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Lake Area Variability Across a Climatic and Vegetational Transect in Southeastern Alberta

Variabilité de la superficie des lacs le long d’un transect climatique et végétal dans le sud-est de l’Alberta

Variabilität der Seen-Oberfläche quer durch ein Klima-und Vegetations-Transect in Südost-Alberta.

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Résumé de l'article

Les superficies de 34 petits lacs constituant un transect à partir de la limite méridionale de la forêt boréale jusqu'à la prairie, dans le sud de l'Alberta. ont été calculées grâce à l'étude de 326 photographies aériennes. Chacun des lacs comptaient au moins six photographies prises à différents mois et échelonnées de 1949 à 1992. Les écarts types de la superficie standardisée des lacs (employés comme indice de la sensibilité de la superficie des lacs aux fluctuations climatiques à court terme) ont été reportés par rapport à l'indice d'humidité. Le nuage de points qui en résulte est commandé par la fonction reliant la sensibilité des lacs à l'humidité du climat régional. Les lacs démontrent une grande sensibilité en prairie où l'évapotranspiration potentielle excède les précipitations, une très forte baisse de sensibilité dans la tremblaie-parc et une très faible sensibilité dans la forêt boréale où les précipitations excèdent l'évapotranspiration potentielle.

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LAKE AREA VARIABILITY ACROSS A CLIMATIC AND VEGETATIONAL TRANSECT IN SOUTHEASTERN ALBERTA

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ABSTRACT Areas of 34 small lakes forming a transect across the southern margin of the Boreal Forest into the Grassland in southern Alberta were obtained from 326 aerial photographs, with at least six photographs for each lake in different months and different years from 1949 to 1992. Standard deviations of standardised lake areas (used as an index of lake area sensitivity to short term climate fluctuations) were plotted against a climatic moisture index; the resulting scatter of points is constrained by a function relating lake sensitivity to long-term regional climatic moisture. The lakes show high sensitivity in the Grassland where potential evapotranspiration exceeds precipitation, a steep drop in sensitivity over a small range of climatic moisture values in the Aspen Parkland, and very low sensitivity in the Boreal Forest where precipitation exceeds potential evapotranspiration.

RÉSUMÉ *Variabilité de la superficie des lacs le long d'un transect climatique et végétal dans le sud-est de l'Alberta.* Les superficies de 34 petits lacs constituant un transect à partir de la limite méridionale de la forêt boréale jusqu'à la prairie, dans le sud de l'Alberta, ont été calculées grâce à l'étude de 326 photographies aériennes. Chacun des lacs comptaient au moins six photographies prises à différents mois et échelonnées de 1949 à 1992. Les écarts types de la superficie standardisée des lacs (employés comme indice de la sensibilité de la superficie des lacs aux fluctuations climatiques à court terme) ont été reportés par rapport à l'indice d'humidité. Le nuage de points qui en résulte est commandé par la fonction reliant la sensibilité des lacs à l'humidité du climat régional. Les lacs démontrent une grande sensibilité en prairie où l'évapotranspiration potentielle excède les précipitations, une très forte baisse de sensibilité dans la tremblaie-parc et une très faible sensibilité dans la forêt boréale où les précipitations excèdent l'évapotranspiration potentielle.

ZUSAMMENFASSUNG *Variabilität der Seen-Oberfläche quer durch ein Klima-und Vegetations-Transect in Südost-Alberta.* Die Ausdehnungen von 34 kleinen Seen, welche ein Transect von der südlichen Grenze des nördlichen Waldgürtels bis zur Prärie bilden, wurden mittels 326 Luftaufnahmen berechnet; dabei hat man mindestens sechs Aufnahmen für jeden See gemacht, in verschiedenen Monaten und verschiedenen Jahren von 1949 bis 1992. Die Standardabweichungen von den standardisierten Seen-Oberflächen (welche als Gradmesser für die Sensibilität der Seen-Oberflächen auf kurzfristige klimatische Schwankungen benutzt wurden) hat man in Bezug auf den klimatischen Feuchtigkeitsindex übertragen: die hierdurch erzielte Streuung von Punkten ist durch die Funktion bestimmt, welche die Seen-Sensibilität mit langzeitiger regionaler klimatischer Feuchtigkeit verbindet. Die Seen weisen eine hohe Sensibilität in der Prärie auf, wo die potentielle Evapotranspiration die Niederschläge übertrifft, eine jähe Abnahme der Sensibilität über einer kleinen Reihe von klimatischen Feuchtigkeitswerten im Aspen Parkland, und sehr niedrige Sensibilität im nördlichen Waldgürtel, wo die Niederschläge höher als die potentielle Evapotranspiration sind.

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INTRODUCTION

Lake level fluctuations have been extensively used as proxy indicators of palaeoclimate (*e.g.*, Benson, 1981; Benson and Thompson, 1987a,b; Benson and Paillet, 1989; Butzer *et al.*, 1972; Harrison *et al.*, 1993; Harrison and Metcalfe, 1985; Hickman *et al.*, 1990; Torgersen *et al.*, 1986; Vance, 1991; Vance *et al.*, 1992). Benson and Paillet (1989) demonstrated that for palaeoclimate studies in arid and semi-arid regions, lake surface area is a better index of climate than lake level, as inflow and evapotranspiration occur mainly across the lake surface rather than through the lake volume. Of course, for a given lake morphometry, lake area, depth, and volume will be strongly correlated, although the relationships are not necessarily linear.

While many studies in arid and semi-arid regions have found lake levels to be highly sensitive to weather (*e.g.*, Digerfeldt, 1986, 1988; Dooge, 1992; Fritz and Krouse, 1973; Harrison, 1988; Harrison and Metcalfe, 1985; Laycock, 1973; Morton, 1978; Stine, 1990; Street-Perrott and Harrison, 1985; Street-Perrott and Roberts, 1983; Teller and Last, 1990; Vance, 1991; Vance *et al.*, 1992), lakes in more humid areas are not generally as useful for palaeoclimate studies (notable exceptions are Digerfeldt, 1988, Gaillard, 1985, Harrison, 1989, and Harrison *et al.*, 1993). This is because humid region lakes, unlike arid and semi-arid region lakes, are controlled more by the level of the outlet sill than by weather. While arid and semi-arid region lakes may rarely fill sufficiently to overflow their sills, humid region lakes are maintained during dry periods by locally recharged ground water and are rarely faced with a water deficit of sufficient duration to reduce them below their outlet sill levels. Only changes of the basin morphometry (including changes to the sill level such as beaver dams or outlet down cutting) or a change in climate sufficient to eliminate the normal excess of precipitation over evaporation will result in more than a minor change in water level.

There have been several correlative studies of lake level fluctuations crossing climate gradients (*e.g.*, Butzer *et al.*, 1972; Street-Perrott and Roberts, 1983; Gaillard, 1985; Harrison, 1989; Harrison and Metcalfe, 1985; Harrison *et al.*, 1993; Schweger and Hickman, 1989; Vance, 1991). Benson (1981) developed a detailed mathematical model of the relationship between Lahontan Basin lake levels and climate, emphasizing the importance of cloud cover as an influence on both precipitation and evaporation. This model was used to evaluate possible palaeoclimates corresponding to known palaeolake levels, but did not address the issue of lake sensitivity to climate change. Almendinger (1990) did examine the sensitivity of lakes to climate change, but only as a function of physiography and soil permeability. Other models have successfully reproduced fluctuations of lakes in response to climate change (*e.g.*, Hostetler and Bartlein, 1990; Hostetler and Benson, 1990), and Bowler (1986) studied the geomorphology and sedimentology of a transect of lakes from humid to arid regions in Australia. Despite the large number of studies of lake area and level changes, there are no published studies of geographic trends in lake sensitivity to less than century scale climate changes.

Here we examine the variability of modern lakes in response to recent climate along a transect of sites extending from a semi-arid region into a sub-humid region in Alberta, to assess the relationship between climate and lake level sensitivity. We further establish a correlation between lake sensitivity and upland vegetation.

THEORY

Lake volume variability is the probability that the lake contains a significantly different amount of water from one observation to the next, and is a function of lake volume responsiveness to weather events and the frequency of weather events capable of producing a response. A large lake with a gently sloping bottom will show greater variability in surface area than will a small steep-sided lake. Thus the sensitivity of lake surface area to small changes in climate is a function of both lake morphometry and lake volume responsiveness to weather.

In considering lake hydrology, it is important to separate the local and distal ground water inputs, as local ground water inputs may vary at short time-scales (seasonally to decadally) according to the local climate. Distal ground water, on the other hand, reflects the climate of some time in the past at some distant location and is presumably more uniform at seasonal to decadal time scales, but may nevertheless exert a strong influence on long-term lake levels (Almendinger, 1990; Digerfeldt *et al.*, 1992). Almendinger (1990) demonstrates through an analytic ground water model that this local/distal distinction is important to understanding lake sensitivity to climate fluctuations, and notes that local ground water recharge has the effect of smoothing seasonal precipitation inputs over a season, allowing a humid region lake to remain full through short periods of drought. Thus humid region lakes are relatively insensitive to short-term climate changes due to local ground water inputs, and are controlled by the level of the sill. That some humid region lakes do vary (*e.g.*, Côté *et al.*, 1990) or have varied in the past (*e.g.*, Digerfeldt, 1986, 1988; Harrison, 1989; Harrison *et al.*, 1993) may be a result of special conditions affecting these lakes such as exceptionally small drainage basins (Harrison, 1989), influence of a nearby river (Côté *et al.*, 1990), or palaeoclimatic fluctuations such that at times in the past the region was semi-arid rather than humid (Harrison *et al.*, 1993). In addition, while the presence of an outlet dampens a lake's response to climate, the outflow volume may vary strongly, both seasonally and over longer time scales.

Where precipitation is a rare event, a lake will almost always be either dry or at a distally recharged ground water controlled level, and thus show very little actual variation through time. It is in the intermediate, semi-arid range that lakes should show the greatest sensitivity to short-term climate fluctuations (Fig. 1). However, lakes which receive substantial distal ground water input will not be as sensitive as those which receive only local inputs; furthermore, lakes with steep sides will vary in volume, but relatively little in area. A lake which receives little or no distal ground water, has a gently sloping bottom, and is in a semi-arid region will thereofre display the greatest sensitivity of surface area to small climate fluctuations.

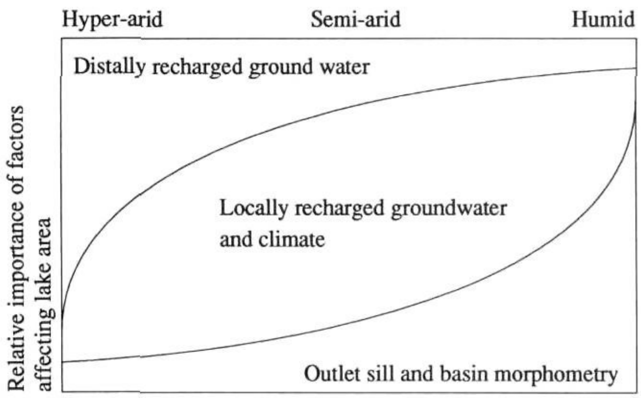

FIGURE 1. Relative importance of different factors in controlling lake levels in different climate zones. Variability in response to climate will be greatest in the semi-arid region where climate and locally recharged groundwater exert the greatest control over lake levels.

L'importance relative des différents facteurs qui déterminent le niveau des lacs selon les régions climatiques. Les réponses au climat seront plus variées dans la région semi-aride où le climat et la nappe phréatique alimentée localement exerce la plus grande influence sur le niveau lacustre.

METHODS

Thirty-four lakes forming a north-south transect through southeastern Alberta were selected from a 1:1,000,000 scale map of Alberta (Fig. 2). All lakes are in till on Mesozoic sedimentary bedrock; although morphometric and hydrologic information is not available for many of the lakes, most are less than 10 m deep and receive most of their water from precipitation within the watershed. The lakes selected were large enough to show on this scale map, but small enough to be covered by a single 1:31,680 scale aerial photograph (a range of about 100-1,000 ha). Lake areas were obtained from aerial photographs available at the Maps Alberta Reference Library. A total of 326 photographs or composite photographs were used; only lakes for which at least six useable, warm season photos taken at different times spanning at least 20 years between 1949 and 1992 were available were included. The lake perimeters and tie-points (road intersections or other distinctive fixed features) were traced onto acetate film. The scale and date of each photograph were noted. The lake area in each photograph was obtained using an Ushikata X-Plan 360d planimeter, and within each set of photographs (*i.e.*, all the photographs for one lake) adjusted to a common scale using the tie-points.

For each lake, the standard deviation of the surface area, expressed as a percentage of its maximum recorded surface area, was calculated as an index of its variability or sensitivity to weather. This index has high values when the lake is highly sensitive, and has low values when the lake sensitivity is low. However, since most months in most years were not covered by a photograph for a given site, there is no guarantee that the full dynamic range of lake area was found for a given lake. For this reason, no meaningful correlation can be calculated between lake sensitivity (as reflected by the standard deviation of lake area) and regional climate, since the regression

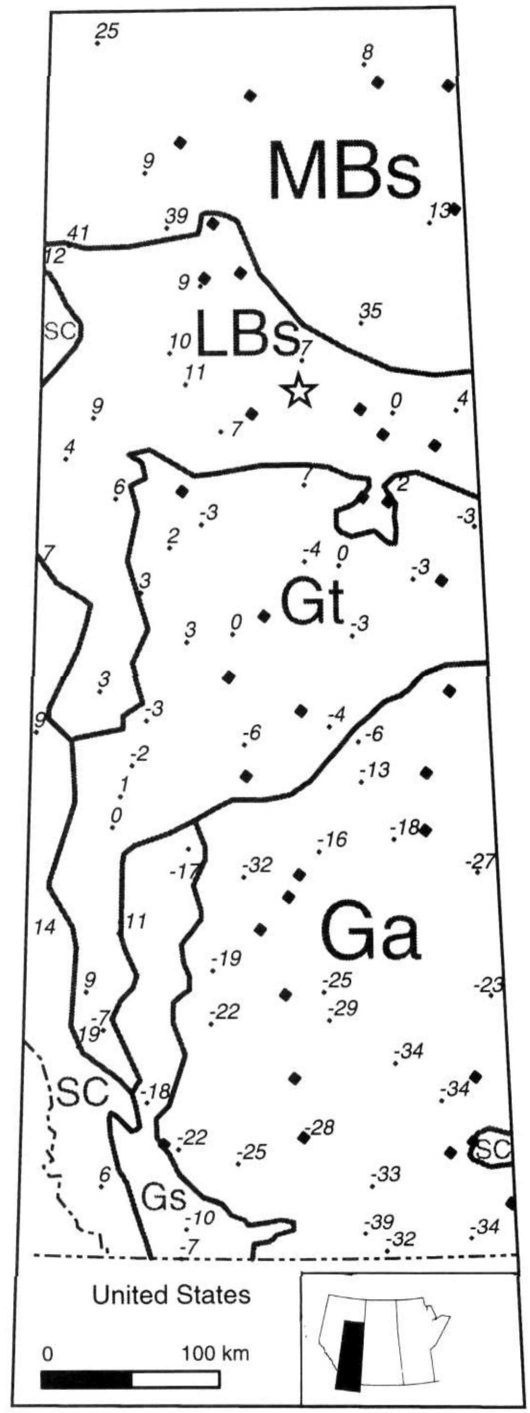

FIGURE 2. Locations of 34 lakes studied (diamonds), climate moisture index values (numbers), vegetation regions (after Ecoregions Workgroup, 1989), and Lofty Lake, Alberta (star). Ecoregions: Ga = arid Grassland; Gt = transitional Grassland (aspen Parkland); LBs = low Boreal sub-humid; MBs = mid-Boreal sub-humid; Gs = subhumid Grassland; SC = southern Cordilleran.

Localisation des 34 lacs à l'étude (losanges) et du Lofty Lake (étoile), indices d'humidité (chiffres) et délimitations des régions végétales (selon Ecoregions Workgroup, 1989). Régions : Ga = prairie aride; Gt = prairie de transition (tremblaie-parc); LBs = région boréale inférieure subhumide; MBs = région boréale moyenne subhumide; Gs = prairie subhumide; SC = sud de la Cordillère.

would be leveraged by the large number of values representing less than the full dynamic range of lake areas; only minimum values are obtainable. Thus the results were analyzed using a bounding curve rather than a regression line.

The degree of measurement error is very difficult to quantify as repeated measurements may include the same repeated biases such as smoothing of small embayments. However, it was found after the initial data were collected that in several instances photographs were taken of the same lake at different scales during the same month, and sometimes even the same week or day (they were excluded from the overall analysis). The variation in measured lake area values for these instances is less than two per cent, suggesting that measurement error contributes a very small portion of the observed variation in lake area.

Climatic moisture index values for Alberta weather stations were calculated (Fig. 2). For this climatic moisture index, climate normals from year-round climate stations in Alberta were accessed from a database provided by Environment Canada containing the 1951-1980 climate normals for temperature and precipitation (Environment Canada, 1982a,b). Maps showing monthly global solar radiation for the period 1967-1976 (Environment Canada, 1985) were digitized on a 2° latitude × 4° longitude grid, and the global solar radiation for each station was then estimated by interpolation from these grid nodes.

The climatic moisture index was calculated for each station by substracting the annual potential evapotranspiration (PET, in cm) from mean annual precipitation (P, in cm). PET was first calculated on a monthly basis (PET_m) using the Jensen and Haise method (Jensen, 1973; Bonan, 1989).

(1) $PET_m = C_T (T - T_x) (R_s / \lambda)$

where T is mean monthly air temperature (°C); R_s is mean monthly global solar radiation (MJ m^{-2} $month^{-1}$); and λ is latent heat of vaporization (24.54 MJ m^{-2} cm^{-1} at 20°C). The parameters C_T and T_x are calculated as:

(2) $C_T = 1/(38 - A/152.5 + 38/(e_2 - e_1))$

(3) $T_x = -2.5\text{-}1.4(e_2\text{-}e_1)\text{-}A/550$

where A is the station's altitude above sea level (m); e_1 and e_2 are the saturation vapour pressures (kPa) at the mean minimum and mean maximum July temperatures, respectively. Annual PET was then obtained by summing PET_m over all twelve months.

This index, hereafter called the P-PET moisture index, correlates strongly with the southern limit of the distribution of conifers throughout western Canada (Hogg, in press). It takes a value of 0 at the approximate location of the limit of conifers; negative values (indicating a normal excess of potential evapotranspiration over precipitation) occur in the Aspen Parkland and Grassland, while positive values (indicating a normal excess of precipitation over potential evapotranspiration) occur in the Boreal Forest (Fig. 2). For this paper, values of the P-PET moisture index were interpolated for each lake.

RESULTS AND DISCUSSION

The cloud of points formed by plotting the standard deviation of per cent lake area versus the P-PET climatic moisture index for 1951-1980 shows a constrained distribution (Fig. 3). The points falling below the bounding curve are most likely the result of imperfect aerial photography coverage (the lack of the full dynamic range of the lake being represented); other factors may include basin morphometry (although some of the lakes have steeper sides and so are less sensitive in area than others, there is no apparent tendency for steep-sided lakes to occur preferentially at the northern or southern end of the transect), and distal ground water inputs (although all the lakes are in till, bedrock aquifers carrying distally recharged groundwater may outcrop in the bottoms of some lakes). Thus the bounding curve can be taken as the function relating lake variability to climatic moisture.

This bounding curve shows an asymptote at slightly positive values of standard deviation of per cent lake area in the sub-humid end of the transect, and much higher values in the semi-arid end. This apparent sigmoidal curve is in theory one end of a normal distribution, in which semi-arid environments show the greatest lake level variability and absolute desert and humid environments show the least variability. This is because a lake in a humid climate will be controlled primarily by the sill, since evaporation rarely exceeds precipitation causing a nearly permanent water surplus which maintains the lake at its highest levels. In absolute desert, on the other hand, precipitation is an extremely rare event, so that incidences of rising lake level will be extremely rare, and lakes will nearly always be at their lowest levels, maintained exclusively (if at all) by distally-recharged (and therefore nearly

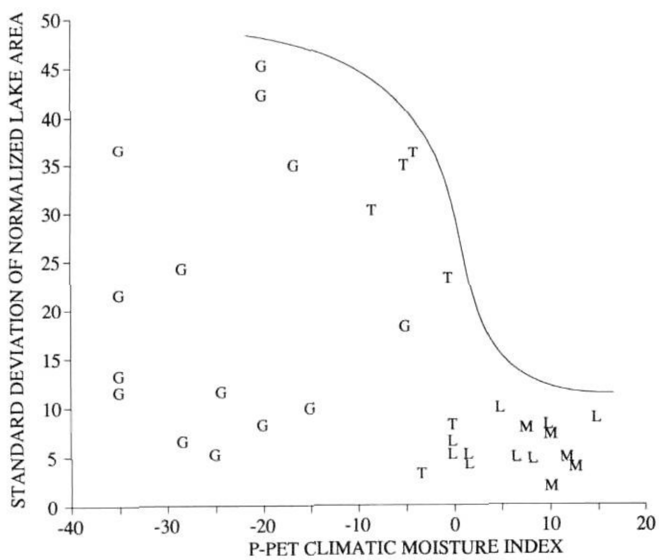

FIGURE 3. Standard deviation as a percentage of maximum lake area vs. climatic moisture. The bounding curve is approximate. G = arid grassland; T = transitional Grassland (Aspen Parkland); L = low Boreal sub-humide; M = mid-boreal sub-humid.

Écart type en tant que pourcentage de la superficie lacustre maximale par rapport à l'indice d'humidité. Le tracé de la courbe est approximatif. G = prairie aride; T = prairie de transition (tremblaie-parc); L = région boréale inférieure subhumide; M = région boréale moyenne subhumide.

unvarying in the short term) ground water. It is only in the semi-arid regions, where precipitation events are not rare but evaporation nevertheless exceeds precipitation that neither the level of the sill nor the level of distally-recharged ground water will exert a controlling influence on lake level.

This agrees well with previous studies in Alberta, which taken together form a transect from the Low Boreal Forest to the Shortgrass Prairie, in which the moister northern sites show less variation in lake level during the last few thousand years than the more southern sites (Hickman *et al.*, 1990; Schweger and Hickman, 1989; Vance, 1991).

That semi-arid regions have the most sensitive lakes is not a new conclusion (*e.g.*, Almendinger, 1990; Harrison, 1989; Harrison *et al.*, 1991; Harrison *et al.*, 1993; Street-Perrott and Harrison, 1985). However, our results indicate a very sharp change in the sensidvity-climate function near the boundary between the Boreal Forest and Aspen Parkland, near the zero isoline of the P-PET climatic moisture index (Figs. 2, 3). This implies that lake sensitivity may be effectively binary: lakes are either sensitive (moisture index <0) or they are not (moisture index >0). It is noteworthy that the mean annual water runoff (Fisheries and Environment Canada, 1978) also shows a sharp regional gradient near the steepest portion of the lake sensitivity curve. Throughout Alberta and Saskatchewan, the quantity of mean annual runoff increases rapidly from <2.5 cm/yr over most of the Grassland and Aspen Parkland regions to >10 cm/yr over most of the Boreal Forest. Thus the reason for the steepness of the sensitivity gradient is clear: lakes in the Boreal Forest, where precipitation generally exceeds potential evapotranspiration and where runoff is substantial, will overflow their sills most years, and thus be controlled more by the sill than by climate. In contrast, lakes in the Aspen Parkland and Grassland, where runoff occurs only in exceptionally wet years, will exhibit a high sensitivity to annual weather. However, such a high sensitivity is probably not applicable to hyper-arid regions, for the reasons previously mentioned.

One caveat raised by the steepness of the sensitivity curve in the region of the Parkland (transitional Grassland) is that an abrupt change in the sensitivity of a lake in the past may not indicate an abrupt change in climate, but rather a crossing of this boundary.

APPLICATION

The lake sensitivity curve can be used to interpret palaeovegetation and probable palaeoclimatic conditions in southeastern Alberta.

Pollen zones 3 and 4 in the pollen diagram of Lofty Lake in central Alberta (Figs. 2,4) were initially interpreted as birch forest and mixed wood forest respectively (Lichti-Federovich, 1970). MacDonald and Ritchie (1986) reinterpreted this pollen diagram using a modern-analogues based approach, noting that while the analogues for these zones are poor, they most strongly resemble parkland pollen spectra. A core from the lake contains sedimentological evidence for a pronounced low water stand from 8700-6290 BP (Schweger and Hickman, 1989). Figure 3 suggests that such a low stand occurred during a period when the P-PET index was negative. This would have made the region too arid to support a forest, and so the no-analogue pollen spectra most likely represent parkland rather than forest, in agreement with MacDonald and Ritchie (1986).

The correlation of lake stability with past climatic conditions and vegetational zones may prove to be a useful tool in the study of past climate fluctuations in this and other regions.

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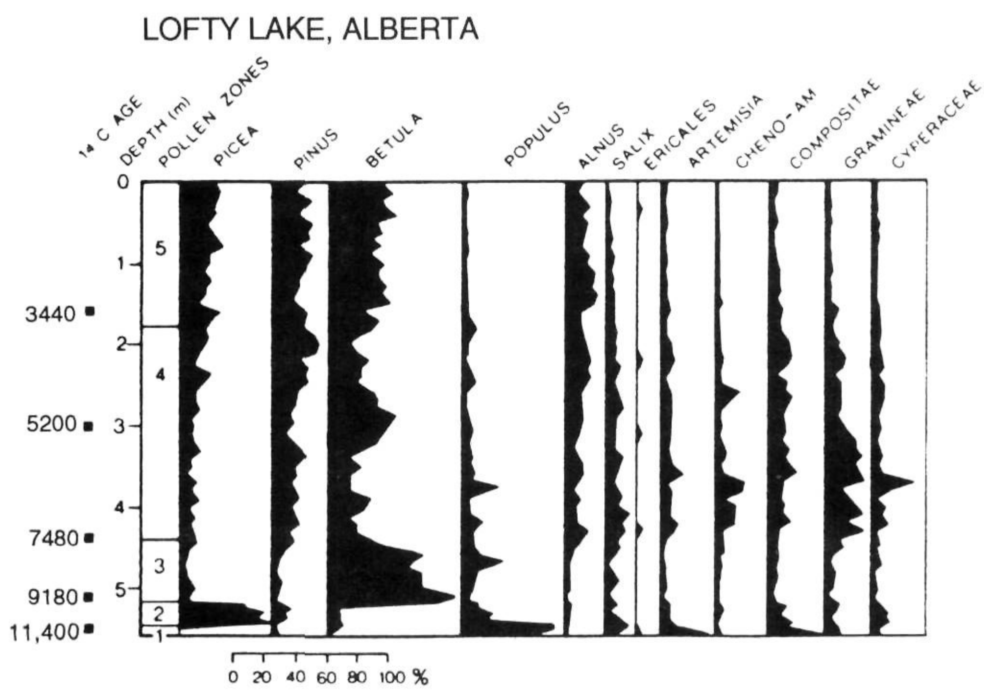

FIGURE 4. Lofty Lake pollen diagram (from MacDonald and Ritchie, 1986, p. 256).

Diagramme pollinique du Lofty Lake (de MacDonald et Ritchie, 1986, p. 256).

on an earlier draft of this paper which have greatly improved this version. We also thank T. Varem-Sanders and the staff of the Maps Alberta Reference Library (Edmonton) for help in obtaining the aerial photography data, and the Atmospheric Environment Service for providing climate data.

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