# Water Level Drawdown Affects Physical and Biogeochemical Properties of Littoral Sediments of a Reservoir and a Natural Lake

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# Water Level Drawdown Affects Physical and Biogeochemical Properties of Littoral Sediments of a Reservoir and a Natural Lake

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## ABSTRACT

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To determine the influence of water level drawdown on littoral areas, we compared the temporal and spatial changes in the water column and sediment in the littoral region of a drinking water reservoir and a natural lake. The reservoir (Sooke) experiences more than six meters of seasonal drawdown compared to a nearby, morphometrically and trophically similar lake (Shawnigan) that experiences less than one meter of drawdown. A greater drawdown in Sooke increased the littoral area and resulted in more littoral water column mixing, more solar warming, and higher PAR at a greater range of littoral depths than in Shawnigan. Based on sediment physical and chemical characteristics, sites farthest from shore were most similar, whereas sites in the drawdown exposure zone of Sooke and the upper littoral area of Shawnigan showed the largest differences. Low macrophyte abundance and loss of fine sediments, nutrients, and organic matter from the drawdown exposure zone in Sooke compared to the equivalent littoral area in Shawnigan suggest that drawdown enhances sediment erosion and focusing. Element and stable isotope ratios of sediment carbon and nitrogen suggest organic matter in the drawdown zone in Sooke is more allochthonous in origin and is coupled more strongly with deeper sites than in Shawnigan. Organic matter source and distribution also suggests that the littoral area extends out farther in Sooke than Shawnigan. This study demonstrates that drawdown has the potential to fundamentally change reservoir littoral sediment and biogeochemical characteristics. Understanding how littoral zones in reservoirs respond to drawdown compared to natural lakes may help water managers make more ecologically informed decisions regarding drawdown impacts on the ecology of littoral zones and water quality.

Key Words: drinking water reservoir, littoral, sediment, macrophyte, nutrient, organic matter, biogeochemistry, stable isotope.

Fluctuating water level is a major physical process that distinguishes many reservoirs from lakes. Drawdown (the withdrawal or reduction in water volume) affects thermal structure, the light environment, and sediment exposure (c.f. Straškraba et al. 1993). While these changes affect biological, chemical, and physical processes and their interactions in the pelagia, they may have even larger effects on littoral areas. The frequency and extent of drawdown causing little or extensive shoreline exposure can determine the presence or absence of littoral communities (Rodhe 1964) and can affect sediment structure and the supply of nutrients, organic materials, and inorganic materials input from erosion (Baxter 1977). However, few studies have examined the impacts of seasonal water level fluctuation on littoral benthic environments in a storage reservoir by comparing seasonal trends in littoral benthic dynamics

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of a reservoir to the seasonal benthic dynamics of a nearby natural lake.

The littoral zone is the most likely habitat to be affected by reservoir drawdown, including some of the fundamental processes such as decomposition, productivity, and trophic interactions among organisms. Drawdown associated changes in sediment nutrient and organic matter (OM) dynamics may affect decomposition rates, feeding patterns of invertebrates and fish, and benthic-pelagic energy flow dynamics in littoral environments (Baxter 1977, Wiens and Rosenberg 1984, Kennedy and Walker 1990). Furthermore, drawdown induced changes to the distribution of sediments, and sources of OM (i.e., Wiens and Rosenberg 1984, Fabre and Patau-Albertini 1986) may affect littoral sediment biogeochemistry. Terrestrial OM in sediments may increase relative to lake-derived OM in littoral areas where drawdown reduces macrophyte abundance and sediments are repeatedly exposed and re-flooded (Quennerstedt 1958, Wagner and Falter 2002). Differences in allochthonous versus autochthonous sources of OM can shape the elemental stoichiometry of food resources available to benthic consumers and decomposers, altering organism metabolism, growth, and reproduction, thus affecting population dynamics, trophic interactions, and gross transfer efficiencies of the benthos (Frost et al. 2002). The application of biogeochemical tracers, used to differentiate between allochthonous and autochthonous carbon sources (LaZerte 1983, Meyers and Ishiwatari 1993, Peterson 1999), has not been widely used to examine sediment processes in reservoirs and lakes under contrasting drawdown. Characterizing and quantifying how contrasting water level drawdown modifies the structure and biogeochemical composition of littoral sediments and OM will significantly enhance our understanding of lake and reservoir ecosystems.

We assessed the temporal and spatial changes in the littoral water column and sediments of a drinking water reservoir during a seasonal drawdown of over six vertical meters in order to examine the impact of drawdown on the littoral environment. We used a nearby, limnologically and morphometrically similar lake with an average seasonal drawdown of less than 0.5 vertical meters for comparison. We qualitatively described the littoral macrophyte communities of the two water bodies. We measured temporal and spatial changes in temperature, oxygen, and light in the littoral water column, and littoral sediment physical structure and nutrient content. We examined elemental ratios and stable isotopes of sediment carbon and nitrogen (TOC:TON ratio, $\delta^{13}C$, and $\delta^{15}N$) to distinguish between allochthonous and autochthonous sources of OM (LaZerte 1983, Meyers and Ishiwatari 1993, Peterson 1999).

# Materials and Methods

## *Study Sites*

The study sites, Sooke Lake Reservoir (Sooke: 48° 31' 30" N, 123° 42' 0" W) and Shawnigan Lake (Shawnigan: 48° 36' 10" N, 123° 37' 30" W), are located on southern Vancouver Island, British Columbia, Canada (Fig. 1). Sooke and Shawnigan are morphometrically similar and both are oligotrophic (Fig. 1; Table 1). They are in adjacent watersheds (4 km apart at the closest point). Both lie in the Nanaimo Lowland Physiographic region, and are dominated by the Coastal Western Hemlock, Very Dry Maritime biogeoclimatic zone (Demarchi 1993, BC Min. of Forests 1994). The south basin axis of both water bodies is NNW. Sooke and Shawnigan have relatively deep north basins (70 m and 53 m, respectively), and shallower south basins (22 m and 27 m). We compared the reservoir (Sooke) that experiences >6 m of drawdown, to the reference lake (Shawnigan) that experiences small (~0.5 m) seasonal fluctuations in water level. Detailed descriptions of the physical limnology of these water bodies are given elsewhere (Nowlin et al. 2004).

Sooke watershed, which includes the primary reservoir (Sooke) supplying drinking water to the city of Victoria and the region, is a closed watershed with no public access. Sooke Lake Reservoir was created by damming Sooke Lake in 1914, and the water level was raised again in 1971 to the current maximum surface area of 605 ha through the creation of a new dam. Water level typically drops by 6 to 9 m during the summer and fall, and the reservoir refills in the winter and spring as a consequence of rainfall that occurs during this time period. Sooke has epilimnetic water withdrawn into the drinking water system from an intake tower at the south end of the south basin. When the reservoir's water level was raised the second time in 1971, the older dam was left in place and is now submerged immediately in front of the intake tower. In summer and fall, when the reservoir is thermally stratified and the outflow to the drinking water system is greatest (Nowlin et al. 2004), the submerged dam functions as a barrier, causing epilimnetic water only to flow over the submerged dam to the intake tower (Stewart Irwin, Capital Regional District, pers. comm.). The contribution of other water loss processes, such as evaporation and evapotranspiration to the water level fluctuations of Sooke are minimal, when compared to the influence of the removal water for drinking water. In contrast, the relatively small water level fluctuations in Shawnigan are the result of seasonal changes in stream inflow, outflow, evaporation, evapotranspiration, and a relatively small amount of

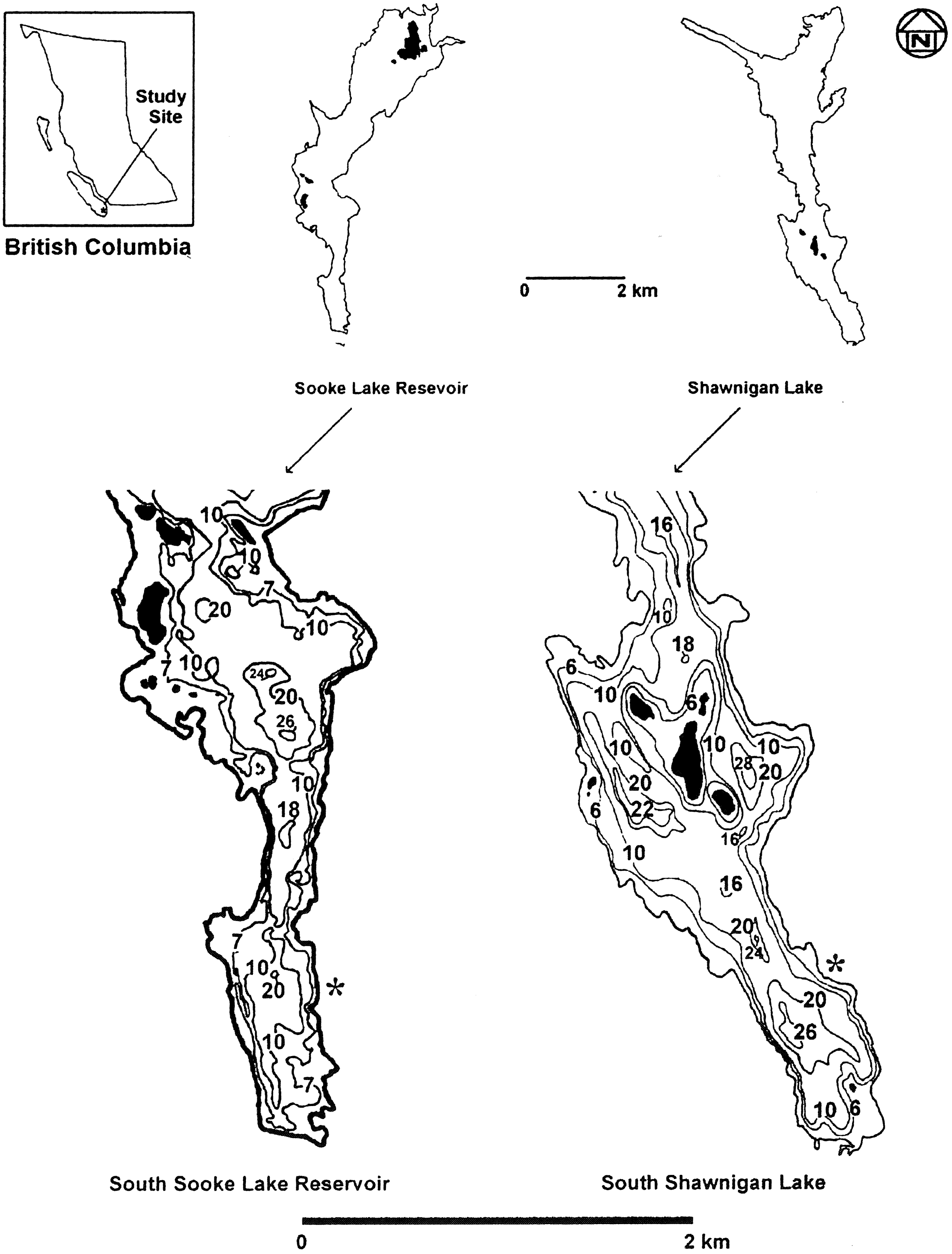

Figure 1.–Location of Sooke Lake Reservoir and Shawnigan Lake in the province of British Columbia. The southern basin of each water body is expanded to show basin bathymetry. The * located on the east shore of the south basin indicates shoreline where transects were placed. Further details on physical characteristics and mean values of selected water column chemical variables are listed in Table 1. Maps were modified from Spafard et al. 2002.

water removal by local water utilities (Nowlin et al. 2004).

## *Sampling Design*

We collected samples from duplicate littoral-pelagic transects along the eastern shore in the southern basin of each water body. We selected sites along the east shore of the south basins for ease of accessibility and similarity of average aspect and slope (< 10%; Figs. 1 and 2A). The effect of slope on sediment characteristics is reduced in lower grade slope areas relative to steep slopes (Håkanson 1982), which allowed us to minimize slope effects in our study. On each transect we established four fixed sampling sites (Sites 1 to 4) at depths of 3.5, 6.5, 9.5, and 12.5 m below the high water level of May 2000 (Fig. 2). Sample collection started in May 2000 when the drawdown in the reservoir was approximately 1 m, and ended in September 2000 when drawdown was approximately 1 m above the average ten-year drawdown level. In both water bodies, we defined the area of sediment exposed and re-inundated during the annual drawdown cycle as the drawdown exposure zone. We sampled four times (23 May, 4 July, 15 August, and 26 September), at each of our sampling sites on each transect. These dates correspond to reservoir drawdown intervals of 1.5 vertical meters (Fig. 2B, C). In each water body, sample collection occurred over a three to four day period.

## *Macrophytes, Water and Sediment Sampling*

Observations and descriptions of the littoral areas and macrophyte communities were made based on a minimum of fifteen hours of SCUBA diving time in each water body. We identified common macrophytes to genus and/or species.

We measured temperature and dissolved oxygen concentration (DO) using a YSI Model 85 at each site on one transect for each sampling period. We determined Secchi depths at the deepest site (Site 4) using a 20-cm diameter black and white disk. Light extinction coefficients (k) were calculated from photosynthetically active radiation (PAR) profiles (Kirk 1994). PAR was measured using flat-plate (cosine-corrected) photocell (Licor Model Li-250). In Sooke, we defined the area from the shoreline at high water level to the compensation depth (1% PAR) at maximum drawdown as the effective littoral zone. In Shawnigan, we defined the area from the shore [land-water interface] to the 1% compensation depth as the littoral zone (Wetzel 1983).

Table 1.–Physical characteristics of Sooke Lake Reservoir and Shawnigan Lake, and mean values of selected water column chemical variables. All concentration values are for the epilimnion during the summer of 2000 (May - September), with the exception of total phosphorus that has values averaged from January - December 2000 to 2001. Nutrients were analyzed following the methods in Standard Methods (APHA 1998) using a Lachat automated ion analyzer (Zellweger Analytics, Quick Chem® 8000).

| | | **Sooke Lake Reservoir** | | **Shawnigan Lake** | |
|---|---|---|---|---|---|
| **Variable** | **Units** | **South Basin** | **Whole Lake** | **South Basin** | **Whole Lake** |
| Elevation | m.a.s.l. | – | 180 | – | 116 |
| Surface area (full stage) | x $10^6$ $m^2$ | 0.45 | 6.05 | 0.57 | 5.52 |
| Mean depth | m | 8.6 | 19.5 | 11.9 | 13.0 |
| Max depth | m | 22 | 70 | 27 | 53 |
| Max length | km | – | 7 | – | 6.9 |
| Max fetch | N-S, km | 1.2 | 5.0 | 1.4 | 5.5 |
| | | **South Basin** | **North Basin** | **South Basin** | **North Basin** |
| Secchi depths | m ± 1 SD | 7.8 (± 1.7) | – | 5.9 (± 0.5) | – |
| Chlorophyll *a* | $\mu g \cdot L^{-1}$ ± 1 SD | 0.6 (± 0.3) | 0.5 (±0.4) | 1.5 (± 0.7) | 1.4 (± 0.7) |
| pH | ± 1 SD | 7.5 (± 0.1) | 7.6 (± 0.2) | 7.5 (± 0.1) | 7.5 (± 0.1) |
| Total inorganic carbon | $mg \cdot L^{-1}$ ± 1 SD | 3.8 (± 0.2) | 3.8 (± 0.2) | 4.0 (± 0.2) | 4.1 (± 0.2) |
| Dissolved organic carbon | $mg \cdot L^{-1}$ ± 1 SD | 2.0 (± 0.2) | 2.0 (± 0.2) | 3.0 (± 0.3) | 3.1 (± 0.3) |
| Total phosphorus | $\mu g \cdot L^{-1}$ ± 1 SD | 3.1 (± 2.5) | 3.3 (± 1.5) | 4.9 (± 1.8) | 4.4 (± 2.1) |
| Total nitrogen | $\mu g \cdot L^{-1}$ ± 1 SD | 70.3 (± 18.3) | 68.3 (± 12.3) | 132.2 (± 29.2) | 129.1 (± 27.0) |

Using SCUBA, we collected the sediment samples with a 10-cm diameter, hand-held corer. We collected three cores at each site on each transect with the exception of 4 July when an additional three cores were collected for sediment particle size distribution and dry bulk density analysis. When taking and handling the cores, extreme care was taken to minimize disturbance at the sediment-water interface. If noticeable disturbance was observed in the core, a new core was taken at a nearby, undisturbed location. To determine particle size distribution and dry bulk density, we analyzed the top 5 cm of sediment pooled from three cores at each site (Pacific Environmental Science Centre (PESC), Environment Canada, Vancouver, BC). Sediment particle size, determined by pipette and dry sieve methods (PESC), was divided into four categories: clay (< 0.002 mm, pipette), silt (< 0.063 and > 0.002 mm, pipette), sand (< 2.00 mm and > 0.053 mm, pipette), and gravel (> 2.00 mm, dry sieve).

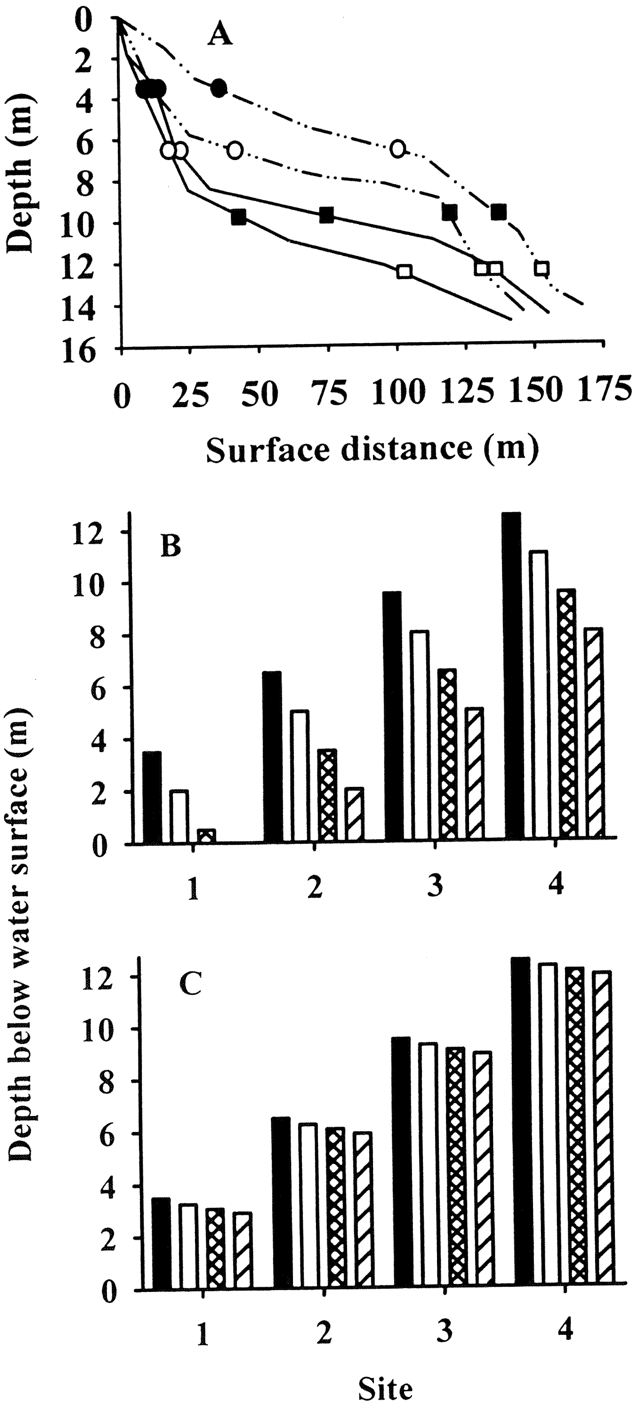

Figure 2.–(A) Slope of littoral-pelagic transects for Sooke (solid lines) and Shawnigan (dash-dot lines). Zero marks the shore (land-water interface). Depth (m) marks distance below water surface from water levels in May 2000. Site 1, closed circle; Site 2, open circle; Site 3, closed square; Site 4, open square. Seasonal depth below water surface (m) at each of the fixed sampling sites in Sooke (B) and Shawnigan (C). Sampling date indicates start date of each sampling period in 2000 (23 May, solid; 04 July, open; 15 August, cross hatch; 26 September, slanted line).

To determine sediment chemistry, we analyzed the top 2 cm of sediment. We dried samples from one core at each site at 60 °C to constant mass, ground the dried sediment with mortar and pestle, and sieved it through a 64 µm mesh. We analyzed the dried sediment for total organic carbon (TOC), total organic nitrogen (TON), $\delta^{13}C$, and $\delta^{15}N$, using an Isochrom Continuous Flow Stable Isotope Mass Spectrometer coupled to a Carl Erba Elemental Analyzer (CHNS-O EA 1108, Environmental Isotope Lab, University of Waterloo, Waterloo, Ontario). Stable isotope ratios were defined as the per mil (‰) deviation from reference standard Pee Dee Belemnite or atmospheric $N_2$. We determined OM (% dry matter [dm]) from three cores at each site by drying sediment samples at 105 °C to constant mass and by ashing at 550 °C for 1 hour. Moisture content was determined prior to ashing samples.

## *Statistical Analysis*

Based upon the experimental design of our study, our initial intent was to compare sediment chemical and physical characteristics (sediment moisture content, TOC, TON, OM, TOC:TON ratios, $\delta^{13}C$, and $\delta^{15}N$) of Sooke and Shawnigan with a repeated measures ANOVA at each site along transects with time as the repeated measure. However, visual examination of the sediment data indicated that the response variables in both lakes did not exhibit variation throughout the duration of the sampling season. To further explore whether time was a significant factor affecting the variation in the response variables, we performed a nested ANOVA (Zar 1999), in which site was nested within lake, and time was nested within site. This analysis allowed us to determine how much of the total variance in each sediment response variable at a site was associated with time. We used variance components to apportion variance to different nested effects. We found that time did not account for a significant component of the variance in moisture content, TOC, TON, OM, TOC:TON ratios, $\delta^{13}C$ (< 0.001% of total variance associated with time, $p > 0.05$), or for $\delta^{15}N$ (< 6.6 % of total variance associated with time, $p > 0.05$). Because time did not account for a significant amount of variance for all response variables, and cores were never taken from the exact same location over the sampling season, we determined that we were justified in using all samples collected from a site over the sampling season as individual replicates, thus increasing the n at each site from 2 to 8.

We made comparisons of the sediment physical and chemical characteristics between sites within a water body in order to determine if sites along the littoral-pelagic transect within a water body differed from each other and if contrasting seasonal drawdown patterns affected littoral-pelagic trends in sediment physical and chemical characteristics. We also made comparisons between the same sites between water bodies (Site 1 in Sooke versus Site 1 in Shawnigan) in order to examine the effects of contrasting drawdown on sediment physical and chemical characteristics at a particular site. To determine whether significant differences existed in the physical or chemical variables at sites within water bodies, we performed a one-way ANOVA with Tukey post hoc pair-wise comparisons if a significant overall treatment effect was detected with the ANOVA. To evaluate whether significant differences existed in the physical or chemical variables between the same sites under contrasting drawdown between Sooke and Shawnigan we performed a series of one-way ANOVA at each site with a Bonferroni adjusted alpha set at 0.0125. Because Site 1 in Sooke was completely exposed by the last sampling date (26 September; see Results), the last date was excluded from all sediment analyses for Site 1 in Sooke. The $\alpha$ was set as $\leq 0.05$ for all analyses and a Bonferonni adjustment on $\alpha$ was performed for all post-hoc and multiple paired comparisons.

# Results

## *Drawdown Dynamics*

Drawdown in Sooke was 7.6 times greater (4.5 m change in vertical distance) than Shawnigan (0.59 m) from the start to the end of sample collection (23 May to 26 September 2000). From initial to final water level drawdown, 15.4 m (12.22 cm·day$^{-1}$) of linear shoreline was exposed in Sooke, which was 17.2 times greater sediment exposure rate than that in Shawnigan (total linear shoreline exposure = 0.9 m; shoreline exposure rate = 0.71 cm·day$^{-1}$).

## *Macrophytes*

Sooke and Shawnigan had contrasting macrophyte communities in the littoral area where sediment samples were collected (Table 2). Macrophyte density was visibly lower in Sooke compared to Shawnigan, and growth was restricted to higher in the littoral zone. Macrophyte growth in Sooke predominantly occurred above the depth of the first sampling site (see Sampling Design), so that most macrophytes became completely exposed by mid August. The composition of macrophytes along the east shore included semi-aquatic and terrestrial plant species. These plants included, but were not limited to, species in the genera *Isoetes*, *Ranunculus*, *Menthes*, *Galum*, *Anacharis*, *Callitrichia* (Table 2). Site 1 in Sooke had sparse growth of *Isoetes*. In contrast the littoral areas in Shawnigan consisted of a visibly denser community of submerged plants compared to Sooke (Table 2). Emergent plants such as *Typha* spp. were present in the upper littoral areas of Shawnigan (above Site 1) (Table 2). In Shawnigan, macrophytes occurred at Site 1 and were dominated by *Potamogeton robinsii* and *P. petersonii*. *Elodea* spp. were also present at these depths. Macrophytes occurred at the depths equivalent to Site 2 in Shawnigan, but were sparse along one transect, and absent from the other transect at that depth.

## *Limnological Characteristics of Littoral Water Column*

Water column temperature differed both temporally and spatially between Sooke and Shawnigan (Fig. 3). Average summer surface temperature (23 May to 26 September) was 2.0°C lower in Sooke (16.2°C) than in Shawnigan (18.2°C). Surface temperature differences between Sooke and Shawnigan declined to ~1°C by 26 September. At comparable sites (i.e., Site 1 in Sooke and Site 1 in Shawnigan), water column thermal gradients (change of temperature with depth) were smaller in Sooke than in Shawnigan (Fig. 3). Differences in thermal gradients between comparable sites in Sooke and Shawnigan increased with site depth. The temperature profiles of the deeper sites in Sooke (3 and 4) were more similar to the temperature profiles of the Shawnigan littoral sites (2 and 3). In Sooke, a defined thermocline (depth of temperature change of ≥1°C per meter) was present only at Site 4 (1.5 m off the bottom) for a portion of the sampling season (Table 3,

Table 2.–General macrophyte distribution and density in Sooke Lake Reservoir and Shawnigan Lake. Overall densities ranging from absent, sparse, common, to dense are listed based on observational diving (minimum of fifteen hours of diving in each water body). Macrophytes present in Sooke and Shawnigan are not limited only to genera listed.

| | **above Site 1** | | **Site 1** | | **Site 2** | |
|---|---|---|---|---|---|---|
| Sooke Lake Reservoir | *Isoetes, Ranunculus, Menthes Galum, Anacharis, Callitrichia* | common | *Isoetes* | sparse | – | absent |
| Shawnigan Lake | *Chara, Potamogeton robinsii, P. petersonii, Elodea* sp., and emergent plants such as *Typha* sp. | dense | *Potamogeton robinsii, P. petersonii, Elodea* sp. | dense | *Potamogeton robinsii, P. petersonii, Elodea* sp. | sparse in some areas, common in some areas |

Fig. 3). For all sites in Sooke, temperature differences between the surface and 0.5 m above the sediments never exceeded 2°C. In Shawnigan, a thermocline was present at Sites 2 and 3 (1.0 to 1.5 m off the bottom) for most of the sampling season and at Site 4 (3.0 to 4.25 m off the bottom) for the entire sampling season (Table 3, Fig. 3). Where a thermocline developed in Shawnigan, temperature differences between the surface and 0.5 m off the bottom were up to 11.5°C.

Dissolved oxygen concentration and the underwater light conditions varied seasonally in both water bodies and were different between Sooke and Shawnigan. In Sooke, DO remained > 7.4 $\text{mg} \cdot \text{L}^{-1}$ at all sites for all sampling dates. In Shawnigan, DO remained > 7.0 $\text{mg} \cdot \text{L}^{-1}$ at all sites for 23 May and 4 July. However, at Shawnigan Site 4, DO concentration below the thermocline dropped to 4.6 $\text{mg} \cdot \text{L}^{-1}$ by 15 August and to 3.0 $\text{mg} \cdot \text{L}^{-1}$ by 26 September. Secchi depths for Sooke and Shawnigan increased in the fall (Table 3). Sites in Sooke had greater PAR reaching the benthos than sites in Shawnigan (Table 3). Light values for Site 1 are excluded from Table 3 because this site became exposed in Sooke, and dense macrophytes interfered with light measurements in Shawnigan. All sites in Sooke remained above the 1% compensation depth on all sampling dates, whereas in Shawnigan, Site 4 was at or below the 1% compensation depth on all sampling dates (Table 3). On 15 August when Sites 2 and 3 in Sooke were at the same depth below the water surface as Sites 3 and 4 in Shawnigan, similar PAR reached the benthos.

## *Physical Structure of Littoral Sediments*

Differences in sediment texture, particle size, bulk density, and moisture between Sooke and Shawnigan were greatest at Sites 1 and 2 and most similar at Sites 3 and 4 (Fig. 4). In Sooke, sediment textural categories were dominated by sandy-loam, loam, and silty-loam in the shallower sites (1 and 2), and silty-clay to silty-clay-loam in the deeper sites (3 and 4). Sites 1 and 2 had a higher percentage of larger size particles (gravel and sand), and Sites 3 and 4 had a higher percentage of smaller sized particles (silt and clay) (Fig. 4A). In contrast, all sites in Shawnigan were dominated by silty-clay-loam mixtures and smaller (silt and clay) sized particles (Fig. 4B). Bulk density decreased with depth in Sooke and was consistent across all sites in Shawnigan (Fig. 4C). In Sooke, sediment at Site 1 had a significantly higher bulk density than at Site 1 in Shawnigan (Table 4, $p < 0.001$). The bulk density of the sediments at Sites 3 and 4 in Sooke was similar to all sites in Shawnigan. The moisture content of the sediment ranged from 29.1% to 91.8% in Sooke and 88.5% to 94.1% in

Table 3.–Site depth (m) by date, depth off bottom (m) of thermocline, % PAR (photosynthetically active radiation) reaching the sediment, and Secchi depths (m) for Sooke Lake Reservoir and Shawnigan Lake for each site for each sampling period. z = depth (m); B = bottom; May = 23 May; July = 4 July; Aug = 15 August; Sept = 26 September. Light values for Site 1 are excluded because this site became exposed in Sooke Lake Reservoir, and the macrophyte bed interfered with light measurements in Shawnigan Lake.

| | z (m) | | | | depth off bottom of thermocline (m) | | | | % PAR reaching the sediment | | | | Secchi (m) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Site | May | July | Aug | Sept | May | July | Aug | Sept | May | July | Aug | Sept | May | July | Aug | Sept |
| **Sooke Lake Reservoir** | | | | | | | | | | | | | | | | |
| 1 | 3.5 | 2.0 | 0.5 | x | x | x | x | | | | | | B | B | B | |
| 2 | 6.5 | 5.0 | 3.5 | 2.0 | x | x | x | x | 9.04 | 13.08 | 22.50 | x | B | B | B | B |
| 3 | 9.5 | 8.0 | 6.5 | 5.0 | x | x | x | x | 7.16 | 5.05 | 9.11 | 11.42 | 6.00 | 6.25 | B | B |
| 4 | 12.5 | 11.0 | 9.5 | 8.0 | x | 1.50 | 1.50 | x | 2.78 | 2.08 | 3.40 | 4.39 | 6.25 | 6.50 | 8.25 | 8.00 |
| **Shawnigan Lake** | | | | | | | | | | | | | | | | |
| 1 | 3.5 | 3.3 | 3.1 | 2.9 | x | x | x | x | | | | | B | B | B | B |
| 2 | 6.5 | 6.3 | 6.1 | 5.9 | 1.00 | 0.50 | 1.00 | x | 2.19 | 4.59 | 10.19 | 5.74 | B | B | B | B |
| 3 | 9.5 | 9.3 | 9.1 | 8.9 | 1.50 | 1.50 | 1.00 | x | 1.37 | 2.06 | 3.64 | 2.63 | 6.50 | 6.50 | 6.25 | 8.00 |
| 4 | 12.5 | 12.3 | 12.1 | 11.9 | 4.25 | 4.25 | 3.00 | 3.00 | 0.38 | 0.60 | 1.55 | 0.63 | 6.50 | 6.50 | 6.25 | 8.00 |

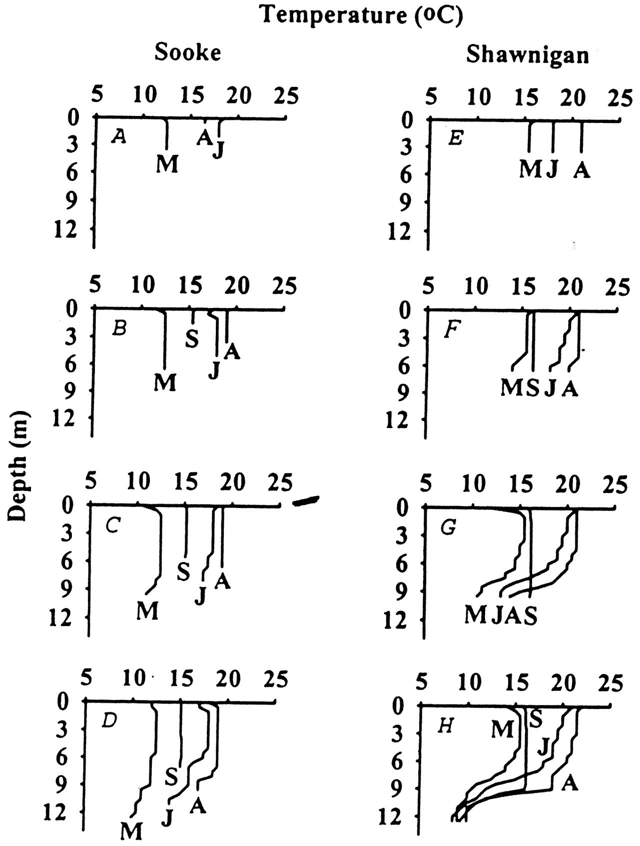

Figure 3.–Seasonal temperature (°C) profiles for Sooke (Sites 1-4, A-D) and Shawnigan (Sites 1-4, E-H). Sampling dates: M= 23 May; J = 04 July; A = 15 August, S = 26 September 2000.

Shawnigan (Fig. 4C). The moisture content of the sediment was significantly lower in Sooke than in Shawnigan at the nearshore sites (Sites 1 and 2) (Table 4, Fig. 4C, $p < 0.001$).

## Chemistry of Littoral Sediments

Within Sooke, sediment TOC at Site 1 was significantly lower than at Site 3, and sediment TON and OM at Site 1 were significantly lower than all other sites ($p < 0.001$). Within Shawnigan, sediment TOC, TON, and OM at Site 1 were significantly higher than at all other sites ($p < 0.001$). Between Sooke and Shawnigan, differences in sediment TOC, TON, and OM were greatest at Site 1 and smallest at Site 4 (Fig. 5). In Sooke, sediment TOC, TON, and OM at Site 1 were significantly lower than at Site 1 in Shawnigan (Table 4, Fig. 5, $p < 0.001$).

Sediment TOC:TON ratios in Sooke decreased from Site 1 to Site 4 (Fig. 6A; 14.4 at Site 1 to 26.6 at Site 4), whereas in Shawnigan, sediment TOC:TON ratios for all sites were similar (Fig. 6A; 14.5 at Site 1 to 15.8 at Site 4). In Sooke, sediment TOC:TON ratios at

Site 1 and 2 were significantly higher than at Site 1 and 2 respectively in Shawnigan (Table 4, Fig 6A, $p < 0.01$).

The spatial distribution of $\delta^{13}C$ and $\delta^{15}N$ in sediments were different between Sooke and Shawnigan. Sediment $\delta^{13}C$ signatures were heavier (less negative) near shore in both water bodies, and became lighter with depth (Fig. 6B). However, this trend was not as great in Sooke when compared to Shawnigan. In Sooke, $\delta^{13}C$ signatures were not different at Sites 2, 3, and 4 ($p > 0.05$). In Sooke, $\delta^{13}C$ signatures at Site 4 were 1.1‰ lighter than Site 1. In contrast, in Shawnigan $\delta^{13}C$ signatures at Site 4 were 1.82‰ lighter than at Site 1 (Fig. 6B). Sediment $\delta^{15}N$ signatures were lighter near shore in Sooke, and increased with depth (Fig 6C). At Site 1 in Sooke, $\delta^{15}N$ signatures were significantly lighter than at Sites 3 and 4 ($p < 0.05$). In Sooke, $\delta^{15}N$ at Site 1 was 1.81‰ lighter than Site 4. Within Shawnigan, on the other hand, $\delta^{15}N$ at Site 1 was only 0.5 ‰ lighter than Site 4. Over all sites, in both water bodies, there was a general shallow to deep relationship between $\delta^{13}C$ and $\delta^{15}N$ (Fig. 7).

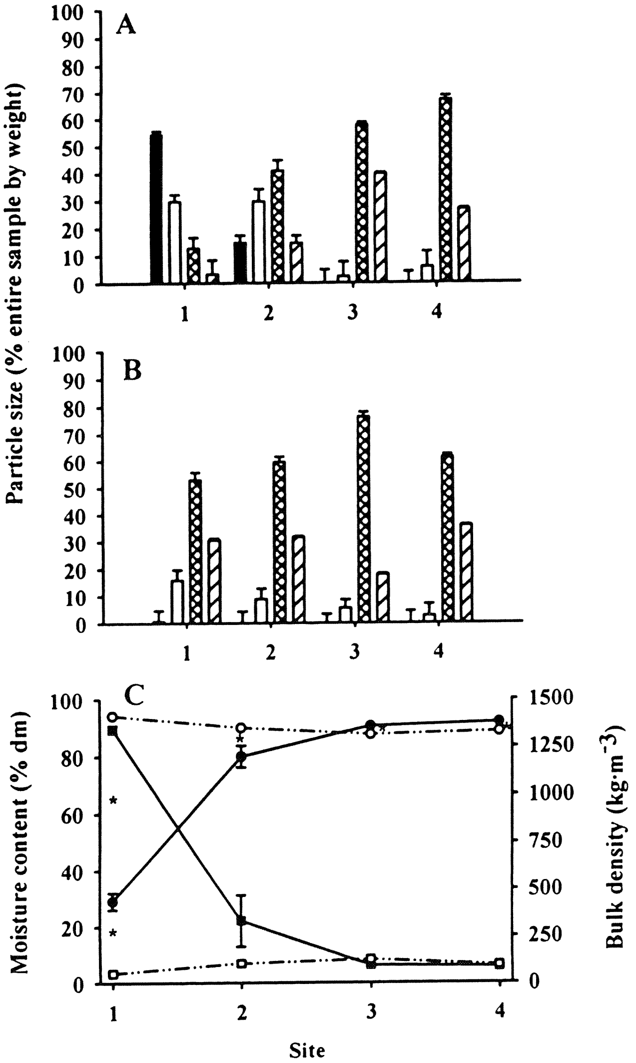

Figure 4.–Sediment particle size distribution (6A, B) for Sooke (A) and Shawnigan (B), Sites 1-4. Particle size: gravel >2.0 mm (solid); sand <2.00 mm > 0.53 mm (open); silt <0.63 mm >0.002 mm (cross hatch); Clay <0.002 mm (slanted line). 6C: Sooke (solid lines) and Shawnigan (dash-dot lines) dry bulk density (kg·m$^{-3}$) (squares) and sediment moisture content (% dm) (circles). Particle size, and bulk density is based on top 5 cm of sediment collected 04 July 2000 (mean and SE of both transects), and moisture content on top 2 cm of sediment collected at all four sampling dates (seasonal mean and SE). Significant differences are marked with asterisks (Table 4).

# Discussion

## *Littoral Macrophytes*

Drawdown notably impacted macrophyte abundance, composition and distribution. The visibly low macrophyte abundance and restriction of growth to high in the littoral zone observed in Sooke is common for water bodies that experience fluctuating water levels (Quennerstedt 1958, Lindstrom 1973, Wagner and Falter 2002). In contrast to the denser macrophyte beds observed in Shawnigan, the fewer macrophytes in Sooke likely reduced shoreline stability and increased erosion and sediment re-suspension (Barko and James 1998). However, plant communities in the upper drawdown zone in Sooke, exposed in the late summer and fall, continued to grow after exposure rather than dieing back. As a result, the plants in this upper drawdown exposure zone may provide more stability for exposed sediments in Sooke than other cold temperate reservoirs where macrophytes are exposed to freezing leaving bare sediments with drawdown (Grimås 1961, 1962).

## *Littoral Water Column Limnological Characteristics*

Results from our study indicate that the littoral water column shifted deeper into the reservoir as the summer drawdown progressed in Sooke, resulting in a larger effective littoral area in Sooke than in Shawnigan. Although the idea that the littoral zone shifts downward with declining water levels in reservoirs appears intuitive and obvious, factors such as the location and rate of water withdrawal may influence how drawdown impacts littoral water column temperature, oxygen, and light profiles. Comparison of temperature and oxygen profiles between Sooke and Shawnigan suggest greater mixing between limnetic layers, a shorter stratification period, and more solar warming at greater depths in Sooke than in Shawnigan. A study of the pelagic environment in Sooke also suggests a shortening of the length of the stratification period when compared to regional stratification regimes and a decreased resistance to water column mixing during the drawdown season (Nowlin et al. 2004).

The lower surface temperatures in Sooke compared to Shawnigan are most likely a consequence of differences in chemical conditions and altitude (meters above sea level) between the two water bodies and not a result of differing drawdown regimes. Several lines of evidence support this hypothesis. First, Shawnigan has slightly higher summer eplimnetic DOC concentrations than Sooke (Table 1). Lakes with higher DOC concentrations retain more solar radiation as heat in surface waters, raising surface water temperatures relative to lakes with lower DOC concentrations (Edmundson and Mazumder 2002). Altitude can also affect lake water temperature (Edmundson and Mazumder 2002), and Sooke is ~60 m higher in elevation than Shawnigan. However, it is unknown whether this difference in altitude is sufficient to cause the observed differences in surface water temperatures between Sooke and Shawnigan. It is unlikely that drawdown caused the differences in surface temperatures between Sooke and Shawnigan because water temperatures collected on approximately the same dates from more voluminous sites within Sooke (the larger north basin) show that these Sooke sites also have lower surface water temperatures than Shawnigan (Nowlin et al. 2004). The effects of drawdown would be presumably greatest in small shallow basins, however, the occurrence of relatively cooler water temperatures in all regions of Sooke suggests a more lake-wide mechanism (such as DOC concentration and altitude) causing cooler temperatures. Further, the short water residence time of the south basin of Sooke associated with drawdown (~9 days; Nowlin 2003) most likely did not cause the observed temperature differences between Sooke and Shawnigan because Sooke flows from north to south and there is little to no difference in surface water temperatures (1-5 m) in the north and south basins throughout the summer (<1 °C difference; Nowlin et al. 2004). Water entering the north basin has more than adequate time to accumulate heat before transport to the south

Table 4.–ANOVA comparison between Sooke Lake Reservoir and Shawnigan Lake sites. Samples from different dates were used as replicates (top 2 cm of sediment: moisture, TOC, TON, OM, TOC:TON ratio, $\delta^{13}C$, and $\delta^{15}N$). Dry bulk density is based on sediments from the top 5 cm for 04 July (N = 4). Values underlined indicate significance at p = 0.0125 (Bonferroni correction). Site df is 1 in all cases.

| | | dry bulk density | % moisture content | TOC $mg \cdot g^{-1} dm$ | TON $mg \cdot g^{-1}$ dm | % organic matter | TOC: TON | $\delta^{13}C$ | $\delta^{15}N$ |
|---|---|---|---|---|---|---|---|---|---|
| Site 1 | df error | 2 | 12 | 12 | 12 | 12 | 12 | 12 | 12 |
| | $F_{1,2}$ | 1703 | 307 | 114 | 295 | 1275 | 35 | 1 | 16 |
| | p value | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.337 | 0.002 |
| | $r^2$ | 0.999 | 0.962 | 0.905 | 0.961 | 0.991 | 0.747 | 0.077 | 0.573 |
| Site 2 | df error | 2 | 14 | 14 | 14 | 14 | 14 | 14 | 14 |
| | $F_{1,2}$ | 1 | 22 | 0 | 13 | 1 | 11 | 1 | 85 |
| | p value | 0.366 | 0.000 | 0.527 | 0.003 | 0.302 | 0.004 | 0.361 | 0.000 |
| | $r^2$ | 0.402 | 0.612 | 0.029 | 0.473 | 0.076 | 0.450 | 0.060 | 0.059 |
| Site 3 | df error | 2 | 14 | 14 | 14 | 14 | 14 | 14 | 14 |
| | $F_{1,2}$ | 1 | 14 | 6 | 22 | 0 | 1 | 73 | 38 |
| | p value | 0.459 | 0.002 | 0.026 | 0.000 | 0.544 | 0.465 | 0.000 | 0.000 |
| | $r^2$ | 0.293 | 0.506 | 0.306 | 0.607 | 0.027 | 0.039 | 0.838 | 0.730 |
| Site 4 | df error | 2 | 14 | 14 | 14 | 14 | 14 | 14 | 14 |
| | $F_{1,2}$ | 3 | 39 | 37 | 11 | 7 | 49 | 10 | 3 |
| | p value | 0.061 | 0.000 | 0.000 | 0.000 | 0.021 | 0.000 | 0.006 | 0.099 |
| | $r^2$ | 0.613 | 0.736 | 0.728 | 0.439 | 0.325 | 0.779 | 0.426 | 0.182 |

basin (mean summer epilimnetic water residence time of Sooke north basin in 2000 = 685 days, Nowlin 2003). Therefore, despite the contrasting drawdown regimes of the two water bodies, it is more likely that differences in surface water temperatures are a function of other lake-specific factors (i.e., DOC or altitude).

Drawdown related changes in temperature, DO concentration, and light can have significant impacts on benthic biota, microbial activity, nutrient dynamics, and OM degradation in reservoirs compared to lakes.

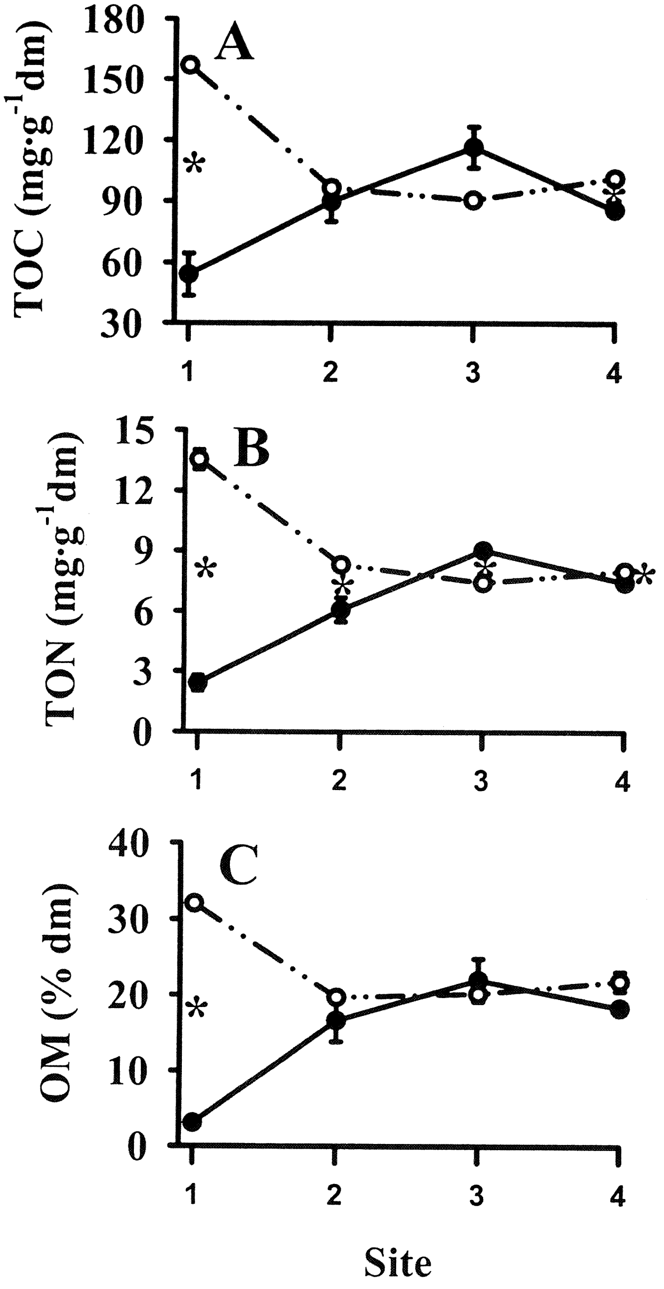

Figure 5.–TOC (mg g$^{1}$ dm) (A), TON (mg g$^{1}$ dm) (B), OM (% dm) (C) from the top 2 cm of sediment for Sooke (solid lines) and Shawnigan (dash-dot lines) (seasonal mean and SE). Significant differences are marked with asterisks (Table 4).

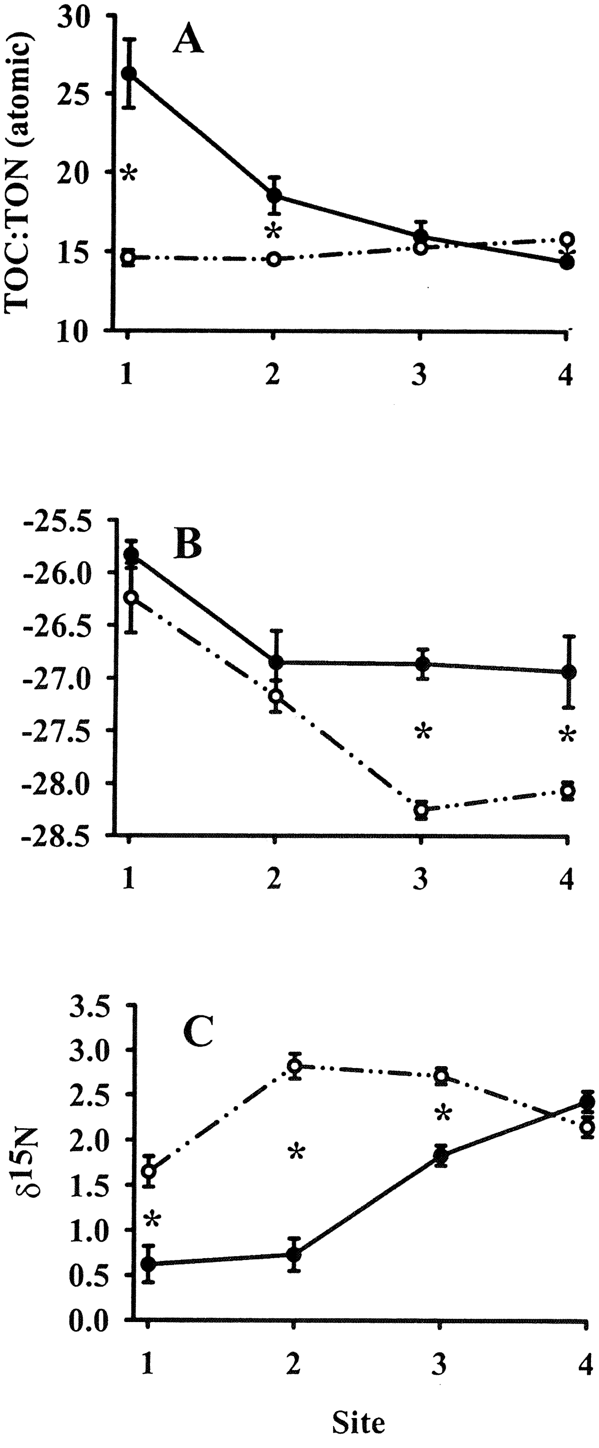

Figure 6.–Sediment (top 2 cm) TOC:TON (atomic) (A.), δ$^{13}$C (B.), and δ$^{15}$N (C) for Sooke (solid lines) and Shawnigan (dash-dot lines) (seasonal mean and SE). Significant differences are marked with asterisks (Table 4).

Water column temperature, oxygen concentration, and light have been shown to affect the composition and life history of benthic invertebrates and algae (i.e., composition, growth, development, fecundity) (Sweeney 1984, Stevenson et al. 1996). Thus, a decrease in stratified areas, a shorter stratification period, and the warming of the water above the littoral sediment in Sooke may reduce large temperature fluctuations at the sediment water interface, which may affect the community composition or life history patterns of invertebrates (Sweeney 1984). A larger drawdown in reservoirs compared to natural lakes may enhance primary productivity of benthic algae by providing a greater availability of light over an extended area of littoral sediment. Additionally under contrasting drawdown, differences in temperature, oxygen concentration, and mixing patterns with sediment exposure, and the shifting littoral water column, may affect littoral nutrient cycling (i.e., retention and release of phosphorus, or decomposition rates) (Watts 2000). Shifts in littoral temperature and oxygen in reservoirs and the associated biological, chemical, and physical changes should be considered when developing models to predict littoral temperature patterns, or nutrient dynamics of reservoirs.

## *Littoral Sediment Structure and Chemistry*

The greatest differences in sediment physical structure and chemistry were between the drawdown exposure zone of Sooke and the equivalent littoral area of Shawnigan. Sites farthest from shore were most similar between Sooke and Shawnigan. We discuss these contrasts between the reservoir and lake first with respect to sediment physical structure, then with respect to macrophytes and sediment chemistry.

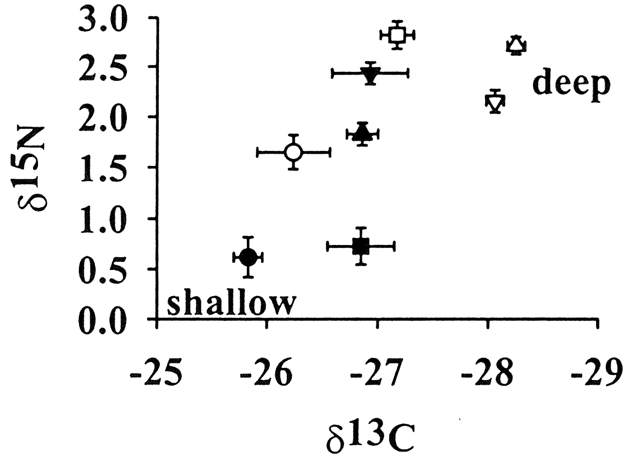

Figure 7.–Sediment (top 2 cm) $\delta^{15}N$ as a function of $\delta^{13}C$ for Sooke (closed) and Shawnigan (open) (seasonal mean and SE). Site 1 (circles), Site 2 (squares), Site 3 (up-pointed triangle), Site 4 (down-pointed triangle).

Drawdown in Sooke caused a significant shift in sediment physical structure compared to Shawnigan. Our results show that water level drawdown in Sooke resulted in larger sediment particle sizes, higher bulk density, and reduced sediment moisture content in the drawdown exposure zone in Sooke compared to the equivalent littoral area of Shawnigan. Our results suggest that the finer silt and clay sized particles were transported from the drawdown exposure zone to deeper areas in the basin, which may have been responsible for the large gradients in sediment structure in Sooke. Likens and Davis (1975) suggested that sediment focusing and littoral erosion are significant processes regulating sediment particle distribution. Wave action, fetch, slope, and lake morphometry impact erosion and sediment focusing and affect the distribution of sediment particles (Håkanson 1981, Hilton et al. 1986). Compared to natural lakes, changes in water level in reservoirs expose larger areas of sediment to wave action, which impacts sediment structure (Baxter 1977). The more consistent distribution of smaller sediment particles in Shawnigan compared to Sooke reflects the smaller changes in water level and thus the smaller area of sediment exposed to shore processes such as wave action.

The lack of a build-up of finer particles closer to shore, and accumulation of finer particles farther from shore in Sooke suggest, in conjunction with identified erosion and accumulation patterns, that repeated annual drawdowns affect the sediment particle distribution differently than do the water fluctuations in Shawnigan. The percent moisture content of the top 2 cm in both systems followed the known relationships between sediment grain size, water content and bulk density. As observed by others (Håkanson 1977, 1981), the bulk density of sediment increased and moisture content declined with increasing sediment particle size. Water content indicates areas of sediment erosion (no deposition of fine materials), transportation (discontinuous deposition of fine materials), and accumulation (continuous deposition of fine materials) (Håkanson 1977). Sediments from the top 1cm with water content less than 50% indicate areas of erosion, between 50% and 75% indicate areas of transportation, and greater than 75% indicate areas of accumulation (Håkanson 1977). Based on these guidelines, Site 1 in Sooke can be characterized to be in the erosion zone. However, our estimates were from the top 2 cm of sediment, an area that may be subject to some compaction. Site 2 can be considered to be on the border between transportation and accumulation zones, and Sites 3 and 4 can be characterized to be in the accumulation zone. In contrast, all Shawnigan sites were characterized to be in an accumulation zone. The shallower sites in Shawnigan do not fit the classic theories on sediment zonation (Håkanson 1977), a situation that is common to littoral areas dominated by macrophytes where the presence of the macrophytes reduces erosion and increases sediment accretion (Barko and James1998).

Other reservoir studies have observed similar patterns of sediment erosion and re-deposition as a function of sediment exposure (i.e., Ostrofsky and Duthie 1978, Fabre and Patau-Albertini 1986, Hall et al. 1999). Overlying trends observed by these studies are a loss of fine sediment particles in the drawdown exposure zone and an accumulation of these particles below the drawdown limit. This pattern was not observed in the comparison lake which does not experience large fluctuations in water level. Because nutrient dynamics and distributions of biological communities are linked to sediment physical characteristics such as particle size, the contrasting physical and chemical characteristics between reservoirs and lakes may lead to a divergence in structure and function of these two ecosystem types (Grimås 1961, Hall et al. 1999).

In addition to changing the physical characteristics of sediments in Sooke, fluctuating water levels were also associated with significant differences in sediment chemistry compared to Shawnigan, suggesting reservoir drawdown may result in a loss of sediment nutrients from the drawdown exposure zone (Watts 2000). Differences in sediment chemistry between Sooke and Shawnigan were greatest in the upper most drawdown zone and this difference declined with depth. Low TOC, TON, and OM content of sediment at Site 1 in Sooke may be attributed to low macrophyte abundance and a loss of organic material and sediment due to erosion and sediment focusing. The high bulk density at Site 1 in Sooke relative to deeper sites and sites in Shawnigan is also indicative of low organic carbon concentration (Menounos 1997, Avnimelech et al. 2001), and suggests a loss of organic material with drawdown. The higher sediment TOC, TON, and OM at Site 1 in Shawnigan was attributed to the higher macrophyte biomass, lower sediment erosion, and lower sediment focusing when compared to Sooke. Reduced nutrients and OM in the drawdown exposure zone of Sooke may have implications for food-web structure and dynamics. Invertebrate and algal composition, distribution, and life-histories are affected by different nutrient and OM levels and distribution (Sweeney 1984, Hillebrand and Kahlert 2001). These differences are additionally of concern in a drinking water reservoir such as Sooke, where algal composition, and algal biomass, and control of algal biomass by grazers can affect the presence and production of harmful and nuisance algal blooms.

## *Sources of Sediment Organic Matter*

Biogeochemical tracers ($\delta^{13}C$, $\delta^{15}N$, and TOC:TON ratios) indicate that shallow sites in Sooke have more allochthonous derived OM than sites in Shawnigan. These tracers are often used to differentiate between autochthonous and allochthonous carbon sources (LaZerte 1983, Meyers and Ishiwatari 1993, Peterson 1999, Elser et al. 2000). Allochthonous derived OM typically has a higher TOC:TON ratio, a higher $\delta^{13}C$ signature, and a lower $\delta^{15}N$ signature than autochthonously derived OM (Hecky et al. 1993, Meyers and Ishiwatari 1993). The high TOC:TON ratio of OM in shallow sites of Sooke compared to Shawnigan suggest a relatively large influence of terrestrial carbon (Meyers and Ishiwatari 1993). The drawdown exposure zone of Sooke may receive terrestrial debris and OM from the surrounding riparian area. In this exposure zone environment, terrestrial-like plants dominated over submerged aquatic macrophytes common in lakes, therefore OM in the sediments in Sooke likely originated in part from this allochthonous production. In contrast, Shawnigan submerged macrophytes likely make a large contribution to OM in the littoral sediments.

The spatial patterns of $\delta^{13}C$ and $\delta^{15}N$ in Sooke and Shawnigan suggest that the source and production of OM matter is different between the water bodies. The $\delta^{13}C$ of sediment OM is similar between shallow sites of Sooke and Shawnigan despite differences in TOC:TON ratios. The terrestrial and littoral $\delta^{13}C$ signatures may be similar between these water bodies. In both water bodies the $\delta^{13}C$ declines with depth, however less so in Sooke. Because pelagic production often has a lighter $\delta^{13}C$ signature than littoral production (Meyers and Ishiwatari 1993), the decline in $\delta^{13}C$ with depth is expected. At deeper sites pelagic production contributes OM to the sediments, whereas at shallower sites benthic production also contributes OM (Meyers and Ishiwatari 1993). Therefore, the higher $\delta^{13}C$ of OM at deeper sites in Sooke compared to Shawnigan may be due to higher contributions of OM from benthic rather than pelagic sources, resulting for example, from increased light penetration with drawdown. Alternatively, wave action and sediment focusing may transport OM from the drawdown exposure zone to deeper sites in the reservoir. The cause of the spatial pattern in sediment $\delta^{15}N$ is less clear. The largest differences between water bodies are at the shallow sites (1 and 2), where $\delta^{15}N$ is lower in Sooke than in Shawnigan. This is consistent with observed differences in TOC:TON ratios implicating a terrestrial influence on the source of OM.

The combination of TOC:TON ratios, $\delta^{13}C$, and $\delta^{15}N$ suggest that the littoral or drawdown exposure zone signatures extend farther from shore in Sooke, and OM in the drawdown exposure zone is more allochthonous in nature than it is in Shawnigan. Though it was not our intent to determine the relative contribution of different sources of OM to the sediments, the patterns we observed suggest spatial variability in the source and distribution of OM between our study reservoir and lake. A more thorough analysis would require isotopic signatures of pelagic, littoral, and terrestrial OM for each study water body. This information would help to determine various mechanisms causing these differences in OM sources and distribution in reservoirs versus natural lakes. Differences in levels of sediment nutrients and the sources and distribution of OM may have fundamental implications for nutrient biogeochemical cycling and population dynamics of benthic biota reliant upon nutrient and OM sources, abundance, and availability.

# Conclusion

This study increases our understanding of the impacts of drawdown on the temporal and spatial changes in the littoral water column and sediment physical and biogeochemical characteristics of lake-reservoirs. Our results (Figs. 8 and 9) show how the littoral environment in the reservoir with annual drawdown is different from the lake with small annual changes in water level. Over the sampling season, the littoral water column shifted laterally with drawdown in Sooke, which increased the effective littoral area and resulted in more littoral water column mixing or diffusion between limnetic layers, a shorter stratification period, and greater solar warming and higher PAR over a greater range of littoral depths. The cumulative affects of repeated annual drawdowns resulted in spatial differences in sediment physical and chemical characteristics in the reservoir compared to the lake (Figs. 8 and 9). Low macrophyte abundance and loss of fine sediments, nutrients, and OM from the drawdown exposure zone in Sooke compared to the equivalent littoral area in Shawnigan suggest that drawdown enhances sediment erosion and focusing (Figs. 8 and 9). The greatest differences in sediment structure and chemistry between Sooke and Shawnigan occurred in the upper littoral/drawdown exposure zone. Sites farthest from shore were least affected by drawdown and sediments were more similar (Figs. 3 and 4). The element ratios of TOC and TON, and stable isotope ratios of $\delta^{13}C$ and $\delta^{15}N$ suggest that the sources of OM in the

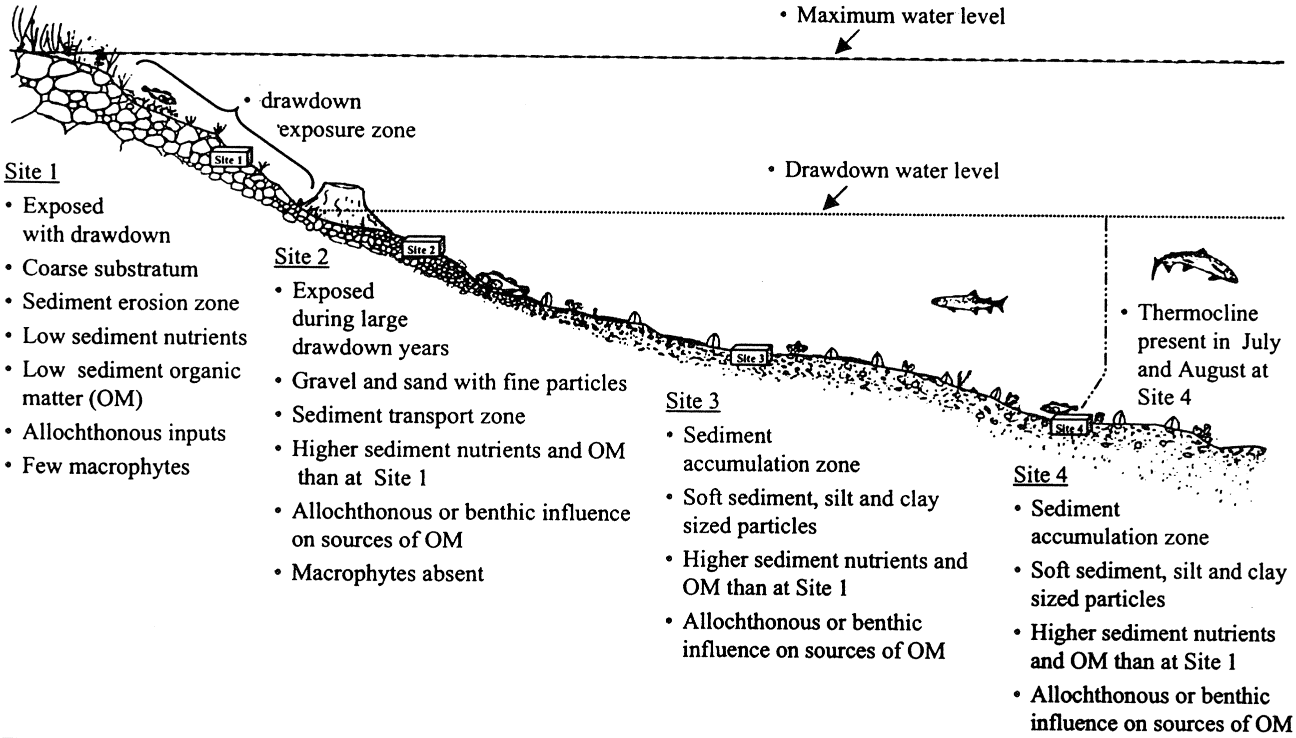

Figure 8.–A schematic cross-section of the effective littoral area in Sooke. Physical and biogeochemical sediment characteristics are summarized along with observations on littoral areas (macrophytes, fish, sponges, and mussels). Observations are based on a minimum of fifteen hours of diving in each water body. See Fig. 9 for comparison.

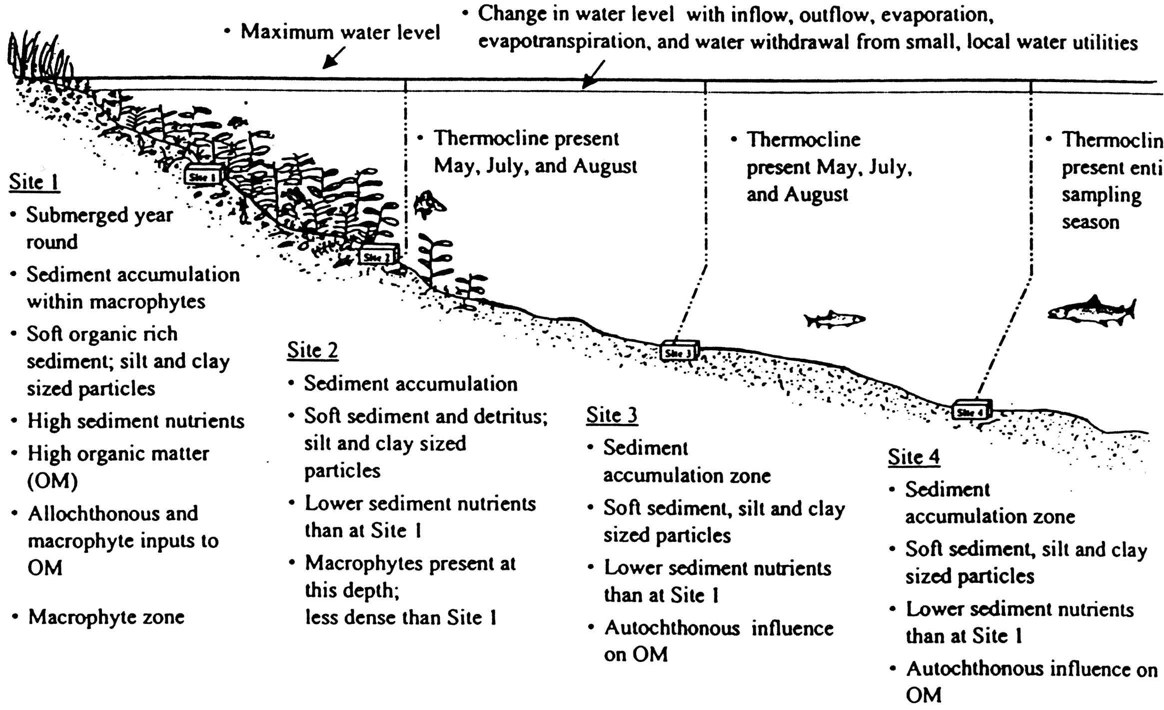

Figure 9.–A schematic cross-section of the littoral area in Shawnigan. Physical and biogeochemical sediment characteristics are summarized along with observations on littoral areas (macrophytes and fish). Observations are based on a minimum of fifteen hours of diving in each water body. See Fig. 8 for comparison.

drawdown exposure zone in Sooke are more allochthonous in origin than in Shawnigan. The sources and distribution of OM also suggests that the effective littoral area extends out deeper in the reservoir under higher drawdown than in the natural lake.

Although results from this study are limited to Sooke and Shawnigan, they suggest that drawdown fundamentally changes reservoirs compared to natural lakes. Reservoir-lake differences in sediment physical and chemical characteristics have implications for the structure and function of biological communities in littoral areas, especially in the drawdown exposure zone. A change in temperature and the quality and quantity of light, a larger littoral area subject to processes such as erosion, a loss of macrophytes as habitat, and changes in the type and availability of nutrients are some factors that contribute to differences in composition, biomass, and productivity of benthic communities between reservoirs and lakes. One of our next steps is to link these differences in sediment physical and biogeochemical characteristics with the structural and functional differences in benthic communities. Using biogeochemical tracers, further research into the mechanisms affecting the sources and distribution of OM may also provide insight into nutrient and foodweb dynamics in reservoirs and lakes under contrasting drawdown.

In order to develop general quantitative models to predict drawdown impacts on sediment physical and biogeochemical characteristics, data from this study should be combined with other lake and reservoir studies to provide a gradient of drawdown regimes, basin morphometries, and trophic status. The ability to predict the impact of repeated drawdown on littoral sediment structure and biogeochemical characteristics would extend the findings from each of the studies, and therefore provide water managers with a more complete understanding of the effects of drawdown on the structure and function of littoral zones. This would allow water utilities to better manage the impacts of drawdown on the ecology of reservoir ecosystems.

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