may respond positively and rapidly to nutrient abatement efforts. Time is of the essence in averting continued lake eutrophication from intensifying sources, and avoiding reinforcing nutrient loadings, such as internal nutrient loading from the lake sediments (Nguyen and Maeda 2016; Putt et al. 2019).

In concert with the quantitative hindcast modeling of Putt et al. (2019), the long-term ecological context afforded by our paleolimnological record, provides system-specific reference conditions and quantitative recovery targets (e.g., ca. 1800-1900 CE) for lake nutrient management. It is of great importance to apply sustainable land use practices, focused on the abatement of nutrient loading from water- and airshed sources to preserve Cultus Lake ecosystem services and its species at risk.

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Table 1. Contributions of different sources of total phosphorus (TP) and nitrogen (TN) to Cultus Lake*.

Sources	TP	TN
Watershed runoffs	53.2 %	72.7 %
From Columbia Valley subwatershed	26.4 %	40.7 %
From other subwatersheds	26.8 %	32.0 %
Direct atmospheric deposition	4.5 %	17.1 %
Septic leachate	19.1 %	9.0 %
Migratory gulls	22.4 %	0.9 %
Sockeye salmon carcasses	0.8 %	0.4 %

*Data from Putt et al. 2019

Table 2. Average ($\pm$ SE) of contemporary (2014-2015) physico-chemical and biological variables of Cultus Lake, British Columbia for mixed (December-April) and stratified (May-November) periods; a) Water column parameters: Schmidt stability index (SSI), surface temperature, hypolimnetic dissolved oxygen (DO) and Secchi depth; b) Epilimnetic and c) Metalimnetic nutrients (total phosphorus (TP), total nitrogen (TN) and dissolved inorganic nitrogen (DIN)), mass DIN:TP, chlorophyll *a* and cyanobacterial biomasses for the euphotic zone.

Variables	Mixed	Stratified
a) Water column variables		
SSI (J m^{-2})	192.3 (9.9)	1862.1 (125.1)
Surface temp. ($^{\circ}\text{C}$)	6.0 (0.3)	18.3 (0.6)
Hypolimnetic DO at 30 m depth (mg L^{-1})	10.5 (0.2)	8.0 (0.3)
Secchi depth (m)	6.4 (0.2)	8.5 (0.2)
b) Epilimnion – euphotic zone		
TP ($\mu\text{g L}^{-1}$)	7.3 (0.3)	4.8 (0.5)
TN ($\mu\text{g L}^{-1}$)	259.36 (5.6)	186.1 (8.1)
DIN ($\mu\text{g L}^{-1}$)	131.7 (5.1)	32.3 (10.9)
Mass DIN:TP	18.2 (0.8)	8.7 (3.4)
Chl <i>a</i> ($\mu\text{g L}^{-1}$)	2.1 (0.3)	2.0 (0.3)
Cyano biomass ($\mu\text{g L}^{-1}$)	1.0 (0.5)	32.2 (7.5)
c) Metalimnion – euphotic zone		
TP ($\mu\text{g L}^{-1}$)	-	7.3 (0.5)
TN ($\mu\text{g L}^{-1}$)	-	229.4 (9.2)
DIN ($\mu\text{g L}^{-1}$)	-	58.3 (11.8)
Mass DIN:TP	-	9.6 (2.3)
Chl <i>a</i> ($\mu\text{g L}^{-1}$)	-	4.1 (0.6)
Cyano biomass ($\mu\text{g L}^{-1}$)	-	36.2 (9.3)

Figures captions

Figure 1. Location of Cultus Lake and its watershed. Cultus Lake, indicated by the blue triangle, is located at about ~50 km east of the outer limit of the Greater Vancouver Regional District, British Columbia, Canada. The star in the lake indicates the coring site. Major creeks, roads, residential communities are shown on the map as well as other relevant sites. Geographic features were retrieved from Geo BC (2017), the digital elevation map from Lehner et al. (2008), and the basemaps from ESRI Canada (2017) and ESRI et al. (2017) for Canada and USA, respectively.

Figure 2. (a) Time series of annual average of regional air temperatures. The grey line and the black line represent the actual air temperatures and the 4-year moving average, respectively. The light grey zones represent the two periods of regional climate warming: 1923-1944 CE and 1977-2008 CE. (b) Boxplots of annual average of regional air temperatures for different periods showing the two regional climate warming periods.

Figure 3. Contemporary time series for 2014 and 2015 of (a) mass dissolved inorganic nitrogen:total phosphorus ratio (DIN:TP), (b) biomasses of cyanobacteria, (c) biomasses of diatoms and, (d) relative abundance of microfossils diatoms in sediment traps (from July 2014 to June 2015 CE). Probabilities of P limitation are indicated in (a) by a dashed line for 50 % threshold (i.e., DIN:TP mass ratio of 2.2) and dotted lines for 25 % and 75 % (i.e., DIN:TP mass ratio of 1.5 and 3.4, respectively).

Figure 4. Centennial time series for sedimentary (a) carbon:nitrogen (C:N) molar ratio, (b) $\delta^{15}\text{N}$, (c) 1st PCA axis of sedimentary pigment data (explaining 55 % of the total variation),

(d) 1st PCA axis of diatom community (explaining 38 % of the total variation), (e) cladoceran fluxes, (f) bosminid carapace length, (g) *Daphnia* spp. post-abdominal claw length, and (h) sockeye salmon historical escapement. The dashed lines represent the breaks identified by CONISS followed by broken-stick analyses, which were done on each indicator group separately. The dates older than 1879 (± 66) CE should be interpreted with care as they are beyond the unsupported ^{210}Pb .

Figure 5. Centennial time series of sedimentary pigment concentrations (nmol of pigment g⁻¹ sediment C) representing siliceous algae and some dinoflagellates (fucoxanthin, diatoxanthin), all algae (*b*-carotene, Chl *a*, pheophytin *a*), total cyanobacteria (echinenone), Nostocales cyanobacteria (canthaxanthin), and UV index (ratio of fossil UV-radiation-specific pigment (compound A) and fossil carotenoid pigments (alloxanthin, lutein+zeaxanthin and diatoxanthin); Leavitt and Hodgson 2001). The dashed lines represent the breaks identified by CONISS followed by a broken-stick analyses. The dates older than 1879 (± 66) CE should be interpreted with care as they are beyond the unsupported Pb^{210} .

Figure 6. Centennial time series of predominant diatom subfossils (> 5 % relative abundance). The dashed lines represent the breaks identified by CONISS followed by a broken-stick analyses. The dates older than 1879 (± 66) CE should be interpreted with care as they are beyond the unsupported ^{210}Pb .

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

[Click here to view linked References](#)

Gauthier et al. 2020; JoPL

Electronic Supplementary Material 1 – Reconstruction of Cultus Lake surface water temperature

To reconstruct the epilimnetic temperatures of Cultus Lake since the late 1800s, air temperature from Agassiz meteorological station (ID 1100120; (http://climate.weather.gc.ca/historical_data) were used. These latter climate data were used because the records of Cultus Lake station do not go back as far in time. Agassiz is located ~20 km north-east of Cultus Lake and average temperatures from both meteorological stations are highly correlated ($R^2 = 0.99$). A linear regression between the contemporary upper column (0-5 m) water temperatures (2001-2002 CE from Shortreed and 2009-2016 CE unpublished data, DFO Lakes Research Program) and corresponding air temperatures was applied and used to estimate the upper water column temperatures of the entire record. As the lake heat budget is affected by other factors than local air temperature (i.e., radiative and non-radiative heat exchange processes), the upper column water temperatures is likely to respond with a delay in relation to air temperatures (Livingstone and Lotter 1998). Consequently, to reconstruct the water temperatures, the air temperatures were associated with the water temperatures a month later in the linear regression (data on a monthly basis; $R^2 = 0.89$; p-value < 0.001; Fig. ESM1).

Figure ESM1. Upper column (0-5 m) water temperatures in relation to air temperatures. The data of the air temperatures were associated with the water temperatures a month later. The dotted lines represent the 95 % confidence intervals and the dashed lines represent the 95 % prediction intervals.

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Electronic Supplementary Material 2 – History of the Cultus Lake watershed

Table ESM2.1 Time of important historical events and disturbances (anthropogenic and climate) in Cultus Lake watershed from ~1850 to present. Anthropogenic disturbances are classified as agriculture, mining, recreation, logging, forest fire, development (related to human expansion in the area). The anthropogenic activities related to salmon research and manipulation are also included in the table.

Year(s)	Event/Disturbance	Category	Ref.
~5000 years ago	Evidence of Chilliwack and Cultus Lake watershed use by First Nations		1
1858	Beginning of Gold rush Use of the trails from Washington state to Cultus Lake.	Mining	2
1859 / 1860	US/Canada border laid out by Royal Engineers.	Development	3
1870 - 1880	Camping at Cultus Lake	Recreation	4
1887	Establishment of the first families in the Columbia Valley	Development	3
1900	Start of logging in the area surrounding Cultus Lake. A road was built for logging that opened the access to Cultus Lake.	Logging	2
1901	Columbia Valley first school established	Development	5
1906	First post office in Columbia Valley – Lindell post office	Development	5
1910	The British Columbia Electric Railway (BCER) completed the construction of a railway line that followed the base of Vedder Mountain along the shore of Sumas Lake.	Development	3
1910	Access to Columbia Valley via Maple Fall (WA, USA) Maple Fall as a booming logging and mining town	Mining / Logging	6
1910	First BC Electric Railway train arrived in Chilliwack (Sardis station). From October 1910 to September 1950, the railway between Chilliwack and Vancouver was running.	Development	7
Prior to 1912	From oral history: “The road was built prior to June 1912” (see p. 35 in Cramer 1992).	Development	5
1912	Provincial government reported that a salmon hatchery would be established around Cultus Lake. Cultus Lake was considered one of the best spawning ground in the Fraser River.	Salmon	2, 8
	- 60,000 sockeye salmon fry released in Cultus Lake - 75,000 sockeye fry released in Sumas lake		
1912	7 additional hatcheries in operation at the end of the year for a total of 58 in operation in BC	Salmon	9
	Millions of sockeye and coho eggs were collected from Sweltzer creek for the Bon Accord and Harrison Lake hatcheries.		
1916	Opening of the salmon hatchery.	Salmon	2

	The hatchery was located on eastern corner of Sweltzer Creek bridge along Columbia Valley Hwy (main hatchery building now the community hall).		
1917	Columbia Valley first school burnt	Fire	5
1919	Second school built in the Columbia Valley established by Campbell River Co. for the children of the workers	Development	5
1920s	Logging reached its peak in the 1920s Connections between Cultus Lake and Chilliwack was established in 1916 when a wagon road was pushed along the lakeside (logging railroad). Campbell River Logging Company commenced logging in the Valley early in the 1920s.	Logging	5, 10
1920s	By the early 1920s, a timber lease of several thousand acres of timbered land in Columbia Valley was purchased. Logging operations in the valley began in 1922 under the name “The Campbell River Timber Co.”; company that logged most of the lower regions of the Columbia Valley.	Logging	5
1920	First permanent housing started to appear around Cultus Lake	Development	2
1924	Park of Cultus Lake created and officially opened on Aug. 6 – park board acquired 63.8 acres Brought establishment of general store, bath house, boats	Recreation	2, 11
1924	The old wagon road became unsuitable for the new cars and the railroad on the Canadian side was abandoned.	Development	5
1924	Forest fire breaking out on the logged-off areas of the timber limits of the Campbell Mills Ltd that destroyed the school at Lindell beach	Fire	5, 12
1925	R. Earl Foerster came to run the hatchery and proposed to establish a research field station.	Salmon	2
1926	Establishment of the research station proposed by Foerster	Salmon	2
1926	Thousands of sockeye salmon marked in Cultus Lake.	Salmon	13
1926	2,000 acres land logged off lands in the Columbia Valley, which burned early in the previous last fall. Opportunity to seed the land for agriculture.	Logging / Fire	14
Late 1920s – early 1930s	Stump farming starts in the Columbia Valley: Opportunity for farming emerged and people removed the stumps by setting them on fire. Major cause of fire in the region.	Fire	5
1930	Golf course built; abandoned in 1933	Recreation	2
1931	Cultus Lake considered as favorite playground of British Columbia	Recreation	15
1932	Cultus Lake Park Board formed	Recreation	4
1932	Vedder Logging Company logged from 1932 to 1940 on Vedder Mountain and along Chilliwack River	Logging	5
1934	Sockeye eggs taken as salmon enter Cultus Lake. Harrison lake hatchery has been reopened and eggs are taken daily by truck from Cultus to a maximum of 20 million eggs (capacity of the Harrison hatchery).	Salmon	16
1934	Devil’s corner on Cultus Lake road was abandoned and a new road was constructed.	Development	4, 17

Mid-1930s	By the mid-1930s, several acres of land were cleared from stumps and small farms were developed.	Agriculture	5
1937	Space for additional cars in the parking lot provided and Maple trees planted adjacent to the recreational playground.	Recreation	18
1937	Preparations for cutting of 150 million feet of timber in Vedder Mountain limits by Vedder River Logging Co. Logging railway line being built on the north side of the hill of Vedder mountain.	Logging	19
1938	Roller skating rink built (where the tennis courts are today).	Recreation	2
1939	Pavilion built for stores and dance hall; dismantled in 1990 280 cottage owners, almost all summer residents	Recreation	2
1940s	As the community of Lindell Beach established, Frosst Creek was diverted from the middle of the beach to the west side of the beach.	Development	20
1940s	Increasing of permanent populations in Cultus Lake	Development	2
1940s	Growth of the dairy industry in the Columbia Valley Clearing of the land for the expansion of the dairy industry The valley prospered from that industry in the 1950s.	Agriculture	5
1942	During 2 nd World War, training base established at Vedder Crossing; receiving over 6,000 troops Cultus Lake evolved from a summer resort to a community	Development	2, 4
1942	Logging around Teapot Hill; camp located near Frosst Creek	Logging	5
1948	Cultus Park board acquired 35 acres from a property called Sunnyside because Westminster Mills failed and closed.	Recreation	2
1948	Fraser Valley flood – Vedder Crossing particularly affected	Climate	2
1948	Creation of Cultus Lake provincial park	Recreation	2, 21
1949	\$25,000 invested into the trout hatchery at Smith falls	Salmon	22
1950s	During the 1950s and 1960s, the dairy industry was the major source of income of the Columbia Valley until 1969 when the farm storage of milk had to be in stainless steel tanks. By 1974, only 2 dairy farms in Columbia Valley	Agriculture	5
1950	Lake froze over the winter. Subsequent melt waters flooded part of the lake.	Climate	2
1951	Forest fire from Columbia Valley (starting point) to north and west along the mountain; burnt west to north-west of Lindell beach, high above Cultus Lake	Fire	23
1951	A little gravel road on the side of the lake went through the Columbia Valley.	Development	24
1953	3 room school built in Cultus Lake	Development	2
1955	10 miles of light and power line extension from Lindell Beach into the Columbia Valley	Development	24
1956	Hydro power reached the Columbia Valley	Development	5

1956	167,000 visitors to Cultus Lake during the year	Recreation	26
1957	Road improvements in the Columbia Valley	Development	5
1957	Marked trout returned to Sweltzer Creek Fish were released from Sweltzer Creek in March 1954, 1955 and 1956; a total of 20,000 fish were released	Salmon	27
1957	Recreational demand in Cultus Lake growing rapidly 180 units addition to Cultus campsites	Recreation	28
1958	Telephone reached the Columbia Valley	Development	5
1958	Brush fire swept through 15 acres of hay field surrounding Sardis	Fire	29
1960	~3,000 fish were accidentally killed by the poison released to combat swimmer's itch The fish killed were part of a scientific experiment conducted by Fisheries and Oceans Canada (DFO) and they lost essential data for their experiment.	Salmon	30
1961	34 acres of bush transformed into campsites and fishing area around Cultus Lake	Recreation	31
1962	Cultus Lake Salmon Research lab built – deal with all salmon species	Salmon	2
1970	Lakeside Marina built on site of former provincial trout hatchery	Development	2
1974	The former hatchery became the community hall after renovation.	Development	32
1979	Twister-like wind wrecks road and houses in Cultus Lake.	Climate	33
1983	Public participated in lake milfoil control campaign.	Invasive species	34
1985	Cultus Lake Water Park and Waterslides built	Recreation	2
1988	New plaza built, burnt down and rebuilt the same year	Development	2
1990	Golf course established; 40 acres golf course opened near Sunnyside campground	Recreation	2, 35
2001	Cultus Lake Salmon Research lab turned into a fish hatchery. In 2000-2001, <i>Parvicapsula minibicornis</i> disease attacking fish kidney caused mortalities in 2/3 of the Cultus Lake sockeye salmon spawners. The sockeye run was earlier that year, which let the time for the disease to kill spawners before they spawned.	Salmon	36
2002	Fish came back early and died before spawning from the same disease than the previous years; problem everywhere in the Fraser Valley	Salmon	37
2002	DFO officials approved native commercial fisheries	Salmon	38, 39
2003	Earlier and earlier run of sockeye coming back to Cultus Lake	Salmon	40
2004	Tagging pikeminnow to know their abundance in the lake; pikeminnow are predators of sockeye fry	Salmon	41

2004	Sockeye fishery had to be closed to protect the Cultus Lake run.	Salmon	42
2004	Cultus Lake sockeye salmon population designated as endangered by COSEWIC, but not federally protected under the Species at Risk Act (SARA) because of high socio-economic cost.	Salmon	43
2005	460 permanent residents and seasonal owners around Cultus Lake	Development	2
2005	Activities at the Vedder Mountain quarry approved by the Ministry of Energy and Mines the previous summer. Amendment to the mining license allows removal of up to 245,000 tonnes/year.	Development	44
2006	Milfoil removal program – \$40,000 invested for this project	Invasive species	45
2007	Northern pikeminnow removal – goal of 18,000 fish removal because they prey on sockeye fry	Invasive species	46
2007	Plan for expansion of Cultus Lake water park approved by Cultus Lake park board	Recreation	47

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Table ESM2.2. Year and burnt area (m²) of each forest fire occurred in the Cultus Lake watershed from 1920 to 2013 along with the cause and geographic coordinates. Data accessed iMapBC application online*.

Fire ID [§]	Year	Cause	Area burned (m ²)	Latitude	Longitude
16	1935	Human	54520.27	49.03670	122.03423
21	1931	Human	4251715.41	49.02094	122.03442
48	1935	Human	76545.54	49.01202	122.03171
49	1935	Human	11263.82	49.02868	122.02415
79	1938	Human	7669919.54	49.02716	122.99853
85	1934	Human	93137.02	49.02717	122.02687
137	1941	Human	693629.36	49.06421	122.00918
227	1934	Human	3525593.28	49.04256	122.06361
252	1947	Human	3350.64	49.03316	122.03882
266	1941	Human	2757985.42	49.05415	122.02527
381	1938	Human	45335.25	49.01391	122.03989
425	1946	Human	699076.53	49.04530	121.92938
651	1938	Human	25341.82	49.06539	122.01846
55a	1932	Human	27040.52	49.02406	122.02183
V00009	1956	Human	1388892.33	49.01374	122.07086
V00009	1956	Human	1531585.93	49.01680	121.94346
V00056	1951	Human	2745442.25	49.07910	121.95421
V00088	1951	Human	20356520.51	49.03715	122.06015
V00309	1958	Human	250799.77	49.01258	121.97270
V00427	1965	Human	1397545.23	49.01306	122.10718
V10027	1982	Human	130856.39	49.04033	122.01999
V10048	1987	Human	1120116.05	49.03999	122.02503
V10050	1987	Human	312602.27	49.04507	122.03544
V10050	1987	Human	612680.40	49.02883	122.08921
V10217	2013	Human	20017.26	49.04504	122.00760

*Province of BC. Data from iMapBC application.

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§ Fire IDs are from the iMapBC application.

Electronic Supplementary Material 3 – Historical and contemporary limnological parameters

Figure ESM3. Boxplots of comparable limnological variables between historical and contemporary monitoring of Cultus Lake. (a) Average water temperature at 0-10 m; (b) Average water temperature at 20-40 m; (c) Schmidt stability index; (d) Dissolved oxygen at 30 m. The periods of limnological monitoring compared are: 1) 1927-1929 CE; 2) 1932-1937 CE; 3) 2001-2003 CE; 4) 2009-2011 CE, and 5) 2014-2015 CE.

Table ESM3. Seasonal average ($\pm$ SE) of contemporary (2014-2015 CE) physico-chemical and biological parameters of Cultus Lake, British Columbia for winter (December to February), spring (March to May), summer (June to August) and autumn (September to November); a) Water column parameters: Schmidt stability index (SSI), surface temperature, temperature at 30 m, hypolimnetic dissolved oxygen (DO) and euphotic zone depth; b) Epilimnetic and c) Metalimnetic nutrients (total phosphorus (TP), total nitrogen (TN) and dissolved inorganic nitrogen (DIN)), chlorophyll *a* and cyanobacterial biomasses for the photic zone (measured with a Secchi disk). NA in the table means that the SE could not be calculated as only one measurement was available for the given period.

Parameters	Winter		Spring		Summer		Autumn	
	2014	2015	2014	2015	2014	2015	2014	2015
a) Water column parameters								
SSI (J m^{-2})	170.9 (0.9)	171.6 (2.8)	359.5 (148.7)	424.9 (193.4)	796.3 (459.7)	673.9 (389.1)	1838.7 (490.6)	1649.4 (359.5)
Surface temp. ($^{\circ}\text{C}$)	5.3 (0.6)	6.3 (0.7)	8.2 (2.5)	8.9 (2.0)	20.7 (2.1)	22.3 (1.4)	17.6 (2.4)	16.4 (1.8)
Temp. 30m ($^{\circ}\text{C}$)	5.3 (0.6)	6.2 (0.8)	4.4 (0.2)	6.0 (0.2)	5.0 (0.1)	6.6 (0.1)	5.3 (0.1)	6.7 (0.1)
Hypo. DO (mg L^{-1})	10.4 (0.6)	9.7 (1.1)	11.5 (0.3)	10.2 (0.6)	9.3 (0.6)	8.3 (0.3)	7.6 (1.0)	5.9 (0.4)
Euphotic zone depth (m)	5.4 (0.2)	7.0 (0.4)	8.2 (1.2)	7.4 (1.1)	8.1 (0.7)	7.5 (0.8)	8.9 (0.2)	8.6 (0.7)
b) Epilimnion – photic zone								
TP ($\mu\text{g L}^{-1}$)	7.6 (0.4)	7.9 (0.1)	5.4 (1.7)	5.8 (1.0)	4.2 (0.5)	4.0 (0.6)	4.9 (0.7)	7.1 (1.0)
TN ($\mu\text{g L}^{-1}$)	240.2 (0.3)	270.8 (7.5)	235.3 (14.7)	253.8 (26.1)	159.3 (12.5)	211.1 (6.7)	155.9 (14.3)	206.5 (12.2)
DIN ($\mu\text{g L}^{-1}$)	124.8 (4.1)	144.7 (8.2)	108.4 (12.5)	135.0 (3.7)	38.9 (24.8)	19.6 (11.7)	9.7 (4.2)	8.8 (4.3)
Chl <i>a</i> ($\mu\text{g L}^{-1}$)	1.5 (0.1)	1.6 (0.4)	2.3 (1.0)	2.5 (0.2)	1.9 (0.5)	2.8 (1.6)	1.8 (0.2)	1.8 (0.2)
Cyano biomass (mg m^{-3})	2.5 (1.3)	0.8 (0.7)	0	0.1 (0.1)	49.0 (9.8)	66.3 (16.5)	24.0 (1.8)	11.1 (1.0)
c) Metalimnion – photic zone								
TP ($\mu\text{g L}^{-1}$)	-	-	3.8 (NA)	5.7 (NA)	7.0 (0.7)	7.2 (0.7)	7.5 (0.9)	9.2 (0.6)
TN ($\mu\text{g L}^{-1}$)	-	-	192.0 (NA)	281.9 (NA)	217.3 (7.9)	241.0 (12.9)	223.5 (29.7)	230.5 (24.1)
DIN ($\mu\text{g L}^{-1}$)	-	-	85.8 (NA)	155.4 (NA)	64.1 (26.4)	39.1 (23.2)	56.48 (19.4)	32.1 (19.8)
Chl <i>a</i> ($\mu\text{g L}^{-1}$)	-	-	2.19 (NA)	2.7 (NA)	4.1 (1.3)	7.2 (1.4)	3.6 (1.2)	2.8 (0.9)
Cyano biomass (mg m^{-3})	-	-	0 (NA)	0.6 (NA)	58.0 (34.2)	42.1 (5.1)	49.1 (21.3)	19.2 (7.3)

Electronic Supplementary Material 4 – Sediment age calculation

The constant rate of supply (CRS) was used to determine age of every interval measured with ^{210}Pb following Binford (1990). The unsupported ^{210}Pb reached a negative value at the interval 22.75–23 cm, which defined the background level and subsequent intervals were removed from the sediment age calculation (the three deepest sediment intervals were removed). The confidence intervals of the sediment age were determined following Binford (1990).

Two different polynomial fits were applied through the top of the core to calculate the sediment age, one of 2nd order and one of 3rd order. To select the best sediment core age-depth model to calculate the age through the core, the Bayesian Information Criterion (BIC) was calculated for each model. Even though the 3rd order polynomial fit was identified as the best model (103.05 for the 2nd order polynomial versus 96.37 for the 3rd order polynomial), an average of both models was calculated to accurately extrapolate the sediment age beyond the background level. The age of each interval was then calculated with this model from the top to the bottom of the core.

Figure ESM4. The radioisotopic ^{210}Pb age model for the gravity core of Cultus Lake, British Columbia, Canada. (a) Unsupported ^{210}Pb activity with core depth. All the data shown here were used for the sediment age calculations. The sediment intervals below 20 cm are not illustrated in the figure as they are beyond the ^{210}Pb background level. (b) Correlation between cumulative dry mass and unsupported ^{210}Pb . (c) Sediment core age-depth model based on both 2nd polynomial fit ($\text{BIC} = 103.05$; $R_{\text{adj}}^2 = 0.98$; open circle) and 3rd polynomial fit ($\text{BIC} = 96.37$; $R_{\text{adj}}^2 = 0.99$; open triangle). The line represents the average between the two polynomial models and the black square are the ^{210}Pb dates from the CRS model. The calculated ^{210}Pb date corresponds well with the ^{137}Cs peak (occurring at 12.375 cm; shown by the circled X).

Table ESM4. CRS model estimated sediment age and age error of each dated interval throughout the core.

Interval (cm)	Estimated year	Age error (year)
0-0.5	2007.96	3.39
1-1.5	2006.48	3.44
3.25-3.5	2001.52	3.69
4.75-5	1995.66	4.06
6.25-6.5	1989.57	4.51
7.75-8	1984.15	4.95
9.25-9.5	1978.05	5.55
10.75-11	1971.00	6.41
12.25-12.5	1962.62	7.72
13.75-14	1951.97	9.88
15.25-15.5	1940.96	12.77
16.75-17	1932.55	15.29
18.25-18.5	1918.14	21.73
19.75-20	1879.07	65.96

Cladoceran remain flux calculations

1- Calculation of sediment rate

$$\text{Sedimentation rate (cm yr}^{-1}\text{)} = (\text{Depth sediment interval } x + 1 / \text{Depth sediment interval } x) / (\text{Date sediment interval } x / \text{Date sediment interval } x + 1)$$

To calculate the sedimentation rate, the average date from the 2nd and 3rd order polynomial models was used.

2- Calculation of cladoceran remain concentration

$$\text{Remain concentration (\# cm}^{-3}\text{)} = \# \text{ remains} / (\text{g sediment analyzed} / \text{sediment density (g cm}^{-3}\text{)})$$

3- Calculation of remain flux

$$\text{Remain flux (\# cm}^{-2} \text{ yr}^{-1}\text{)} = \text{remain concentration (\# cm}^{-3}\text{)} / \text{sed. rate (cm yr}^{-1}\text{)}$$

Electronic Supplementary Material 5 – Diatom taxa grouped for Principal Component Analysis

Table ESM5. Taxa groups prior to Principal Component Analysis (PCA); a) Species with a relative abundance $\geq 1\%$ in at least three different intervals; b) Other species grouped by morphological and functional groups to have a relative abundance $\geq 1\%$ in at least three different intervals.

Groups	
a) Species abundance $\geq 1\%$ in at least 3 different intervals	
1.	<i>Achnanthyidium minutissimum</i> (Kützing) Czarnecki 1994
2.	<i>Amphora pediculus</i> (Kützing) Grunow in Schmidt et al. 1875
3.	<i>Asterionella formosa</i> Hassall 1850
4.	<i>Aulacoseira ambigua</i> (Grunow) Simonsen 1979
5.	<i>Aulacoseira subarctica</i> (Otto Müller) Haworth 1990
6.	<i>Lindavia comensis</i> (Grunow) Nakov, Guillory, M.L. Julius, E.C.Ther. and A.J.Alverson 2015 (previously <i>Cyclotella comensis</i> Grunow in Van Heurck 1882)
7.	<i>Lindavia michiganiana</i> (Skvortzov) Nakov, Guillory, M.L. Julius, E.C.Ther. and A.J.Alverson 2015 (previously <i>Cyclotella michiganiana</i> Skvortzow 1937)
8.	<i>Discostella stelligera</i> (Cleve and Grunow) Houk and Klee 2004 / <i>Discostella pseudostelligera</i> (Hustedt) Houk and Klee 2004
9.	<i>Lindavia intermedia</i> (Manguin ex Kociolek and Reviere) Nakov et al. ex Daniels et al. 2016 (previously <i>Cyclotella bodanica</i> var. <i>intermedia</i> Manguin ex Kociolek and Reviere 1996)
10.	<i>Pseudostaurosira brevistriata</i> (Grunow) D.M.Williams and Round 1987
11.	<i>Stephanodiscus medius</i> H. Håkansson 1986
12.	<i>Stephanodiscus minutulus</i> (Kützing) Cleve & Möller 1882 / <i>Stephanodiscus parvus</i> Stoermer & Håkansson 1984
b) Grouped taxa to reach $\geq 1\%$ in at least 3 different intervals	
13.	Assymetrical biraphids (<i>Amphora pediculus</i> excluded) <i>Amphora copulata</i> / <i>Amphora minutissima</i> / <i>Amphora ovalis</i> / <i>Amphora</i> sp. / <i>Cymbella cymbiformis</i> / <i>Cymbella frequens</i> / <i>Cymbella</i> c.f. <i>turgida</i> / <i>Encyonema minutus</i> / <i>Encyonema</i> sp. / <i>Encyonopsis descripta</i> / <i>Encyonopsis subminuta</i> / <i>Gophonema angustatum</i> / <i>Halampahora thumensis</i> / <i>Hippodonta capitata</i> / <i>Hippodonta hungarica</i> / <i>Hippodonta</i> sp. / <i>Rhoicosphenia</i> sp.
14.	Symmetrical biraphids <i>Amphipleura pellucida</i> / <i>Brachysira neoexilis</i> / <i>Cavinula scutelloides</i> / <i>Craticula riparia</i> / <i>Diploneis elliptica</i> / <i>Diploneis onbologella</i> / <i>Eolimna</i> sp. / <i>Geissleria acceptata</i> / <i>Navicula cryptocephala</i> / <i>Navicula cincta</i> / <i>Navicula crytotenella</i> / <i>Navicula menisculus</i> var. <i>upsaliensis</i> / <i>Navicula onbologa</i> / <i>Navicula praeterita</i> / <i>Navicula radiosa</i> / <i>Navicula</i> c.f. <i>uteroehlii</i> / <i>Navicula viridula</i> / <i>Navicula vulpina</i> / <i>Navicula</i> sp. / <i>Pinnularia</i> sp. / <i>Stauroneis</i> c.f. <i>anceps</i> / <i>Stauroneis</i> sp.
15.	Monoraphids (<i>Achnanthyidium minutissimum</i> excluded) <i>Achnanthyidium exiguum</i> / <i>Achnanthyidium</i> c.f. <i>kriegeri</i> / <i>Achnanthyidium pyrenaicum</i> / <i>Achnanthyidium rivulare</i> / <i>Achnanthyidium</i> c.f. <i>rosenstockii</i> / <i>Achnanthyidium subhudsonis</i> / <i>Cocconeis neothumensis</i> / <i>Cocconeis placentula</i> / <i>Cocconeis pseudothumensis</i> / <i>Gliwiczia</i> c.f. <i>calcar</i> / <i>Karayevia clevei</i> / <i>Karayevia laterostrata</i> / <i>Karayevia</i> sp. / <i>Karayevia</i> c.f. <i>suchlandtii</i> / <i>Planothidium</i> sp. / <i>Planothidium conspicua</i> / <i>Planothidium dubium</i> / <i>Planothidium frequentissimum</i> / <i>Planothidium haynaldii</i> / <i>Planothidium hustedtii</i> / <i>Planothidium joursacence</i> / <i>Planothidium</i> c.f. <i>stewartii</i> / <i>Planothidium zeigleri</i> / <i>Psammothidium</i> c.f. <i>curtissimum</i> / <i>Rossithidium pusillum</i>
16.	Small araphids <i>Diatoma mesodon</i> / <i>Pseudostaurosira neoelliptica</i> / <i>Pseudostaurosira parasitica</i> / <i>Pseudostaurosira robusta</i> / <i>Punctastriata</i> c.f. <i>pinnata</i> / <i>Staurosira construens</i> / <i>Staurosira construens</i> var. <i>binodis</i> / <i>Staurosira construens</i> var. <i>venter</i> / <i>Staurosirella lapponica</i> / <i>Staurosirella leptostauron</i> / <i>Staurosirella martyi</i> / <i>Staurosirella pinnata</i>
17.	Long araphids <i>Fragilaria capucina</i> / <i>Fragilaria crotonensis</i> / <i>Fragilaria gracilis</i> / <i>Fragilaria mesolepta</i> / <i>Fragilaria nanana</i> / <i>Fragilaria radians</i> / <i>Fragilaria</i> sp. / <i>Fragilaria syngrotesca</i> / <i>Fragilaria tenera</i> / <i>Fragilaria vaucheriae</i> / <i>Hannea arcus</i> / <i>Synedra cyclopum</i> / <i>Synedra</i> c.f. <i>famelica</i> / <i>Tabularia fasciculata</i> / <i>Tabellaria fenestrata</i>
18.	Other benthics <u>Epithemioid</u> : <i>Epithemia adnate</i> / <i>Epithemia</i> c.f. <i>sorex</i> / <i>Rhopalodia gibba</i> / <i>Denticula tenuis</i> <u>Nitzschoid</u> : <i>Nitzschia</i> c.f. <i>gracilis</i> / <i>Nitzschia communis</i> / <i>Nitzschia fonticola</i> / <i>Nitzschia recta</i> / <i>Nitzschia paleo</i> var. <i>tenuirostris</i> / <i>Nitzschia sinuata</i> var. <i>tabellaria</i> / <i>Tryblionella</i> sp. <u>Surirelloid</u> : <i>Entomoneis paludosa</i> / <i>Surirella amphioxys</i> / <i>Surirella</i> sp.

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Electronic Supplementary Material 6 – Results from CONISS analysis on geochemical data

Figure ESM6. Dendrogram from CONISS analysis on geochemical data (molar C:N ratios, $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$). The red boxes indicate the zones identified by the broken-stick model.

Electronic Supplementary Material 7 – Boxplots of paleolimnological indicators for different time periods

Figure ESM7. Boxplots of paleolimnological indicators for different time periods: 1) 1892-1922 CE, 2) 1923-1944 CE; 3) 1945-1976 CE; 4) 1977-2008 CE. (a) Sedimentary pigment echinenone; (b) Bosminid fluxes; (c) *Daphnia* fluxes; (d) Bosminid carapace length; (e) *Daphnia* post-abdominal claw length. The numbers besides each box represent the sample size. The sample size for cladoceran data are only indicated in (b) as they are the same for all the cladoceran data.

Electronic Supplementary Material 8 – Entire sediment record for indicators used

Figure ESM8.1 Entire sediment record for geochemical indicators. (a) % carbon, (b) % nitrogen, (c) molar carbon:nitrogen, (d) $\delta^{13}\text{C}$, (e) $\delta^{15}\text{N}$. The dashed lines represent the breaks identified by CONISS analyses. The dates older than 1879 (± 66) CE should be interpreted with care as they are beyond the unsupported Pb^{210} .

Figure ESM8.2 Entire sediment record of all measured sedimentary pigment concentrations (nmol of pigment g⁻¹ sediment C) and UV index (ratio of fossil UV-radiation-specific pigment (compound A) and fossil carotenoid pigments (alloxanthin, lutein+zeaxanthin and diatoxanthin)). The dates older than 1879 (± 66) CE should be interpreted with care as they are beyond the unsupported Pb²¹⁰.