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Effects of Water Level Fluctuation and Short-Term Climate Variation on Thermal and Stratification Regimes of a British Columbia Reservoir and Lake

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ABSTRACT

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Stratification and thermal regimes of a reservoir with fluctuating water levels were compared to a natural lake of similar morphometry and trophic status over a two-year period (2000-2001) in coastal British Columbia, Canada. We compared the timing and duration of stratification, summer heat budgets and heat fluxes in two morphometrically contrasting basins of Sooke Lake Reservoir and Shawnigan Lake (one shallow and one deep basin per water body). In the second year of the study, a 100-year drought allowed us to compare responses of a reservoir and a lake to contrasting years of climatic conditions. Loss of volume from the reservoir during summer and fall caused stratification and thermal regimes to differ from Shawnigan Lake, but the magnitude of these differences was mediated by basin morphometry. Duration of summer stratification, timing of heat content, and the relative importance of seasonal heat fluxes in the shallow basin of Sooke Lake Reservoir were most different from Shawnigan Lake. While there were no major differences between years for Shawnigan Lake, contrasting years in precipitation and hydrology caused Sooke Lake Reservoir stratification and thermal regimes to differ between years. The magnitude of differences between years was mediated by basin size, with the shallower reservoir basin having greater differences between years. Our results indicate that reservoir physical processes are sensitive to short-term changes in hydrology, and that the combined impacts of short-term climate variation and anthropogenic manipulation of hydrology may be greater in shallow reservoir ecosystems.

Key Words: reservoir limnology, drawdown, heat budget, climate variability, stratification, thermal regimes, mixing regimes.

Annual cycles of thermal stratification, water temperature and heat content fundamentally influence the ecology of lakes and reservoirs. Water column mixing and annual thermal regimes affect nutrient cycling (James 1990, Soranno et al. 1997), plankton species composition (Proulx et al. 1996) and organism growth rates (Edmundson and Mazumder 2001). Historically, limnologists have recognized the ecological importance of lake physical conditions and have examined these processes in individual lakes (Likens and Johnson 1969, Ambrosetti and Barbanti 2001) and at the regional scale (Benson et al. 2000, Edmundson and Mazumder 2002). However, most studies that have formed our current understanding of mixing and thermal regimes have been conducted in north temperate lakes of glacial origin (but see Kling 1988, Gellar 1992).

In contrast to natural lakes, reservoirs have received less intensive study from limnologists. Despite the dominance of natural lakes in the literature, limnologists have identified physical processes unique to reservoirs that influence their ecology and water quality (Ford 1990, Kennedy 2001). Reservoirs typically have more variable and complex hydrology than natural lakes, due to anthropogenic manipulation of inflows and outflows (Ford 1990). Reservoirs commonly experience relatively large water level fluctuations associated with operation (Ryder 1978, Straškraba et al. 1993). Annual water level fluctuations (hereafter known as drawdown and recharge) in north temperate reservoirs generally follow a pattern in which the reservoir is recharged in the winter or spring and drawn down over the summer or winter.

The continuous removal of reservoir volume over the summer (when inflows are low) can affect the length of summer stratification (Barone and Naselli-Flores 1994, Effler and Bader 1998) and be a significant term in heat budgets (Barone et al. 1993, Owens 1998c). In contrast, natural lakes exhibit a period of hydraulic stagnation in summer characterized by low or absent inflows and outflows. Therefore, the management practice of removing substantial water volume over the course of the summer may cause a reservoir to significantly differ from seasonal stratification and thermal regimes of nearby natural lakes subject to the same meteorological conditions.

The magnitude of impacts from seasonal drawdown on reservoir physical processes is dependent upon factors including reservoir-specific hydrology and morphometry (Straškraba et al. 1993), and interannual climatic conditions (Owens et al. 1986). Interannual climatic variability, in particular, influences stratification and thermal regimes of reservoirs and natural lakes (Effler et al. 1986, Fee et al. 1996, Snucins and Gunn 2000). Variation of meteorological parameters such as precipitation may be of concern for reservoirs, because reservoir ecology is closely coupled with their hydrology (Ford 1990). Reduced precipitation can affect regional hydrology, resulting in reduced stream inputs to lakes and reservoirs (Schindler et al. 1996). If sufficient water is unavailable to completely recharge a reservoir that experienced a relatively large summer drawdown, the influence of drawdown on physical processes during the following summer may be magnified due to lower reservoir water levels prior to the summer drawdown period. For example, a reservoir with relatively low water levels at the beginning of the summer drawdown period may have faster flushing rates and a shorter stratification period duration when compared to a summer in which the reservoir completely recharged prior to the drawdown season. Therefore, examining the effects of climatic variability on physical processes in reservoirs and natural lakes offers an opportunity to further understand the relative sensitivity of both systems to variation in climatic conditions.

In the study presented here, we examined the effects of summer drawdown on the mixing patterns and thermal regimes over a two-year period in a reservoir and a natural lake in coastal British Columbia, Canada. We examined the effects of a relatively large percentage of volume removal over the summer and early fall on water column stratification, water temperatures and heat budgets of Sooke Lake Reservoir, and compared these seasonal regimes to Shawnigan Lake, a nearby natural lake of similar size, morphometry and trophic status. The comparison of Sooke Lake Reservoir and Shawnigan Lake allowed us to quantitatively assess the magnitude of the impacts of summer drawdown on the timing of reservoir thermal and stratification regimes in reference to conditions in a nearby similar natural lake (Straškraba et al. 1993, Kennedy 2001).

We further examined the relative magnitude of drawdown effects in relation to interannual variability in climatic conditions. During the second year of the study (2001), Sooke Lake Reservoir did not completely recharge prior to the summer drawdown period due to lower than average precipitation during the preceding recharge period (winter 2000 – spring 2001). Contrasting years of climatic conditions, in terms of precipitation, offered a unique opportunity to compare responses of an anthropogenically-manipulated reservoir and a natural lake to short-term changes in precipitation.

Methods

Study Sites

Sooke Lake Reservoir (Sooke) is located on

Vancouver Island, British Columbia, Canada (Fig. 1). The reservoir was created in 1914 by damming the outlet of Sooke Lake, which discharges into the Sooke River. Sooke is classified as a lake-reservoir, which differs from a run-of-the-river reservoir (Straškraba et al. 1993). Sooke serves as the main drinking water supply for the city of Victoria (population ~300,000). Approximately 90% of annual water inflow to the reservoir comes in October to April as rain-generated stream flow, and after the reservoir refills in winter and spring, a relatively large volume spills over the dam (1999-2000 recharge period total dam spill volume = 34 x 10^6 $m^3 \cdot year^{-1}$; mean flow rate = 0.34 x 10^6 $m^3 \cdot day^{-1}$). In late spring and early summer, stream inflow to the reservoir declines and drinking water consumption increases, causing the reservoir to decrease in volume until the late fall, when rainfall increases again. Both the drinking water intake and the dam allow for the outflow of epilimnetic water only.

Sooke has three main basins (Fig. 1). The largest basin at the north end of the reservoir (north basin) is relatively deep (Z_{max} = 70 m) and receives the majority of stream input, when compared to the south basin (Z_{max} = 22 m) (Fig. 1, Table 1). The north and south basins of Sooke represent physical environments that differ morphometrically and hydrologically (Table 1). Basins within the same water body that differ morphometrically (shallow versus deep) can create ecologically distinct environments (Frenette et al. 1996, Proulx et al. 1996). Therefore, we examined responses of the north and south basins of Sooke to seasonal drawdown in order to gain insight into the potential responses of relatively deep versus shallow systems to summer drawdown.

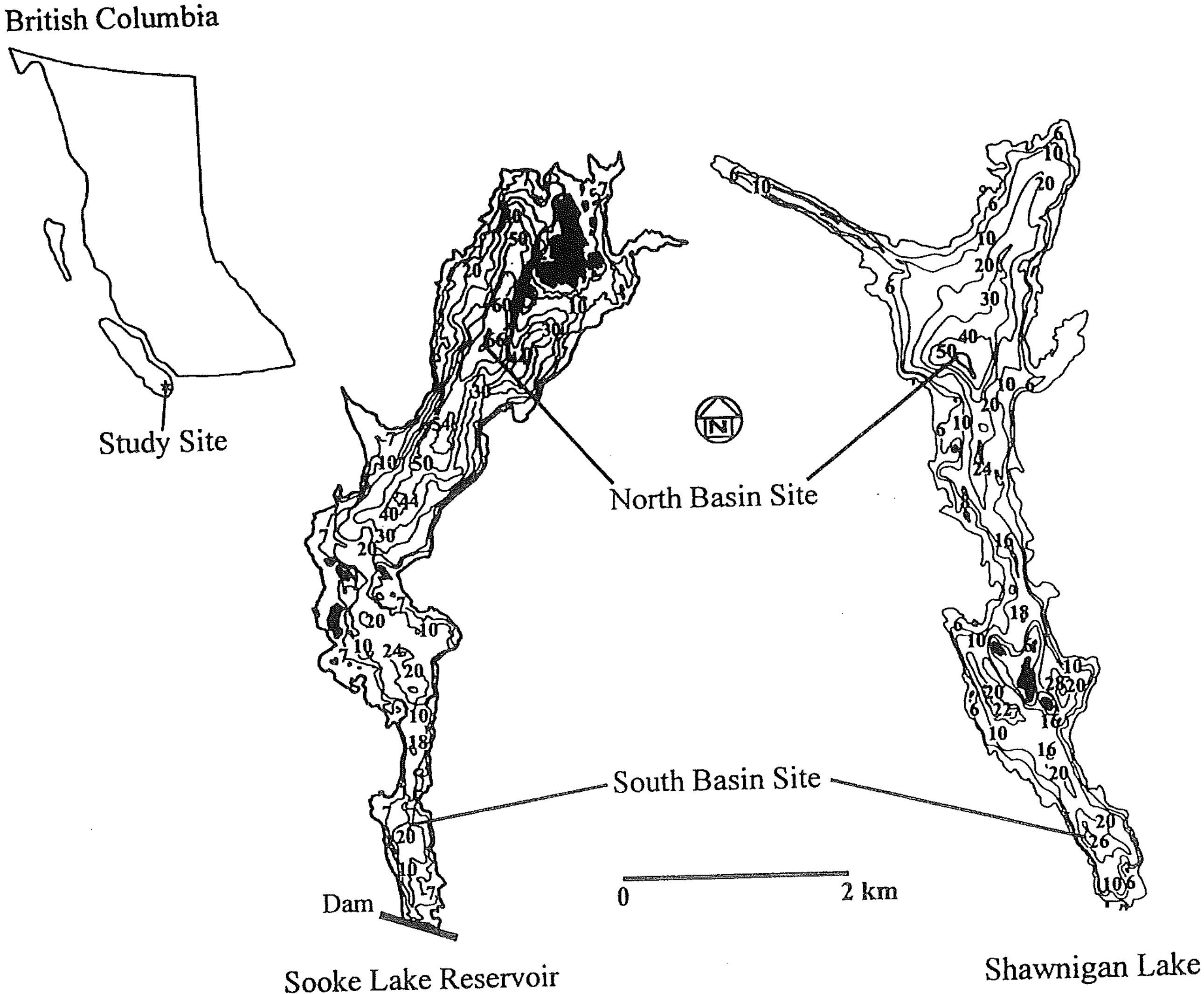

Figure 1.–Bathymetric maps of Sooke Lake Reservoir and Shawnigan Lake, indicating their location in British Columbia and the north and south basin sampling sites in each water body.

Table 1.–Morphometry, hydrology, water clarity, nutrient concentrations and plankton biomass of the north and south basins of Sooke Lake Reservoir and Shawnigan Lake. Surface areas and volumes are full-stage values and water exchange rates are the mean of January - December 2000 and 2001. Nutrient and Chl-a values are summer (May - September) epilimnetic means of 2000 and 2001.

		Sooke Lake Reservoir			Shawnigan Lake		
		Whole Lake	**North Basin**	**South Basin**	**Whole Lake**	**North Basin**	**South Basin**
Lat, Long	N, W	48°33', 123° 41'	–	–	48° 37', 123° 38'	–	–
Elevation	m	180	–	–	116	–	–
Max Length	km	7.0	–	–	6.9	–	–
Max Fetch	N-S, km	5.0	4.1	1.2	5.5	3.7	1.4
Catchment Area	km^2	87	–	–	69.4	–	–
Surface Area	x 10^6 m^2	6.0	4.3	0.5	5.5	3.6	0.6
Max Depth	m	70	70	22	53	53	27
Mean Depth	m	19.5	23.2	8.6	13.0	14.3	11.9
Volume	x 10^6 m^3	117.9	100.5	3.9	71.9	51.1	6.8
Water Exchange Rate	yr^{-1} (± 1 SD)	0.7 (± 0.27)	–	–	0.5 (± 0.14)	–	–
Secchi depth	m (± 1 SD)	–	8.5 (± 2.0)	7.4 (± 1.7)	–	5.9 (± 0.5)	5.9 (± 1.9)
Light Extinction Coefficient	m^{-1} (± 1 SD)	–	0.3 (± 0.05)	0.4 (± 0.05)	–	0.4 (± 0.08)	0.4 (± 0.06)
Chlorophyll *a*	µg · L^{-1} (± 1 SD)	–	0.7 (± 0.4)	0.9 (± 0.3)	–	1.3 (± 0.64)	1.5 (± 0.74)
Total phosphorus	µg · L^{-1} (± SD)	–	3.1 (± 1.5)	3.3 (± 1.5)	–	4.9 (± 1.8)	4.4 (± 2.1)
Total nitrogen	µg · L^{-1} (± 1 SD)	–	80.9 (± 13.3)	85.6 (± 20.4)	–	152.4 (± 26.5)	153.4 (± 24.2)
DOC	mg · L^{-1} (± 1 SD)	–	2.0 (± 0.3)	2.0 (± 0.3)	–	3.1 (± 0.31)	3.1 (± 0.29)

Shawnigan Lake (Shawnigan) is a lake of glacial origin located 4 km to the northeast of Sooke, primarily used for recreation, but a limited amount of water is withdrawn for local residents. Shawnigan has three main basins: a larger, deeper north basin (Z_{max} = 53 m) and a shallower south basin (Z_{max} = 27 m) separated by a middle basin (Fig. 1, Table 1). Inflows to Shawnigan follow the same seasonal pattern as Sooke (Nordin and McKean 1984). Shawnigan flows from the southern end to an outlet stream at the north end of the lake. We selected sampling sites in the north basin and south basin of the lake. While the direction of flow through Sooke and Shawnigan differs (Sooke flows north to south and Shawnigan flows south to north), the selection of morphologically similar sites within each water body allowed us to examine the seasonal mixing and thermal patterns in morphometrically similar basins in a reservoir and a natural lake under contrasting summer drawdown regimes.

Both water bodies are warm monomictic (Wetzel 2001), due to the mild climate in the North American coastal Pacific Northwest. In winter, minimum water temperatures typically reach ~5°C and permanent ice cover does not occur (W. Nowlin and Capital Regional District Water Department, unpubl. data). Both water bodies are oligotrophic, with Shawnigan having slightly higher Chl-a and nutrient concentrations than Sooke (Table 1), which may be due to development in the watershed. Sooke has a protected watershed with no public access and Shawnigan has ~600 houses within 1 km of its shoreline.

Meteorological and Hydrological Data

Meteorological data were obtained from a station on the Sooke Dam. Summer mean daily air temperature, solar irradiance and wind speed were calculated from hourly measurements taken at the meteorological station from 1 May - 30 September 2000 and 2001. Irradiance was measured on a Li-Cor LI-90SZ pyrheliometer and wind speed and direction were taken with an anemometer. Daily precipitation measurements have been taken at Sooke since 1895, and a 104-year average (excluding 2000 and 2001) of both total annual and total monthly precipitation were calculated.

Water surface elevations (meters above sea level – m.a.s.l.) of both water bodies were obtained from staff gauges. Daily measurements of water surface elevation were collected for Sooke and measurements were taken from Shawnigan every two to three weeks. Staff gauge measurements were used to calculate whole lake and basin water volumes using bathymetry (Spafard et al. 2002). The movement of water into and out of Sooke and Shawnigan was examined over the study period. We considered the only major inflows for both water bodies to be streams and the major water outputs to be lake surface evaporation, stream outflow (for Shawnigan) or the dam spillway and the drinking water intake (for Sooke). We did not estimate non-channelized surface runoff or subsurface inflows and outflows because estimates of these parameters are difficult to obtain (Winter 1985) and are likely small contributions to the water balance when compared to the fluxes examined by this study. We obtained inflow data for all major creeks discharging into Sooke from weir gauges maintained by the Capital Regional District (CRD) Water Department. Weirs recorded total daily flow volumes and monthly inflow rates ($x10^6$ $m^3 \cdot day^{-1}$) were calculated. Water inflow rates into the north and south basins were calculated separately, based upon location of inflowing creeks. Regular weir gauge measurements of inflowing creeks were not available for Shawnigan. However, the British Columbia Ministry of Environment, Lands and Parks (now BC Ministry of Water, Land and Air Protection) had previously conducted a long-term detailed study of Shawnigan Lake hydrology (Nordin and McKean 1984). We obtained a 15-year data set of monthly total creek discharge into the lake. Since creek flows in this region are tightly coupled with rainfall, we predicted total monthly inflow to Shawnigan from total monthly precipitation records from the Sooke Lake Reservoir dam meteorological station for the same 15-year time period. Total monthly rainfall (PCP_M in mm) predicted total monthly lake inflow (V_I in $x10^6$ m^3) reasonably well ($V_I = -166853.6 + 21134.5\ PCP_M + 79.12\ PCP_M^2$, $r^2 = 0.851$, $P = 0.0002$). We used this model to estimate total monthly inflow to the whole lake, the north basin and the south basin using monthly precipitation data.

Monthly estimates of surface evaporation from the entire water body and individual basins were obtained with the model of Morton (1979). Outflow data for Sooke were obtained from flow measurements taken from the dam and at the drinking water chloramination plant (downstream in the distribution system and gravity fed from the drinking water intake). Both outflows measured the total volume discharged over a 24-hour period. Shawnigan Lake total monthly outflow volume (V_O in $x10^6$ m^3) was from the difference of incoming and outgoing flows, according to

$$V_O = V_I - \Delta V_L - V_E \qquad (1)$$

where V_I is the total monthly inflow, ΔV_L is the change in water volume of the entire lake over the month interval and V_E is the total monthly evaporation volume.

Longitudinal flow of water can be important in the transfer of heat and materials within a water body, potentially affecting physical dynamics (Owens 1998b), therefore we examined these water movements within the water bodies. Because Sooke flows north to south and Shawnigan flows south to north, the transfer of volume out of the north basin of Sooke (to the south basin) and out of the south basin of Shawnigan (to the north basin) was estimated with the following equation

$$V_{IBT} = \Delta V_B - (V_I - V_E) \tag{2}$$

where V_{IBT} is the monthly interbasin transfer volume (x10^6 m^3), ΔV_B is the change in basin volume over the interval, V_I is the inflow volume to the basin, and V_E is the evaporation loss volume. The interbasin transfer volumes into the south basin of Sooke (from the north) and into Shawnigan north basin (from the south) were calculated using Equation 2, but subtracting ($V_I - V_E - V_O$) from ΔV_B, where V_O is the basin outflow volume (either the stream outflow for Shawnigan or the sum of the drinking water outflow and the dam spill for Sooke).

Stratification and Thermal Regimes

Sooke and Shawnigan were sampled from early May to late November at the north and south basin sites (Fig. 1) at least every three weeks in 2000 and at least every two weeks in 2001. Water temperature was measured with a YSI Model 58 every 1 m, except through the metalimnion, where we measured temperature every 0.5 m. At greater water depths when temperature changes with depth were minimal, we took measurements approximately every 5 m. We interpolated temperatures to every 0.5 m depth.

On each sampling date, we determined whether the water column was thermally stratified through inspection of the temperature profile. When there was a region in the water column where the rate of temperature change was ≥1°C·m^{-1}, we considered the water column to be thermally stratified. The epilimnion was defined as starting at lake surface and down to, but not including, the depth where the rate of temperature change was ≥1°C·m^{-1}, the metalimnion was the portion of the water column that exhibited temperature change of ≥1°C·m^{-1}, and the hypolimnion was from the bottom of the metalimnion to the sediments. If the water column was not stratified, we considered the water column equivalent to the mixed layer (epilimnion). Thermocline depth was defined as the depth within the metalimnion that exhibited the greatest density change with depth. The relative thermocline depth (α of Gorham and Boyce 1989) was calculated as the ratio between thermocline depth and maximum water depth of the basin at the time of sampling.

We calculated Schmidt stability indices (S) of all basins on each sampling date. S is the quantity of energy (per unit surface area) required to instantaneously mix the entire water column to an isothermal temperature, without addition or subtraction of heat (Wetzel 2001). S (g-cm·cm^{-2}) was calculated using

$$S = \frac{1}{A_0}\sum (z - z^*)(\rho - \rho^*)\mathrm{A}_z\mathrm{d}z \tag{3}$$

where A_0 is lake or reservoir surface area, z^* is the water column depth at which the mean water column density occurs, ρ^* is the water density at the depth of mean density (z^*), and A_z is the lake surface area at depth z. Calculations for all water depths (z) and water densities (ρ) were summed over a dz interval of 0.5 m.

On each sampling date, volume-weighted epilimnetic and hypolimnetic temperatures (T_E and T_H, respectively) were calculated using

$$T_E \; or \; T_H = \frac{1}{V_W}\sum_{z=1}^{z=n} t_z V_z \tag{4}$$

where V_W is the volume of the layer on a sampling date, t_z is the temperature of a depth interval in that layer, V_z is the volume of the depth interval and n is the number of depth intervals. The summation was taken over all depths at 0.5 m increments from the initial depth of the layer to the bottom of the layer. We calculated the seasonal mean epilimnetic ($\bar{T}_E$) and hypolimnetic ($\bar{T}_H$) temperatures of each basin as the mean of all sampling dates in which the basin was thermally stratified.

We calculated Birgean summer heat budgets (θ_S) for each site within both water bodies. Most studies define θ_S as the amount of heat necessary (per unit surface area) to raise a lake from 4°C to the maximum summer heat content (Wetzel 2001). This definition is difficult to apply to Sooke and Shawnigan because both water bodies typically do not reach 4°C in the winter. Therefore, for the purposes of this study, we defined θ_S as the amount of heat required (per unit surface area) to raise water temperature in early May to the date of maximum summer heat content in summer. This definition shortens the effective heating season and leads to lower summer heat budget estimates than those calculated by other studies. However, this method allowed us to standardize the starting point of the heating season and estimate the date of maximum heat content of the basins (see below). To estimate θ_S for each basin (Wetzel and Likens 2000), we calculated the volume of 0.5 m depth intervals in each basin and multiplied the volume by the temperature of the interval to yield heat content (watts) (Edmundson and Mazumder 2001, Edmundson and Mazumder 2002). Heat content of all intervals was summed and divided by the surface area of the basin, yielding megawatt $\cdot$ m^{-2}. We plotted basin heat content as a function of the day-of-year number (DOY) and fitted a 3rd or 4th order polynomial function. The date of maximum heat content (H_M) for the basin was estimated by taking the first derivative of the function, setting the solution to zero and solving for x. To calculate the predicted heat content on this date (θ_{HM}), we used the predicted date of maximum heat content in the fitted function and solved through substitution. To calculate θ_S of each basin, we subtracted the observed heat content of each basin in early May (from 2 - 10 May 2000 and 2001) from θ_{HM}.

To gain further insight into the relative importance of the different seasonal heat fluxes associated with water movement (Owens et al. 1998c, Wetzel and Likens 2000), we examined heat fluxes in each water body in relation to hydrological inputs and outputs. In Sooke, we calculated heat fluxes into the reservoir from hourly temperature measurements of all major inflowing streams. Mean monthly stream water temperature was multiplied to monthly flow volume, yielding monthly stream heat input (watts $\cdot$ day^{-1}). Regular data on stream water temperature was not available for the inflowing creeks of Shawnigan. We obtained 5 years of hourly temperature data from a nearby stream (Rithet Creek) very similar to Shawnigan inflowing streams. We regressed mean monthly stream water temperature (T_I) as a function of mean monthly air temperature (T_A) and found that, on a monthly time scale, air temperature predicted stream water temperature very well ($T_I = 3.12 + 0.282\ T_A + 0.0263\ T_A^2$, $r^2 = 0.959$, $P < 0.0001$), and used this function to estimate mean monthly water temperature of streams discharging into Shawnigan. For both water bodies, we calculated monthly inflow heat fluxes (Φ_I) by dividing the total heat input by average water body or basin surface area for the time period. Monthly heat fluxes out of Sooke and Shawnigan were calculated by multiplication of outflow and evaporation volumes to mean monthly volume-weighted epilimnetic temperatures (T_E), because both Sooke and Shawnigan only discharge surface water. When Sooke and Shawnigan were not stratified, we used the mean monthly volume-weighted water column temperatures (T_W – calculated using Equation 4). These values were used to calculate heat fluxes out of Sooke through the drinking water inflow (Φ_{DW}), and the dam spillway and the Shawnigan outflow (Sooke dam spill and Shawnigan stream outflow both denoted Φ_S). We estimated the interbasin heat transfer (Φ_{IBT}) for each basin by multiplying interbasin transfer volume by T_E or T_W, depending upon whether the basin was stratified. All values were converted to fluxes by dividing the heat transfer by the surface area of the water body or basin.

Results

In 2000, Sooke water level decreased by 6.25 m from mid-April to late-November (Fig. 2). Reservoir total volume decreased by 30.3 x 10^6 m^3 over this period, a 70% loss of volume from the south basin and a 26% loss of volume from the north basin. During the same period, Shawnigan depth decreased 0.52 m (4.6% volume loss) (Fig. 2). Sooke did not completely recharge to full stage water depth and volume during the 2000-2001 recharge period (October 2000 – April 2001) and was 2.72 m below full stage prior to the start of the 2001 drawdown season (Fig. 2). At the point of maximum drawdown in 2001, the volumes of the south and north basin of Sooke were 0.94 x 10^6 m^3 (full stage = 3.81 x 10^6 m^3) and 70.2 x 10^6 m^3 (full stage = 98.65 x 10^6 m^3), respectively. Shawnigan completely refilled prior to the summer of 2001 and had a total water depth reduction of 0.52 m (4.4% volume loss) over the summer and fall of 2001 (Fig. 2).

Sooke did not completely recharge to full-stage prior to the summer 2001 drawdown season because of lower than average precipitation in the 2000-2001 recharge period. Monthly rainfall totals in the fall and winter of 2000 were equivalent to a 100-year drought, making the total annual 2000 rainfall 583 mm lower than the long-term annual average (1642 mm $\cdot$ year^{-1}) (Fig. 3a and 3b). This period of below-average rainfall persisted until the spring of 2001, but monthly totals were close to long-term monthly means by fall 2001 (Fig. 3b). Mean summer air temperature, total daily irradiance and wind speed were remarkably similar between summers (Table 2), suggesting the principal meteorological difference between the two summers was the decrease in precipitation preceding the summer of 2001.

The drought in the 2000-2001 recharge period was associated with a 50% reduction in stream flow to Sooke and Shawnigan, compared to the 1999-2000 recharge period (Fig. 4). Both water bodies had similar seasonal stream inflow patterns and exhibited the same stream inflow reduction during the 2000-2001 winter drought. However, the relative importance of the various water exports from the two water bodies differed. In Sooke, over the two-year study period, drinking water consumption removed a total of 111 x 10^6 m^3 of water, a volume greater than the dam spillway (34 x 10^6 m^3) or evaporation (10.9 x 10^6 m^3). On a basin-specific basis in Sooke, evaporative losses were never greater than drinking water withdrawal losses (the drinking water intake in the south basin and the interbasin export out of the north basin). The greatest drinking water outflow rates in Sooke were observed from May-October (0.13 – 0.26 x 10^6 m^3 $\cdot$ day^{-1}), however,

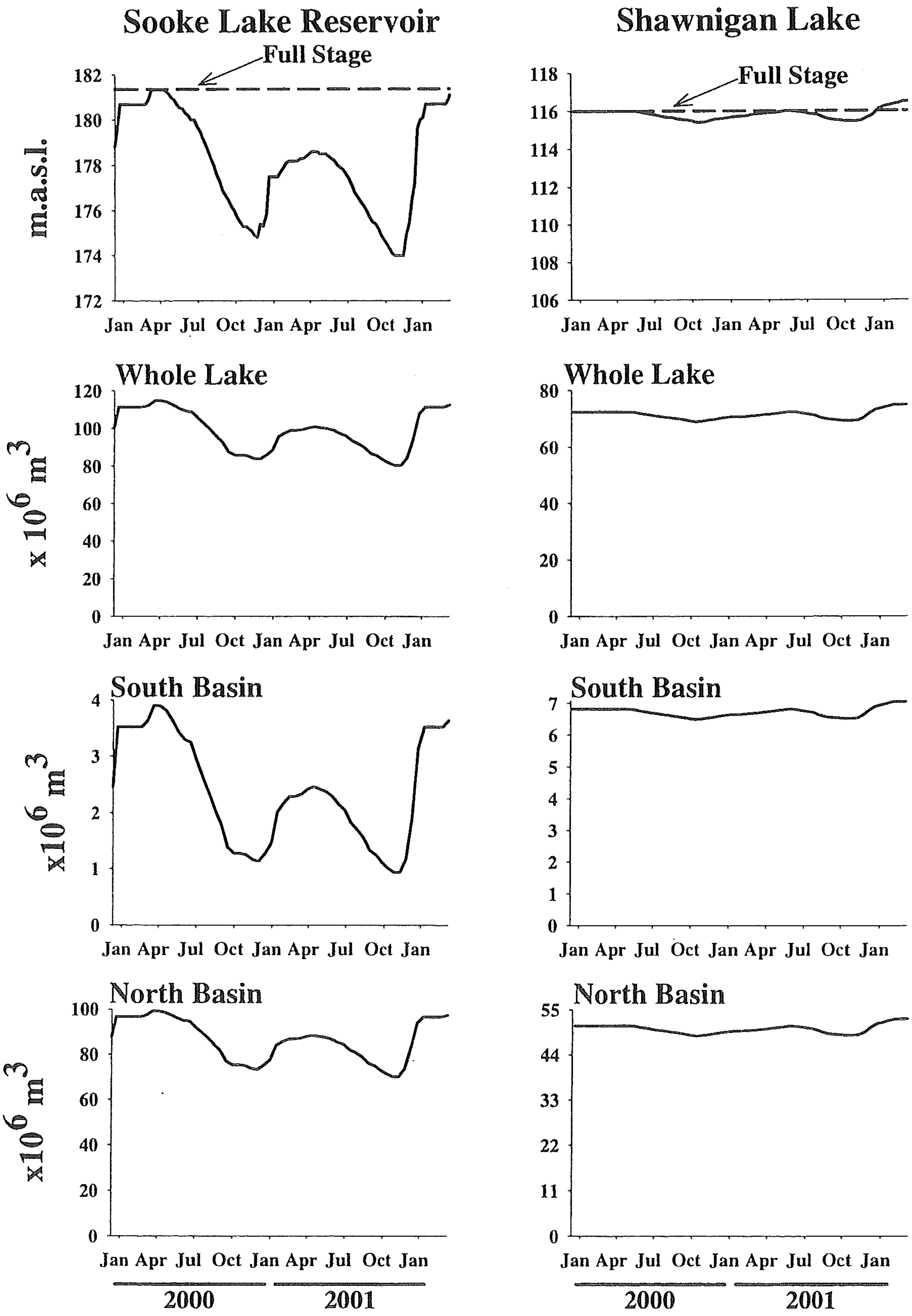

Figure 2.–Water surface elevation (in meters above sea level – m.a.s.l.), total water body volumes, and north and south basin volumes of Sooke Lake Reservoir and Shawnigan Lake from December 1999 - March 2002.

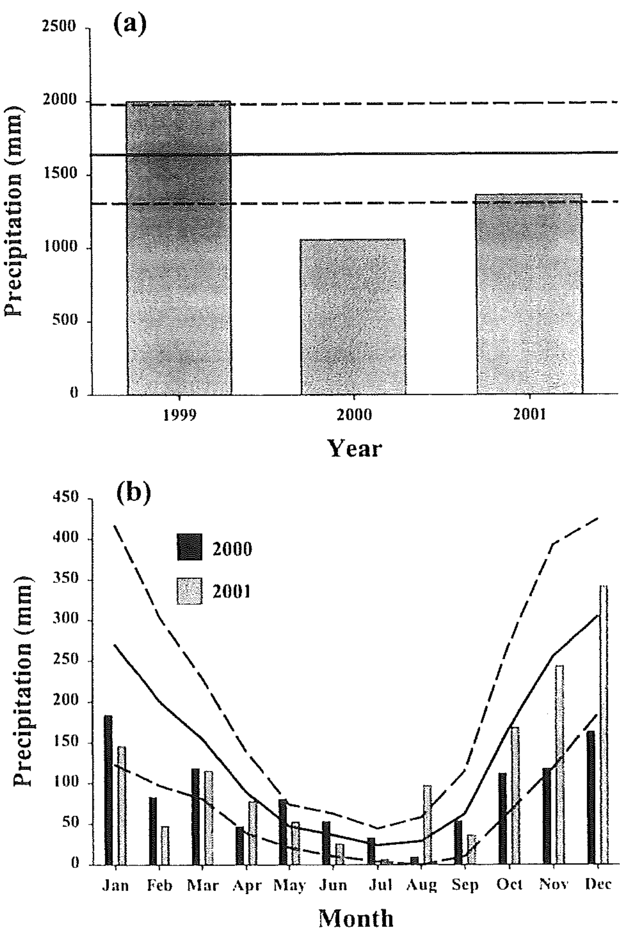

Figure 3.–Precipitation (mm) data from the Sooke Lake Reservoir Dam meteorological station. (a) Total annual precipitation 1999-2001. Solid line is 104-year mean (1895-1999) and dashed lines are ±1 standard deviation. (b) Monthly precipitation totals for 2000 and 2001. The solid line is the 104-year mean for each month and dashed lines are ±1 standard deviation.

maximum drinking water outflow rates and total withdrawal volumes were lower in 2001 due to water use restrictions in response to the lower reservoir levels. In Shawnigan, much smaller summer decreases in volume led to rapid lake volume recharge and a tighter coupling of lake inflows and outflow (Fig. 4). Evaporation was the dominant loss from Shawnigan during both summers (May-September 2000 and 2001 total evaporation loss = 8.58 x10^6 m^3) and exceeded stream outflow (2000 and 2001 total stream outflow volume = 6.44 x10^6 m^3).

Both basins of Sooke were stratified for shorter periods of time than both basins of Shawnigan in both summers (Table 3). Stratification of the south and north basins of Sooke was not observed until mid-June in 2000, approximately one month after stratification in both basins of Shawnigan, but all basins destratified during the same time period. In 2001, the south basin of Sooke had a stratification period approximately two weeks shorter than the previous year and ~1.5 months shorter than the stratification period of both basins of Shawnigan. Shawnigan had little variation in the duration of the stratification period between years.

Temperature profiles from all basins exhibited strong vertical temperature gradients through most of the summer period (Fig. 5). Surface temperatures in all basins did not exceed 24°C during the summer and hypolimnetic temperatures showed a gradual warming from May-September in both years (Fig. 5). Epilimnetic depth was generally greater in both basins of Sooke than in Shawnigan (Fig. 5, Table 4). In both water bodies, the larger north basins had deeper epilimnetic depths when compared to their corresponding south basins (Table 4). The relative thermocline depth (α - proportion of the water column above the thermocline) also followed a similar trend, with the northern basins of both water bodies having a smaller proportion of the water column above the thermocline than in the shallower south basins (Table 4).

Longitudinal temperature gradients (north basin versus south basin) at specific depths (1, 5 and 10m) within both water bodies were less than vertical temperature gradients (Fig. 6). Longitudinal temperature gradients in the surface waters (1 and 5 m) in both water bodies were small (on average ≤1°C difference between north and south basins of both water bodies) suggesting minimal impediment to mixing between

Table 2.–Mean summer (1 May-30 September) daily meteorological conditions (air temperature, solar irradiance, and wind speed) at the Sooke Lake Reservoir Dam meteorological station in 2000 and 2001. Minimum and maximum daily values are also given.

	Air Temperature (± 1 SD) (°C)		Irradiance (± 1 SD) kwatt·m^{-2}·day^{-1}		Wind Speed (± 1 SD) m·s^{-1}	
	Mean	Min, Max	Mean	Min, Max	Mean	Min, Max
2000	13.9 (± 3.3)	6.4, 20.9	4.8 (± 1.7)	0.8, 7.7	9.4 (±1.9)	5.9, 18.2
2001	13.7 (±3.1)	6.4, 20.0	4.9 (± 1.7)	0.08, 7.6	8.9 (± 2.1)	3.9, 14.4

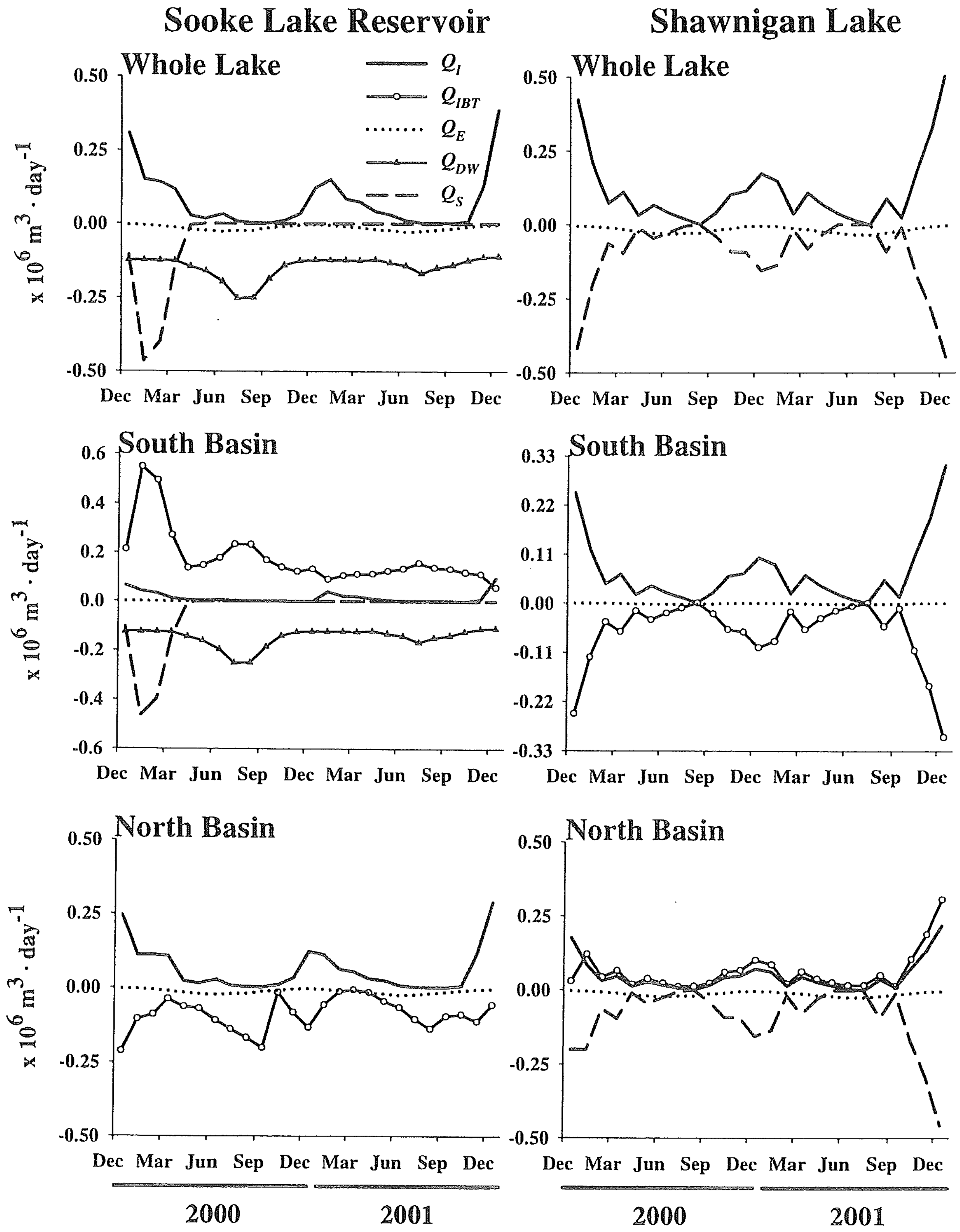

Figure 4.–Monthly water flow rates (x10^6 m^3 · day^{-1}) of Sooke Lake Reservoir and Shawnigan Lake from December 1999 - January 2002. Flow rates of stream inflow (Q_I), interbasin water transfer (Q_{IBT}), evaporation (Q_E), the drinking water outflow (Q_{DW}) and the Sooke Lake Reservoir dam outflow or the Shawnigan Lake outflow stream (both denoted Q_S) are presented for the whole water bodies and for the individual basins. Negative values are water losses and positive values are water inputs.

Table 3.–Observed duration of the stratification period in the north and south basins of Sooke Lake Reservoir and Shawnigan Lake. Duration of stratification (number of days) was determined from the date on which stratification was initially observed to the last date stratification was observed. Observed dates are the calendar dates of the observed stratification period.

	2000		2001	
	Stratification Peroid (no. of days)	Observed Dates	Stratification Period (no. of days)	Observed Dates
Sooke Lake Reservoir				
South Basin	113	19 June - 10 Oct	98	21 June - 28 Sept
North Basin	113	19 June - 10 Oct	126	7 June - 11 Oct
Shawnigan Lake				
South Basin	153	11 May - 11 Oct	161	8 May - 16 Oct
North Basin	153	11 May - 11 Oct	147	22 May - 16 Oct

surface waters between basins (Fig. 6a, b, d, e). At lower depths (10 m) temperature differences were greater than in the surface waters. In Sooke, water at 10 m in the south basin was consistently ≥3 °C cooler than in the north basin (Fig. 6c). Shawnigan also exhibited a similar longitudinal temperature gradient at 10 m (Fig. 6). Higher temperatures at 10 meters in the north basins of both water bodies reflect the relatively deeper epilimnia of the north basins than in the south basins (Fig. 5, Table 4). Longitudinal temperature gradients between basins at the same depths suggest that deeper waters between basins likely faced impediment to mixing and reflect basin-specific, rather than lake-wide, heating processes in both water bodies.

Average volume-weighted epilimnetic temperatures ($\overline{T_E}$) were similar in all basins (Table 5). Sooke south basin had the highest volume-weighted hypolimnetic temperatures ($\overline{T_H}$) of all basins in 2000 and 2001 (Table 5). Sooke south basin exhibited the smallest temperature differences between the epilimnion and hypolimnion (Table 5).

Maximum Schmidt stability (S) increased with basin volume (Fig. 7), but interannual differences in basin volume associated with the 2000-2001 drought affected maximum summer S of both basins of the reservoir. Maximum observed S of the south basin of Sooke was 408.77 g-cm·cm^{-2} in 2000 and 185.8 g-cm·cm^{-2} in 2001, a 55% reduction in 2001 (Fig. 7). Similarly, the north basin of Sooke experienced a 20% reduction in maximum S in 2001, when compared to 2000. The south basin of Shawnigan had no change in maximum S between years and the north basin had a greater maximum S in 2001 than in the summer of 2000 (Fig. 7).

Birgean summer heat budgets (θ_S) increased with basin size (Fig. 8). The smaller Sooke south basin volume in 2001 caused a 31% decrease in θ_S in 2001, when compared to the previous year (2000 = 2.6 megawatt·m^{-2}, 2001 = 1.8 megawatt·m^{-2}). θ_S of the north basin of Sooke and both basins of Shawnigan were not different between years. The timing of the date of maximum heat content (H_M) of the south basin of Sooke was affected by the relatively large volume reductions (Fig. 8). H_M of Sooke south basin was approximately 2 weeks earlier than all of the other basins in 2000. In 2001, during the period of low water levels, H_M was >5 weeks earlier than the other study basins. The north basin of Sooke and both basins of Shawnigan had H_M dates very close to one another in both summers.

The drinking water withdrawal out of Sooke was the largest heat flux out of the reservoir, especially during the summer and fall (Fig. 9). On a whole reservoir basis, the total flux out of the lake in the May – October period associated with the drinking water outflow (Φ_{DW}) was 7 – 10 times greater than evaporation losses (Φ_E). The magnitude of heat fluxes associated with the withdrawal of water from the two Sooke basins differed (Φ_{IBT} in the north basin and Φ_{DW} in the south basin). The maximum summer heat flux out of the north basin associated with the removal of water (Φ_{IBT}) was 2.78 and 2.91 megawatts m^{-2}·day^{-1} in 2000 and 2001, respectively. The south basin exported heat at a maximum rate more than an order of magnitude greater than the north basin in both summers (2000 = 49 megawatts m^{-2}·day^{-1}, 2001 = 30.2 megawatts m^{-2}·day^{-1}). In contrast to Sooke, the dominant heat flux out of Shawnigan in the summer – fall period was evaporation (Φ_E) (Fig. 9). On average, from April – September of both years, total evaporative heat losses were 12 times greater than the heat flux out of the lake outflow stream.

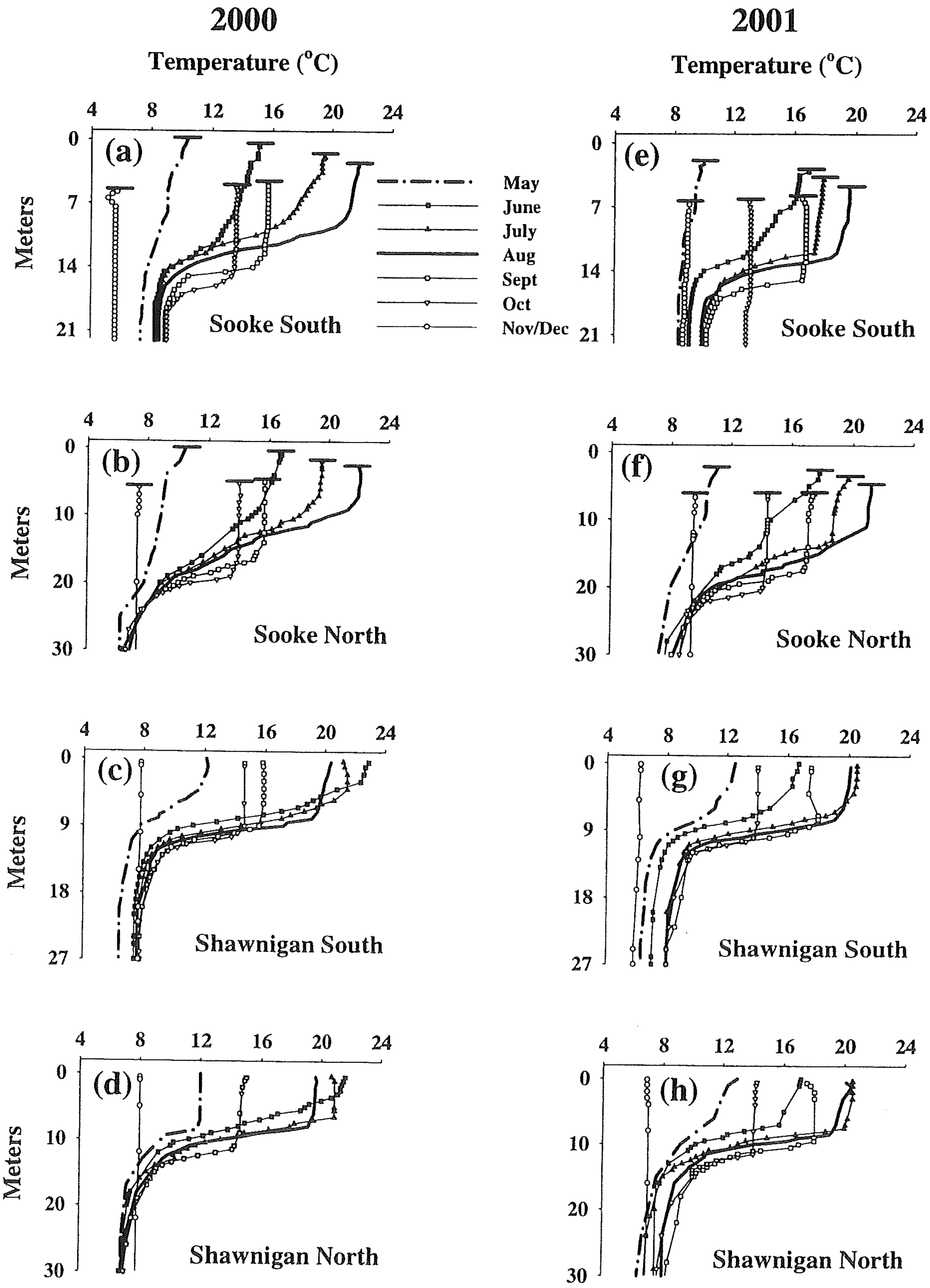

Figure 5.–Examples of monthly temperature profiles in 2000 (a-d) and 2001 (e-h) from Sooke south basin (a, e), Sooke north basin (b, f), Shawnigan south basin (c, g) and Shawnigan north basin (d, h). The lines at the top of the Sooke temperature profiles represent basin water level. No lines are presented for Shawnigan because the water level only decreased ≤0.5 m in both years.

Table 4.–Mean epilimnetic depth (m) and relative thermocline depth (α) during the summer stratification period for the north and south basins of Sooke Lake Reservoir and Shawnigan Lake. Values are calculated from all sampling dates during the stratification period for each basin. Values in parentheses are the range observed during stratification.

	2000		2001	
	Epilimnetic Depth (m)	α	Epilimnetic Depth (m)	α
Sooke Lake Reservoir				
South Basin	9.0 (7.0 - 10.0)	0.59 (0.49 - 0.69)	8.4 (7.5 - 9.5)	0.55 (0.51 - 0.60)
North Basin	10.6 (6.0 - 14.0)	0.18 (0.13 - 0.23)	10.9 (7.5 - 15.0)	0.19 (0.12 - 0.24)
Shawnigan Lake				
South Basin	6.7 (4.5 - 9.5)	0.31 (0.22 - 0.42)	6.6 (4.0 - 9.5)	0.32 (0.26 - 0.40)
North Basin	7.8 (0.11 - 0.22)	0.17 (4.0 - 11.0)	7.6 (6.0 - 11.0)	0.16 (0.14 - 0.23)

Discussion

Lakes within the same region typically exhibit a high degree of temporal coherence in seasonal thermal conditions, and deviation of individual lakes from regional thermal regimes can be due to basin morphometry and water clarity (Fee et al. 1996, Benson et al. 2000). In the study presented here, despite similar morphometry and trophic states, seasonal stratification and thermal regimes differed between the morphometrically similar basins of Sooke Lake Reservoir and Shawnigan Lake. Contrasting drawdown regimes of the two water bodies caused the timing and duration of stratification, summer heat budgets and the relative importance of seasonal heat fluxes to differ, despite exposure to identical climatic conditions. Furthermore, the responses of the stratification and thermal regimes of the two water bodies to the drought of 2000-2001 differed because of human manipulation of the hydrology of Sooke Lake Reservoir. The magnitude of these impacts, however, were mediated by interbasin differences in morphometry, as observed by the greater interannual differences in stratification and thermal regimes in the south basin than in the north basin of Sooke.

Sooke Lake Reservoir was stratified for shorter periods of time than Shawnigan Lake in both years. Removal of reservoir volume over the summer and fall can shorten the stratification period (Effler and Bader 1998, Owens 1998c) or cause polymictic conditions (Barone and Naselli Flores 1994). Sooke experienced a later onset of summer stratification than Shawnigan (2 – 4 weeks later), which may be related to relatively higher flow rates out of the reservoir during the spring and early summer. Flow within reservoirs associated with inflows and discharge can create complex stratification patterns or prevent stratification if flow rates are great enough (Ford 1990, Townsend 1998). While the stream inflow rates into both water bodies were similar during May – June of 2000 and 2001 (Sooke May – June 2000 and 2001 mean inflow rate = 0.02×10^6 $m^3 \cdot day^{-1}$, Shawnigan mean inflow rate = 0.04×10^6 $m^3 \cdot day^{-1}$), the outflow rates were 8 times greater in Sooke (Sooke May – June 2000 and 2001 outflow rate = 0.16×10^6 $m^3 \cdot day^{-1}$, Shawnigan May – June 2000 and 2001 outflow rate = 0.02×10^6 $m^3 \cdot day^{-1}$). The timing of destratification in the fall of both years was similar between Sooke and Shawnigan, except for Sooke south basin in the second year of the study. In 2001, when reservoir water levels were lower, Sooke south basin destratified more than a month before the other basins. It is not unexpected that Sooke south basin had an earlier turnover date in 2001 because relatively shallow basins with warmer hypolimnetic temperatures are more likely to have earlier fall turnover dates than deeper lakes (Nürnberg 1988).

Lake heat budgets increase with lake depth, volume and surface area (Gorham 1964, Timms 1975) and in our study, Birgean summer heat budgets (θ_S) increased with basin size. θ_S values had little variation between years in the north basin of Sooke and both basins of Shawnigan, however, in 2001, Sooke south basin experienced a ~30% reduction in θ_S from the previous year. The reduction in θ_S in 2001 was due to the comparatively smaller basin volume and the removal of warmer epilimnetic water from the basin continuously through the summer. In addition, the relatively large volume of epilimnetic water removed from the south basin of Sooke affected the timing of the date of maximum heat content (H_M). H_M is often consistent at

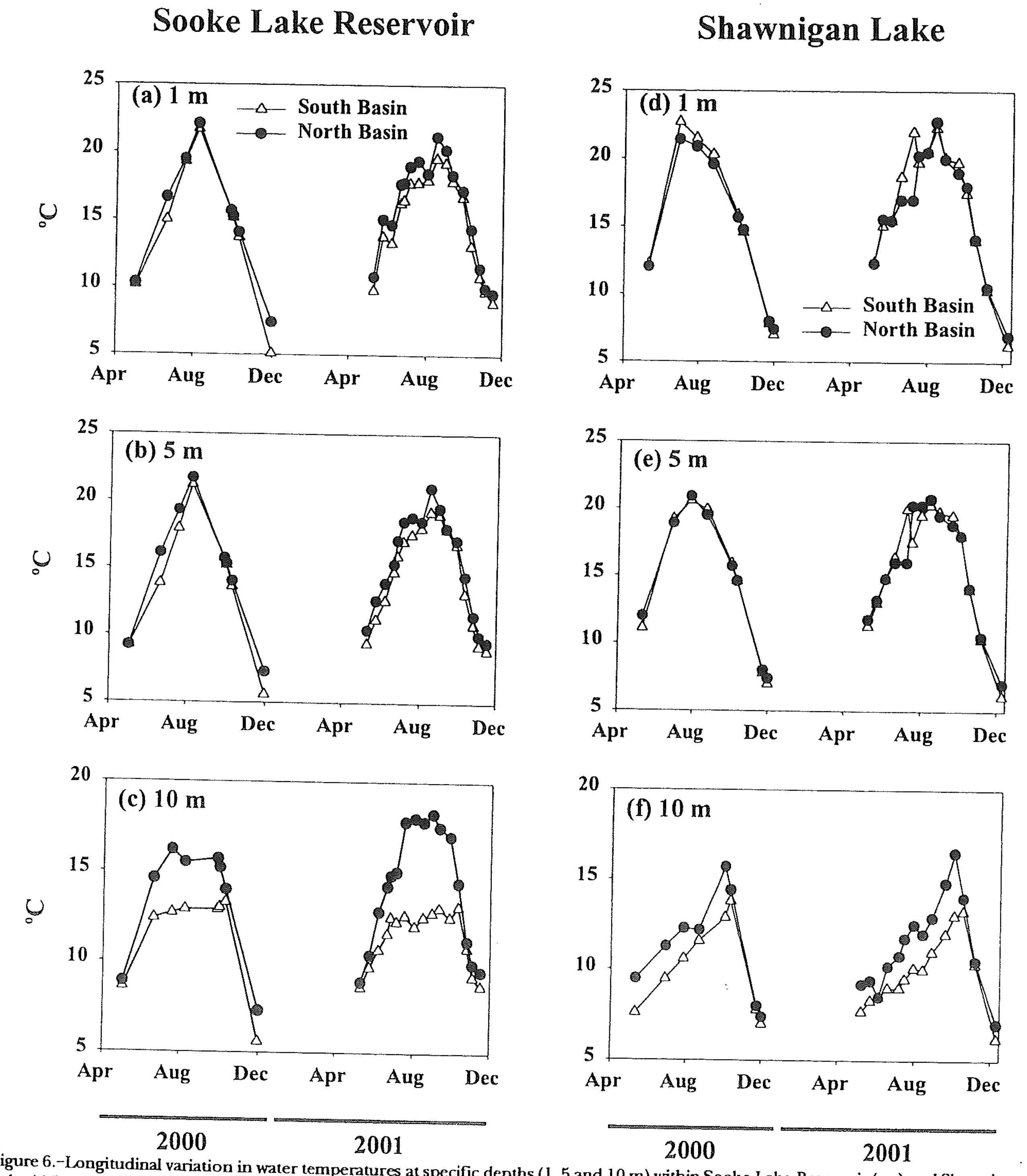

Figure 6.–Longitudinal variation in water temperatures at specific depths (1, 5 and 10 m) within Sooke Lake Reservoir (a-c) and Shawnigan Lake (d-f) from April 2000 - Dec 2001.

a regional scale, even among lakes representing a wide range of surface temperatures and optical properties (Edmundson and Mazumder 2002). H_M of the south basin of Sooke was two weeks earlier in 2000 and more than five weeks earlier in 2001 than H_M of the other study basins. We also observed a decoupling of the dates of maximum surface water temperature and H_M in the south basin of Sooke. Maximum epilimnetic temperatures occurred in all basins in late July to mid-August in both years, which coincided with H_M dates of the north basin of Sooke and both basins of Shawnigan. The assumption of synchrony in the dates of maximum

Table 5.–Mean (± 1 SD) volume-weighted epilimnetic (*TE*) and hypolimnetic (*TH*) temperatures (°C) for the north and south basins of Sooke Lake Reservoir and Shawnigan Lake in 2000 and 2001. Means for *TE* and *TH* were calculated from all volume-weighted temperatures obtained on sampling dates in which a basin was thermally stratified.

	Sooke Lake Reservoir		Shawnigan Lake	
	South Basin		South Basin	
	TE	*TH*	*TE*	*TH*
2000	16.4 (±3.0)	9.3 (±0.5)	17.5 (±4.0)	8.2 (±0.6)
2001	17.5 (±1.3)	10.5 (±0.6)	17.5 (±3.3)	8.2 (±0.7)
	North Basin		North Basin	
	TE	*TH*	*TE*	*TH*
2000	17.0 (±2.9)	7.5 (±0.8)	17.2 (±3.7)	7.6 (±0.1)
2001	17.4 (±2.2)	8.6 (±0.4)	17.6 (±2.6)	7.9 (±0.5)

heat content and the dates of maximum surface temperature made by previous studies (Edmundson and Mazumder 2001, Edmundson and Mazumder 2002) may not be applicable to reservoirs that experience relatively large summer epilimnetic withdrawals.

Removal of significant volumes of epilimnetic water from reservoirs will dissipate heat at high rates, creating large summer heat sinks from reservoirs (Martin and Arneson 1978, Kennedy 2001). In contrast, discharge of cooler, deeper waters of the meta- or hypolimnion may cause the reservoir to function as a seasonal heat trap, due to the retention of warmer epilimnetic waters. The discharge of epilimnetic water during the summer and early fall from Sooke was the largest heat export from the reservoir. In the south basin of Sooke the drinking water withdrawal removed up to 50 megawatts $m^{-2} \cdot day^{-1}$, while in the north basin the volume of water exported was similar, the per unit surface area heat flux was approximately 10 times less. In contrast to Sooke, evaporation dominated summer heat losses

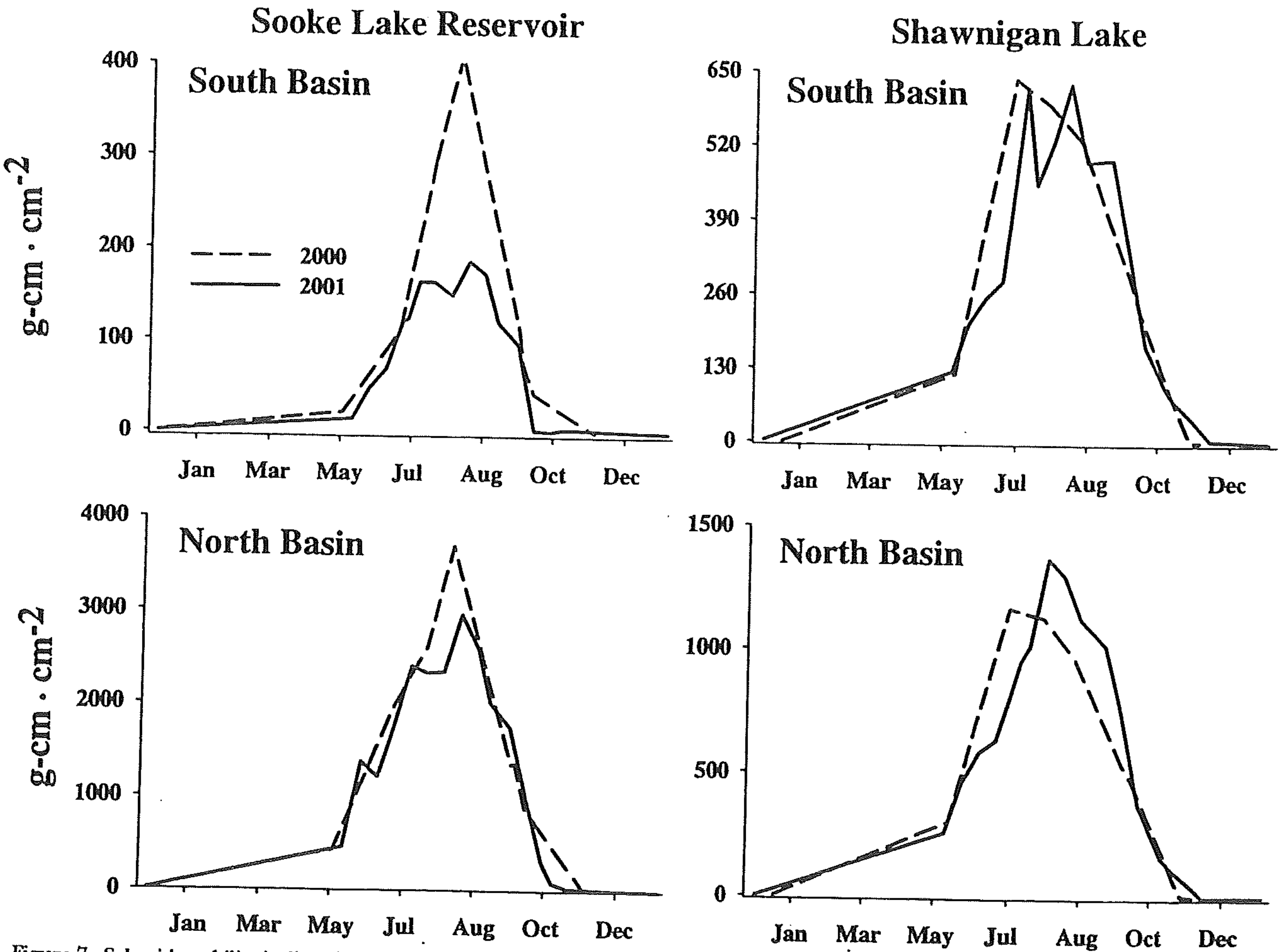

Figure 7.–Schmidt stability indices (*S*) for the north and south basins of Sooke Lake Reservoir and Shawnigan Lake in 2000 and 2001. The dashed line is 2000 and the solid line is 2001.

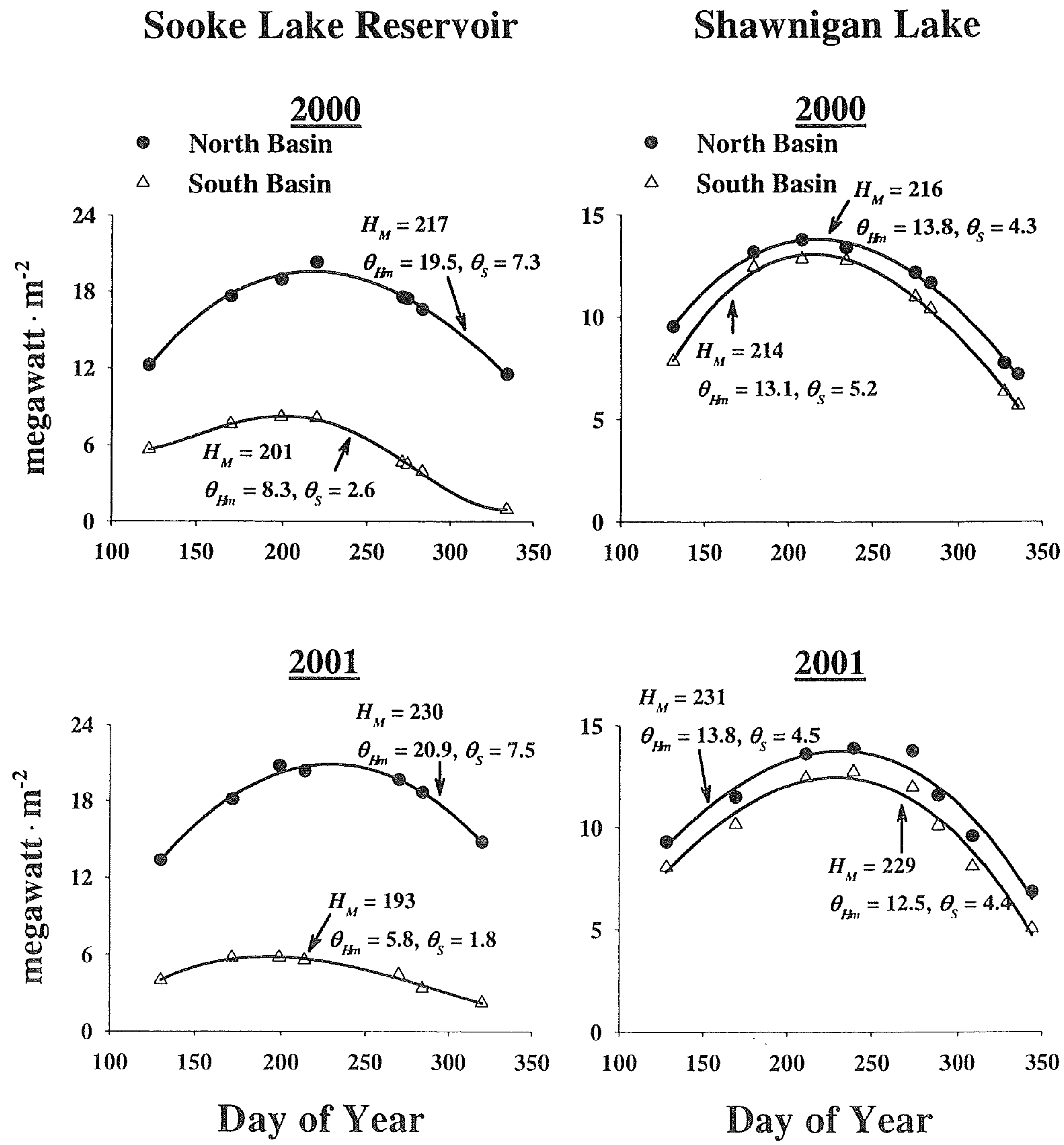

Figure 8.–Birgean summer heat budgets for the north and south basins of Sooke Lake Reservoir and Shawnigan Lake in 2000 and 2001. Heat content (megawatt·m^2) is plotted as a function of day of year (DOY). A 3rd or 4th order polynomial is fitted to the data and used to predict date of maximum heat content (H_M), the heat content of the basin on the date of maximum heat content (θ_{H_m}) and to calculate the Birgean summer heat budget (θ_S). Values for H_M, θ_{H_m} and θ_S (in megawatt·m^2) for each basin are given next to each line.

from Shawnigan, which corresponds with classical models of lake seasonal heat fluxes (Hutchinson 1957, Wetzel 2001). Shawnigan also discharges surface water, but total evaporative heat losses from April–September of both years were more than an order of magnitude greater than the total lake outflow heat losses.

Long- and short-term decreases in precipitation have been associated with changes in lake water clarity, ion and nutrient concentrations and mixing regimes (Schindler et al. 1996, Schindler et al. 1997, Webster et al. 2000). The effects of interannual changes in precipitation on reservoir ecosystems have received

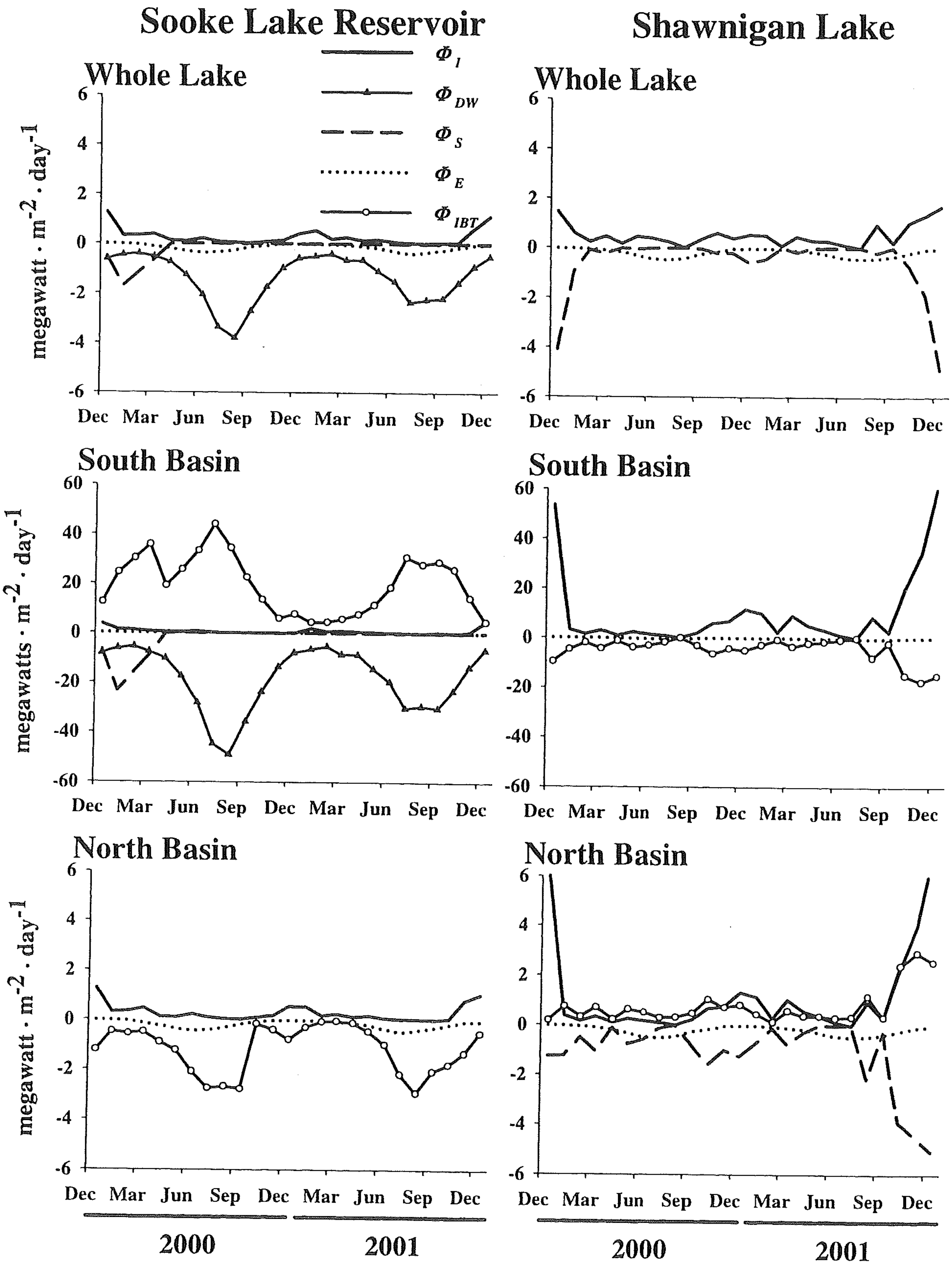

Figure 9.–Monthly heat fluxes (megawatt $m^{-2}\cdot day^{-1}$) into and out of Sooke Lake Reservoir and Shawnigan Lake from December 1999-January 2002. Heat fluxes from the inflowing streams (Φ_I), the drinking water outflow (Φ_{DW}), the Sooke dam spill or the Shawnigan Lake outflow stream (both denoted Φ_S), evaporation (Φ_E), and the interbasin transfer of heat (Φ_{IBT}) are presented for the whole water body, the north and the south basin of both water bodies. Negative heat fluxes are heat losses from the system and heat influxes are positive values.

comparatively less attention (LaBounty and Sartoris 1981), and even less information is available on the comparison of responses of lakes and reservoirs to short-term changes in precipitation. The cumulative effect of climate and human activity on freshwater ecosystems has received recent emphasis and has underscored the lack of knowledge about the potential synergistic effects of climate and anthropogenic stressors (Schindler 2001). In our study, reservoir stratification and thermal regimes were more sensitive to short-term changes in precipitation than the adjacent natural lake because the reservoir experienced large water level fluctuations associated with drinking water withdrawal. The shallower south basin had a much greater sensitivity to both stressors when compared to the north basin of the reservoir. The combined impacts of seasonal water level fluctuations and climate variability present ecological and management implications for reservoir systems. For example, the drawdown of a basin during the summer could lead to destratification and subsequent entrainment of nutrient-rich hypolimnetic water into the illuminated surface waters in the warmer portion of the growing season, rather than in the fall when water temperatures are considerably lower. In years where reservoir water levels are low due to decreased precipitation, the stratification period may be further shortened, leading to an even earlier turnover date. In addition, basin morphometry should also be considered when considering the impacts of water level fluctuations and climate variability. The stratification and thermal regimes of relatively shallow and less voluminous basins are likely to exhibit higher sensitivity to the combined impacts of water level fluctuations and short-term climate variation. Therefore, future research should focus on the interaction of reservoir hydrology and climate variability, and the implications for the ecology and management of reservoir systems.

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