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Partitioning impacts of climate and regulation on water level variability in Great Slave Lake

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Summary Water level observations and a daily water balance model are used to build a naturalized water level history for Great Slave Lake dating back to the 1967 completion of the W.A.C. Bennett Dam in the Peace River basin headwaters. Comparison of water level observations dating back to 1938 and water balance scenarios for 1964–1998 assist in constraining the probable magnitude and likely direction of climate and regulation impacts on the water level history of the lake. Overall, the first-order analysis suggests that the effect of flow regulation has been to dampen annual water level variability by about 20 ± 2 cm, to reduce annual maximum water levels by about 14 ± 3 cm and to shift peak water levels earlier in the season by about 30 ± 8 days. Meanwhile, climate forcing has tended to enhance water level variability by 8 ± 2 cm, to enhance maximum water levels by 10 ± 3 cm and to advance the timing of maximum water levels slightly (11 ± 8 days). Climatic and regulation impacts appear to have generally counter-balanced changes in amplitude of water level changes and magnitude of peak levels but have cumulatively contributed to a seasonal shift toward earlier peak water levels in the lake.

Introduction

Great Slave Lake (28,568 km^2) is situated along the main stem of the Mackenzie River system (Fig. 1), and functions as a hydrologic, biogeochemical and sedimentary regulator for roughly 50% of annual basin runoff (~290 km^3) to the Arctic Ocean. Several recent studies have focused on the hydrologic functioning of the lake including outlet hydraulics (Hicks et al., 1995), water budget (Kerr, 1997), evaporation (Blanken et al., 2000), and ice phenology (Menard et al., 2002). In addition, a recent hydroclimatic analysis by Gibson et al. (2006) illustrated that interannual water level variations in Great Slave Lake (GSL) during 1934–1998 have been controlled mainly by riverine inputs to the lake from the Slave River, which drains the Peace and Athabasca River basins situated in the southern headwater regions of the Mackenzie drainage basin (Fig. 1). Although the study concluded that precipitation variability

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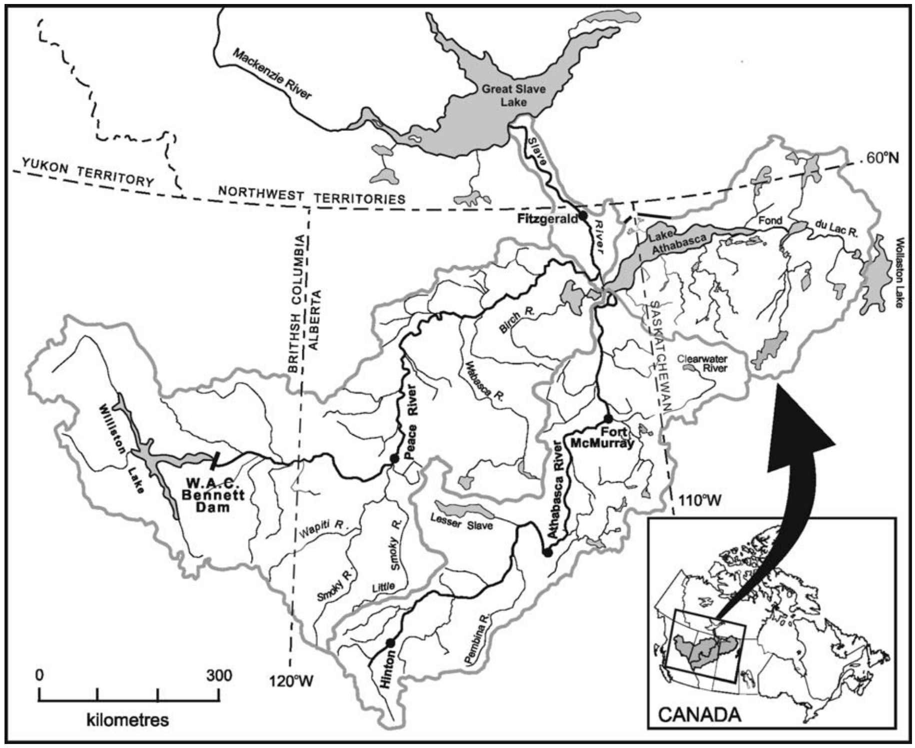

Figure 1 Map of Peace-Athabasca basins, the primary source of riverine input to Great Slave Lake, showing location of the W.A.C. Bennett Dam.

in the Peace-Athabasca basins has been the dominant driver of interannual GSL water level variations over the past seven decades, the effects of regulation of the Peace River was shown to have had a significant impact on the seasonal timing of water level variations, based on comparisons between pre- and post-regulation water level records. Water balance ''normals'' for 1964—1998, a period during which 86% of riverine inputs to GSL were gauged, indicate that about 74% of inflow to Great Slave Lake originates from the Peace-Athabasca catchments that enter the lake via the Slave River, whereas 21% is derived from other catchments bordering Great Slave Lake, and 5% from precipitation on the lake surface. An estimated 94% of water losses occur by riverine outflow to the Mackenzie River and 6% by evaporation from the lake surface (Gibson et al., 2006).

Abstraction of water to fill the Williston Reservoir, formed by construction of the Bennett Dam in the Rocky Mountain headwaters of the Peace River accounted for temporary diversion of 41 km^3 of riverine discharge to the lower Peace-Slave River system during 1968—1971, an amount of water equivalent to 1.4 m depth over the surface of GSL (Gibson et al., 2006). Due to operating requirements of the hydroelectric facility, the dominant ongoing regulatory effect on downstream areas is a reduction of peak flows during the high spring and summer flow periods when water is being retained, and an increase in flows from power generation during the normal low-flow winter months when electrical demand is highest (Peters and Prowse, 2001). While comparisons of pre- and post-regulation conditions have permitted basic assessments of regulatory impacts to be made for GSL, separation of the effects of climate variability from regulation has not been previously undertaken. Given the strong relationship between seasonal GSL water levels and outflow to the Mackenzie River (Kerr, 1997; Gibson et al., 2006), and the observed seasonal variation in wind seiche events, which are known to play a role in shaping the hydrodynamics of the Slave River delta (Gardner et al., 2006), it is plausible that regulation has had a measurable influence in re-shaping the lake-delta-river system (English et al., 1997).

As a corollary to the study by Gibson et al. (2006), we apply a calibrated water balance model, a stage-discharge routing algorithm, and naturalized flow simulations from the Slave River (Peters, 2003) to build a naturalized scenario of GSL water balance and water level conditions during the regulated (1968—1996) period. The naturalized scenario reflects the probable response of GSL if the Williston reservoir project had not been undertaken, and provides a basis for unraveling the specific impacts of regulation versus climate variability. The available datasets allow for comparison of pre-regulation and naturalized simulations of post-regulation conditions as well as a check on performance of the water balance model during the post-regulation period. Overall, as we show, the results suggest that climatic and regulation impacts have broadly counter-balanced changes in amplitude of water level changes and magnitude of peak levels but have cumulatively contributed to a shift toward earlier peak water levels in the lake. Implications for delta hydrology and outflows to the downstream Mackenzie River system are discussed.

Methods

Water level records for four stations on GSL (Ft. Resolution, Snowdrift, Hay River, Yellowknife) were averaged to obtain a composite daily record of lake level variations dating back to 1938. For comparison, a daily water balance model of GSL was also used to test predictability of lake levels assuming storage changes were controlled by the water balance according to

$$\Delta V = I + P - Q - E \pm G \pm \text{error} \tag{1}$$

where ΔV is the daily change in lake storage (m^3/s), I is the riverine inflow rate (m^3/s), P is precipitation rate on the lake surface (m^3/s), Q is daily rate of riverine outflow (m^3/s), E is evaporation rate (m^3/s) and $\pm G \pm$ error is combined groundwater exchange and error (m^3/s). Lake level variations were calculated using $\Delta WL = \Delta V/A$ where A is area of the lake (assumed constant at 28,568 km^2). Detailed descriptions of these datasets and a long-term water balance summary for the period 1964–1998 are provided elsewhere (Gibson et al., 2006). Note that the water balance model was run on a daily time-step but was annually calibrated using a constant inflow scaling factor to match the water level records on January 1 of each year. This was required to prevent interannual drift.

For simulation of GSL water levels under naturalized conditions, a naturalized flow record for the Slave River was substituted for the observed Slave River flow record. Peters (2003) utilized naturalized Peace River flow data (Peters and Prowse, 2001) in the ONE-D Hydrodynamic Model of the PAD (Environment Canada and BC Environment, 1995) to remove the influence of hydroelectric reservoir operation on the Peace River and rock-fill weirs on two outflow channels of the PAD (PAD-IC, 1987) to a naturalized estimate of daily discharge on the Slave River (Outflow boundary of the ONE-D Model). An additional routing module was developed for this study to simulate lake outflow. The routing module was constructed from three simple regression models (Fig. 2) that relate outflow from the GSL to lake level under ice-covered (January–April), transitional (November–December, May–June) and open-water periods (July–October). Despite weaker relationships between lake level and discharge in the winter and transitional months than in open-water periods ($r^2 = 0.5$–0.53 vs. $r^2 = 0.88$, respectively; see Fig. 2), it was still possible to predict lake outflows reliably using the developed algorithm (Fig. 3).

Table 1 illustrates some of the key comparisons that can be made between the pre-regulation water levels and post-regulation observations/simulations to partition the climate and regulation signals. As noted, comparisons between observed pre-and post-regulation records provide a combined estimate of climate and regulation impacts.

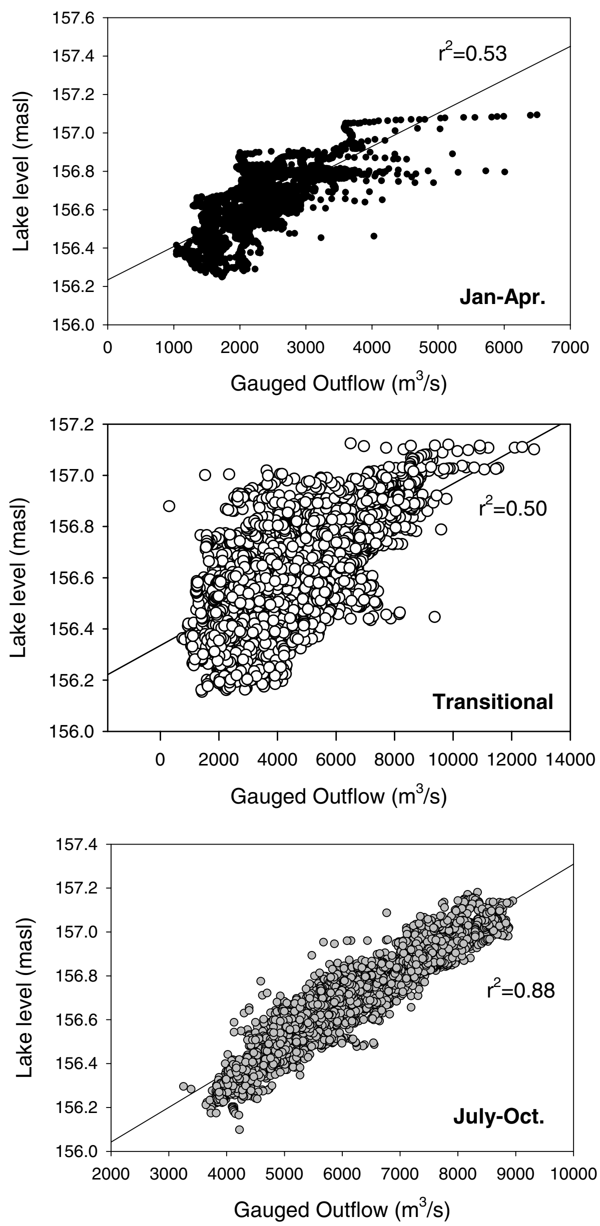

Figure 2 Relationship between lake level and outflow from Great Slave Lake for ice-covered months (January–April), for transitional months (May, June, November, December) and for ice-free months (July–October).

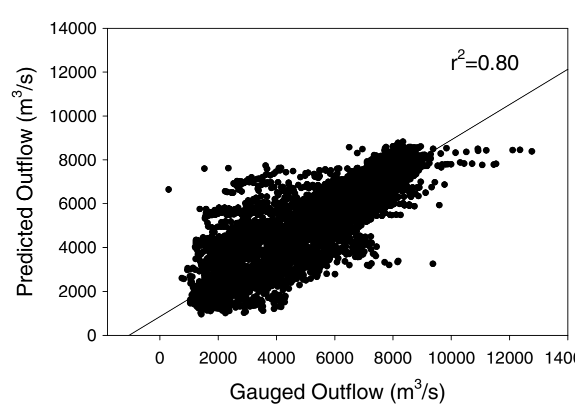

Figure 3 Measured versus modeled daily outflows from Great Slave Lake for 1964–1998. Modelled outflow is based on the seasonal stage-discharge relationships given in Fig. 2.

Table 1 Comparative analysis cross-table showing main signals examined from specified (row heading:column heading) scenario pairs

Post-regulation	Pre-regulation Observed WL	Post-regulation	
		Observed WL	Naturalized WL
Observed WL	Climate + Regulation		Regulation ± model Performance
WB simulation			
Base case WL		Model performance	
Naturalized WL	Climate ± Model performance		

Results and discussion

Comparison between measured GSL lake levels and post-1964 water balance simulations of the lake levels are illustrated in Fig. 4. The water balance scenarios include: (i) a base case with observed inflows/outflows, and (ii) a naturalized case with naturalized inflows, and outflows calculated from the stage-discharge routing algorithm. No attempt was made to simulate water balance prior to 1964 owing to lack of basic gauging records for many of the key tributaries (see Gibson et al., 2006). Frequency distributions for key indices are shown for pre- and post-regulation periods (Figs. 5–7 and Table 2). An annual time-series comparing the observed and simulated, naturalized maximum and minimum lake level (Fig. 8) and a seasonal summary of pre- and post-regulation water levels (Fig. 9) illustrate some important comparisons discussed below. Note that the period of filling of the Williston reservoir (1968–1971) is excluded from the analysis.

Pre-regulation vs. post-regulation lake levels

Differences in GSL lake levels during 1938–1967 (pre-regulation) and 1972–1996 (post-regulation) are found to be statistically significant at the $p = <0.001$ level, based on Mann–Whitney Rank Sum Test. These differences are attributed to the combined effects of regulation and climate impacts (see Table 1). Comparisons between median values of selected observed water level statistics for pre- and post-regulation periods reveal that annual amplitude of water level variations is reduced slightly for post-regulation (0.45 m vs. 0.56 m; Fig. 5b vs. Fig. 5a, respectively), annual maximum water level is reduced slightly (156.86 masl vs. 156.90 masl; Fig. 6b vs. Fig. 6a, respectively), and maximum water levels occur earlier (early August vs. late July; Fig. 7b vs. Fig. 7a, respectively). The distributions in Figs. 5ab–7ab display a notable reduction of kurtosis in the post-regulation period suggesting a systematic reduction in the peakines of the amplitude variations, maxima, and timing of maximum water level. The positively skewed timing distribution, which retains the appearance of a natural hydrograph during pre-regulation era (Fig. 7a) also shifts significantly towards a more normal distribution in the post-regulation era (Fig. 7b). As summarized in Table 2, the most discernible changes between the two periods is, a modest reduction in variability and increase in normality of water level conditions. Shifts in the seasonality of water level changes (Fig. 9) emphasize the impact of slower, more continuous release of water from the Williston reservoir in the Peace River headwaters during the winter and transitional months, and reduction of peak flows in spring/summer. This mimics the changes that have occurred in Peace River discharge (Peters and Prowse, 2001).

Model performance

In general, the base case simulation is found to be in broad agreement with observations in terms of predicting the form and direction of seasonal water level changes in most years (see Fig. 4). The most systematic differences between the base case model and observations (i.e. often the model predicts higher-than-observed lake levels in late summer, and lower-than-observed lake levels in winter) is attributable to the use of an empirical routing algorithm to simulate outflow. The algorithm, developed based on average long-term conditions, captures only 80% of variability in the outflow, and therefore tends to exaggerate the lake storage effect, especially in summer (Fig. 9). At times, differences between the model and observations may also in part be due to declines in areal coverage of the gauging records, as between 10% and 16% of the catchment area was ungauged in any given year, as well as uncertainty due to streamflow measurement error, which typically ranges from ±5% for direct measurements using current meters to ±10 for indirect measurements using rating curves at well-maintained stations (Tillery et al., 2001).

Comparisons between observations and base-case statistics during 1972–1996 suggests reasonable agreement between annual amplitude of water level variations (0.45 m vs. 0.47 m; Fig. 5b vs. Fig. 5c, respectively), annual maximum water levels (156.86 masl vs. 156.89 masl; Fig. 6 vs. Fig. 5c, respectively), and maximum water levels (late June vs. early July; Fig. 7b vs. Fig. 5c, respectively). Differences between observations and the base case simulation, also statistically significant at the $p = <0.001$ level, usefully constrain the potential annual uncertainty in the model (Table 2), and importantly suggest that noise due to model performance does not overwhelm the primary climate and regulation signals that control water level variability. Median statistics suggest these annual differences amount to about ±0.02 m amplitude, ±0.03 m for maximum water level, and about ±8 days for timing of the annual water level maximum (Table 2). This measure of model uncertainty appears reasonable, and is basically consistent with estimates obtained from differences in the standard deviations of the distributions shown in Figs. 5bc through 7bc, which yield ±0.03 m, ±0.01 m, and ±7 days for the amplitude, maximum and timing diagnostics, respectively.

The model also adequately captures the general shape of the distributions (see Figs. 5–7b vs. Figs. 5–7c) although is slightly peakier in all cases than the observations (higher kurtosis), and is slightly positively skewed in terms of water level variability and maximum level. This tendency of the base case model to overestimate summer water levels by up to 5 cm or so is likely responsible for overestimated water levels in the lake in summer (see also Fig. 9), an artifact that is expected to be carried over into the naturalized scenarios. It is important to consider this particularly when comparing model simulations and observations in the following sections.

Climate impacts on lake level

Comparison of pre-regulated and naturalized simulations suggest that statistically significant climate-driven changes in water level variability have also occurred. Comparisons between median values of selected water level statistics for pre-regulation and the naturalized, post-regulation

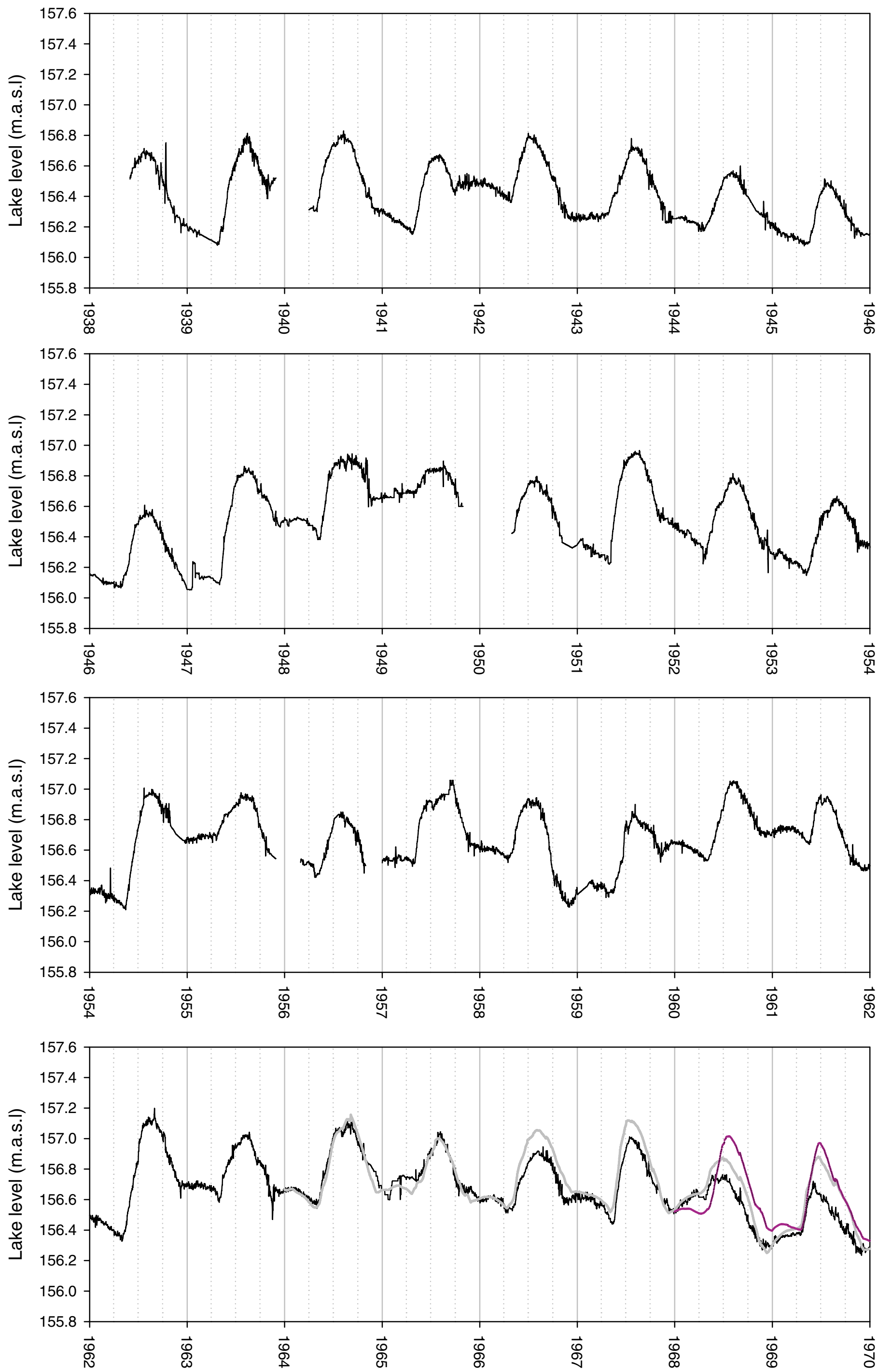

Figure 4 Observed (heavy black), simulated (grey) and naturalized (thin black) water levels in GSL, 1938–1998.

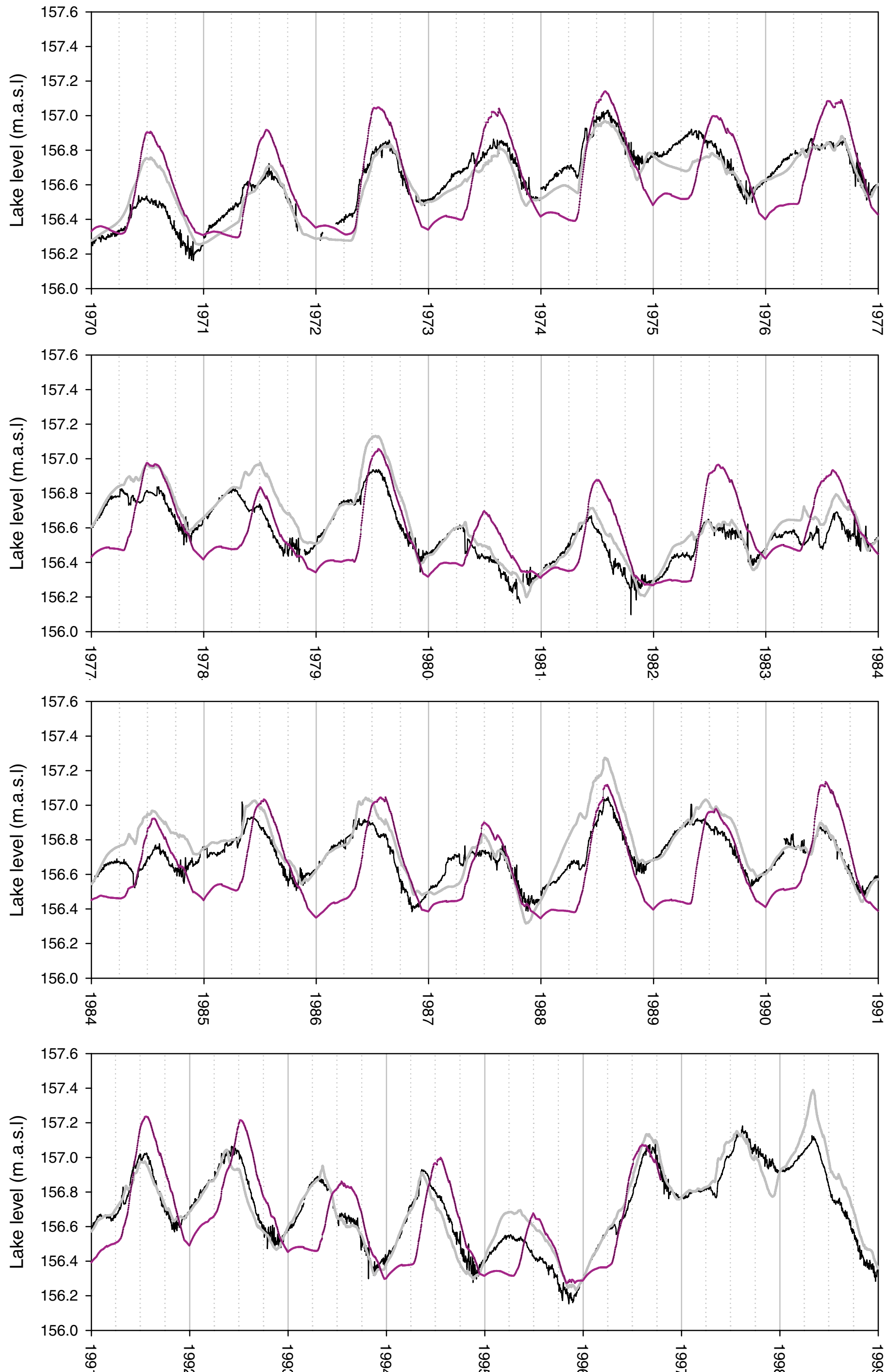

Figure 4 (*continued*)

scenarios indicates that climate has contributed to an increase in the amplitude of water level variations (0.64 m vs. 0.56 m; Fig. 5d vs. Fig. 5a, respectively), an increase in the annual water level maximum (157.00 masl vs. 156.90 masl; Fig. 6d vs. Fig. 6a, respectively), and a modest advance in the timing of the water level maximum (late July vs. early August; Fig. 7d vs. Fig. 7a, respectively). This finding is reasonable considering that precipitation in the Peace-Athabasca basin has increased by about 7% (32 mm/yr) between 1928 and 1967 (462 mm/yr) and 1972–1996 (494 mm/yr) (CRU TS 2.0 $0.5^\circ \times 0.5^\circ$ gridded dataset; Mitchell et al., 2004; see also Mitchell and Jones, 2005). This reflects a depth-equivalent over the lake of 0.68 m/yr. Overall, the results of the naturalized scenario and the precipitation data both suggest that higher lake levels and higher outflows would likely have been maintained if GSL was an exclusively climate-driven system. It is interesting to note that the derived climate-driven forcing toward earlier peak water levels is consistent with observations of earlier spring snow cover disappearance in Northern America since the 1950s (e.g. Frei et al., 1999). Similarly, Dye (2002) concluded that the snow-free period during 1972–2000

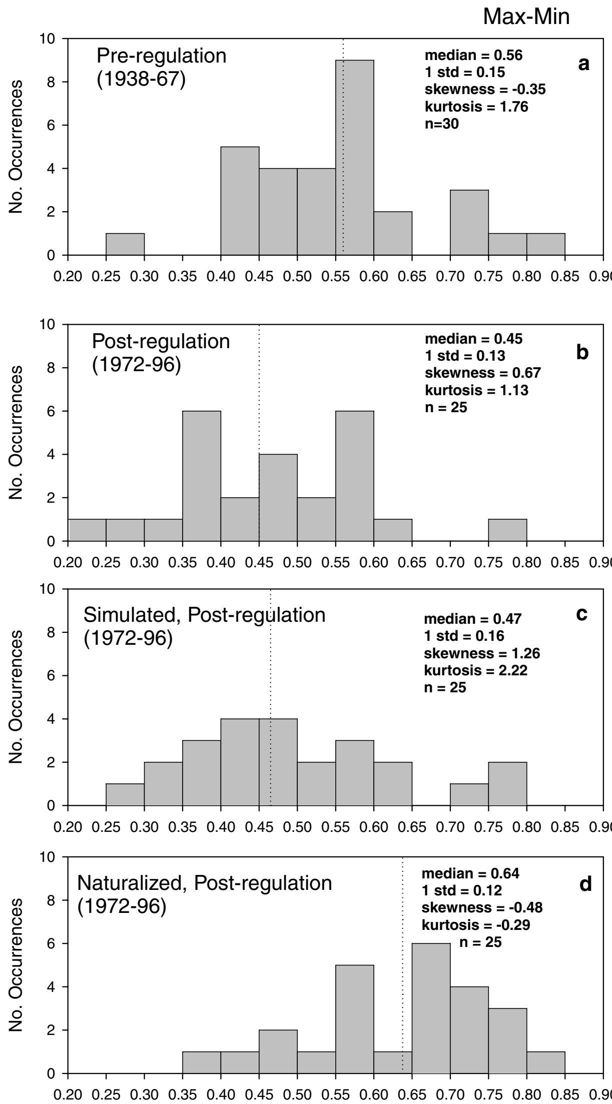

Figure 5 Frequency distribution of observed and simulated annual water level changes in GSL. Units are metres. Dashed vertical line indicates median water level. Related distribution statistics are shown (see text for discussion). std is standard deviation.

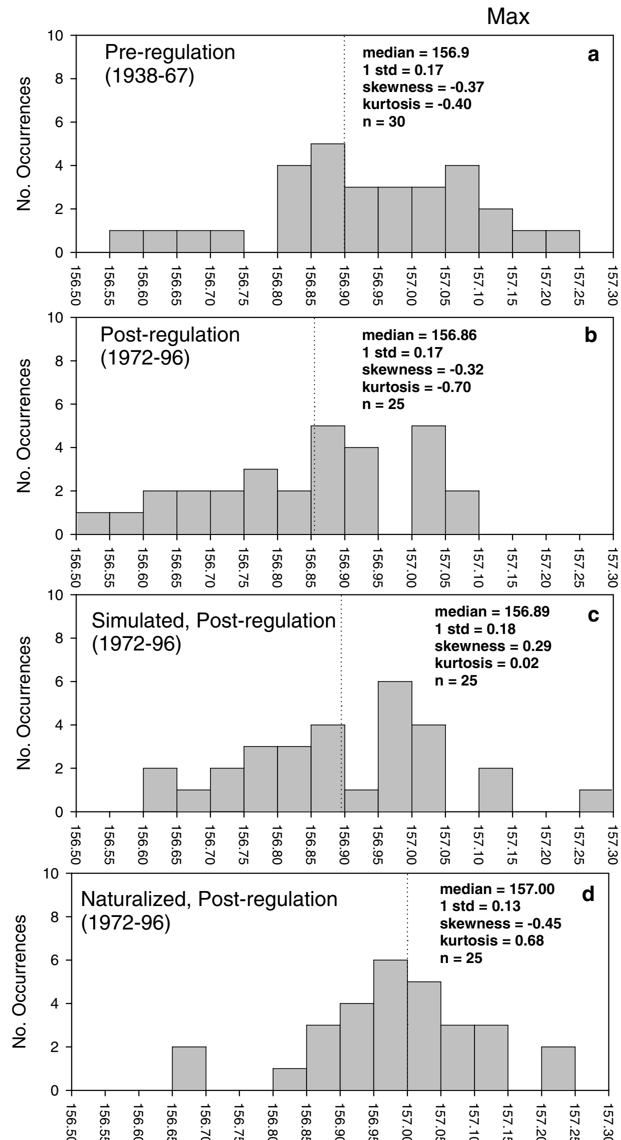

Figure 6 Frequency distribution of observed and simulated annual maximum GSL water levels. Units are metres above sea level. Dashed vertical line indicates median masl. Related distribution statistics are shown (see text for discussion).

(essentially the post-regulation period used in this study) has increased by 5—7 days per decade, with a progression of 3—5 days per decade in the date of last-observed snow cover in spring (Dye, 2002).

Comparison of the seasonal cycle of lake level in pre-regulation and naturalized simulations (Fig. 9) reveals remarkable similarity in timing and shape of the monthly shifts, which improves confidence in the ability of the model to reproduce basic seasonality. The signal that emerges from this comparison is that naturalized flow would likely have enhanced the lake level by 10 ± 5 cm or so on average in July/August.

Regulation impacts on lake level

Comparison of naturalized and base case water balance simulations provides preliminary insight into the influence of regulation on GSL lake level. Regulation only effects are obtained, as shown in Table 2, by subtracting the climate-driven impacts from the combined climate/regulation signal. Comparisons are also made between statistically significant differences between median values of selected water level statistics for naturalized and base case simulations. These suggest that regulation alone has caused the amplitude of annual water level variations to be reduced slightly (0.47 m vs. 0.64 m; Fig. 5c vs. Fig. 5d, respectively), annual maximum water level to be reduced slightly (156.89 masl vs. 157.00 masl; Fig. 6c vs. Fig. 6d, respectively), and produced earlier maximum water levels (early July vs. late July; Fig. 7c vs. Fig. 7d, respectively). This effect is particularly evident when examining the mean seasonal cycles of water level (Fig. 9). The net effect of regulation on maximum and minimum annual water levels (see also Fig. 8)

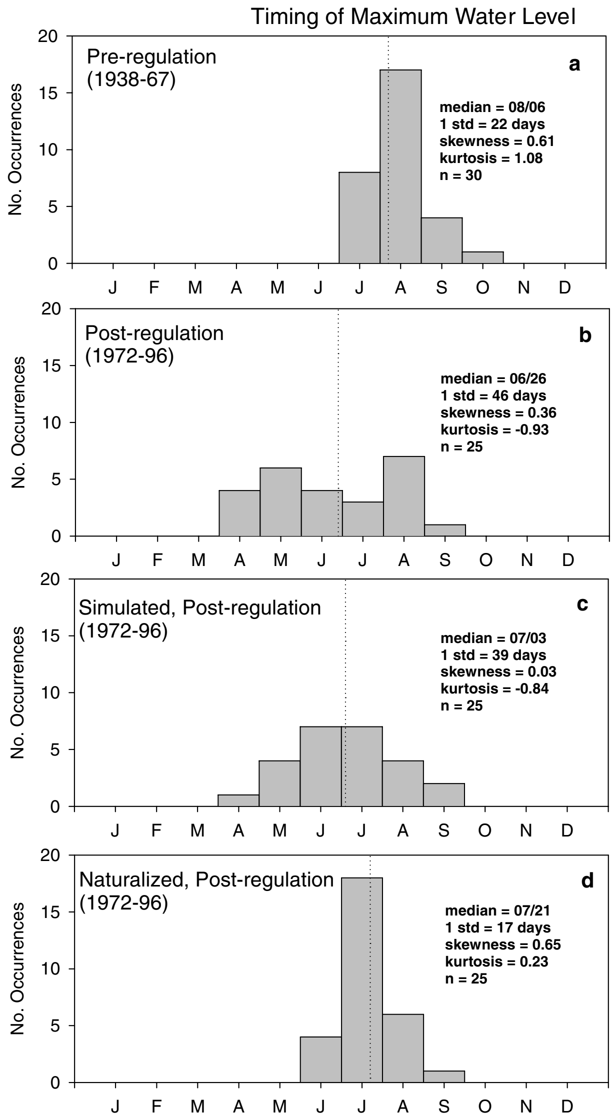

Figure 7 Frequency distribution showing the timing of observed and simulated peak annual GSL water levels. Dashed vertical line indicates median water level. Related distribution statistics are shown (see text for discussion).

shows the predicted year-to-year differences in lake level in naturalized and regulated states.

While reduced water level variability and reduction in magnitude of extreme high water levels are straight-forward, commonly-observed consequences of regulation, the deduced regulation-driven hastening of peak water levels in the post-regulation period by some 30 ± 8 days (see Table 2) requires some additional explanation. It is important to note that large unregulated rivers in the region such as the Peace, Athabasca and Slave Rivers are/were generally characterized by low-flows in winter (November to March), high-flows in late spring (June) following April/May snowmelt, and a gradual decline in flow throughout late summer and autumn. Regulation in the headwaters of the Peace River has modified this natural snowmelt-driven cycle in the lower reaches of the Peace River (Peters and Prowse, 2001), and further downstream in the Slave River, which derives about 66% of its flow from the Peace (English et al., 1997). Late winter flows in the Slave R. at Fitzgerald have doubled (from 1000 m^3/s to 2000 m^3/s) compared to pre-regulation, whereas June maximum flows have been reduced by about 30%, from about 7000 m^3/s to 5000 m^3, as a result of the operational need to store snowmelt runoff over spring/summer and release it slowly over the course of the fall and winter to generate power. GSL, which derives roughly 50% of its total water input from the Peace River, now has a significant regulation signal, maintaining higher winter and spring water levels and reduced spring/summer water levels (Fig. 9). As the lake tends to receive less of its riverine input during the freshet period and more during other times of the year including late winter and spring, it peaks earlier in the season at lower levels. Summer water levels in GSL also begin to decline earlier in the post-regulation period as considerable quantities of peak flow are retained in the reservoir.

Implications for the Slave River Delta and Mackenzie River

Interactions with Great Slave Lake are the primary influence on the hydrological and ecological conditions in the Slave River Delta (SRD). Surveys of the SRD have shown that a very low slope of between 7 and 15 mm/km characterizes the zone from the outer delta to 14 km upstream, approximately at the first major bifurcation of the Slave River. Erosion, sedimentation and flooding in the delta is therefore strongly affected by water level fluctuations on the order of 10—20 cm, smaller than interannual differences in lake levels produced by varying hydro-climatic conditions (i.e., between wet and dry years), less than the seasonal changes in water level produced by flow regulation, and of a magnitude commonly exceeded during late summer and fall wind seiche events (see Gardner et al., 2006). An assessment of flow channels and riparian zones (Prowse et al., 2004) suggests that the delta drainage system has not been stable over the last half-century. A time series of 15 air-photo mosaics spanning the period 1930—1999 indicates that drainage mainly occurred through the central delta channels during 1946—1960. A major shift eastward to the ResDelta (East) channel was observed in 1966 and thereafter. Importantly, this shift occurred prior to the system being regulated in 1967 and is interpreted as being the result of natural processes.

Overall, SRD morphology has likely been affected by channel migration, flow regulation and climate variability (see also Prowse et al., 2004). In the case of GSL levels, the pre- and post-regulation/naturalization analysis presented here provides additional insight into the potential for modifying in-delta processes. A general reduction in peak-annual water levels by 5—20 cm for individual years, and a reduced frequency of lake-generated flood events may lead to a long-term enhancement of delta progradation and subsequent shifts or drying in pre-existing lake and wetland regimes. Notably, however, climatic factors have generally been acting in the opposite direction to increase peak water levels and thereby limit delta progradation. In the

Table 2 Partitioning summary of climate and regulation impacts on annual water level range (ΔWL range), annual water level maximum (ΔWL_{max}) and timing of water level maximum (t_{max}) in GSL

	ΔWL range (m)	ΔWL_{max} (m)	Δt_{max} (days after July 31)
Climate + Regulation[a]	−0.11	−0.04	−41
Model performance[b]	0.02	0.03	8
Climate[c]	+0.08 ± 0.02	+0.1 ± 0.03	−11 ± 8
Regulation[d]	−0.19 ± 0.02	−0.14 ± 0.03	−30 ± 8

Note all comparisons are based on median values from pre-regulation (1938–67) and post-regulation (1972–1996) periods shown in Figs. 5–7.

[a] Based on observed pre- and post-regulation data comparison.
[b] Based on absolute difference between base case and observed post-regulation data.
[c] Based on difference between pre-regulation and naturalized, post-regulation data.
[d] Based on difference between 1 and 3 above.

case of delta flooding, it is expected to remain highly dependant on the co-incidence of high water levels and wind seiche events. As a result of the shift toward earlier peak water levels in summer with a greater water-level variability and seiche frequency in the late summer, it would appear that conditions have become less favourable to delta flooding. Although an ice-jam study of the SRD was not part of this research program, ice-jam flooding is known to be a regular occurrence at river-lake confluences (e.g., Beltaos, 1995).

Given the apparent effects of upstream flow regulation on the seasonality of lake levels, it is likely that outflows to the downstream Mackenzie River would also experience some degree of seasonal dampening from regulation. As suggested by this analysis, however, reduced intra-seasonal variability is likely to be partially compensated for by increased climate variability. An analysis of intra-annual flow variations for regulated and unregulated conditions should be a focus of future research. Such work should also include an evaluation of the role of lake storage/release over multi-season periods, particularly those characterized by exceptional and prolonged storage or releases of water by upstream sources of regulation that are known to produce inter-annual lagged effects on the magnitude of flow from the lake (e.g.. Woo and Thorne, 2003). To aid in such analyses, it is further recommended that a hydraulic model of the GSL system, which includes the influence of ice on flow, be developed to more accurately simulate the flow and water level of the system. Such a refinement will be required to fully test the veracity of this simplified, modelling approach, especially use of an empirical outflow algorithm. Future analysis of regulation and climate effects on the downstream Mackenzie River, and in particular comparisons of climate-only driven variability in Great Bear Lake, a non-regulated large lake in the Mackenzie Basin, will further improve upon the understanding of the role of large lakes in the Mackenzie River Basin.

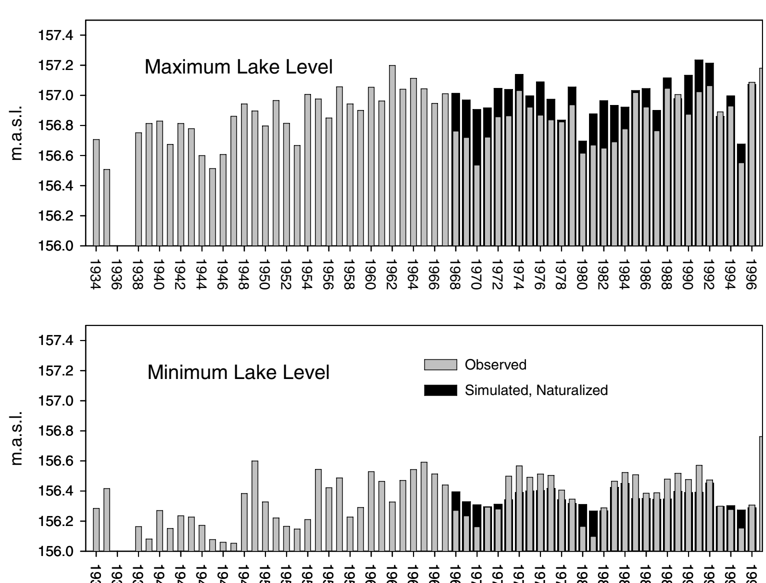

Figure 8 Annual times series of observed and simulated, naturalized GSL water levels.

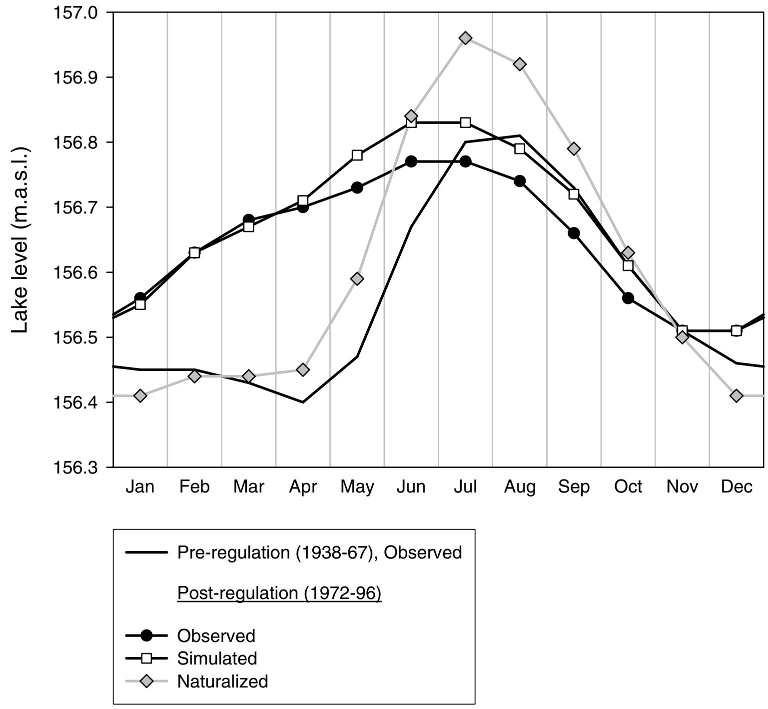

Figure 9 Summary of seasonal cycles in GSL water levels: measured and modelled.

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