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PREDICTING LAKE TROUT PRESENCE AND ABSENCE IN SASKATCHEWAN LAKES USING HABITAT CRITERIA

by

© ROBERT G. WALLACE

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ABSTRACT

Habitat characteristics (morphometry, physicochemistry, temperature, oxygen, and biota) and fish species data were extracted from reports of lake surveys on 330 lakes in central and northern Saskatchewan. Differences in the habitat of lakes, and criteria to predict lake trout presence or absence, were examined using non-parametric statistical methods. Habitat differed significantly between lakes with and without lake trout, and several variables predicted lake trout status at 90 % or better accuracy.

In Precambrian shield lakes, lake trout need a minimum of 2 hm^3 water below 15°C and above 6 $mg.L^{-1}$ oxygen (96 % accuracy) or 10 hm^3 water between 6° and 15°C, during early to late summer. These threshold volumes appear to determine population survival during a critical period, which may be relatively brief. This may be related to observed densities of lake trout and to the presumed minimum number of mature lake trout in each lake.

The importance of maximum depth is believed to be due to its effects on temperature, oxygen, and/or sediment conditions. Clearing of spawning areas by wave action is predictable from simple wave models using depth and fetch.

Mean summer Secchi transparency of 4.2 m or greater predicts lake trout presence with 88 % accuracy. Lake trout populations may require that light sufficient for vision or

sensible to lake trout visual pigments (i.e. 510-540 nm wavelength) extends into the zone of suitable temperature. The theoretical lower depth of daylight-type vision by lake trout is predictable from the Secchi transparency of the water. Multiple discriminant analysis showed that Secchi transparency and the minimum volume of 6 to 15°C water contributed consistently to multivariate predictions of lake trout status.

Non-shield lakes apparently must have much greater volumes of water of suitable temperature and oxygen during summer than shield lakes. The effects of shallower morphometry and greater waterlevel variations in non-shield lakes are only part of the reason. Post-glacial immigration routes and/or climatic conditions are believed to have restricted lake trout to larger lakes in the non-shield region.

Lake surveys are not completely representative of Saskatchewan lakes, particularly very small (<10 km^2) lakes. Corrections for preferential surveying of larger lakes and lakes with lake trout present are essential for meaningful extrapolation of predictions. Several good criteria of lake trout status (e.g. maximum depth, stratification, minimum volume of 6 to 15°C water) can be reliably estimated from easily obtained survey, topographic, or other data. This allows the estimation of the total number of lake trout lakes in the shield region of Saskatchewan.

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INTRODUCTION

Management of fisheries resources in Saskatchewan and most other provinces requires an understanding of the number of lakes containing each fish species and the sustainable supply which is available for perceived demands. Recent and future increases in accessibility of northern Saskatchewan lakes, which are within the natural range of lake trout (Salvelinus namaycush), mean that this species faces increased exploitation. Studies on a few specific fisheries annually do not provide a satisfactory basis for management (Wallace 1984). Only relatively large lakes are amenable to management based on monitoring of trends and the accompanying evolution of suitable regulation.

Resource managers require methods to predict the occurrence and sustainable yield of lake trout, particularly in numerous small lakes and preferably without a survey of each lake. Central and northern Saskatchewan has an estimated 91,700 lakes, of which about 83,200 are on the Precambrian shield. Management of fisheries in these smaller lakes requires that an understanding of the resource has been established. Very small lake trout lakes may, in fact, be depleted in a single weekend of fishing (Ryder and Johnson 1972). The pace of exploitation of new resources far outstrips the acquisition of detailed information on preferred species.

The first objective of the present study was to develop and validate predictions for the presence or absence of lake trout in Saskatchewan lakes. Habitat variables from surveys of 330 lakes north of 53°N were evaluated. Some variables were recommended by other field or laboratory studies (see Background studies), while some were created to assess presumed critical requirements.

The second objective was to estimate good criteria of lake trout status, using variables which are most easily obtained during surveys or are available from other sources (e.g. topographic maps, remote sensors, or climatic records).

The third objective was to assess and correct any bias in predictive criteria due to non-random selection of lakes for surveying, and to estimate the total number of lake trout lakes in Saskatchewan.

This study was based on data from the provincial lake survey program begun in the 1930's, as were many earlier limnological and fisheries studies. The development of morphoedaphic indices of fish productivity relied on these surveys and data on fish harvests (Rawson 1952, Ryder 1965, Ryder *et al*. 1974, Oglesby 1977, Matuszek 1978). Other studies examined morphometry of shield lakes (Koshinsky 1970), invertebrates in relation to habitat (Murray 1974), and general limnology of large lakes (Rawson 1960). Potential uses of these surveys include seasonal thermal trends (e.g. Rawson 1936, Atton 1953, Shuter *et al*. 1983), lake survey optimization (Hakanson 1978), net saturation (e.g. Kennedy 1951), and water chemistry variability, particularly in recent consultant studies (e.g. Beak 1979).

The emphasis on the effects of present habitat conditions on present-day lake trout distribution in Saskatchewan results from an assumption about post-glacial access. That is, that lake trout immigrated primarily from a Mississippi refugium via early Glacial Lake Agassiz (McPhail and Lindsey 1970, Black 1983), thereby gaining access to all of the study area.

BACKGROUND STUDIES

Lake morphometry has frequently been cited as important to lake trout biology. In temperate regions, lakes with greater mean or maximum depths contain lake trout populations (Scott and Crossman 1973) more frequently than other lakes. The few lakes south of the Precambrian shield in Saskatchewan in which lake trout occur naturally have mean depths of 13 m or more and maximum depths of at least 30 m (Marshall and Johnson 1971). Surveys of about 5,000 lakes in Ontario showed that lake trout occurred in only 14 % of lakes with mean depth 12 m or less and in only 11 % with maximum depth of 30 m or less (Martin and Olver 1976).

As mean depth is significantly related to water area of lakes worldwide and in northern Saskatchewan (Neumann 1959, Liaw and Atton 1981b), area may be a general predictor of lake trout occurrence. On the shield, the ratio of mean to maximum depth depends on lake area (Koshinsky 1970). Volume of lakes may be more important to lake trout than depth or water area, particularly the volume of the hypolimnion due to the narrow thermal tolerances of lake trout.

Temperature preferences of about 12^{o}C (Ferguson 1958, McCauley and Tait 1970) and oxygen requirements of 3 to 6 mg.L^{-1} (Gibson and Fry 1954, Davis 1975) are well known for lake trout. The presence of lake trout in shallow, northern lakes suggests that temperature conditions override depth *per* *se* (McPhail and Lindsey 1970). The minimum volume of water below 12 to 15°C and above 4 to 6 $mg.L^{-1}$ oxygen in early to late summer may be a reasonable index of critical conditions. In temperate lakes, mid-summer surface temperatures are frequently unsuitable and the degree of stratification becomes important. Thermocline behaviour may be predictable from area, fetch, and other habitat variables (Shuter *et al*. 1983, Ragotzkie 1978). Hypolimnetic oxygen behaviour is more complex (Cornett and Rigler 1979, Patterson *et al*. 1985).

Physical and chemical characteristics of lakes are important to lake trout. Water transparency as measured by Secchi disk depth was dominant (along with mean depth) in discriminating lake trout lakes from others in Ontario (Johnson *et al*. 1977). Only 10 % of Ontario lakes with Secchi depth less than 5 m have lake trout populations (Martin and Olver 1976). Lake trout are found in fewer than 5 % of Ontario lakes with total dissolved solids (TDS) over 100 $mg.L^{-1}$ (Martin and Olver 1976), and have been termed an "index species" of oligotrophy (Ryder 1972). TDS ranges widely in Saskatchewan lakes from less than 10 to more than 300,000 $mg.L^{-1}$ (Liaw and Atton 1980), and limits natural populations of several fish species in some lakes (Rawson and Moore 1944). The upper osmoregulatory limit for lake trout is about 12,000 $mg.L^{-1}$ NaCl (Boulva and Simard 1968 cited in Fargher 1977).

METHODS

Description of study area

All of Saskatchewan, except the extreme southwest, was covered by Wisconsinan glaciation. The southern part of the study area shows the predominantly flat to gentle topography of lacustrine plains, with some rolling uplands of ground moraine (Richards and Fung 1969). The northern part is Precambrian shield and Athabascan sandstone plain, with gentle to strongly rolling topography (Koshinsky 1970) and some rugged bedrock. The climate is a cold continental type, with prevailing westerly to northerly winds and semi-arid to sub-humid moisture conditions. Mean annual air temperatures are 2.5 to -5°C; frost-free periods are 100 to fewer than 60 days. Most climatic and vegetational zones change from southwest to northeast (see maps in Richards and Fung 1969).

Lakes cover about 10 % of Saskatchewan. Watersheds include the Gulf of Mexico (Missouri river system), Hudson Bay (Qu'Appelle, Winnipegosis, Saskatchewan, Churchill, and Kazan), Arctic (Mackenzie), and large internal drainages in south-central and southwestern areas (Atton and Merkowsky 1983). Fall freeze-up of small to large lakes coincides with the 3-day to 40-day average air temperature reaching 0°C, respectively (Ragotzkie 1978). Spring break-up is more complex as it depends on snow and ice conditions, spring temperature and wind patterns, and river inflows, but generally coincides with an average temperature of 5°C.

Lake surveys

All Saskatchewan lakes located between 53°N and 60°N latitude which were surveyed between 1930 and 1982 were used in the analysis. Using only known lake trout lakes would have prevented any effective prediction of suitable and unsuitable conditions for this species.

Published and manuscript reports provided information on 330 lakes which were surveyed by the provincial Department of Parks and Renewable Resources (formerly Department of Tourism and Renewable Resources and Department of Natural Resources), the federal Canadian Wildlife Service, and several environmental consulting firms (Appendix A).

Adherence to standardized methods in most studies meant that available data were fairly consistent from the 1930's onward. Lakes which lacked one or more habitat variables were nonetheless included, as correlations among variables allowed for the estimation of some missing data. Inclusion of these incomplete lake surveys was intended to reduce bias, as surveys were more likely, more intensive, and more often repeated on larger lakes and in more accessible areas (Liaw and Atton 1981).

Almost all variables available from lake surveys were considered, with closer scrutiny given to more probable predictors. Survey data were usually from the earliest lake survey reported. About 1 % of data were randomly selected and checked for errors of interpretation and transcription during extraction from the reports. All data were checked following entry into the computerized data base for errors of transcription. Later, correlations between many pairs of variables revealed several outliers which were re-checked against the source reports. To minimize systematic subjectivity on my part, variables were amended only if they had been misquoted (e.g. transposed) or deleted only if the original author had noted unusual conditions (e.g. non-filtered turbid water samples) or technical problems (e.g. faulty oxygen meter).

Survey variables were assigned to six arbitrary categories in the data base: location, morphometry, physicochemistry, temperature-oxygen, biota, and winter chemistry (Table 1). Lake survey methods and descriptions of basic and derived habitat variables are shown in Appendix B. Fish species collection methods and nomenclature are given in Appendix C.

Habitat data from a randomly selected 20 % of the lakes were set aside for later validation of predictions. These data were assiduously ignored and all predictive criteria were established on the basis of the remaining 262 lakes.

Table 1. List of names and brief descriptions of most habitat variables which were used in the present study.

Variable	Units	Description
Location		
LKNAME	...	lake name
LKNO	...	lake number
LATD	°N	latitude (decimal equivalent)
LONGD	°W	longitude (decimal equivalent)
NORD	...	nordicity (see Appendix B)
GEOZONE	...	five bedrock zones
WSHED	...	watershed
ALT	m	altitude
RANDOM	...	random subset of lakes
REF1	...	primary lake survey report
REF2	...	secondary lake survey report
Morphometry		
WAREA	km^2	water area
VOLUME	hm^3	water volume (million m^3)
ZBAR	m	mean depth
ZMAX	m	maximum depth
SHOLEN	km	shoreline length (including islands)
SHODEV	...	shoreline development
FETCH	km	fetch length
ORIENT	°	orientation of fetch
FLUSH	yr	theoretical flushing time
SAn	%	area strata (see Appendix B)
DAn	m	area strata contours
SVn	%	volume strata (see Appendix B)
DVn	m	volume strata contours

continued

Table 1. continued.

Variable	Units	Description
Physicochemistry		
SECCHI	m	Secchi depth (less than ZMAX)
PHOTOZ	m	photogenic depth
COLOUR	Pt	summer surface sample
PHMINS	...	minimum summer surface pH
PHMINB	...	minimum summer bottom pH
TDS	$mg.L^{-1}$	total dissolved solids, mid-summer
TOTALK	$mg.L^{-1}$	total alkalinity, methyl orange as $CaCO_3$, summer
SPCON	uS	specific conductivity, summer surface
LOSSIG	$mg.L^{-1}$	loss on ignition, summer surface
CA	$mg.L^{-1}$	calcium, summer surface
MG	$mg.L^{-1}$	magnesium, summer surface
NA	$mg.L^{-1}$	sodium, summer surface
...	$mg.L^{-1}$	all others are named similarly
Temperature-Oxygen		
TMAXS	^{o}C	maximum summer surface temperature
TMAXB	^{o}C	maximum summer bottom temperature
STRAFN	...	degree of stratification
OMINS	$mg.L^{-1}$	minimum summer surface oxygen
OMINB	$mg.L^{-1}$	minimum summer bottom oxygen
HIGH6MG	m	depth of shallowest 6 $mg.L^{-1}$ oxygen, deepest station (see Appendix B)
VOL6MG	hm^3	minimum volume with $\geq$ 6mg.L^{-1} oxygen
T15T6U	m	upper and lower depths of deepest
T15T6L	m	$15^{o}C$ and same-day $6^{o}C$, resp.
VOLT15T6	hm^3	minimum volume of 6 to $15^{o}C$
T15O6U	m	upper and lower depths of deepest
T15O6L	m	$15^{o}C$ and 6 $mg.L^{-1}$ oxygen, resp.

continued

Table 1. continued.

Variable	Units	Description
VOLT1506	hm^3	minimum volume $\leq 15^oC$ and $\geq 6\ mg.L^{-1}$
T1504U	m	upper and lower depths of deepest
T1504L	m	15^oC and $4\ mg.L^{-1}$ oxygen, resp.
VOLT1504	hm^3	minimum volume $\leq 15^oC$ and $\geq 4\ mg.L^{-1}$
T1206U	m	upper and lower depths of deepest
T1206L	m	12^oC and $6\ mg.L^{-1}$ oxygen, resp.
VOLT1206	hm^3	minimum volume $\leq 12^oC$ and $\geq 6\ mg.L^{-1}$
<u>Biota</u>		
NETDRY	$kg.ha^{-1}$	net plankton, average dry weight
NETORG	$kg.ha^{-1}$	net plankton, average organic weight
BENNOA	number/ m^2	benthic fauna, summer average weighted by area strata
BCn	taxon	faunal identification categories
BCn%	%	faunal composition by numbers
BENDRY	$kg.ha^{-1}$	benthic fauna, dry weight, summer average weighted by area strata
<u>Winter physicochemistry</u>		
WINDATE	month	winter sample date
OWINS	$mg.L^{-1}$	surface oxygen near ice cover
OWINB	$mg.L^{-1}$	bottom oxygen
PHWINS	...	surface pH near ice cover
...	...	all others are named similarly

a AAAn designates a multiple variable name using different n suffixes.

The representation of all Saskatchewan lakes by the set of lakes which were surveyed was assessed by comparing the distributions of (i) fish species in surveyed lakes with more extensive species lists, and (ii) several habitat variables with larger (presumably less biased) lake sets. The relative frequency of lake trout and others in surveyed lakes and in lakes reported by Atton and Merkowsky (1983) was assumed to reflect intensities of collection and/or species biases in the study. Two habitat variables (water area and TDS, see Table 1) were available in lake sets which nominally covered the entire province. Furthermore, water areas in two studies of small lakes (Koshinsky 1968, Beak 1979) were compared to those of nearby lakes in surrounding 10 x 10 km or 5 x 10 km area. These two studies were intuitively more representative of water areas than other surveys.

Prediction of lake trout presence

Univariate criteria

All habitat variables available for 100 or more lakes (and also COLOUR) were examined for potential as univariate predictors of lake trout presence. Median differences between lakes with and without lake trout were tested by the non-parametric, two-tailed Mann-Whitney procedure (SAS 1982 p.206, Conover 1971). This tested whether a habitat variable tended to differ (i.e. larger or smaller) between these two classes of lakes. The statistical assumptions are: lakes are randomly and independently selected from each class population, and habitat variables are continuous so that tied values were infrequent (Conover 1971). The univariate criteria for predicting lake trout status in individual lakes were determined by ranking variable values in descending order, interpolating criteria which misclassified (approximately) equal numbers of lakes belonging to each class, and comparing known and predicted status to obtain the error rate of prediction. This method is non-parametric, but assumes that lakes are randomly selected at least in the region of overlap of the two classes along a variable axis (Conover 1971, Knoke 1982). If this is not true, then the resultant criteria will over-estimate the numbers of over-represented lakes in future samples. The restriction of equal numbers of misclassifications has advantages over some alternatives (Lachenbruch 1975 p.15 and 87). Minimizing the total number of misclassifications can result in criteria which will not predict any lake trout in future samples, if lake trout lakes are relatively few. Minimizing the seriousness or cost of errors, which might be an objective of management, requires an estimate of social or economic costs of false positive or negative errors.

Variables were considered to be useful if they had significant median differences and error rates less than 25 %. These initial error rates are usually optimistic as the same sample of lakes is used to create and test the criteria (Lachenbruch 1975, Dillon 1979).

Shield and non-shield criteria

Water area, volume, and temperature-and-oxygen criteria were examined for differences in lake trout requirements in shield and non-shield lakes. Three issues were examined: (1) Anomalies in the set of lakes available may lead to spurious differences. (2) Morphometry and recent waterlevel fluctuations may differ between non-shield and shield lakes. (3) Post-glacial access routes and/or warmer and drier climatic conditions may have affected lake trout populations in part of the study area, according to literature sources (e.g. Stewart and Lindsey 1983, Christiansen 1979, Ritchie 1976, Wilson 1981).

(1) Anomalies

The representation of shield and non-shield lakes in surveys was compared to the estimated total number of lakes in each region.

Random subsets of shield lakes were examined to test the probability of similar differences for approximately equal numbers of shield and non-shield lakes. Enlarging the smaller non-shield subset of lakes for this comparison was impossible, except by the replication of data using the "bootstrap method" (Diaconis and Efron 1983).

Gradients within the shield area were examined by dividing these lakes into three groups (i.e. south of 56°N, 56 - 58°N, and north of 58°N). Separate univariate criteria for each group were compared to each other and to non-shield criteria.

Trends between water area, volume, and temperature-oxygen volumes in shield and non-shield lakes were compared.

(2) Recent conditions

Waterlevels Analysis of recent area, volume, and other variations were necessarily indirect for several reasons. Long-term trends were available only from federal-provincial records of lake waterlevels. Variability in surveyed lakes was largely unavailable as few lakes had both lake surveys and waterlevel records available. Furthermore, many lake surveys were based on arbitrary or estimated elevations so equivalence between data sets could not be established.

Waterlevels were analyzed for all lakes: (i) situated north of 52°N in Saskatchewan or neighbouring areas of Alberta or Manitoba; (ii) with at least 10 years of daily summer waterlevel records (based on a common elevation or "hydrological datum"); and (iii) with no significant man-made regulation of flows, or for years prior to this regulation.

The summer minimum for each year and each lake was defined by the lower of the July or August minimum daily waterlevel. Low waterlevels in typical and extreme years were predicted from polynomial regressions of observed waterlevels versus cumulative probability. Recent waterlevel variations were defined as the difference between predicted low summer waterlevels for typical years (i.e. cumulative 50% probability, or median) and extreme years (i.e. cumulative 1% probability, or nominally 1 in 100 years). The effects of bedrock geology and water area were tested by the step-down method of linear regression and analysis of co-variance (Freund and Minton 1979 p.224).

Morphometry Changes in water volume due to waterlevel variations required the interpolation of volume-at-depth for available lakes. All lakes with volumetric data of ±20% precision were used (see VOLT15T6' in Appendix B). Both relative volume (%) and absolute volume (hm^3) were examined for arbitrary depths.

Residual Volumes Relative and absolute residual volumes were estimated for waterlevel variations predicted from water area and relative and absolute volumes-at-depth, with or without the effects of bedrock geology.

Multivariate criteria

Trial transformations (i.e. logarithmic, logarithmic^2, inverse, square root, and inverse hyperbolic sine) were applied to useful variables which were non-normally distributed within the classes (Kolmogorov-Smirnov test of Gold in SAS 1983). Transformations which yielded normality, or at least near-symmetry, in both classes were used in multivariate analyses. Several pairs of variables were plotted and linear criteria of lake trout status were determined, again by misclassifying equal numbers of each class. With the exception of depth versus water area, most pairs were used only to assess marginal habitat (see below).

Multiple discriminant analysis (MDA) was used to improve the prediction of lake trout status. Basically, MDA separates or discriminates between classes (e.g. lake trout and non-lake-trout lakes) by compounding two or more variables, neither of which is able to effect this alone, into a single criterion (Solberg 1978, Lachenbruch 1975).

Different versions of MDA were used: (1) Stepwise MDA assessed the relative discriminatory potential of variables which were good univariate predictors, and selected variables for inclusion or deletion according to sequential F-tests (STEPDISC in SAS 1982). (2) Classification MDA assessed the accuracy of classification by linear MDA and by nearest-neighbour MDA (DISCRIM in SAS 1987). Error rates were determined by resubstitution and cross-validation (i.e. "apparent error rates" and "leaving-one-out method", respectively, of Lachenbruch 1975) in the initial set of lakes, and by use of the reserved set of lakes (Hocking 1976, Dillon 1979). (3) Canonical MDA created a canonical variate or axis of lake trout status in Saskatchewan lakes for description and comparison with other studies (CANDISC in SAS

1982). Canonical MDA maximizes between-class variations in habitat, relative to within-classes, using k-1 axes for k classes (Lachenbruch 1975).

The assumptions of MDA for optimal results are: (i) the frequency distribution of all variables is multivariate normal in each class; (ii) the variance-covariance or dispersion is the same in both classes; (iii) the class is correctly assigned in all observations; and (iv) observations are randomly selected from the population and there are few, if any, missing variables (Lachenbruch 1975, Solberg 1978, Knoke 1982).

If variables are not multivariate normal, then selection of variables in stepwise MDA and error rates in classification MDA may be seriously biased (Dillon 1979). Approximately normal variables provide lower and more equal error rates in classes (Lachenbruch, Sneeringer, and Revo 1973). If necessary, normality was assumed, for "if the normality assumption is violated, the practitioner is faced with the most difficult task of specifying the appropriate joint probability distribution" (Dillon 1979 p.372). Canonical MDA explicitly does not depend on normality of variables to create an axis, but does if optimal classification is expected (Lachenbruch 1975 p.10, Solberg 1978 p.212 and 220).

The requirement of equal variance-covariance is "unlikely to be satisfied with ecological data" (Green and Vascotto

1978) and is frequently ignored (Johnson et al. 1977). This affects the tests of significance, error rates, and the optimal classification rules in linear MDA (Dillon 1979). One effect of linear MDA is to preferentially classify observations into the class with the greater dispersion (Solberg 1978). Nonetheless, the quadratic MDA which was developed for unequal dispersions is more sensitive to non-normality and small sample sizes, and is not always recommended in practice.

If the status of some lakes is incorrect, then classes appear more alike and discrimination is more difficult (Solberg 1978). These errors frequently tend to occur near the borderline between classes, in which case the apparent error rates are not at all reliable (Lachenbruch 1975).

"In practice, the robustness problems just discussed may be secondary to the problem of missing values" (Lachenbruch 1975 p.49). In addition, non-biased sampling of lakes is a fundamental assumption (Solberg 1978, Knoke 1983), as it is in most statistical methods. These latter concerns were assessed and minimized as far as practicable (see Estimation of missing data and Validation and extrapolation).

Using non-parametric nearest-neighbour MDA, each observation is classified into the class with the highest probability density according to class frequencies among the k neighbouring observations (Lachenbruch 1975, SAS 1987). Five neighbours were used, largely due to available sample sizes and the lack of clear rules for optimal k (SAS 1987). The need for multivariate normality and equal dispersion is obviated, but that for correct status, complete surveys, and random sampling is presumed.

Multicollinearity, which is a high degree of linear correlation among independent variables (Freund and Minton 1979), was expected in this study. For example, the area, volume, maximum depth, and shoreline length of lakes are intuitively correlated. The absence of multicollinearity is not an assumption, yet its presence complicates MDA (Lachenbruch 1975). Multicollinearity of continuous variables may reduce the usefulness of additional variables: each improves discrimination only if its correlation with the present variable(s) is quite large and positive or is negative (Lachenbruch 1975). It produces large variances of all coefficients, so that selected subsets of variables can change easily with new observations (SAS 1987). It presumably makes predictions unreliable for individual observations which lie outside the multivariate dispersion of data (even if not outside the ranges of separate variables), as in multiple regressions (Freund and Minton 1979 p.118).

Estimation of missing data

Estimation of missing habitat data was necessary, since very few lakes had the full set of useful variables available. Missing data were estimated for the more promising variables from (more or less redundant) correlated variables (Frane 1976). Data from all available lakes were used, rather than only the random subset. Estimation of total dissolved solids (TDS) from specific conductivity (SPCON) or alkalinity (TOTALK) is a common example of this approach (Ryder 1965, Liaw and Atton 1980).

Statistical complications are common among the large number of variables available in large data sets (Frane 1976, Hocking 1976). Judicious selection is necessary to prevent unwieldy regressions, mis-specification of regressors, and imprecision of coefficients (Freund and Minton 1979). In this study, all-subset and stepwise regressions preceded multiple linear regressions, which included analysis of residuals and multicollinearity (SAS 1982, Freund and Minton 1979). All-subset regression (SAS 1982) yields alternative regressions with similar predictive ability, but using variables that are sometimes easier to obtain and/or to interpret. Subsets were selected by the Cp-statistic to ensure that unused variables were non-essential (Hocking 1976), although the test itself is less reliable in the presence of multicollinearity (Freund and Minton 1979 p.120). Multicollinearity affects stepwise regressions by biasing the entry or deletion of all but the first variables (Freund and Minton 1979).

Supplementary data and analyses were required to predict non-stratification in lakes with high flushing rates, and to assess the influence of surficial geology in a lake basin on maximum lake depth (see Appendix G).

Marginal habitat

Misclassifications were assessed to determine whether intuitive definitions of "marginal habitat" apply to the presence and absence of lake trout. Relative abundances were not available in this study. In the first method, the frequency of major classification errors for each lake estimated its marginality. Misclassifications of shield lakes within $\pm$ 10 % of the criterion of lake trout presence were considered minor, while those outside this zone were considered major. The second method analysed trends in specific lakes between the better predictors (i.e. single and paired variables) and other variables.

Validation and extrapolation

The criteria of lake trout presence were validated using the actual and predicted status in the 20 % of lakes which were reserved for this purpose. Univariate criteria were designed to predict the status of individual lakes.

Extrapolation to all lakes was based on the probability of lake trout presence at each habitat value, using logistic, actual, and polynomial probability curves. Logistic regression (CATMOD in SAS 1987) produces anti-symmetric probabilities of presence in habitat x of:

$$P = 1 / (1 + e^{B0 + B1(x)})$$

where B1(x) can be one or more coefficients and variables. In its multivariate form it is an alternative to MDA (Lachenbruch 1975, Solberg 1978, Efron 1975), but no stepwise method was available (SAS 1987). The requirement for normality of variables is more relaxed than in MDA (Solberg 1978), but anti-symmetry and random sampling are necessary. If classes of lakes are sampled non-randomly, the logistic intercept (i.e. B0) at least is affected (Lachenbruch 1975). Actual asymmetric probabilities were calculated from the proportion of lake trout lakes in running subsets of 5 to 10 lakes. These points were fitted using stepwise polynomial regressions:

$$P = A_0 + A_1 x + A_2 x^2 + \ldots + A_5 x^5$$

(see Appendix F).

The effects of variables missing from incomplete surveys (see Representative lakes) and/or preferential surveying of lake trout lakes were assessed. The preference toward lake trout lakes was judged to be several-fold higher than non-lake-trout lakes (Minns 1986). To avoid exaggerating this factor, 6-fold was assumed for very small lakes (< 10 km^2), 4-fold for small lakes (10 - 50 km^2), and 2-fold for medium lakes (50 - 100 km^2); no preference was used for larger lakes. Data for randomly selected lakes were deleted from the set (i.e. 5/6 of very small, 3/4 of small, and 1/2 of medium lake trout lakes) to give a more representative set.

Extrapolation to determine the total numbers of lake trout lakes in the shield region of Saskatchewan was based on: (i) the probability of lake trout presence in habitat interval x; and (ii) the distribution of habitat interval x in the 83,241 shield lakes. Water area (WAREA) and the minimum volume of suitable temperature (VOLT15T6) were used in extrapolation. The distribution of habitat values was estimated for lakes shown on randomly selected, topographic map sections (each 10 x 10 km, or 5 x 10 km weighted by a factor of 2 when lakes were numerous), stratified by latitude and bedrock geology. Lakes were assigned a water area of 0.01 km^2 if they were estimated to be < 0.02 km^2 by a "dot grid" on 1:50000-scale maps. Since the distributions were highly skewed and these small lakes were imprecisely measured, only the cumulative probabilities 0.5, 0.75, 0.9, 0.95, and 0.99 of log WAREA and log VOLT15T6 > x were fitted. The data at probability 0.9965 of WAREA and the largest WAREA and VOLT15T6 were added into these distributions.

RESULTS

Unless specifically noted, results concern only the 262 lakes which were used to develop criteria (Figure 1) and not the lakes reserved for validation of these criteria.

Fish species

Fish species compositions were known in 228 lakes or about 87 % of the 262 lakes. Species were unknown primarily in very small lakes in the Key Lake area (16 lakes), Prince Albert National Park (8 lakes), and other localized areas. At least 10 lakes in the Key Lake area were wholly or partially drained for open-pit uranium mining before complete species compositions were known (P. Courtney, Environment Dept., Key Lake Mining Corp., pers. comm.).

About 37 native fish species were revealed in the lake surveys. This is 80 % of the 46 native species known from this area and 64 % of the provincial native species (from maps in Atton and Merkowsky 1983). In addition, lake surveys revealed 2 of the 6 introduced and accidental species known from north of 53°N. Several reported *Coregonus* species (e.g. *C. artedii*, *C. nigripinnis*, and *C. zenithicus*) cannot reliably be differentiated (Kooyman 1970). They represent only two species (i.e. *C. artedii* and *C. zenithicus*) (Clarke 1973) and were included in the *C. artedii* complex of McPhail and Lindsey (1970).

Figure 1. Locations of 262 lakes used in the present study to develop predictions of lake trout presence or absence. The solid line marks the southern edge of common lake trout occurrence; the hatched line marks the southern boundary of sporadic lake trout occurrence. The dotted line marks the southern edge of the Precambrian shield region; solid circles represent shield lakes and open circles, non-shield lakes. Numbers in circles represent the numbers of lakes coincident at a point.

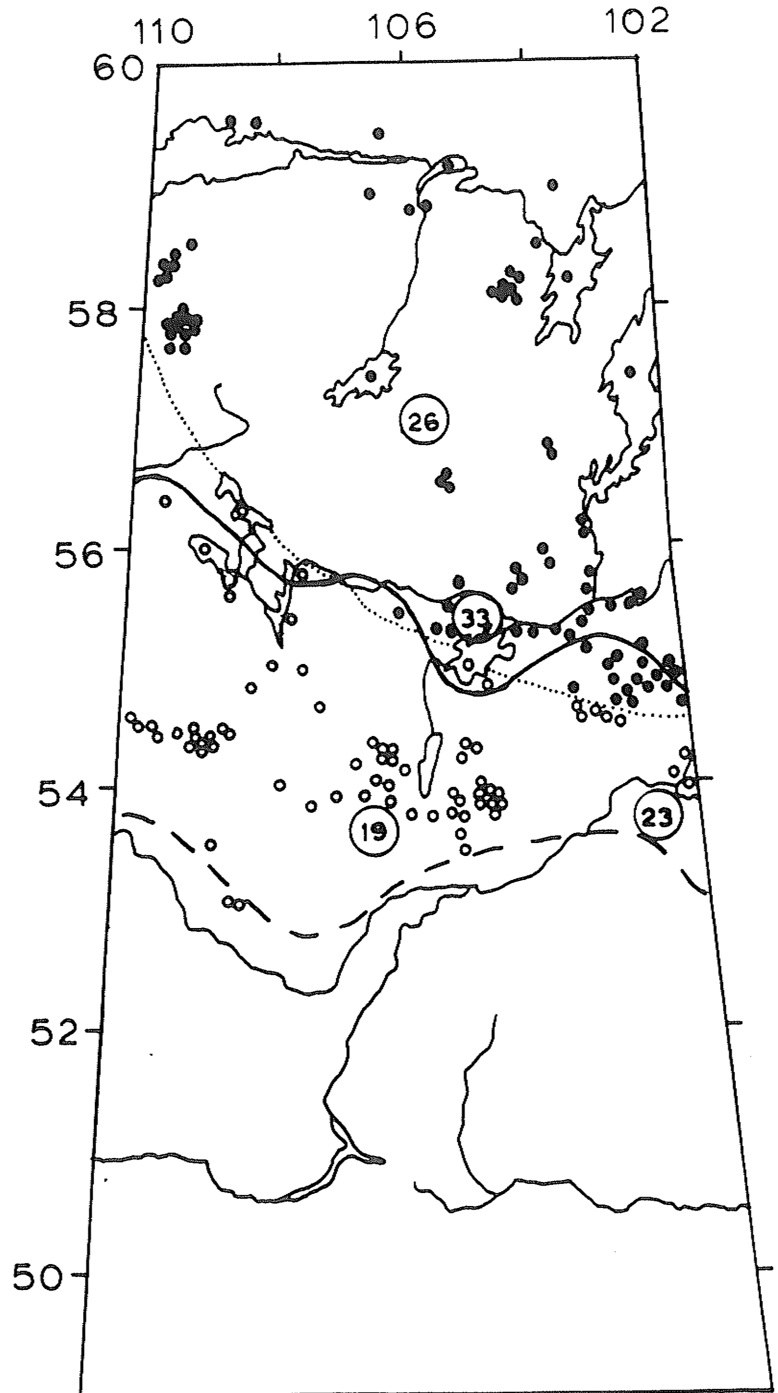

110
106
102
60
58
56
54
52
50
26
33
19
23

Table 2. Numbers of fish species present in each surveyed northern Saskatchewan lake.

Lake set	Number of lakes	Number of species[a]					
		0-4	5-9	10-14	15-19	20+	Mean
		%	%	%	%	%	%
All	228	36.9	25.7	19.1	15.7	2.6	8.0
Bedrock geology:							
Shield	117	29.1	25.6	20.5	22.2	2.6	9.2
Non-shield	111	44.2	26.1	18.0	9.0	2.7	7.0
Water area[b]:							
Very large	11	0	9.1	18.2	72.7	0	14.7
Large	16	0	0	43.7	37.5	18.8	16.1
Medium	17	0	11.7	35.3	47.1	5.9	14.6
Small	48	14.6	22.9	35.4	22.9	4.2	9.8
Very small	133	55.6	33.1	9.0	2.3	0	4.9

a "Regular species" only (see Appendix C).
b VL is >250 km^2, L is >100-250 km^2, M is >50-100 km^2, S is >10-50 km^2, and VS is $\leq$10 km^2. Data are missing in 3 lakes.

Most lakes which were surveyed (i.e. 63 %) contained fewer than 10 fish species. More species tended to occur in shield lakes and in larger lakes (Table 2). Shield lakes which were surveyed were generally larger than non-shield lakes. Lakes over 50 km^2 water area averaged about 15 species each, while small lakes of 10-50 km^2 averaged 10 species, and very small lakes under 10 km^2 averaged 5 species.

Table 3. Occurrences of preferred fish species in 228 surveyed Saskatchewan lakes north of 53°N.

	Number of lakes							
		Bedrock geology		Water area[b]				
Species[a]	All	Shield	Non-shield	VL	L	M	S	VS
Lake trout	46	36	10	5	8	4	11	18
Lake whitefish	138	87	51	11	16	17	37	56
Northern pike	196	113	83	11	16	17	44	105
Walleye	100	50	50	10	14	13	32	31

a Lake trout, lake whitefish, walleye, and northern pike are preferred by sport and commercial fisheries.
b VL is >250 km^2, L is >100-250 km^2, M is >50-100 km^2, S is >10-50 km^2, and VS is $\leq$10 km^2.

Lake trout occurred in 46 or 20 % of the lakes and were absent from 182 lakes (Table 3). This species occurred in 4 of the 11 different associations of major species (i.e. lake trout, lake whitefish Coregonus clupeaformis, northern pike Esox lucius, and walleye Stizostedion vitreum). Lake trout were found most commonly with both lake whitefish and northern pike, and less frequently with walleye as the fourth species. They were rarely found as the sole major species and only rarely in other associations (Table 4). In very small lakes 10 km^2 or less, lake trout were seldom associated with walleye. Only one very small lake contained both species (Table 4), although lake trout occurred in 18 of

Table 4. Associations of preferred fish species in surveyed northern Saskatchewan lakes.

Species association[a]	All lakes	Bedrock geology		Water area[b]				
		Shield	Non-shield	VL	L	M	S	VS
LT WF NP WA	18	11	7	4	6	2	5	1
LT WF NP X	26	23	3	1	2	2	6	15
LT WF X X	1	1	0	0	0	0	0	1
LT X NP X	1	1	0	0	0	0	0	1
X WF NP WA	74	37	37	6	8	11	25	24
X WF NP X	18	14	4	0	0	2	1	14
X WF X X	1	1	0	0	0	0	0	1
X X NP WA	7	2	5	0	0	0	2	5
X X NP X	52	25	27	0	0	0	5	46
X X X WA	1	0	1	0	0	0	0	1
X X X X	29	2	27	0	0	0	4	24
Total	228	117	111	11	16	17	48	133

a LT=lake trout, WF=lake whitefish, NP=northern pike, WA=walleye, X=absence.

b Missing for 3 lakes. VL is >250 km^2, L is >100-250 km^2, M is >50-100 km^2, S is >10-50 km^2, and VS is $\leq$10 km^2.

these lakes and walleye in 31 lakes. Independently distributed species would be expected to co-occur in about four lakes, if species competition and/or habitat selection were not operating. By comparison, lake trout and lake whitefish co-existed in 17 very small lakes, about twice as many as expected for independently distributed species. Most medium and larger lakes over 50 km lacked only lake trout (57 %) or walleye (11 %) and seldom any other preferred species.

About 31 % of surveyed lakes on the Precambrian shield contained lake trout, in contrast to only 9 % in non-shield lakes (Table 5).

Survey habitat variables

Only 8 variables were available for 200 or more lakes: LAT, LONG, NORD, and WAREA which were available from independent sources (e.g. topographic maps) and VOLUME, ZBAR, ZMAX, and TMAXS which required specific fieldwork (Table 1). Another 27 variables were available for 100 to 199 lakes, while 9 (all winter physicochemistry variables) were available for fewer than 50 lakes each (see Appendix D).

Combinations of several habitat variables were available for more lakes than would be expected if each variable had been collected independently of others. Subsets of six variables were available for 1.7 to 3.6 times more lakes than expected (Table 6).

Table 5. Number of surveyed northern Saskatchewan lakes with lake trout present.

Lake trout	Number of lakes	Shield lakes: Athabasca AT	Shield lakes: Boundary BA	Shield lakes: Shield SH	Non-shield lakes: Boundary BD	Non-shield lakes: Sedimentary SE
Present	46	6	5	25	3	7
		25%	100%	28%	9%	9%
		.... 31%			... 9% ...	
Absent	182	18	0	63	31	70
		75%	0%	72%	91%	91%
		.... 69%			.. 91% ...	

A composite description showed that the median 50% of surveyed lakes were between:

$54^{o}04'$ and $56^{o}42'$ N latitude (LAT, n=262),

0.6 and 29.7 km^2 water area (WAREA, n=248),

2.6 and 8.8 m mean depth (ZBAR, n=215),

2.1 and 4.4 m Secchi depth (SECCHI, n=176),

40 and 213 $mg.L^{-1}$ TDS (n=197),

19.0 and $22.0^{o}C$ maximum surface temperature (TMAXS, n=208),

and 0.0 and 24.0 hm^3 (i.e. million m^3) minimum volume of water between 6 and $15^{o}C$ (VOLT15T6, n=157, see Appendix D).

Table 6. Number of lakes with combinations of habitat variables available in relation to the number expected for independent collections of variables.

Number of lakes		
Available	Expected	Habitat variables[a]
All lakes:		
123	70	WAREA TDS ZMAX TMAXS FETCH SECCHI
78	22	VOLUME SHODEV BENDRY OMINB VOLT15T6 TOTALK
102	42	ZBAR TDS TMAXB SECCHI VOLT1506 NORD
Shield lakes:		
75	44	WAREA TDS ZMAX TMAXS FETCH SECCHI
68	29	VOLUME SHODEV BENDRY OMINB VOLT15T6 TOTALK
62	36	ZBAR TDS TMAXB SECCHI VOLT1506 NORD
Non-shield lakes:		
48	26	WAREA TDS ZMAX TMAXS FETCH SECCHI
10	3	VOLUME SHODEV BENDRY OMINB VOLT15T6 TOTALK
40	11	ZBAR TDS TMAXB SECCHI VOLT1506 NORD

a See Table 1 for variable names.

Representative lakes

Limitations of the surveyed lakes as representatives of all northern Saskatchewan lakes were observed. These necessitated more complex approaches to prediction and extrapolation to all lakes than originally foreseen, particularly for extrapolation to all lakes.

Comparisons of fish species compositions in lakes which were surveyed and in lakes from other studies were inconclusive. Only 239 lakes north of $53^{O}N$ were available for comparison (Atton and Merkowsky 1983), many of which were the same lakes used in the present study. In general, the present surveys were no more biased towards the major species than the broader lake set. In both sets 12 % of lakes contained no socio-economically preferred species (i.e. lake trout, lake whitefish, northern pike, or walleye) (Table 7). In northern drainage basins, a higher proportion of lakes which were surveyed contained preferred species (i.e. 12 % *versus* 0 % and 5 %), indicating bias towards these species. Distributional records in the southern basin were similarly biased (i.e. 28 % *versus* 12 %). Nonetheless, surveyed lakes showed no greater tendency than distributional records to have lake trout present. In comparison to distributional records, surveys were biased towards lakes with northern pike and lake whitefish (Table 7).

Table 7. Occurrences of preferred fish species in northern lakes in the present study and in Saskatchewan lakes in other distributional studies north of 53°N.

Lake set	Number of lakes	Species present				
		Preferred[a]				Others only
		LT	WF	WA	NP	
		%	%	%	%	%
Arctic and Kazan basins[b]:						
Atlas lakes[c]	51	59	65	35	82	12
Surveyed lakes	27	56	78	30	96	0
Churchill basin:						
Atlas lakes	122	30	70	64	76	12
Surveyed lakes	118	23	74	55	93	5
Saskatchewan Basin[d]:						
Atlas lakes	66		...			12
Surveyed lakes	83	5	36	33	72	28
All basins:						
Atlas lakes[e]	239			...		12
Surveyed lakes	228	20	60	44	86	12

a Lakes with other species are noted only if no preferred species are present.

b Drainage basins as defined by Atton and Merkowsky (1983).

c From lake files (J. Merkowsky, pers. comm.).

d Basins 73-86 and 73-89 to 73-93 inclusive (Atton and Merkowsky 1983) were used to approximate this region.

e Five surveyed lakes had no fish species present, which would not occur in the atlas records.

The distribution of water area (WAREA) in lake surveys did not correspond to the estimated total distribution of either shield or non-shield lakes. Very small lakes were seriously under-represented and all others over-represented (Table 8, Figure 2). A set of 8,540 very small lakes under 10 km^2 and 30 lakes over 10 km^2 area would represent all shield lakes proportionally. Two other studies of very small lakes under 10 km^2 in localized areas near Lac La Ronge and Key Lake were more representative (Koshinsky 1968, Beak 1979)(Table 9). However, even these latter studies under-represented lakes under 0.05 km^2 and over-represented lakes over 0.2 km^2 (Kolmogorov-Smirnov one-tailed test $P<0.05$ (Conover 1971, Elderton and Johnson 1969)). Nonetheless, further comparisons of lakes over 0.05 km^2 and with known fish species showed no conclusive differences between lakes in these studies and nearby lakes (Kolmogorov-Smirnov $P>0.10$).

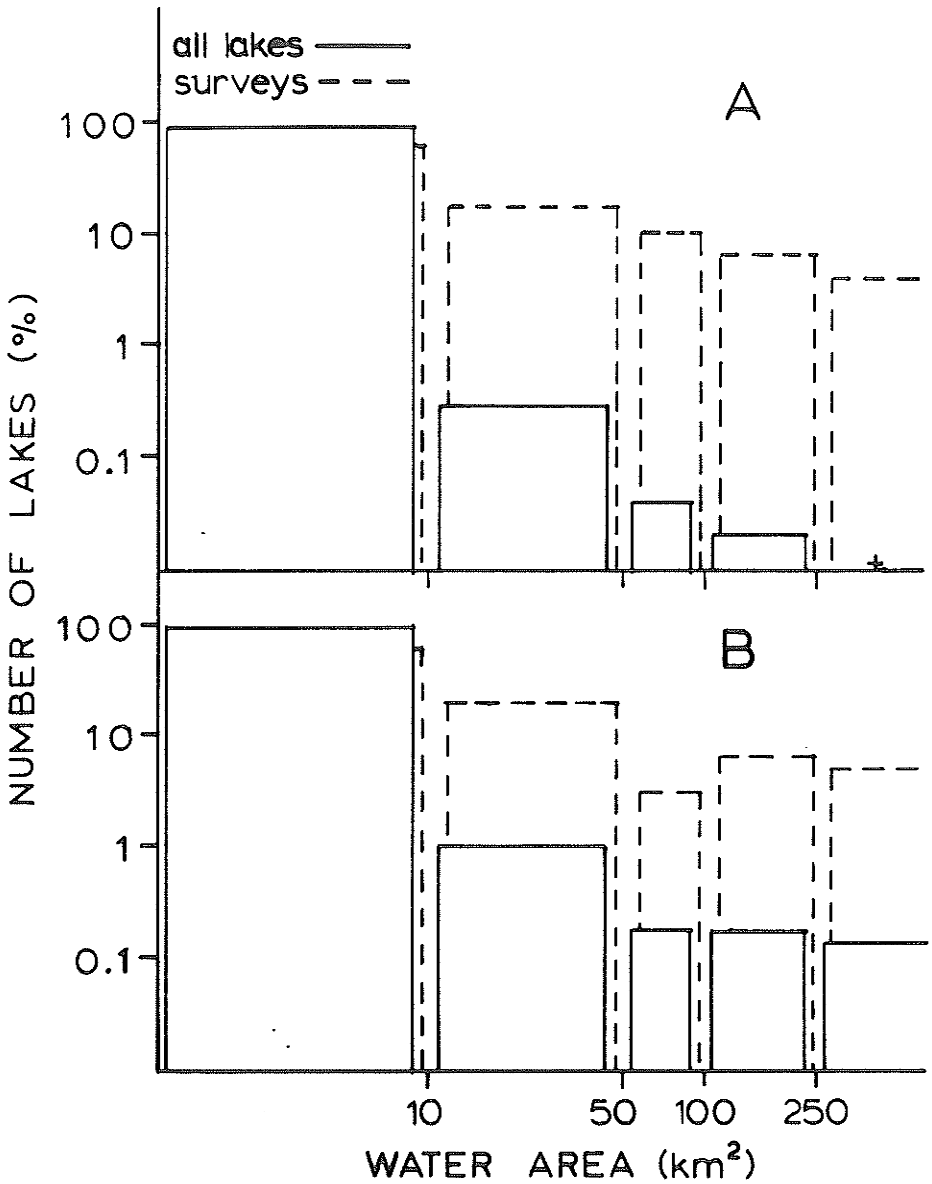
Table 8. Comparison of water areas of lakes in the present study to all Saskatchewan lakes north of 53°N.

Lake set	Number of lakes	Water area[a] VL	L	M	S	VS
		%	%	%	%	%
Shield lakes:						
Surveyed	126	3.97	6.35	10.32	17.46	61.90
All lakes[b]	83,241	0.01	0.02	0.04	0.28	99.65
Non-shield lakes:						
Surveyed	122	4.92	6.56	3.28	21.31	63.93
All lakes[b]	8,477	0.14	0.17	0.18	1.00	98.51

a VL is >250 km^2, L is >100-250 km^2, M is >50-100 km^2, S is >10-50 km^2, and VS is $\leq$10 km^2.

b Very small lakes were estimated by subsamples and other lakes were counted (A. R. Murray, Fisheries Branch, March 1984, pers. comm.).

Figure 2. Number of lakes in each interval of water area. All Saskatchewan lakes north of 53N and the surveyed lakes used in the present study are shown for the shield (panel A) and non-shield (panel B) regions.



all lakes
surveys
A
B
100
10
1
0.1
NUMBER OF LAKES (%)
10
50
100
250
WATER AREA (km²)

Table 9. Comparison of water areas of lakes in studies near La Ronge and Key Lake to nearby lakes.

Water area (km^2)	Number of lakes					
	La Ronge area[a]		Key Lake area[b]		Combined areas[c]	
	Study	Nearby	Study	Nearby	Study	Nearby
	%	%	%	%	%	%
$\leq$0.05	0	54.3	22.7	81.5	...	...
0.05- 0.1	18.2	12.6	9.1	8.2	...	...
0.1 - 0.2	6.1	9.1	3.6	4.4	...	...
0.2 - 0.5	27.3	9.8	27.3	3.2	...	...
0.5 - 1.0	18.2	7.5	13.6	1.2	38.1	51.1
1.0 - 2.5	12.1	4.3	4.5	0.6	23.8	28.9
2.5 - 5.0	12.1	1.6	9.1	0.6	28.6	13.3
5.0 -10.0	6.1	0.8	0	0	9.5	4.4
>10.0	0	0	0	1.0	0	2.2
Number	33	254	22	248	21	45

a Surveys by Koshinsky (1964, 1968) regarding new Highway 2 route, compared to nearby lakes in 700 km^2 area.

b Surveys by Beak (1979, excluding Russell and Martin lakes) regarding a mine, compared to nearby lakes in 200 km^2 area.

c Data were further restricted to surveyed lakes with known fish species and lakes over 0.5 km^2 area.

TDS distributions of surveyed lakes were compared to TDS in 419 lakes from an acid-rain study (Liaw and Atton 1980) and to the estimated TDS of all lakes north of 53°N. Surveyed lakes tended to be lower in TDS than lakes in the acid-rain study (Table 10), although the latter study itself was questionably representative (see Discussion). In comparison to all shield lakes, surveyed lakes tended to under-represent TDS below 50 $mg.L^{-1}$ and over-represent TDS above 100 $mg.L^{-1}$. In non-shield areas, surveyed lakes over-represented TDS below 100 and above 200 $mg.L^{-1}$ slightly (Table 10). These discrepancies were not statistically significant by the Kolmogorov-Smirnov test ($P>0.10$ using discrete classes) in either shield or non-shield lakes. Furthermore, the highest TDS of any lake trout lake in 175 surveyed lakes was 186 $mg.L^{-1}$ (see Appendix D), and lakes with lower TDS were reasonably well represented.

Table 10. Comparison of total dissolved solids (TDS) in surveyed lakes to other Saskatchewan lakes north of 53°N.

Lake set	Number of lakes	TDS (mg.L^{-1})					
		0-20	20-50	50-100	100-200	200-500	500+
		%	%	%	%	%	%
Shield:							
Acid rain[a]	158	4	32	54	9	0	0
Surveyed	99	13	42	30	14	0	0
All lakes[b]	83,241	...75...		24	1	0	0
Non-shield:							
Acid rain[a,c]	261	0	0	3	32	65	0
Surveyed	98	0	2	11	34	46	7
All lakes[b]	8,477	0	0	7	45	33	15

a From Figure 2 in Liaw and Atton (1980).

b Estimated by planimetry of TDS areas (Figure 1 in Liaw and Atton 1980) and numbers of lakes in each 2° latitude (A. R. Murray, March 1984, pers. comm.).

c Region differs marginally from surveyed region (see zones B and C in Liaw and Atton 1980).

Prediction of lake trout presence

Descriptions of lake trout lakes were not useful in predicting lake trout suitability. Nonetheless, certain characteristics of the lakes in the present study were noteworthy.

All 46 of the lake trout lakes were situated north of 54^{o}N latitude, extending from Manitoba to Alberta. No natural lake trout populations exist south of this in Saskatchewan (Marshall and Johnson 1971). Most lake trout lakes were large, deep, clear, cold, and low in minerals and benthic fauna (Appendix D). About 75% were:

greater than 7.05 km^2 in area or 92.8 hm^3 in volume,
deeper than 8.0 m mean depth or 31.1 m maximum depth,
clearer than 4.4 m Secchi disk depth or 11.5 Pt colour units,
cooler than 9^{0}C maximum bottom temperature or with at least 21.7 hm^3 water between 6^{0}C and 15^{0}C,
and below 95 $mg.L^{-1}$ TDS or 7.2 $kg.ha^{-1}$ dry weight of benthic fauna.

The size of trout lakes also meant that shoreline lengths and fetches were typically long. Flushing time was available for only 9 lake trout lakes, but was as short as 0.7 years. Minimum summer oxygen concentrations at the bottom were below about 3 $mg.L^{-1}$ for one-quarter of the lake trout lakes.

<u>Univariate criteria</u>

Many variables revealed significant differences between lakes with and without lake trout. In general, 42 of 50 variables examined differed significantly ($P \leq 0.05$) in their medians (Appendix E). Within the shield and non-shield areas, 35 and 31 variables (respectively) differed significantly. The ranges of some variables across and within these two major geological zones is important (see Discussion).

Fewer variables showed acceptably low classification error rates for lake trout presence and absence. In general, 27 variables misclassified 25 % or fewer lakes and only 3 variables achieved 10 % or fewer (i.e. VOLT15O6', VOLT15O4', and VOLT12O6' in Table 11). (Recall that primed VOLTnnOn variables denote acceptable precision of $\pm 20\%$ for volume strata of lake, see Appendix B). In the shield area, 11 of the 17 acceptable variables were temperature-oxygen indices and 2 variables achieved 10 % or less misclassification (i.e. VOLT15O6' and VOLT15O4'). In the non-shield area, 12 potential predictors related to location, morphometry, and temperature-oxygen conditions; three variables achieved 10 % or less misclassification (i.e. ZBAR, ZMAX and T15T6L in Table 11). Several variables were otherwise acceptable, but available in too few lake trout lakes to be considered reliable (see Appendix E).

Table 11. Univariate predictions of lake trout presence or absence by habitat variables. Only variables which have error rates of 25 % or less and represent 10 or more lakes with lake trout present are shown.

Variable[a]	Lake trout Present	Lake trout Absent	Classification Criterion of presence	Classification Errors(%)[b]
Location:				
LATD	46	182	> 56.525^{0}N	20
NORD	46	182	> 7.042	21
Morphometry:				
WAREA	46	179	> 46.7 km^2	24
VOLUME	44	157	> 430.01 hm^3	21
ZBAR	44	156	> 9.65 m	14
ZMAX	46	178	> 32.65 m	11
Physicochemistry:				
SECCHI	42	131	> 4.54 m	14
PHOTOZ	42	138	> 4.54 m	13
TDS	38	137	< 40.5 $mg.L^{-1}$	21
SPCON	32	118	< 41.0 uS.cm-1	21
CA	37	136	< 4.30 $mg.L^{-1}$	22
MG	36	136	< 1.55 $mg.L^{-1}$	22
NA	35	131	< 1.28 $mg.L^{-1}$	22
HCO3	29	127	< 21.0 $mg.L^{-1}$	21
Temperature-Oxygen:				
TMAXB	43	139	< 7.45 C	19
OMINS	41	133	> 8.35 $mg.L^{-1}$	24
HIGH6MG	39	130	> 23.0 m	17
T15T6L	43	139	> 29.5 m	19
VOLT15T6'	39	116	> 24.00 hm^3	14
T15O6L	36	127	> 24.5 m	17
VOLT15O6'	34	110	> 3.29 hm^3	7

continued

Table 11. continued

Variable	Lake trout		Classification	
	Present	Absent	Criterion of presence	Errors(%)
T15O4L	36	125	> 29.5 m	14
VOLT15O4'	34	106	> 16.29 hm^3	10
T12O6L	36	126	> 26.5 m	17
VOLT12O6'	34	107	> 1.04 hm^3	9
Biota:				
BENNOA	36	116	< 720 m-2	24
BENDRY	38	116	< 4.65 $kg.ha^{-1}$	19
SHIELD LAKES				
Morphometry:				
ZBAR	34	77	> 8.30 m	17
ZMAX	36	79	> 31.15 m	16
Physicochemistry:				
SECCHI	36	69	> 4.15 m	12
PHOTOZ	36	71	> 4.15 m	11
Temperature-Oxygen:				
TMAXB	10	62	< 7.70 C	19
OMINS	8	59	> 8.17 $mg.L^{-1}$	24
HIGH6MG	8	57	> 26.5 m	19
T15T6L	33	74	> 28.5 m	25
VOLT15T6'	30	62	> 10.33 hm^3	12
T15O6L	31	72	> 26.5 m	20
VOLT15O6'	29	61	> 2.15 hm^3	4
T15O4L	31	70	> 29.5 m	21
VOLT15O4'	29	59	> 7.39 hm^3	9
T12O6L	31	71	> 28.5 m	20
VOLT12O6'	29	60	> 0.84 hm^3	11

continued

Table 11. continued

	Lake trout		Classification	
Variable	Present	Absent	Criterion of presence	Errors(%)
Biota:				
BENNOA	30	67	< 758 m-2	25
BENDRY	32	67	< 4.65 $kg.ha^{-1}$	21
NON-SHIELD LAKES:				
Location:				
LATD	10	101	> 54.950^{0}N	14
LONGD	10	101	< 102.192^{0}W	16[c]
NORD	10	101	> 0.958	14[c]
Morphometry:				
WAREA	10	100	> 201.4 km^2	16
VOLUME	10	80	> 1400.00 hm^3	16
ZBAR	10	79	> 12.30 m	9
ZMAX	10	99	> 36.50 m	7
SHOLEN	10	51	> 130.4 km	23[c]
Temperature-Oxygen:				
TMAXS	10	78	< 18.60 C	23[c]
TMAXB	10	62	< 7.45 C	17
T15T6U	10	65	> 16.5 m	17
T15T6L	10	65	> 32.5 m	5

a See Table 1 for variable names.

b Overall error rate for same lakes using criteria shown.

c Some criteria showed no significant difference in medians in Mann-Whitney tests (P>0.05, see Appendix E).

Shield and non-shield criteria

Many of the better predictors of lake trout presence were related to size of the lake, encompassing both morphometric and temperature-oxygen conditions. Comparisons of criteria of lake trout presence showed that non-shield lakes must be larger and deeper than shield lakes. For example, non-shield lakes with WAREA greater than 201 km^2 and shield lakes greater than 27 km^2 (i.e. a 7.5-fold difference) were predicted to have lake trout (Table 12). This was initially assumed to be indicative of generally shallower morphometry, warmer conditions, and perhaps more frequent wind-circulation in non-shield lakes.

Inexplicably, non-shield lakes also required 10- to 43-fold greater volumes of suitable temperature and oxygen (e.g. VOLT1506 of 69 *versus* 2 hm^3). No other criteria showed differences of even 5-fold between shield and non-shield lakes.

(1) Anomalies

Non-shield lakes, particularly lake trout ones, were represented better than their shield counterparts. The 10 non-shield lake trout lakes in this study were a high proportion of the 14 known in Saskatchewan (Marshall and Johnson 1971). The 122 surveyed non-shield lakes were a higher proportion of the estimated total of 8,477 lakes in this region than the 126 surveyed shield lakes out of a total of 83,241 shield lakes (see Table 8).

Table 12. Criteria of lake trout presence or absence in shield and non-shield lakes.

	Criteria of presence[a]				Errors (%)	
Variable	Shield	Non-shield	Units	Factor[b]	Shield	Non-shield
WAREA	26.8	201.4	km^2	7.5	31	16
VOLUME	217.7	1400.0	hm^3	6.4	27	16
ZBAR	8.3	12.3	m	1.5	17	9
ZMAX	31.2	36.5	m	1.2	16	7
VOL6MG'	150.9	1583.5	hm^3	10.5	29	15
VOLT15T6'	10.3	204.2	hm^3	19.8	12	6
VOLT15O6'	2.2	69.0	hm^3	32.1	4	7
VOLT15O4'	7.4	202.9	hm^3	27.5	9	4
VOLT12O6'	0.8	35.7	hm^3	42.6	11	8

a See Table 11 or Appendix E.

b Defined as non-shield criterion divided by shield criterion.

Random subsets of shield lakes were examined for VOLUME and VOLT15T6' only. VOLUME was one of the variables most amenable to assessment of recent conditions (see below) and VOLT15T6' represented an intermediate difference of 19-fold between shield and non-shield lakes. For these two criteria, mean non-shield requirements remained 2.4 to 7.4-fold greater than for small samples of shield lakes. Twelve small-sample replicates showed VOLUME criteria of 551 to 772 hm^3 compared to 1400 hm^3 for non-shield lakes, and VOLT15T6' criteria of 18 to 55 hm^3 compared to 204 hm^3 (Table 13).

The mean small-sample shield criteria for VOLUME and VOLT15T6' were both greater than the full-sample shield criteria (i.e. 591 to 218 and 27 to 11, respectively). The ratios of small-sample to full-sample criteria were inversely related to the ratios of small-sample to full-sample trout incidence. That is, a subset of lakes of which 11 % had lake trout showed a criterion about 31/11 times that of a set of which 31 % had lake trout (see VOLUME above).

Shield criteria showed little evidence of a gradient with latitude. Only WAREA showed an orderly sequence to smaller criteria in more northerly lakes (Table 14). Most other variables showed minimal criteria for lakes between 56^0 and 58^0N, which may reflect some aspect of lake-size bias or small sample sizes. Overall there was little indication of differences within the shield area comparable to those between shield and non-shield areas.

Table 13. Small-sample criteria of lake trout presence or absence in shield lakes.

Replicate	Classification: Criterion of presence	Errors (%)
VOLUME[a]		
1	> 571.45 hm^3	14
2	605.16	11
3	571.45	14
4	571.45	14
5	571.45	14
6	614.86	11
7	571.45	14
8	571.45	14
9	571.45	14
10	550.82	16
11	550.82	16
12	771.92	9
Mean	591.14	13
VOLT15T6'[b]		
1	> 33.12 hm^3	10
2	17.81	16
3	23.79	10
4	34.60	6
5	22.39	16
6	23.36	10
7	23.79	13
8	22.64	10
9	55.28	6
10	23.79	13
11	23.79	10
12	25.38	13
Mean	27.48	11

a Ten trout and 77 non-trout lakes, compared to 10 and 80 (respectively) for non-shield VOLUME sample.

b Nine trout and 54 non-trout lakes, as for non-shield VOLT15T6' sample.

Table 14. Univariate predictions of lake trout presence or absence in subareas of the shield region.

Variable	Number of lakes with lake trout		Classification[a]	
Subarea	Present	Absent	Criterion of presence	Errors(%)
WAREA:				
Shield	36	79	> 26.8 km^2	31
N of 58^o	11	10	7.7	19
56-58^o	13	13	9.5	38
S of 56^o	12	56	52.8	26
Non-shield	10	100	201.4	16
VOLUME:				
Shield	34	77	> 217.68 hm^3	27
N of 58^o	9	10	219.95	11
56-58^o	13	13	82.62	15
S of 56^o	12	54	317.65	27
Non-shield	10	80	1400.00	16
VOL6MG':				
Shield	29	62	> 150.90 hm^3	29
N of 58^o	7	6	218.90	15
56-58^o	11	11	82.54	18
S of 56^o	11	45	215.45	29
Non-shield	7	48	1583.50	15
VOLT15T6':				
Shield	30	62	> 10.33 hm^3	12
N of 58^o	8	6	24.65	14
56-58^o	11	11	2.01	5
S of 56^o	11	45	10.46	11
Non-shield	9	54	204.21	6
VOLT1506'[b]:				
Shield	29	61	> 2.15 hm^3	4
N of 58^o	7	5	2.2-40.9[c]	...
56-58^o	11	11	0.62	9
S of 56^o	11	45	2.25	4
Non-shield	5	49	69.05	7

a Approximately equal numbers of presence and absence are misclassified.

b VOLT1504' and VOLT1206' show similar differences.

c Delineation is too broad to give reliable criterion.

Shield and non-shield lakes showed similar declines in volume requirements as temperature-oxygen conditions became more restrictive (Table 15). For example, restricting VOLUME to volume of 6 to 15^{0}C temperature (i.e. VOLT16T6') caused decreases of 95 % in shield and 85 % in non-shield criteria. Parallel tendencies suggested similar limnological and physiological mechanisms in lakes and lake trout in the two regions. Nonetheless, some irregularities occurred in these trends. Restricting VOLUME to VOL6MG' in non-shield lakes caused the requirement to increase 13 %, in contrast to a decrease of 31 % in shield lakes. This suggested a greater need for suitable summer oxygen and/or greater seasonal or annual variability in non-shield lakes. In non-shield lakes, cooler water was relatively less important than higher oxygen levels as criteria decreased 48 % and 66 %, respectively. In shield lakes, cooler water was almost as important as higher oxygen.

(2) Recent conditions

Drought conditions which may have caused differences between shield and non-shield lakes for lake trout, were expected to show: (1) volumes under extreme low waterlevels which were notably less than under typical conditions, and (2) significant differences in this effect between shield and non-shield lakes (Figure 3).

Table 15. Changes in criteria of lake trout presence or absence as temperature-oxygen conditions became more restrictive.

Restriction	Change in criteria (%)	
	Shield	Non-shield
VOLUME to VOLT15T6'	- 95	- 85
VOLUME to VOL6MG'	- 31	+ 13
VOLT15T6' to VOLT15O6'	- 79	- 66
VOLT15O6' to VOLT12O6'	- 61	- 48
VOLT15O4' to VOLT15O6'	- 71	- 66

<u>Waterlevels</u> Summer waterlevels were available for 10 or more years for 33 lakes (Figure 4 and Appendix F). One third were shield lakes, which were predominantly over 100 km^2. Non-shield lakes represented water areas both larger and smaller than the criterion of lake trout presence (Table 16). Step-wise polynomial regression produced relatively simple predictive equations (Appendix F). Some examples of the variety of waterlevel fluctuations are shown in Figure 5.

Figure 3. The hypothetical effect of waterlevel variations and/or morphometry on the apparent volume required by lake trout. If shield and non-shield lakes differ as shown, the same actual requirement for volume during years of low water would give rise to different apparent requirements during typical years.

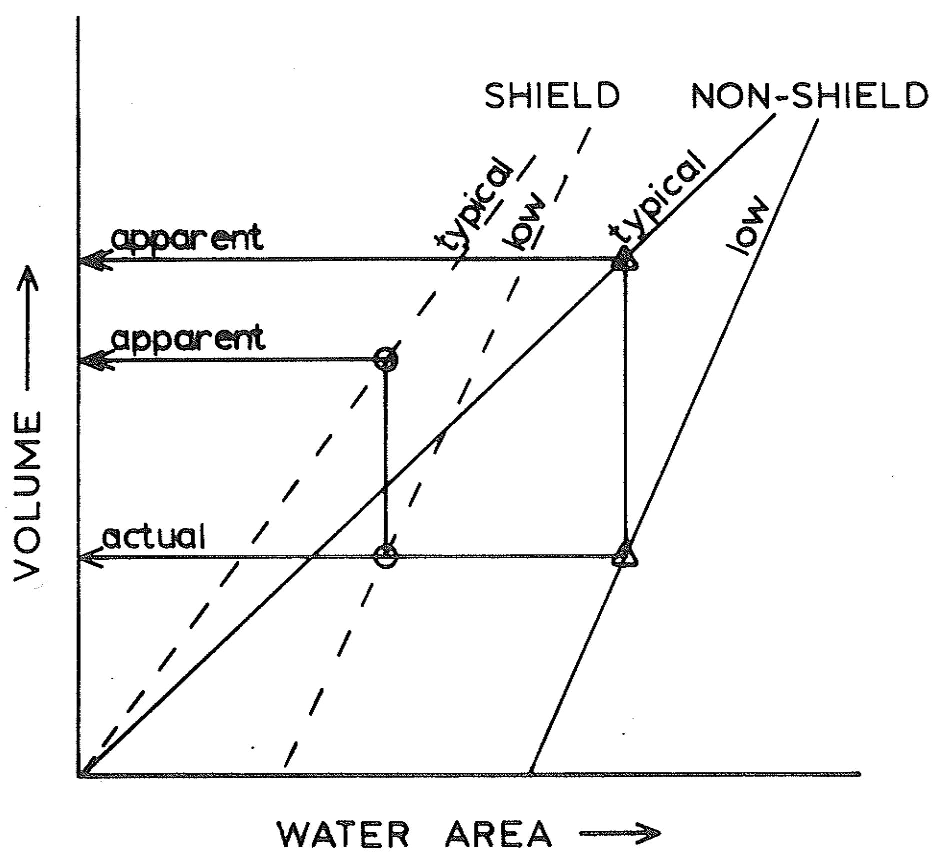

SHIELD
NON-SHIELD
typical
low
typical
low
apparent
apparent
actual
VOLUME
WATER AREA

Figure 4. Lakes with summer waterlevel data available for 10 or more years. Solid circles represent shield lakes and open circles, non-shield lakes.

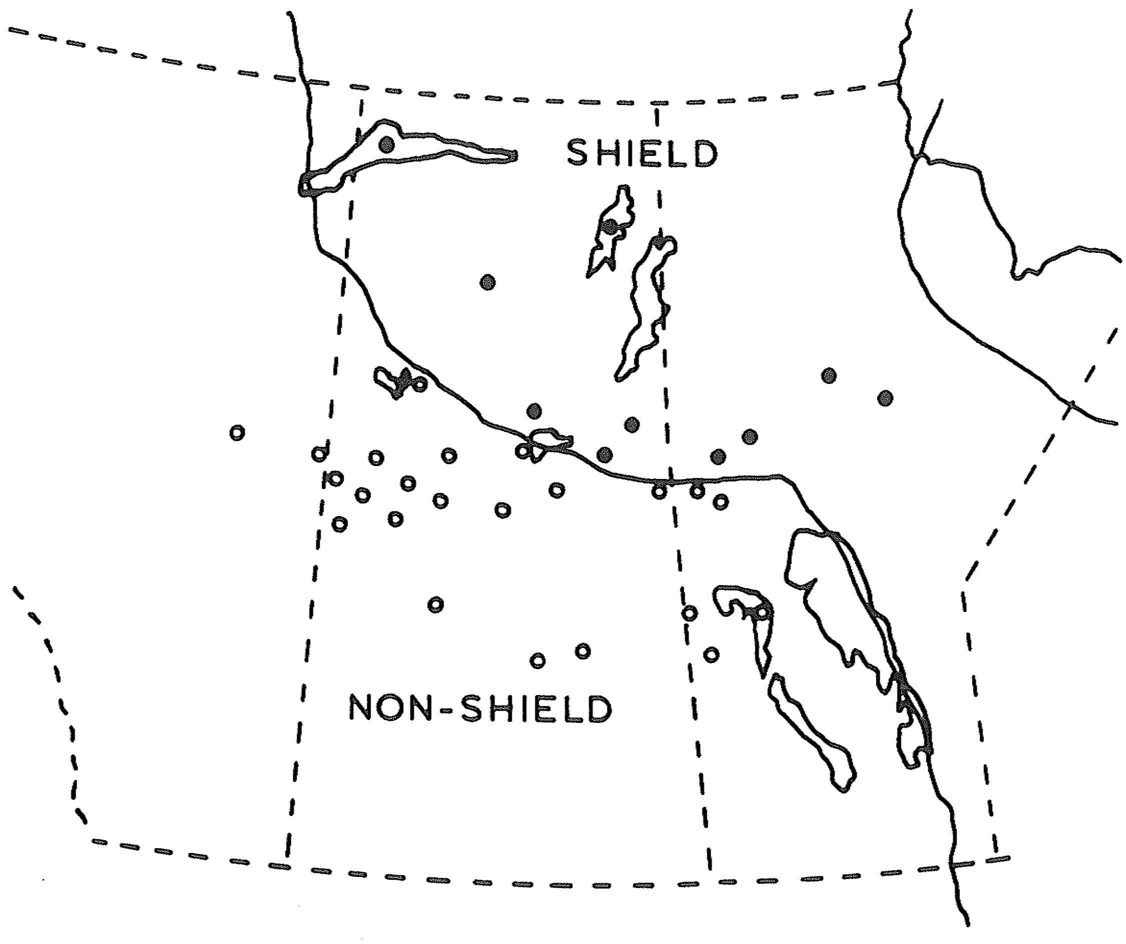

SHIELD
NON-SHIELD

Table 16. Number of lakes which have ten or more years of July-August waterlevel data available.

Bedrock geology	Number of lakes	Water area[a]				
		VL	L	M	S	VS
Shield	10	4	4	0	2[b]	0
Non-shield	23	9	2[b]	6	6	0

a VL is >250 km^2, L is >100-250 km^2, M is >50-100 km^2, S is >10-50 km^2, and VS is $\leq$10 km^2.

b Criterion of lake trout presence lies in this area category.

Waterlevel variations (i.e. typical year minus the lowest 1 in 100 years) which were based on extrapolations of observed waterlevels (see Appendix F), ranged from 0.070 to 1.862 m but seldom exceeded 1 m. Shield and non-shield lakes showed increasing waterlevel variations with larger lake area (Figure 6). Although overlap of data was considerable, separate regressions for shield and non-shield lakes were statistically better than parallel lines or a single regression line (Appendix F).

Morphometry The 209 lakes available for volume-at-depth analysis represented all categories of bedrock geology and lake area (Table 17). This set included the subset of lakes which were otherwise reserved for later testing of predictive models.

Relative water volume changes caused by waterlevel declines of 0.5 to 2.0 m were considerably greater in small lakes than larger lakes, as expected. A single regression was suitable for 0.5 m, but separate regressions for shield and non-shield lakes were required for 2.0 m (Figure 7 and Appendix F).

Absolute volume below 2.0 m was greater in larger lakes than smaller, as expected. The relationship to water area was again significantly different for shield and non-shield lakes (Appendix F). Shield lakes of 100 km^2 had volumes below 2 m depth which were 1.5 x greater than non-shield lakes of similar area (Appendix F).

Figure 5. Variety of observed and predicted low July-August waterlevels. Only observations which do not lie on the line are shown.

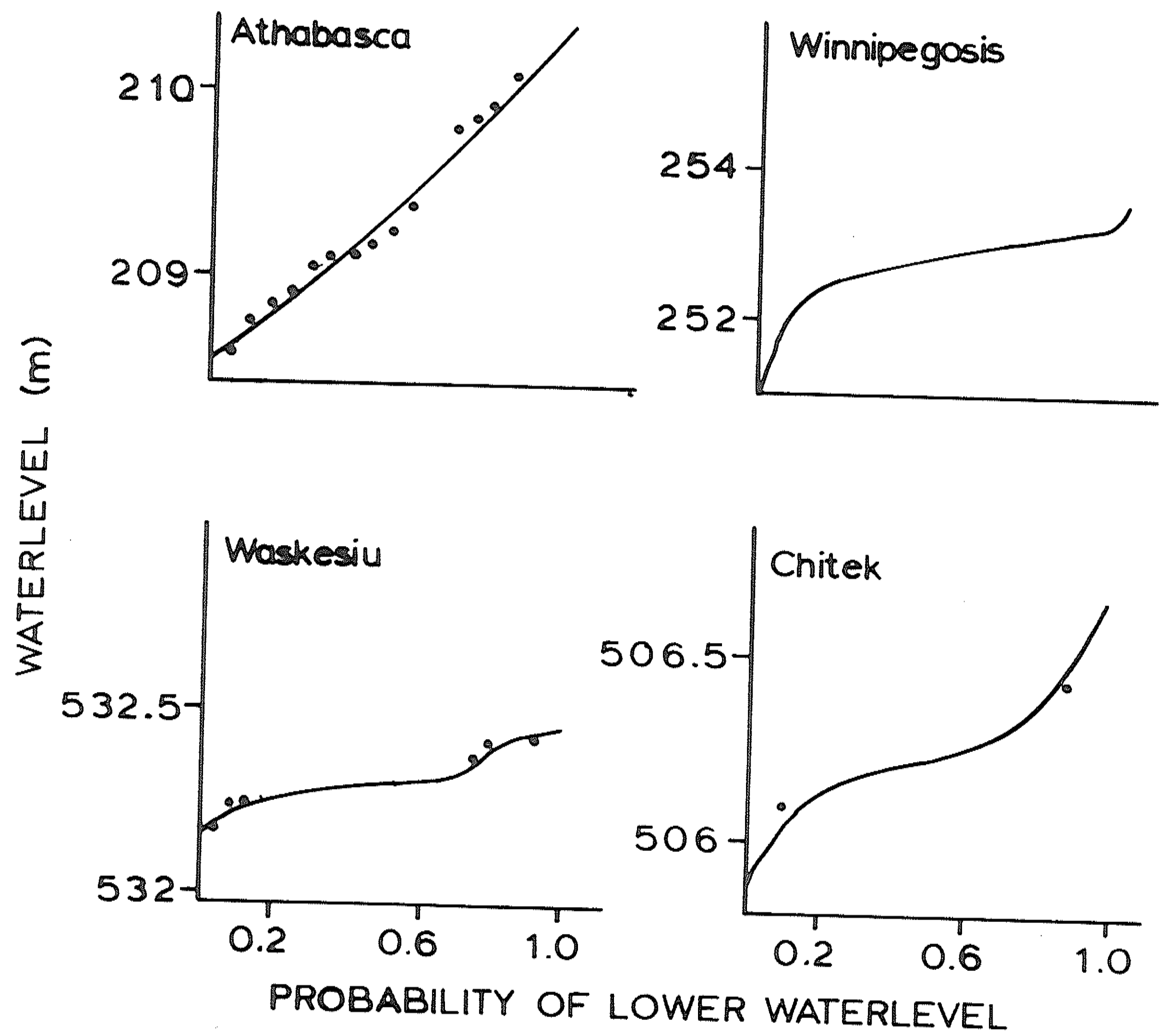

Athabasca
210
209
Winnipegosis
254
252
Waskesiu
532.5
532
Chitek
506.5
506
0.2
0.6
1.0
0.2
0.6
1.0
WATERLEVEL (m)
PROBABILITY OF LOWER WATERLEVEL

Figure 6. Waterlevel variations (i.e. typical year minus lowest 1 in 100 years) in relation to water area. Circles represent variations as extrapolated from observed waterlevels; lines represent regressions of these variations on water area.

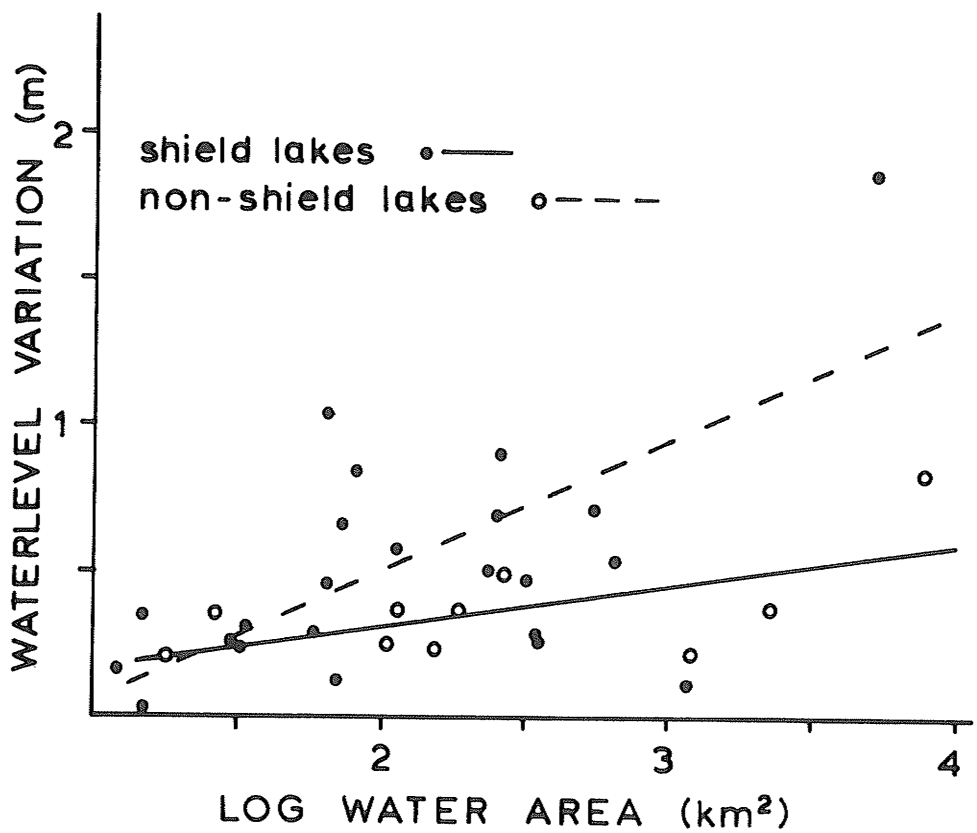

WATERLEVEL VARIATION (m)
2
1
shield lakes
non-shield lakes
2
3
4
LOG WATER AREA (km²)

Table 17. Number of lakes used in the present study which have volume-at-depth data available.

Bedrock geology	Number of lakes	Water area[a]				
		VL	L	M	S	VS
Shield	124	6	9	11	24	74
Non-shield	85	10	12	8	21	34

a VL is >250 km^2, L is >100-250 km^2, M is >50-100 km^2, S is >10-50 km^2, and VS is $\leq$10 km^2.

Residual volumes Residual water volume (i.e. the volume below the predicted 1 in 100 year low summer waterlevel) increased with increasing water area, in spite of concurrently greater waterlevel variations. Shield and non-shield lakes differed significantly in regressions of both (1) residual volume against expected waterlevel variation (Figure 8) and (2) residual volume against water area.

The combined effects of waterlevel variation and morphometry suggest that shield lakes of 10 to 100 km^2 lost 2 to 3 % of volume and similar non-shield lakes 3 to 6 % of volume during extreme low summer waterlevels in the last 100 years (Table 18). (Recall that this loss is from a typical summer low, rather than from any seasonal high waterlevel).

Figure 7. Regressions of relative volume above 2 m depth on water area, separately for shield and non-shield lakes (see Appendix F).

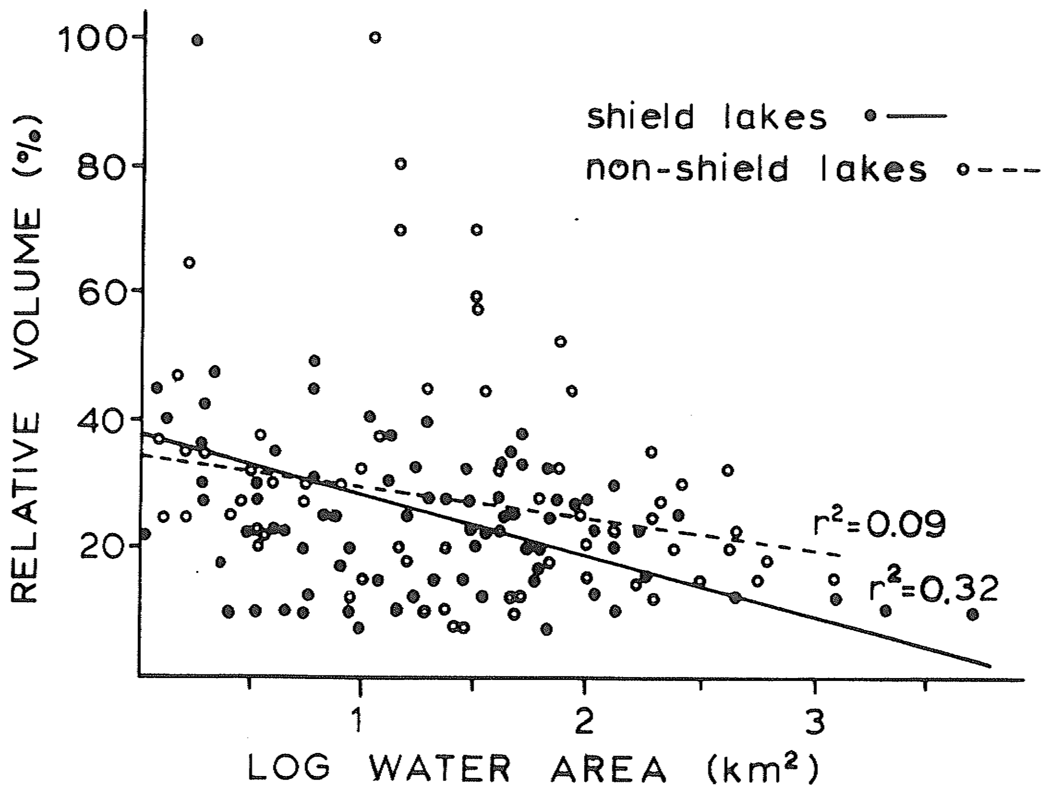
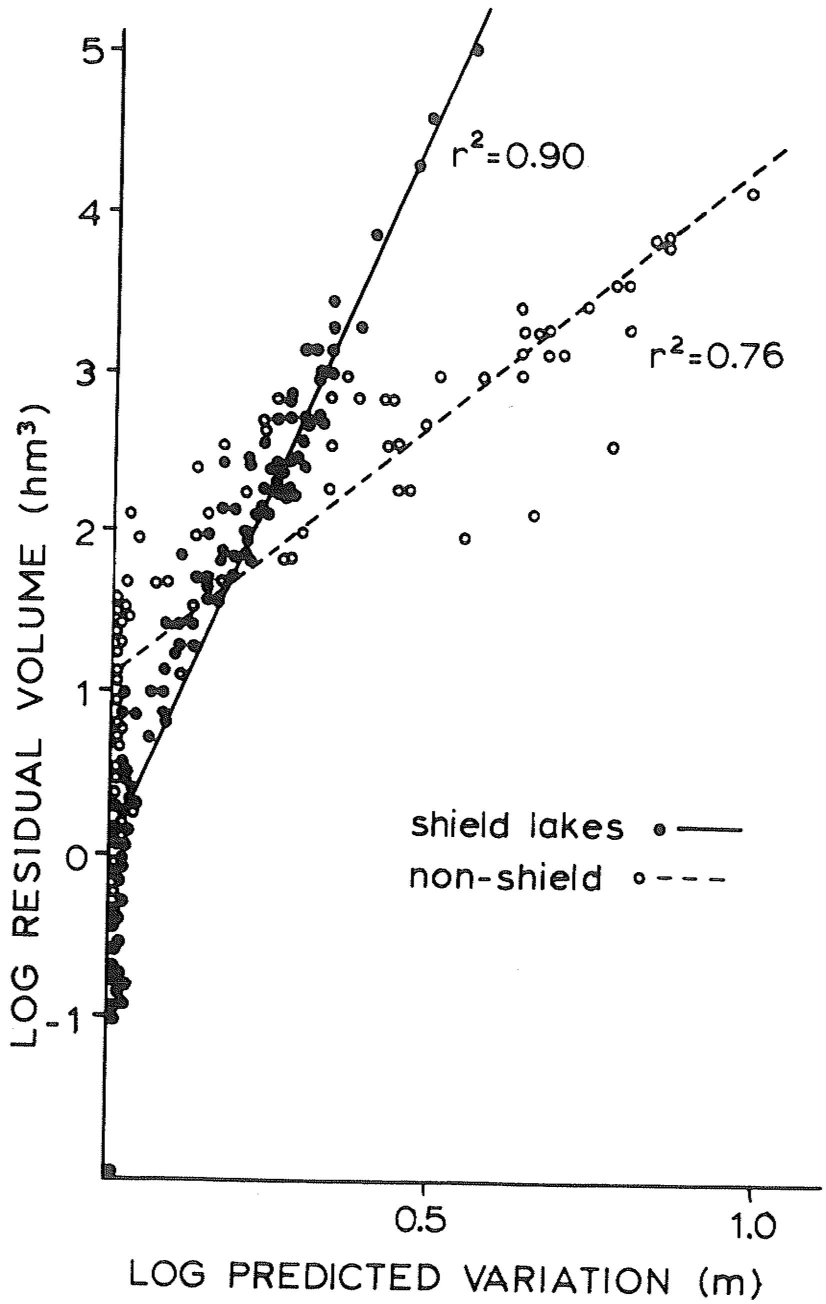

RELATIVE VOLUME (%)
100
80
60
40
20
shield lakes
non-shield lakes
r^2=0.09
r^2=0.32
1
2
3
LOG WATER AREA (km^2)

Figure 8. Regressions of residual volume on predicted waterlevel variations, separately for shield and non-shield lakes (see Appendix F).



LOG RESIDUAL VOLUME (hm³)
5
4
3
2
1
0
-1
r²=0.90
r²=0.76
shield lakes
non-shield
0.5
1.0
LOG PREDICTED VARIATION (m)

Table 18. Expected loss of water volume from the combined effects of waterlevel variations and morphometry.

Lake set	Area (km^2)	Volume: Residual (hm^3)	Total (hm^3)	Loss (%)
Shield	10	67.24	68.82	2
	100	910.12	942.54	3
Non-shield	10	56.60	58.33	3
	100	637.24	679.36	6

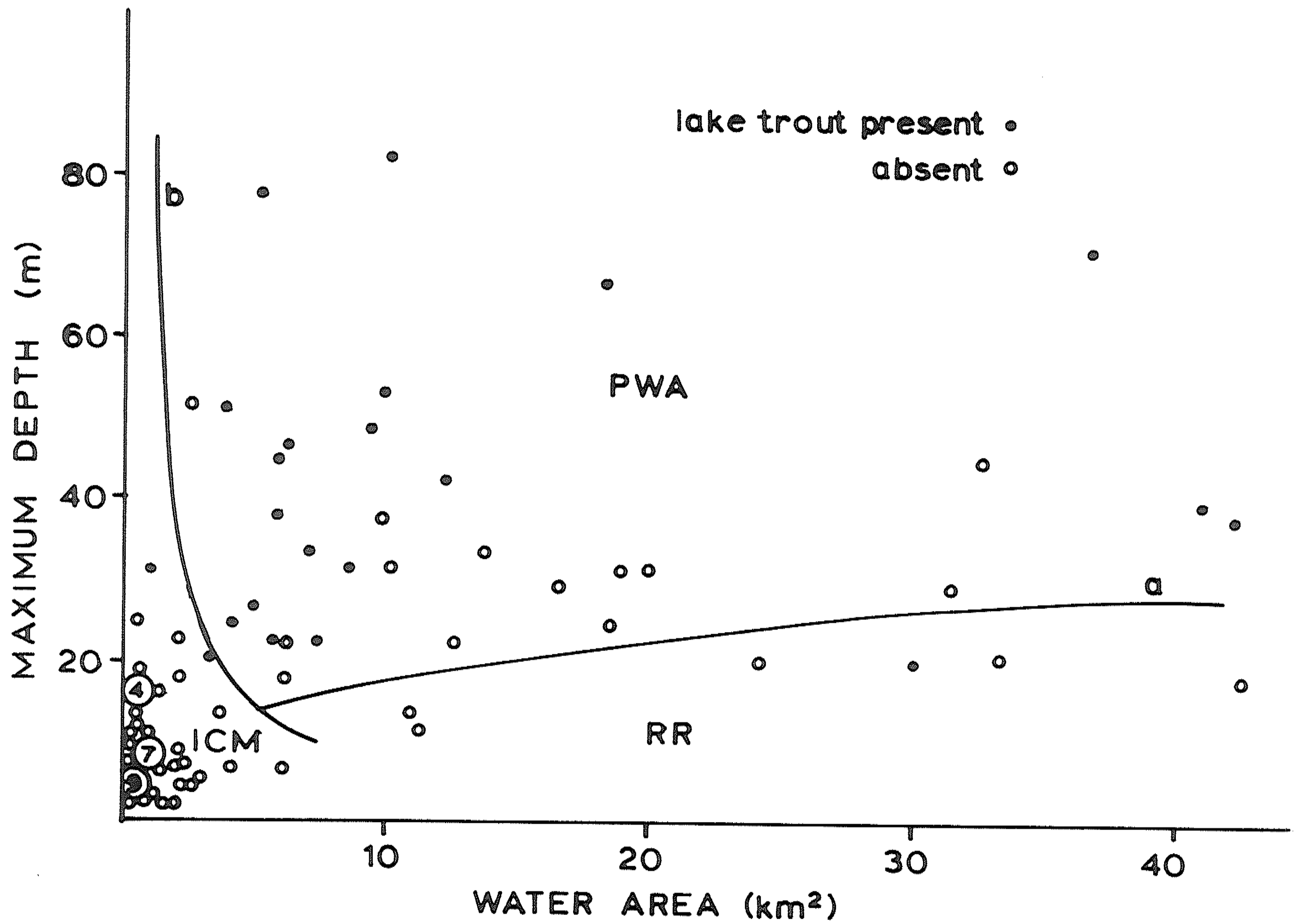
Multivariate criteria

Depth and water area A model of the influence of depth and lake area on sedimentation (Hilton 1985) correctly predicted the lake trout status in 86 % of shield lakes. The regions and boundaries were adopted from Hilton (1985): the peripheral wave action (PWA) boundaries were a minimum volume of 23.6 hm^3 (line b) and a minimum depth of one wavelength at wind speeds of 20 m.s-1 (line a, modified from Smith 1979); the intermittent complete mixing (ICM) boundary was a maximum volume of 23.6 hm^3; and the random redistribution (RR) boundary was a maximum depth of one wavelength, as above (Figure 9).

Wave action in large deep lakes creates turbulence and resuspends sediments from near the shore, which are redeposited in off-shore areas (model PWA of Hilton 1985, Hakanson 1977 cited in Hilton 1985). Autumn overturn in small deep lakes resuspends sediments from the entire lake bed, which are redeposited in proportion to the depth of overlying water (model ICM). Both mechanisms result in a net transport of sediments from shallow to deeper areas. By contrast, shallow lakes are susceptible to periodic open-water resuspensions and redepositions over the entire lake. These do not transfer sediments from shallow into deeper zones (model RR).

Multiple discriminant analysis Stepwise rankings of variables in discriminant analyses showed that some variables were consistently ranked highly, particularly SECCHI and VOLT15T6 (Table 19). When both SECCHI AND VOLT15T6' were available, ZBAR, ZMAX, VOLUME, VOL6MG', and VOLT15O6' were left aside. Only when one was not available (e.g. subsets 2 and 3, see Table 19) did other variables contribute significantly. VOLT15T6 was ranked more highly than volumes of suitable oxygen or temperature-oxygen in direct comparisons (e.g. subset 3).

Figure 9. Lake trout presence and absence in Saskatchewan lakes in relation to predicted sediment distribution. The model by Hilton (1985) implies clearing of spawning sites above and to the right of the solid line (see text). Numbers in circles represent the number of lakes coincident at a point.



lake trout present
absent
MAXIMUM DEPTH (m)
80
60
40
20
WATER AREA (km²)
10
20
30
40
PWA
RR
ICM
a
b
4
7

Table 19. Stepwise ranking of variables in multiple discrimination of lake trout presence and absence.

Ranking of variable	Subsets of variables and lakes (1) All	(1) Shield	(2) All	(2) Shield	(3) All	(3) Shield	(4) All	(4) Shield
First	VOLT15T6[a]	SECCHI	SECCHI	SECCHI	VOLT15T6	VOLT15T6	VOLT15T6	SECCHI
Second	SECCHI	VOLT15T6	SHODEV[b]	WAREA	VOL6MG	VOL6MG	SECCHI	VOLT15T
Third		BENDRY			VOLT1506		BENDRY	BENDRY
...	...	...	...	...	...	...	...	...
	BENDRY	ZBAR	ZBAR	ALT[b]	VOLT1504	VOLT1506	VOLT1506	ZMAX
Aside	TDS	ZMAX	PHMINS[b]	ZBAR	VOLT1206	VOLT1206	TDS	TDS
	PHMINS[b]	TDS	INVALK[c]	INVALK[c]		VOLT1504	VOLUME	VOLT150
ZMAX	VOL6MG	WAREA	PHMINS			ZMAX	VOLUME	
	VOL6MG	PHMINS[b]	ALT[b]	SHODEV[b]				
	ZBAR							
Number of lakes:								
	91	57	39	32	138	87	92	57
Number of lakes with lake trout present/absent:								
	29/62	24/33	18/21	16/16	34/104	29/58	28/64	24/33

a Constant 10^{-6} was added to VOLT15T6 and VOL6MG and 10^{4} to VOLT1506, VOLT1504, and VOLT1206 before log transformation.

b This variable is not log transformed.

c INVALK is defined as 100/TOTALK.

Classification errors of lake trout status using MDA ranged from 2 to 12 % for 3 subsets of variables and 4 MDA methods (Table 20). These apparent error rates (from re-testing the initial set of lakes) are comparable to those of univariate criteria. The cross-validation rates of 6 to 16 % are more reliable as each lake was classified using the rule determined from the other n - 1 lakes (Lachenbruch 1975, Dillon 1979). Some error rates for the reserved set of lakes were very low, but the small sample sizes of 3 to 27 lakes suggest these rates should be viewed with caution.

The non-parametric nearest-neighbour MDA was comparable in accuracy to the linear MDA. Both methods showed slightly lower cross-validated error rates when prior probabilities of each class were assumed to be equal (Table 20).

The canonical standardized coefficients showed that the relative importance (SAS 1987) of log SECCHI was similar to log VOLT15T6' (see coefficients 0.695 and 0.719, respectively) and greater than log WAREA, after adjusting for the dispersion of each variable. Altitude (ALT) was also relatively influential in the smallest set of 32 lakes. The raw coefficients were applicable to unadjusted habitat data of lakes in the shield region of Saskatchewan.

Table 20. Classification and description of lake trout presence and absence using multiple discriminant analysis.

Numbers of lakes			Classification errors (%)[a]			
Lake trout			Linear		Neighbour	
Present	Absent	Test	Proportional	Equal	Proportional	Equal
1) log SECCHI, log VOLT15T6′, log BENDRY[b]						
28	52	16	10% 14% 0%	12% 12% 0%	8% 10% 0%	2% 6% 0%
2) log SECCHI, log WAREA[b]						
36	69	27	7% 11% 4%	10% 10% 12%	7% 13% 7%	10% 10% 4%
3) log SECCHI, log WAREA, ALT, log ZBAR, INVALK[c], PHMINS, SHODEV						
16	16	3	9% 16% 0%	9% 16% 0%	12% 16% 0%	12% 16% 0%

Corresponding canonical equations:

1) Canonical = 3.240 log SECCHI + 0.198 log VOLT15T6′ - 1.010 log BENDRY (raw coefficients)
= 0.695 log SECCHI + 0.719 log VOLT15T6′ - 0.388 log BENDRY (standardized)

2) Canonical = 5.981 log SECCHI + 0.585 log WAREA (raw coefficients)
= 1.301 log SECCHI + 0.593 log WAREA (standardized)

3) Canonical = 3.374 log SECCHI + 0.369 log WAREA + 0.009 ALT + 1.402 log ZBAR
- 0.100 INVALK - 0.451 PHMINS + 0.018 SHODEV (raw coefficients)
= 0.901 log SECCHI + 0.341 log WAREA + 0.809 ALT + 0.448 log ZBAR
- 0.555 INVALK - 0.151 PHMINS + 0.117 SHODEV (standardized)

a Errors were determined by resubstitution and cross-validation (Lachenbruch 1975) in the initial data set, and by use of the reserved data set, respectively.

b Subsets correspond to those in Table 19.

c INVALK is defined as 100/TOTALK.

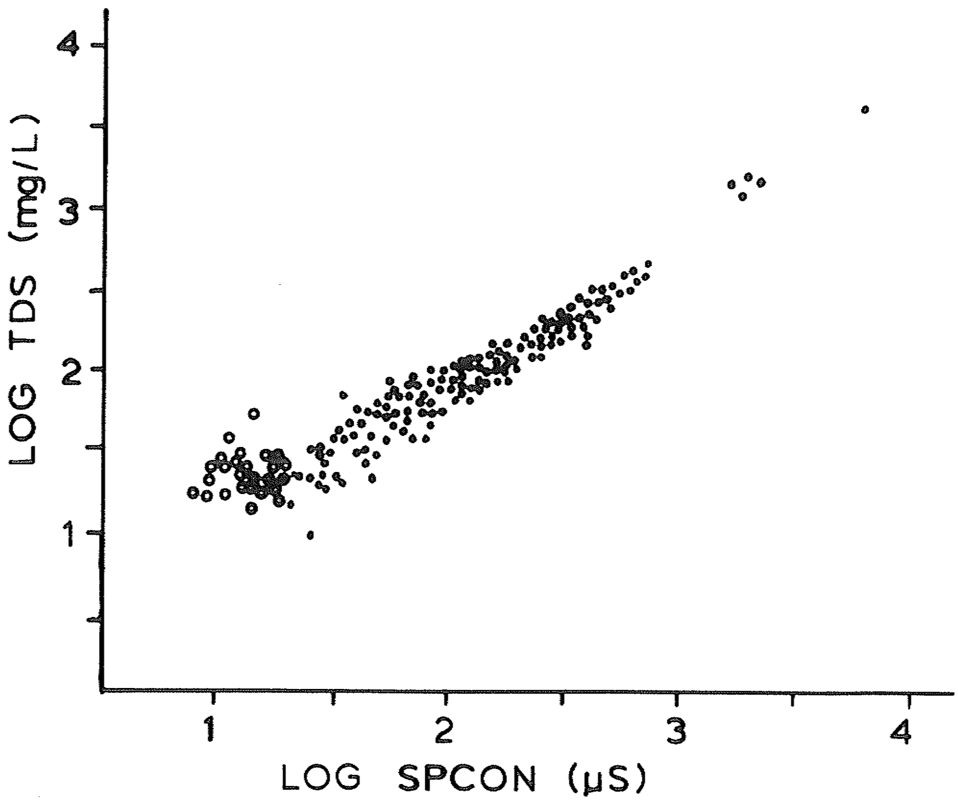
Estimation of missing data

TDS from SPCON Correlation of TDS with SPCON was well defined (Figure 10). Separate regressions were indicated for shield and non-shield lakes (Table 21). Two studies by consultants were excluded because methods used were different than in all other surveys of shield lakes (see Appendix G).

SHODEV and RLOGSHOD SHODEV and RLOGSHOD were potential indicators of depth, wind-protection, and other conditions. SHODEV is the ratio of actual shoreline length to the circumference of a circle of equal area. Separate regressions of log SHODEV on log WAREA were indicated for shield and non-shield lakes (Table 21). RLOGSHOD, or the deviation of actual SHODEV of any lake from that predicted by its water area, is an alternative index to SHODEV itself (Koshinsky 1970). The predicted SHODEV was derived separately for shield and non-shield lakes. The ratio of actual to predicted minimized the correlation of RLOGSHOD with log SHODEV (see Appendix G). RLOGSHOD was a frequent predictor in stepwise regressions, typically after WAREA and concurrent with FETCH (Appendix G).

ZMAX and ZBAR Regressions of ZMAX on subsets of morphometric variables showed that log WAREA and log FETCH

Figure 10. Relationship between log TDS and log specific conductivity (SPCON) in central and northern Saskatchewan lakes (solid circles). Open circles represent lakes in the Key Lake and Midwest Lake areas which were excluded (see Appendix G).



LOG TDS (mg/L)
4
3
2
1
1
2
3
4
LOG SPCON (µS)

Table 21. Useful regressions of habitat criteria using more numerous or more available habitat variables.

Regressions (multiple R^2,n)
<u>All lakes:</u>
log TDS = 0.142 + 0.880 log SPCON (R^2=0.95,n=186)
log SHODEV = 0.318 + 0.184 log WAREA (R^2=0.40,n=237)
log SHODEV = 0.354 + 0.243 log WAREA - 0.109 log FETCH (R^2=0.44,n=219)
log ZMAX = 1.112 + 0.438 log WAREA - 0.4 log FETCH (R^2=0.39,n=249)
log ZBAR = 0.694 + 0.271 log WAREA - 0.243 log FETCH (R^2=0.29,n=229)
log VOLUME = 0.554 + 1.151 log WAREA (R^2=0.93,n=274)
log T15T6U = 0.936 + 0.427 log WAREA - 0.504 log FETCH (R^2=0.46, n=189)[a]
log T12O6U = 0.959 + 0.399 log WAREA - 0.410 log FETCH (R^2=0.50, n=183)[a]
<u>Shield lakes:</u>
log TDS = 0.167 + 0.878 log SPCON (R^2=0.79,n=77)
log SHODEV = 0.384 + 0.250 log WAREA (R^2=0.73,n=152)
log SHODEV = 0.429 + 0.329 log WAREA - 0.164 log FETCH (R^2=0.74,n=144)
log ZMAX = 1.212 + 0.556 log WAREA - 0.619 log FETCH (R^2=0.50,n=145)
log ZBAR = 0.684 + 0.242 log WAREA - 0.165 log FETCH (R^2=0.32,n=143)
log VOLUME = 0.636 + 1.159 log WAREA (R^2=0.96,n=151)
<u>Non-shield lakes:</u>
log TDS = -0.087 + 0.956 log SPCON (R^2=0.96,n=109)
log SHODEV = 0.188 + 0.130 log WAREA (R^2=0.25,n=85)
log SHODEV = 0.036 - 0.141 log WAREA + 0.574 log FETCH (R^2=0.,n=75)
log ZMAX = 0.910 + 0.162 log WAREA + 0.062 log FETCH (R^2=0.32,n=104)
log ZBAR = 0.696 + 0.297 log WAREA - 0.313 log FETCH (R^2=0.24,n=86)
log VOLUME = 0.419 + 1.182 log WAREA (R^2=0.90,n=123)

Table 21. cont'd.

Regressions (multiple R^2,n)
<u>Stratified lakes:</u>
log T15T6U = 0.847 + 0.243 log WAREA - 0.134 log FETCH (R^2=0.74,n=93)[a]
log T1206U = 0.872 + 0.151 log WAREA + 0.095 log FETCH (R^2=0.76,n=90)[a]
log VOLT15T6 = -0.805 - 0.290 log WAREA + 2.612 log FETCH (R^2=0.31,n=87)
log VOLT15T6 = 3.545 - 0.935 log WAREA + 3.641 log FETCH - 0.219 TMAXS (R^2=0.37,n=87)
<u>Non-stratified lakes:</u>
log T15T6U = 1.062 + 0.749 log WAREA - 1.100 log FETCH (R^2=0.49,n=80)[a]
log T1206U = 1.077 + 0.754 log WAREA - 1.123 log FETCH (R^2=0.47,n=77)[a]
<u>Non-riverine lakes with non-zero VOLT15T6[b]:</u>
log VOLT15T6 = -0.025 + 1.070 log WAREA + 0.397 log FETCH (R^2=0.90,n=75)
log VOLT15T6 = -0.288 + 1.193 log WAREA + 0.888 log SECCHI - 0.154 RLOGSHOD (R^2=0.91,n=75)
<u>Lakes with non-zero VOLT15T6:</u>
log VOLT15T6 = -0.008 + 1.080 log WAREA + 0.188 log FETCH (R^2=0.84;n=88)
log VOLT15T6 = -0.799 + 1.097 log WAREA + 1.428 log SECCHI (R^2=0.88,n=88)

a Lakes with T15T6U or T1206U = 0 m were excluded (i.e. TMAXS $\leq$ 15 or 12°C, respectively).

b Non-riverine lakes have Froud index $\leq$ 0.03 (see STRAFN).

were important, explaining 39 % of total variation in all lakes (Table 21). Separate regressions explained about 50 and 32 % of variation in shield and non-shield lakes, respectively. Lakes oriented more northeasterly had greater maximum depth; the increase in correlation due to orientation was minor (Appendix G). Similarly, indices based on surficial geology (e.g. rocks, morainal, glaciofluvial, and organic material prevalence) did not improve estimation significantly in shield lakes (see Appendix G). ZBAR or mean depth was less predictable than maximum depth. The best predictions explained only 32 and 24 % of variation in shield and non-shield lakes, respectively (Table 21).

VOLUME Lake volume was clearly related to water area alone. This single predictor explained 96 and 90 % of variation in shield and non-shield lakes, respectively (Table 21). Other variables were not explored although FETCH, FETDEV, and ORINW may be useful.

STRAFN The presence of stratification in lakes is well predicted from ZMAX and WAREA and other morphometric indices. The degree of stratification was simplified to "no" (none or weak) or "yes" (moderate, strong, very strong). The boundary condition based on WAREA (Gorham 1980 cited in Cruikshank 1984) correctly classified 77 % of 225 lakes. An empirical boundary condition derived in the present study using FETCH:

$\log ZMAX\ (m) \geq 0.78 + 0.42 \log FETCH\ (km)$

correctly classified 82 % of 199 lakes (see Appendix G). These predictions are based on morphometry and the effects of wind-generated turbulence.

Stratification can also be prevented or disrupted by rapid water exchange in "riverine" situations. The Froud index of relative flow-through (Orlob 1983) explained the observed non-stratification of several lakes which according to morphometric criteria alone ought to stratify. The Froud criteria appeared to be:

F in non-stratified lakes > 0.03

F in stratified lakes < 0.03 (see Appendix G).

When riverine lakes were excluded using the Froud index, the alternate boundary condition for FETCH was:

$\log ZMAX\ (m) \geq 0.82 + 0.50 \log FETCH\ (km)$.

This correctly classified stratification in 86 % of 185 lakes (Figure 11). Attempts to use estimated maximum depth in boundary conditions were unsuccessful, as stratified and non-stratified lakes overlapped in plots.

The maximum depth of 15^0C during open water (T15T6U) was assessed as a potential contributor to VOLT15T6. Regressions of log T15T6U on subsets of variables showed that log WAREA and log FETCH were important, explaining about 46 % of total variation in all lakes (Table 21). In stratified lakes, log WAREA and log FETCH explained 74 % of variation in log T15T6U

(Table 21). In this respect, the maximum depth of 15^{0}C behaved similarly to the thermocline in other studies (see Discussion). Nonetheless, the use of TMAXS was necessary for predictive-quality equations and explained 78 % of total variation; most other regressions were only marginally acceptable (Hocking 1976)(Appendix G). The NW-component of fetch (ORIFET) or elongation (FETDEV) was necessary for predictions, presumably to represent wind-driven mixing.

VOLT15T6 Two distinct classes of lakes occurred: those with some VOLT15T6, which was apparently related to WAREA and FETCH, and those with none (Figure 12). Regressions of log VOLT15T6 on morphometry and climate revealed strong correlations only for certain types of lakes. In non-riverine lakes with non-zero volume of 6 to 15^{0}C water, VOLT15T6 was estimable at R^2=0.91 (Table 21). Regressions using WAREA, SECCHI, RLOGSHOD, and/or TMAXS were marginally acceptable for prediction; estimations using only WAREA and FETCH were not acceptable statistically by comparison to other regressions using more more variables (see Appendix G). Furthermore, non-zero VOLT15T6 was estimable at R^2=0.88 in all lakes (Table 21). This class does not require knowledge of ZMAX or discharge and regressions are similar, though less precise. Estimation was achieved in 152 shield lakes using area and fetch (and any others with these simple data), compared to 109 lakes with measured VOLT15T6.

Figure 11. Delineation of stratified and non-stratified lakes using maximum depth and fetch (hatched line). Lakes which were riverine according to the Froud index were excluded (see text).

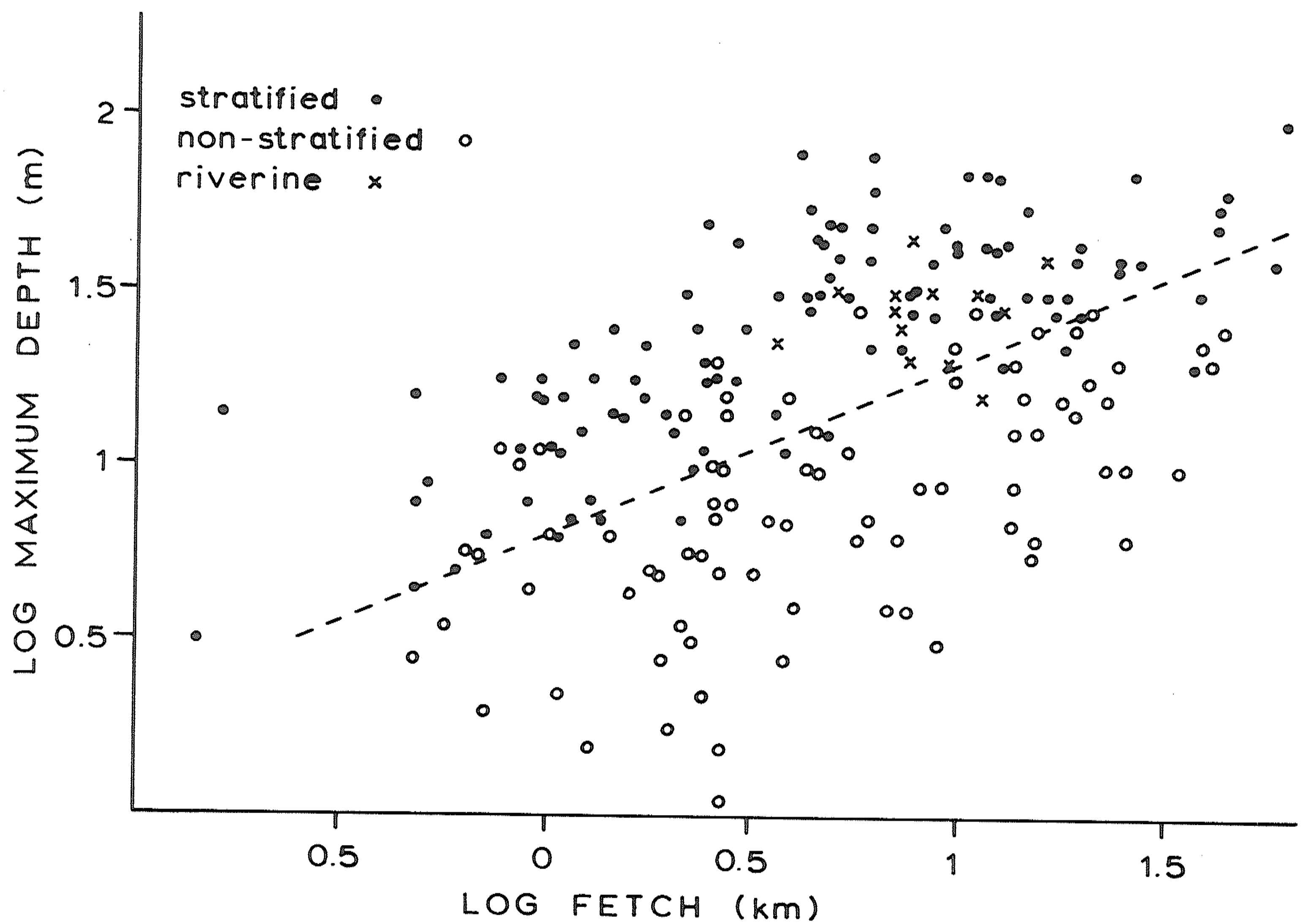
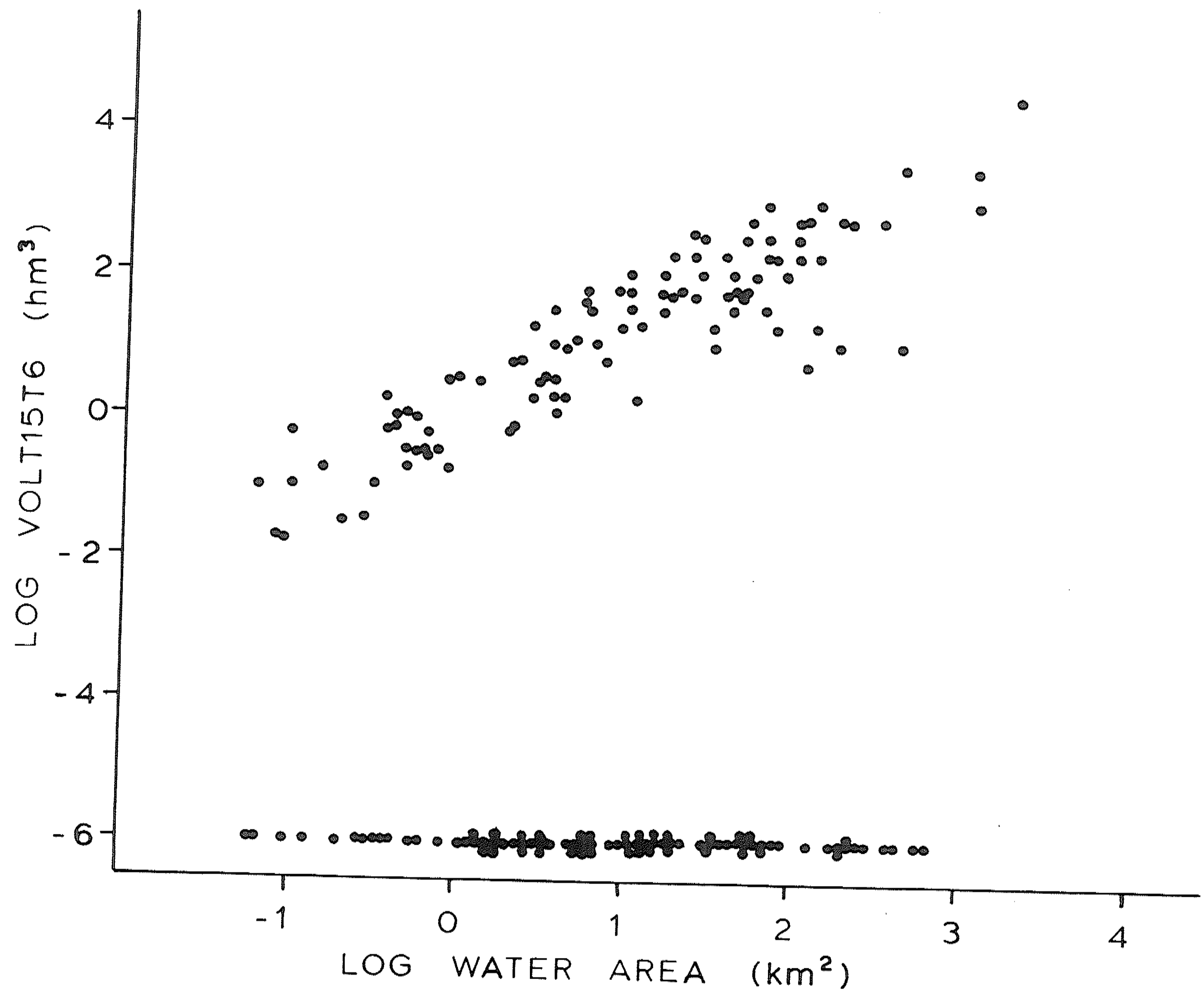

stratified •
non-stratified o
riverine x
LOG MAXIMUM DEPTH (m)
2
1.5
1
0.5
0.5
0
0.5
1
1.5
LOG FETCH (km)

Figure 12. Two distinct relationships of log VOLT15T6 to log water area in Saskatchewan shield and non-shield lakes. Lakes with non-zero VOLT15T6 have a logarithm greater than -6.


LOG VOLT15T6 (hm³)
4
2
0
-2
-4
-6
-1
0
1
2
3
4
LOG WATER AREA (km²)

By comparison, the best correlations for stratified and non-stratified lakes were $R^2=0.37$ and 0.18, respectively (Table 21, Appendix G). Similarly, regressions explained only 15 and 54 % of variation in lakes predicted to stratify and not to stratify by the fetch-boundary condition.

VOLT15O6 The Secchi depth criterion of 4 m predicted suitable conditions with 84 % accuracy in 86 shield lakes (Appendix G). Transparency was a good predictor of the existence of a minimum volume of water having temperature below $15^{o}C$ and oxygen above 6 $mg.L^{-1}$.

Marginal habitat

The occurrence of major misclassifications increased fairly regularly as the accuracy of the criteria declined. VOLT16T6' correctly classified 96 % and definitely misclassified 3 % of shield lakes, and VOLUME 71 % and 28 %, respectively (Table 22). Minor errors were lower at 0 to 6%, but not regular in occurrence. In addition, lakes in which lake trout were considered to be transient or extinct, or were unverified by surveys (i.e. presumably of lower abundance) had only slightly lower occurrences in these zones. Analyses were not suitable for non-shield lakes since post-glacial immigration and/or climate (rather than present habitat) may be dominant influences in this region.

Table 22. Minor and major misclassifications of lake trout presence or absence in shield lakes by selected variables.

Variable[a]	Number of lakes	Misclassifications (%) None	Minor	Major
VOLT1506'	90	96	1	3
VOLT1504'	88	91	0	9
PHOTOZ	107	88	4	8
ZMAX	115	84	6	10
TMAXB	110	81	3	16
BENDRY	99	79	2	19
COLOUR	50	72	6	22
VOLUME	111	71	1	28

a See Table 1 for variable names.

Specific shield lakes which were misclassified by more accurate variables had a clear tendency to be misclassified more frequently by other variables (Table 23). Since this is based on specific lakes, it is not merely a generality over all lakes. Given this tendency, about 72 % of lakes for which any criterion was perfect would be misclassified by other variables (Figure 13). Some lakes were definitely misclassified by very many or very few variables (e.g. Middle Foster and Riou lakes, respectively), but it was not common.

Table 23. Misclassifications of lake trout presence or absence in particular shield lakes by selected variables.

Lake	Variable or pair[a]										
	1	2	3	4	5	6	7	8	9	10	11
Dickens	X				X	X		X			
Middle Foster	X	X	X	X	X	X	X	X	X	X	X
Mirond	X	X			X		X		X	X	
Sandy	X	X	X	X	X		X		X	X	X
Contact		X					X		X	X	
Haugen		X							X		
McDonald		X	X	X			X		X	X	X
Wapata		X				X		X			
Wathaman		X			X		X		X	X	
Bartlett			X	X	X	X		X	X	X	
Karl Ernst			X	X	..	..	..	..			X
Mackay			X							X	X
Mullock			X	X	X	X					X
Richter			X	X							X
Wood			X	X							X
Hatchet	..	..	..	X		X	..	..		..	X
Upper Foster				X	X	X	X		X		X
Riou				X							X
Wildnest	..	..	..	X			X	..	X	..	
Hebden					X	X		X	X	X	
Key					X	X		X			
Mekewap					X	X		X			X
Trout					X				X	X	
Wierzycki					X	X	X	X	X	X	
Hourglass						X		X			
McIntosh						X					
McMahon	..	..	..			X	..	..		..	

continued

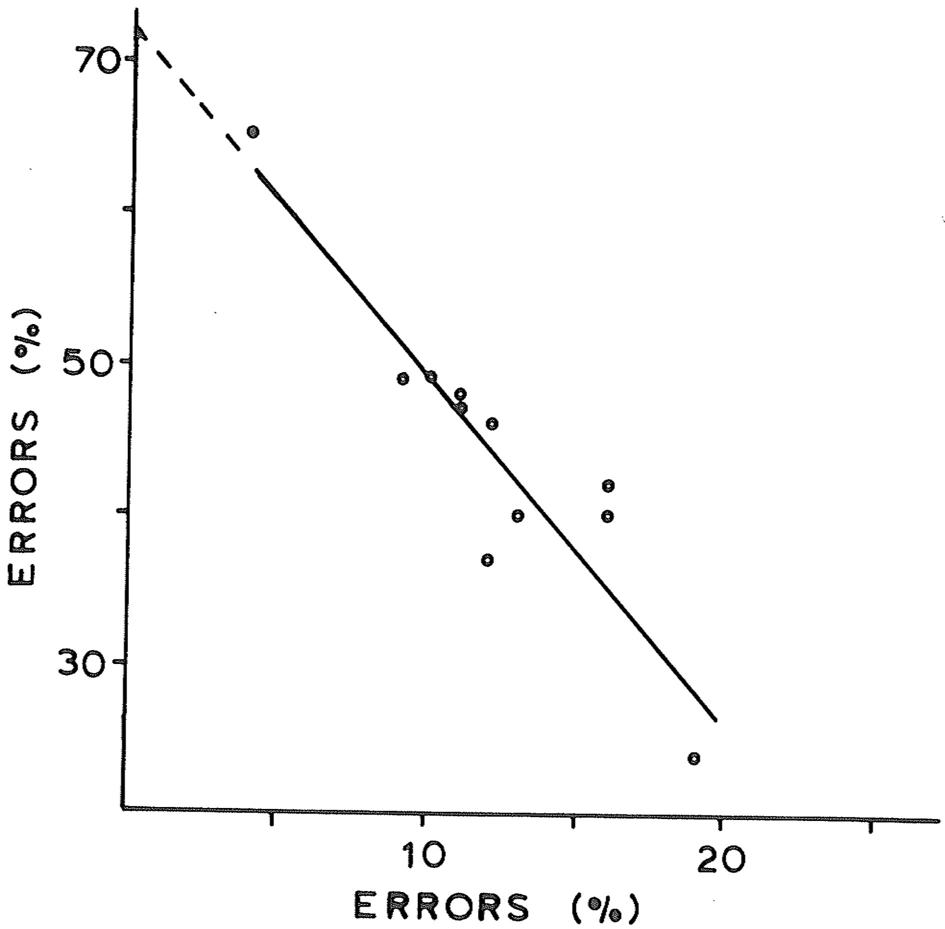
Table 23. continued.

Lake	Variable or pair										
	1	2	3	4	5	6	7	8	9	10	11
Cluff							X				
Fafard							X		X	X	
Giles	..	..	..		..	..	X	..		..	
Jan									X	X	
Mountain	..	..	..					..	X		
Ourom									X	X	
Baldhead											X
Carswell											X
Five Fingers											X
Hunter Bay											X
Lower Foster											X
Pechey											X
Reindeer											X
Sim											X
Upper Seahorse											X
Accuracy (%)	96	91	90	89	89	88	88	87	84	84	81
Errors (%)[b]	65	49	49	48	47	37	46	40	40	42	24

a X are misclassifications, blanks are correct, and .. are missing data. Variables and pairs are: 1 = VOLT1506', 2 = VOLT1504', 3 = VOLT1506' and TMAXB, 4 = ZMAX and TMAXB, 5 = ZMAX and PHOTOZ, 6 = PHOTOZ, 7 = ZMAX and BENDRY, 8 = VOLT1506' and PHOTOZ, 9 = ZMAX, 10 = VOLT1506' and ZMAX, and 11 = TMAXB.

b Errors are overall misclassifications by remaining variables of lakes which have been misclassified by named variable.

Figure 13. Trend of the error rate of ten variables (vertical axis) and of a single variable (horizontal axis). The hatched line extrapolates to an intercept of 72 % of lakes.



70
50
30
ERRORS (%)
10
20
ERRORS (%)

Validation and extrapolation

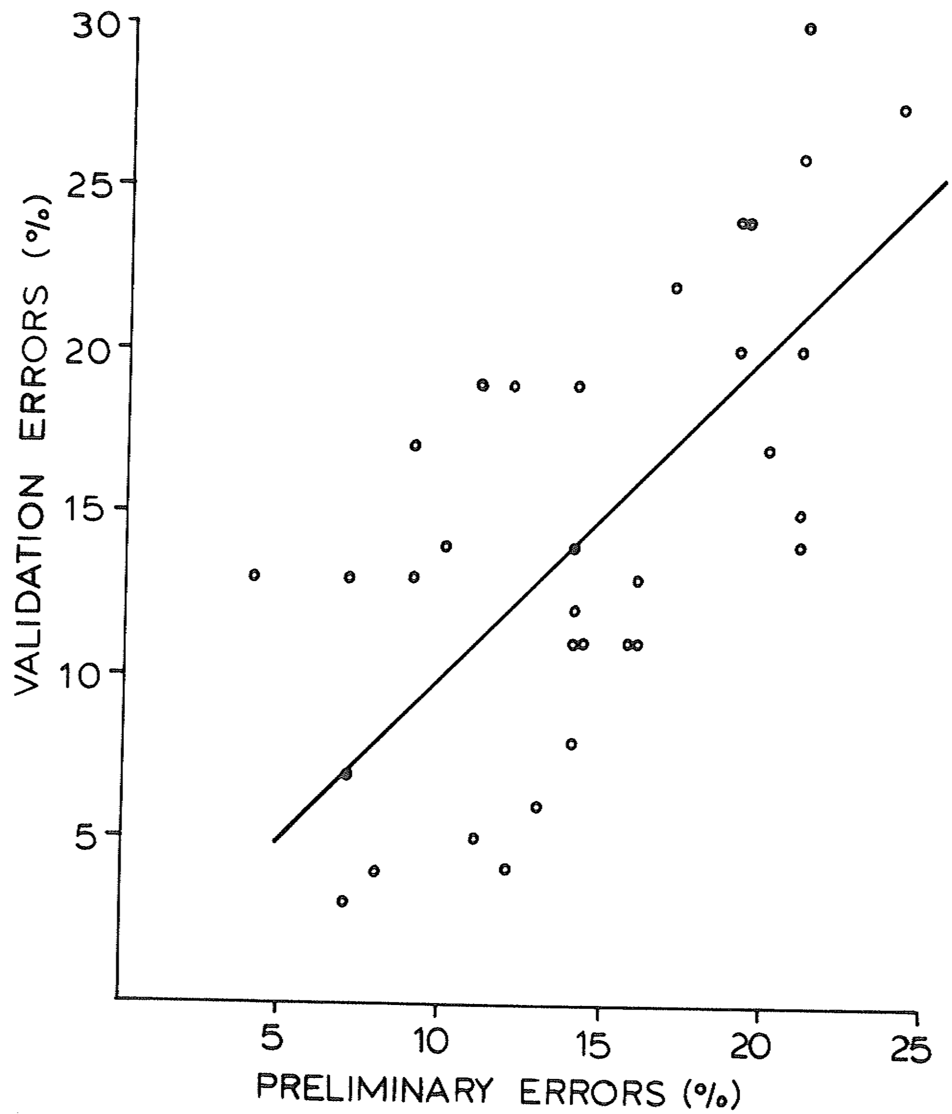
The accuracy of most criteria was similar for the 68 reserved lakes and the preliminary 262 lakes (Figure 14). Notable differences were observed for SECCHI in shield lakes and ZMAX in non-shield lakes (i.e. greater accuracy), and VOLT15O6' in shield lakes and VOLUME in all lakes (i.e. lesser accuracy). The numbers of reserved lakes with known species and habitat ranged from 28 to 65, correspondingly less in separate shield and non-shield classes. Final criteria based on all available 330 lakes were within ± 10 % of preliminary criteria with some exceptions (Table 24). These were WAREA, VOLUME, VOLT15T6', VOLT15O6', VOLT15O4', and VOLT12O6'.

Using log VOLT15T6, the probability of trout presence at habitat x decreased when corrections for incomplete surveys in some lakes and for preferential surveying of lake trout lakes were made (Table 25). As an example, the probability was 10 % at log VOLT15T6=-0.4 (i.e. 0.4 hm^3) for the biased set of lakes and log VOLT15T6=0.6 (i.e. 4.0 hm^3) for the doubly corrected set (Figure 15). Actual asymmetric, logistic, and polynomial trends behaved similarly.

The distribution of estimated log VOLT15T6 in 1450 randomly selected shield lakes showed a median about 0.014 hm^3. The proportion of lakes with log VOLT15T6 > x was well described by the exponential curve:

$$P = 0.030344\ e^{-1.668805\ x} \qquad (n=6,\ r^2=0.997)$$

Figure 14. Relationship between errors of univariate criteria in preliminary and validation sets of lakes. The line indicates perfect agreement between these two sets.



30
25
20
15
10
5
VALIDATION ERRORS (%)
5
10
15
20
25
PRELIMINARY ERRORS (%)

Table 24. Validation and final univariate criteria of lake trout presence and absence in surveyed Saskatchewan lakes.

Variables	Validation errors (%)[a]	Final classification Number of lakes	Criterion of presence	Errors(%)
Location:				
LATD	17	293	> 56.58	19
NORD	15	293	> 6.86	19
Morphometry:				
WAREA[b]	28	289	> 52.9	25
VOLUME[b]	30	257	> 490.13	23
ZBAR	12	257	> 9.70	14
ZMAX	5	287	> 32.65	9
Physicochemistry:				
SECCHI	11	226	> 4.35	12
TDS	14	226	< 40.0	19
SPCON	20	195	< 39.65	21
Temperature-Oxygen:				
TMAXB	24	237	< 7.80	20
VOLT15T6'[b]	19	168	> 31.80	17
VOLT15O6'[b]	13	159	> 3.29	9
VOLT15O4'[b]	14	152	> 19.80	11
VOLT12O6'[b]	17	155	> 0.47	12
Biota:				
BENDRY	20	199	< 4.60	17
SHIELD LAKES				
Morphometry:				
ZBAR	22	138	> 8.10	19
ZMAX	11	142	> 31.15	15
Physicochemistry:				
SECCHI	4	132	< 4.10	12

continued

Table 24. continued

Variables	Validation errors (%)[a]	Final classification: Number of lakes	Criterion of presence	Errors(%)
Temperature-Oxygen:				
TMAXB	24	135	< 8.25	21
VOLT15T6'[b]	19	107	> 11.63	13
VOLT15O6'[b]	13	105	> 2.15	6
VOLT15O4'	13	102	> 7.40	10
VOLT12O6'[b]	19	104	> 0.47	12
Biota:				
BENDRY	26	122	< 4.60	23
NON-SHIELD LAKES				
Location:				
LATD	14	147	> 54.88	15
NORD	11	147	> 0.96	14
Morphometry:				
WAREA	11	146	> 219.1	14
VOLUME[b]	13	119	> 1661.0	13
ZBAR	0	119	> 12.3	7
ZMAX	3	145	> 39.0	7
Temperature-Oxygen:				
VOLT15T6'[c]	13	61	> 195.86	10
VOLT15O6'[b,c]	7	54	> 37.77	7
VOLT15O4'[b,c]	8	50	> 166.41	8
VOLT12O6'[b,c]	14	51	> 4.06	12

a Errors from use of preliminary criteria (Table 11) on 20 % of lakes which were reserved.

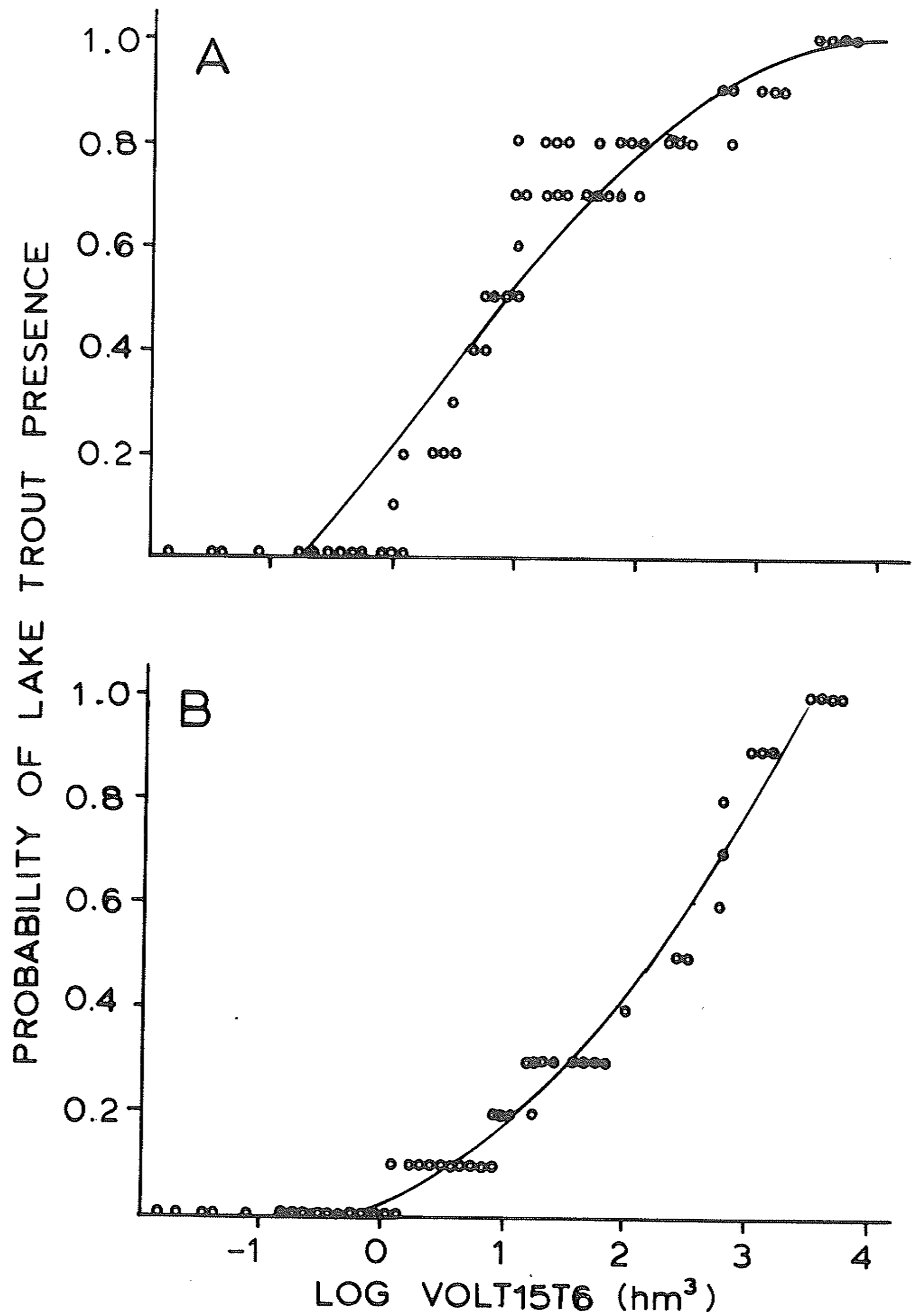
b Final criterion differs by > ± 10 % from preliminary.

c See Table 12 for preliminary criteria.

Table 25. Effects of incomplete surveys on some lakes and preferential surveying of lake trout lakes on the probability of trout presence according to log VOLT15T6.

Set of lakes	Preference towards lake trout: None	Preference towards lake trout: 6,4,2-fold
Log VOLT15T6 known:		
Univariate	1.023	1.529
(% errors, n)	(11%,91)	(8%,74)
Logistic B0	1.9099	3.1844
B1	-1.8610	-1.7563
P=0.1	0.191	0.562
P=0.5	0.782	1.813
P=0.9	1.372	3.064
(% errors,n)	(11%,91)	(8%,74)
Polynomial A0	0.22372	0.06097
A1	0.30921	0.12524
A2	...	0.04846
A3	-0.00756	...
A4	...	-0.00081
(R^2,n)	(0.94,92)	(0.98,75)
Missing log VOLT15T6 estimated:		
Univariate	1.235	1.728
(% errors,n)	(14%,113)	(9%,91)
Logistic B0	2.3778	3.8883
B1	-1.9576	-1.9499
P=0.1	0.092	0.867
P=0.5	1.215	1.994
P=0.9	2.7	3.121
(% errors,n)	(13%,113)	(5%,91)
Polynomial A0	0.08346	0.02605
A1	0.34611	0.08822
A2	0.10290	0.05240
A3	-0.05940	0.00268
A4	...	-0.00062
A5	0.00187	...
(R^2,n)	(0.95,114)	(0.99,92)

Figure 15. The probability of lake trout presence according to log VOLT15T6: (A) using only known habitat data and assuming no preferential surveying of lake trout lakes, and (B) correcting for missing habitat data and for assumed preference towards lake trout lakes.



A
B
1.0
0.8
0.6
0.4
0.2
PROBABILITY OF LAKE TROUT PRESENCE
-1
0
1
2
3
4
LOG VOLT15T6 (hm³)

The estimated number of lake trout lakes in Saskatchewan ranged from 1778 using the biased criteria to 333 using the doubly corrected criteria of lake trout proportions (Table 26). Most of the difference in numbers occurred among the very numerous, very small lakes. The biased probability predicted 319 lakes over 10 hm^3 (equivalent to about 6.6 km^2) and the corrected, 155 lakes of this size. Use of smaller habitat intervals would change both biased and corrected estimates, particularly for very small lakes, as the probability of lake trout presence and the number of lakes is changing rapidly within each interval.

Table 26. Estimates of the total number of lake trout lakes in the shield region of Saskatchewan. Predictions are based on log VOLT15T6 under conditions of (A) no preference, or (B) assumed preference towards lake trout lakes (see text).

Log VOLT15T6 (hm^3)	Shield lakes		Proportion with lake trout present		Number of lake trout lakes	
	Proportion	Number	A	B	A	B
-1	0.83900	69839.2	0	0	0	0
-0.5	0.09110	7583.3	0.03503	0	265.6	0
0	0.03955	3292.2	0.14689	0.00652	483.6	21.5
0.5	0.01717	1429.2	0.30055	0.05481	429.5	78.3
1	0.00745	620.1	0.45138	0.12615	279.9	78.2
1.5	0.00324	269.7	0.59370	0.22546	160.1	60.8
2	0.00140	116.5	0.72184	0.35290	84.1	41.1
2.5	0.00061	50.8	0.83014	0.50769	42.2	25.8
3	0.00026	21.6	0.91293	0.68811	19.7	14.9
3.5	0.00011	9.2	0.96452	0.89152	8.9	8.2
4	0.00005	4.2	1.00	1.00	4.2	4.2
Total	0.99994	83236.0	...	...	1777.8	333.0

DISCUSSION

The lake surveys initiated in the 1920's in Prince Albert National Park (Rawson 1936) and continued by the province since 1950 (Saskatchewan 1947) comprise invaluable baseline data for this and other studies. Due to adherence to standardized methods in provincial and many consultant surveys, available data were remarkably consistent from the 1930's well into the 1970's (see Rawson 1936, Reed 1959, Koshinsky 1968, Tones 1979, Dean 1981). Undoubtedly this restricted innovative methods (e.g. Rawson 1953, Koshinsky 1968 p.245 and 271) and reduced attention to factors in fisheries management other than habitat (Kallemeyn 1969). Nonetheless, the consistency and length of surveys were valuable in this study.

As a direct result of consistent methodology over 30 years, subsets of habitat variables were available for several times as many lakes as statistically expected. Inter-relationships among variables allowed the estimation of missing variables to further augment the dataset. This consistency largely overcame the lack of comparability of non-standard surveys (e.g. Beak 1979). Likewise, the fact that most surveys extended from late spring-early summer to late summer-early fall allowed fairly detailed coverage. This provided seasonal trends in temperature and oxygen profiles, TDS during the optimal mid-July to mid-August period, and seasonal averages of benthos, plankton, and fish abundance (Rawson 1936, Shuter et al. 1983, Ryder 1965, Matuszek 1978). These important facets are often unavailable from more cursory surveys (e.g. Mayhood et al. 1973, Falk 1979).

Representative lakes

A major concern of this study was whether lakes which have been surveyed are representative of all Saskatchewan lakes, and to mitigate bias if this was not so. This allowed the identification of the important biological factors and the use of classification criteria on other sets of lakes. In a study of species associations in 2500 Ontario lakes, Johnson et al. (1977) noted that using only lakes with at least one species present "tended to give a distorted sample of the conditions that determine presence/absence of any one of the ... species". Even with both lake trout and non-lake-trout lakes included, the magnitudes of univariate or multivariate criteria depend on the density of lake trout and non-lake-trout lakes in the sample. For that reason, formal rules of multiple discriminant analysis require randomness across classes (Knoke 1982).

The most direct definition of "representative" is in terms of fish species compositions. Nonetheless, comparisons of species in these surveyed lakes and in other sets of lakes were inconclusive. Both the lakes used in this study and 239 lakes in an atlas of fish distribution (Atton and Merkowsky 1983) lacked preferred species in 12 % of cases. In northern drainage basins, surveys were relatively biased toward lakes with preferred species (i.e. Arctic, Kazan, and Churchill basins, see Table 7), presumably because greater logistical difficulties led to more critical selection of lakes for surveys. In southern areas, distributional records were relatively biased in favour of lakes with preferred species (i.e. Saskatchewan River basin, see Table 7), presumably due to greater interest and easier access to lakes with socio-economically preferred species. This reasoning suggests intuitively that the surveyed lakes had no greater tendency to have lake trout than those lakes with distributional records, which themselves were biased. Other studies have seldom accomplished more objective species comparisons. Although only 2 % of Ontario lakes were surveyed, Martin and Olver (1976) noted that about 50 % of the estimated total number of lake trout lakes were included. Obviously, studies can avoid this problem by surveying all or almost all lakes in an area (e.g. Beamish et al. 1976, Harvey 1978).

The comparison of surveyed lakes with respect to lake areas was more conclusive. Generally, larger lakes were over-represented in surveys by comparison to all Saskatchewan lakes or even nearby lakes. "Very small" lakes were under-represented in surveys, sometimes exceedingly so, even in studies concerned primarily with very small lakes (Table 9). The reasons are logistic and socio-economic. True representation of shield lakes by a set of 8,540 very small lakes and 30 lakes over 10 km^2 would involve considerable problems of access and greater effort to attain minimum samples in each lake. Given the large-scale fisheries in many larger lakes and the trend of more species in each larger lake, demands for surveys on larger lakes are more justifiable and have taken precedence (Minns 1986).

Studies aimed specifically at very small lakes were satisfactorily representative of lakes over 50 ha (Table 9). The smallest lake trout lake among 225 lakes was 91 ha (see Appendix D), implying that lakes over 50 ha include the region of transition from absence to presence. Thus, criteria of area and correlated variables based on these study lakes should be more reliable than criteria from the larger set.

The comparison of TDS with a larger data set was more complex. Surveyed lakes did not appear comparable to lakes in Liaw and Atton (1980), even though most were included in the latter study. Since the latter required only single water chemistry samples, it was potentially more representative. Nonetheless, Liaw and Atton (1981) later noted a bias in their set towards larger, higher-TDS lakes. Only 36 % of their shield lakes had TDS of 50 $mg.L^{-1}$ or lower, yet 75 % of the shield region is in this category.

The present study appears to be more representative of TDS in shield lakes than was Liaw and Atton (1980). Correlated variables such as alkalinity (TOTALK), calcium (CA), and magnesium (MG) (Liaw and Atton 1981) are presumably similar.

Prediction of lake trout presence

Descriptions of lake trout lakes in Saskatchewan may not be comparable to those for other regions. The lowest or highest value of any habitat variable is too dependent on numbers of lakes examined and regional variability in lakes for all but anecdotal purposes. Martin and Olver (1976) reported the smallest lake trout lake of about 5,100 Ontario lakes was 4.4 ha, in contrast to 91.1 ha in the present study of 225 lakes. Yet samples of 225 lakes from their larger set would undoubtedly show a higher minimum on average, just as some of the thousands of unsurveyed Saskatchewan lakes less than 91 ha presumably have lake trout.

Furthermore, descriptions of lake trout lakes are counter-productive for predicting the suitability of other lakes. Firstly, there is no objective way to choose among the minimum, median, maximum, or other quantile of any variable as a reasonable descriptor. Secondly, any such descriptor would only be predictive if it were erroneously inferred that lake trout were present in similar lakes. For example, all lake trout lakes in the present study were over 13.5 m maximum depth and 75 % were over 31.1 m (Appendix D). Neither descriptor is intrinsically better and neither predicts lake trout in all lakes over 13.5 m or even in 75 % of lakes over 31.1 m deep.

The significant differences for many habitat variables between lake trout and non-lake-trout lakes have various explanations. Some of the 42 variables which differed significantly are undoubtedly important per se, while others are more likely important due to correlations with other variables. For example, given the stenothermal nature of this species, the maximum temperature in the hypolimnion of a lake is a likely proximate cause of lake trout absence or presence (see below). However, greater maximum depth of a lake is believed to be indirectly important (McPhail and Lindsey 1970) only insofar as it increases the probability of a thermocline and suitable hypolimnetic temperatures. Other variables (such as total alkalinity) differed significantly between lake trout and non-lake-trout lakes over the survey region, but not within the shield and non-shield areas separately (Appendix E). This may reflect trends in alkalinity from an area of infrequent lake trout presence to one of greater frequency, rather than suitability of individual lakes themselves. An analogous argument by Prepas (1983) disputed the predictive usefulness of TDS for fish productivity.

As post-glacial dispersal and climatic conditions confound the prediction of lake trout presence in non-shield lakes, the following discussion will focus on useful criteria of shield lakes (Table 11).

Temperature

The temperature preference of lake trout is an important factor in their presence or absence. The existence of water below 7.7°C at the lake bottom (TMAXB) or water of 6°C at 28.5 m depth (T15T6L) both imply hypolimnetic temperatures in the preferred range of 12 to 15°C. (Maximum surface temperatures were above 13°C in all 208 lakes examined and above 19°C in 75 % of lakes.).

Yearling lake trout have upper lethal temperatures of 22 to 23.5°C when acclimated at 8 to 20°C in laboratory studies (Gibson and Fry 1954). Yearling lake trout have a "final preferendum" of 11.7°C (McCauley and Tait 1970), which is the "temperature around which all individuals will ultimately congregate, regardless of their thermal experience before being placed in the gradient" (Fry 1947). Some salmonids show changes of ± 2 to 4°C in preferred temperatures caused by starvation (Javaid and Anderson 1967). Yearling lake trout preferred temperatures of 0 and 3°C below this preferendum when fed *ad libitum* and below maintenance rations, respectively (Mac 1985). Otherwise, "the lake trout ... not only shows no seasonal differences in thermal preference, but it is even more extreme in that its acute thermal preferenda apparently are unaffected even by acclimation temperature" (McCauley and Huggins 1979).

Lake trout and other salmonids show close agreement between laboratory and field observations (Ferguson 1958). Summer concentrations of lake trout occur within $\pm 3^{o}C$ of this preferendum, generally $2^{o}C$ cooler: 8-$10^{o}C$ in Lake Louisa (Ontario), 7-$13^{o}C$ in Cayuga Lake (New York), 8-$11^{o}C$ in Lac La Ronge (Saskatchewan), 8-$10^{o}C$ in Redrock Lake (Ontario), and $11^{o}C$ in Mooseland Lake (Maine)(McCauley and Tait 1970, Ferguson 1958).

The minimum volume of water between 6 and $15^{o}C$ (VOLT15T6') quantifies the critical habitat, rather than simply implying it exists, as do the other criteria. Accordingly, the error in prediction was reduced from 19 or 25 % to only 12 % of lakes. Furthermore, this criterion can be estimated from readily available data on water area and fetch (Table 21). The lower boundary of $6^{o}C$ in VOLT15T6 reflects the indirect effects of optimal growth at 6 to $8^{o}C$ and 10 to $12^{o}C$ in yearling trout fed above maintenance ration and *ad libitum*, respectively (O'Connor *et al*. 1981). The excluded volume below $6^{o}C$ is assumed to represent a small proportion of total volume in most lakes.

Oxygen

Oxygen is another important factor in lake trout presence or absence in shield lakes. In laboratory studies, yearling trout required at least 3 $mg.L^{-1}$ oxygen at 9.5 to 16°C for standard metabolic respiration (i.e. lowest rate for quiescent fish)(Gibson and Fry 1954). The same trout showed that active respiration during swimming was restricted by oxygen levels below about 6 to 7 $mg.L^{-1}$ at 9 to 18°C. Field studies found similarly that lake trout in Lac La Ronge migrated from cooler to warmer water when oxygen declined to about 4 $mg.L^{-1}$, but did not migrate further from oxygen of about 7.5 $mg.L^{-1}$ (Rawson and Atton 1953). Fewer than 10% of Ontario lakes had lake trout present if hypolimnetic August oxygen was below 4 $mg.L^{-1}$ (Martin and Olver 1976).

The criterion of minimal surface oxygen (OMINS) above 8.2 $mg.L^{-1}$ presumably distinguishes eutrophic from meso- or oligotrophic lakes. It would not usually distinguish non-stratified from stratified lakes and was relatively imprecise. The higher error rate of 29% for VOL6MG', in contrast to 12% for VOLT15T6', implies that the minimum volume of water oxygenated above 6 $mg.L^{-1}$ does not quantify critical habitat as precisely as does temperature. However, given that minimum oxygen needed by lake trout may be 3 to 5 $mg.L^{-1}$ (Gibson and Fry 1954, Davis 1975), the volume of water above 4 $mg.L^{-1}$ may have been a better criterion for oxygen (Rawson and Atton 1953).

Most of the literature on oxygen has focussed on low oxygen as a limiting factor (see reviews by Fry 1971, Jones and Randall 1978, and Holeton 1980). It may also be important at concentrations above 4 to 6 $mg.L^{-1}$. Oxygen below 10 to 12 $mg.L^{-1}$ or high carbon dioxide concentrations reduce sustainable speeds of salmonids (Dahlberg et al. 1968 cited in Beamish 1978). The most efficient swimming over a given distance for salmonids occurs at a rate of respiration about twice standard metabolic level (Jones and Randall 1978). Holeton (1980) suggested that many pelagic fish which inhabit the photic zone may only realize their full aerobic potential under hyperoxic conditions. Anaerobic sprinting or "burst" swimming "... may well be restricted by moderate oxygen deficiency" (Beamish 1978 p.158). Nonetheless, it is still debated whether hyperoxic conditions increase performance (Holeton 1980, Jones and Randall 1978).

Metabolic "scope for activity" is the difference between maximal active and minimum standard respiratory rates. Scope increases when oxygen increases above atmospheric saturation and indicates "incipient limiting" conditions higher than usually believed (Brett 1964, Fry 1971 p.43 and 59). This is seldom tested experimentally, but may reveal the benefits of potentially high oxygen conditions at depth (see below).

Temperature-Oxygen

These factors in concert exert a strong influence on lake trout presence. A minimum volume of water with temperature less than 12-15^{o}C and oxygen greater than 4-6 $mg.L^{-1}$ appears to be essential in shield lakes. The best predictor (i.e.

VOLT1506') indicates that a minimum volume of 2.15 hm^3 of water below 15°C and above 6 $mg.L^{-1}$ oxygen is required during summer. The higher error rates of VOLT1504' and VOLT1206' may imply that 6 $mg.L^{-1}$ oxygen and 15°C are more reliable indices for populations than 4 $mg.L^{-1}$ and 12°C, respectively.

A more precise version of this minimum volume would consider spatial and temporal variations (e.g. Jensen and Chen 1986), possible life-stage differences (e.g. Coutant 1985), and a minimum duration of restricted temperature and oxygen conditions. The estimate of the minimum volume of suitable temperature and oxygen in this study assumed uniform thermal and oxygen conditions across the lake. The effects of decomposition on near-bottom oxygen concentrations (Rawson 1936) may extend up to 6 m from the sediments (Jones 1982 cited in Fulthorpe and Paloheimo 1985). This effect would cause an increasing over-estimation of the minimum volume with decreasing lake depth in shallower lakes, until stratification no longer occurred in polymictic lakes. Temperature-oxygen data were available at 150 limnological stations for 970 occasions on 77 of these surveyed lakes. Nonetheless, not all depth-profiles had data at suitable intermediate depths, no objective means of weighting each station or interpolating temporally were known, and considerable effort would have been required.

Similar criteria include the use of the mid-summer fraction of lake volume below 10°C and above 6 $mg.L^{-1}$ oxygen to assess impacts on lake trout habitat from nutrient loading (Genge 1986; R. Genge, Ontario Min. Environment, pers. comm.). Guidelines such as (1) a minimum of 1.5 m of water below 13^{o}C and above 5 mg.L^{-1} oxygen in mid-August (Minnesota 1982) and (2) a minimum of 3 m below 10^{o}C and above 5 mg.L^{-1} oxygen (Ontario 1977) are clearly related. Although their accuracy is not known, these rules deserve further evaluation in light of their simplicity. An early example of such thinking was the explanation of cisco (_C. artedii_) presence and abundance in Indiana lakes on the basis of the depth of water below 20^{o}C and above 3 mg.L^{-1} oxygen at "maximum stagnation" (Frey 1955).

The success of the minimum volume of suitable temperature and oxygen suggests that a maximum density of lake trout is sustainable and/or a critical minimum number of reproductive lake trout is needed to initiate or maintain a population. Reviews by Healey (1978) and Martin and Olver (1980) indicate densities of 0.8 to 14 lake trout per hectare in 14 lakes across North America. Another seven lakes have densities of 0.5 to 13 (Bailey 1977, Ball 1985, Chen 1979, George 1985, Martinot 1978, Sawchyn 1987). Five lakes for which volumetric data are available have densities of 26 to 332 mature lake trout per hm^3 of suitable temperature and/or oxygen (Bailey 1977, Martinot 1978, Chen 1979, Sawchyn 1987). Recent programs of introduction or restoration of lake trout presume that a minimum critical number is necessary (Hatch

1984, Loftus 1986). The criteria of VOLT15T6 and VOLT15O6 (Table 11) imply critical minimum numbers of 608 to 893 and 55 to 714 mature trout, respectively, in each lake. VOLT15T6 may be estimable in more lakes with known numbers of lake trout (see Appendix G). Nonetheless, problems in identifying depleted populations (e.g. Paterson 1968, George 1985), with the reliability and comparability of estimates of trout density (Healey 1978), and with species or limnological anomalies remain. A clearer view of minimum numbers or maximum density will require published assessments such as Bridges and Hambly (1971) and Hitchins and Samis (1986).

The suggestion of a maximum density and critical number assumes that most populations have not evolved the specialized reproductive strategies postulated for Arctic populations by Johnson (1976). Lake trout in severe climates frequently show bimodal size composition, divergent growth at maturity, slow growth, and low fecundity (Benoit and Power 1981). This is thought to represent adaptation for reproductive stability under extreme and variable conditions (Johnson 1976, but see Power 1978). These indicators, and others such as uniformly large body sizes of trout, intermittent spawning, and variable year-class abundances also occur in more southerly lakes. Examples are Contact Lake (Koshinsky 1964), Bartlett and Haugen lakes (Koshinsky 1968), Swan Lake (Paterson 1968), Squeers Lake (Ball 1985; H. Ball, Lakehead Univ., pers. comm.), and Crean Lake (Cuerrier

1952). These are typically small lakes with marginal conditions for lake trout. These reproductive strategies may allow the critical minimum number of lake trout to be lower or the maximum density of lake trout to be higher.

The discussion above assumes that the minimum volume is not a requirement of a forage species such as cisco, rather than of lake trout per se. This assumption is likely valid, even though cisco is a common food of lake trout (Scott and Crossman 1973, Kerr 1971b). Cisco prefer temperatures of 12°C or lower and oxygen of 4 $mg.L^{-1}$ or higher (Rudstam and Magnuson 1985), but they are generally tolerant of higher temperatures and lower oxygen (Ferguson 1958, 20°C and 3 $mg.L^{-1}$ by Frey 1955). Furthermore, lake trout are present in lakes which lack cisco (e.g. Martin 1966, Murray 1979, Paterson 1968, Donald and Alger 1986).

The volumes used in this study represent a thermal and/or oxygen "squeeze" (Coutant 1985) during open-water season. The demonstrated hypothesis is that presence or absence is determined during the most critical period, which may be as brief as several days. Temperature is treated as a "lethal" or "tolerance" factor (Fry 1971) of lake trout presence. Seasonal trends and annual variability in relation to a threshold or critical volume determine long-term population survival, and perhaps reproductive strategies. This complements the conclusion of Christie and Regier (1986), that the sustainable yield of lake trout is determined by the cumulative volume of water of suitable temperature over the open-water season. In their view, temperature is a "controlling" factor (Fry 1971) of growth, abundance, and productivity, implicitly at levels above the threshold. A comparison of the critical and cumulative indices to presence, abundance, and sustainable yields in small to large lakes with stable to variable conditions may confirm this interpretation.

Depth

Lake depth is a good predictor of lake trout presence in shield lakes: lakes require a minimum 31.2 m maximum depth or 8.3 m mean depth (Table 11). Mean depth was a very important factor in the discrimination of lake trout and non-lake-trout lakes in Ontario (Johnson *et al*. 1977). Mean and maximum depths are closely correlated in many regions (Koshinsky 1970, Ryan 1980, Gorham 1958), so are discussed almost interchangeably.

Mean depth has been shown to be important in regional studies of winter hypoxia in very small lakes. Even in eutrophic lakes with high summer algal concentrations, a deeper lake fully "charged" with oxygen during autumn turnover may have reserves to withstand over-winter loss of oxygen (Barica and Mathias 1979). In shallower lakes (say, less than 5 m mean depth), winter conditions are dependent on mean depth or lake volume and late summer algal and/or macrophyte densities. Relative amount of the littoral zone is frequently correlated with the depth of lakes (Johnson *et al*. 1977). Most southern Saskatchewan lakes are more-or-less eutrophic, in contrast to most shield lakes which are oligotrophic and seldom develop winter anoxia (Barica and Mathias 1979, Schindler 1971). Data on over-winter oxygen conditions were scarce in the present study, precluding assessment of this factor (see Appendix D).

There appears to be little indication of a physiological basis for depth as a direct factor in lake trout presence. Some potential mechanisms are that the hydrostatic pressure induced by depth improves swimming and therefore feeding efficiency by this predator, reduces oxygen demands and/or increases uptake, or improves metalimnetic or hypolimnetic oxygen concentrations. In sustained swimming, the adaptive mode for salmonid fish (Webb 1984), frictional drag is the major resistance (relative to inertia). Drag varies with density and viscosity of water, surface area of the fish, and speed to the exponent 1.5 to 2 (Webb 1978). Hydrostatic pressure at 10 to 30 m reduces seawater viscosity by much less than 4% (Gordon 1970). However, water viscosity increases 15% between 15 and 10^{o}C (CRC 1968 p.F36). Accordingly, temperature selection, size of fish, and swimming speed would appear to be considerably more important than hydrostatic pressure for efficiency of swimming.

Hydrostatic pressure allows greater absolute oxygen concentrations in water (Ricker 1934) and increased oxygen uptake as the potential oxygen difference across the gill surface is increased (Jones and Randall 1978). Absolute saturation at depth can be several-fold greater than saturation in surface waters, by about 1 atmosphere for each 10 m of depth. Nonetheless, depth does not by itself increase oxygen concentrations above the 12 to 13 $mg.L^{-1}$ attained during spring turnover (Ricker 1934). Metalimnetic oxygen maxima above 13 $mg.L^{-1}$, however, may be caused by the photosynthesis of algae adapted to low temperatures and relatively low light (Eberly 1964) or littoral macrophytes (Dubay and Simmons 1979). These maxima may be temporary or persist throughout stratification. They are more frequently found in smaller lakes with greater relative depth (Wetzel 1983). Nonetheless, the relative depth of 115 shield lakes in the present study was only 55 % accurate as a criterion of lake trout presence. Lake trout were much more common in lakes of greater area and volume than in smaller lakes with similar relative depth. This suggests that metalimnetic maxima may be infrequent occurrences and/or dependent on several factors rather than solely on relative depth. Transparency to stimulate photosynthesis in the metalimnion is obviously one co-requisite (Fulthorpe and Paloheimo 1985).

Transparency

Transparency of the lake was the next most useful predictor at 88 % accuracy in shield lakes (Table 11). Lakes required a summer mean Secchi disk depth of 4.15 m or greater to have lake trout present, similar to other studies. Data from Martin and Olver (1976) suggest a criterion of about 5 m in shield and non-shield lakes. Lake trout and non-lake-trout lakes in Ontario were discriminated by Secchi transparency and depth combined (Johnson et al. 1977). However, transparency was relatively unimportant among five variables in the discrimination of northwestern Ontario lakes (Hamilton et al. 1980), possibly due to interference by coloured matter (Ryan 1980).

Transparency may be a factor in lake trout presence due to photosynthetic generation of oxygen (see above), correlation of oxygen conditions with coloured matter and nutrient concentrations, or visual requirements.

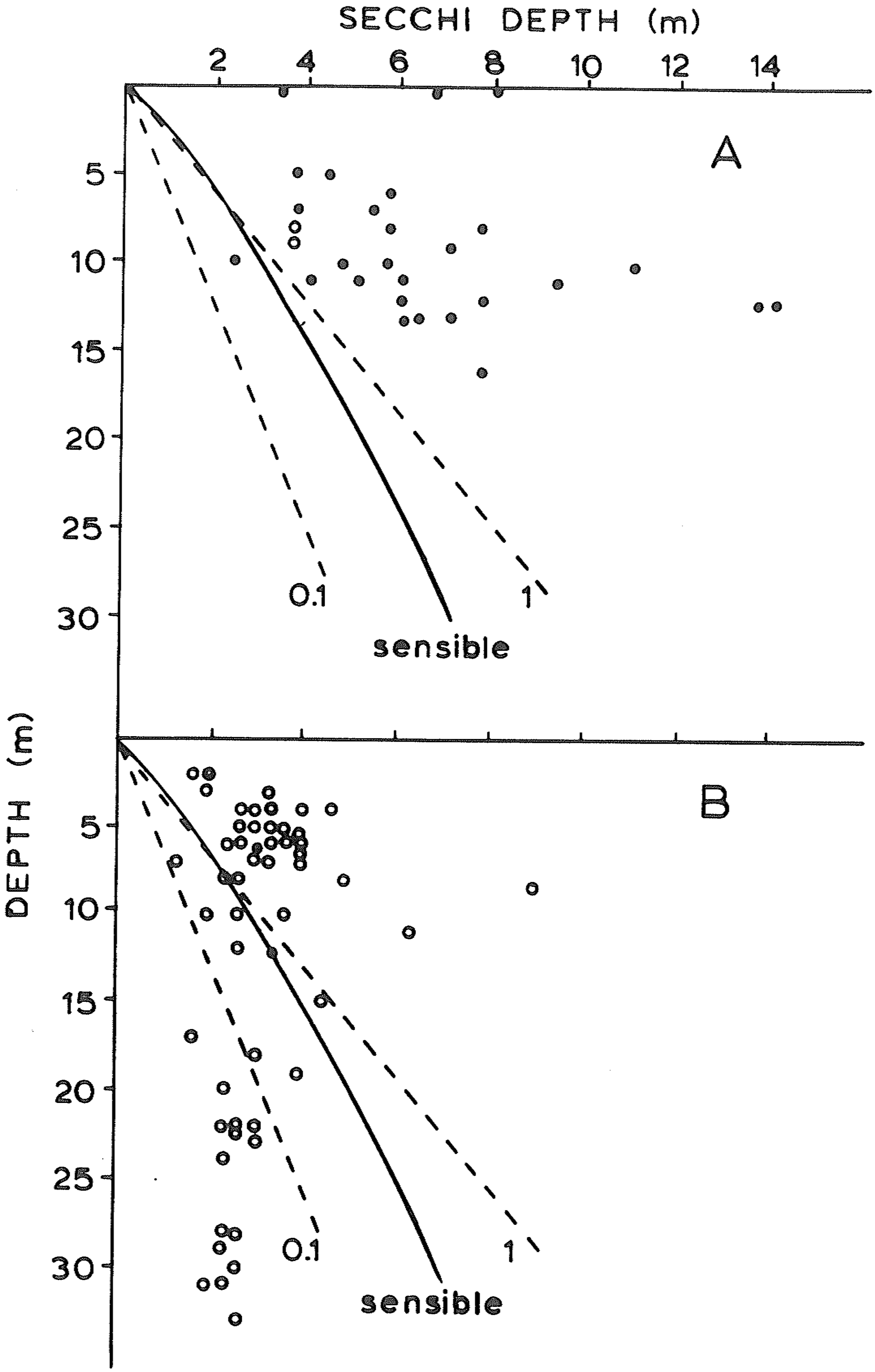
In most shield lakes, Secchi depth is closely related to concentrations of dissolved and colloidal colouring matter (e.g. humic substances) (Koshinsky 1968, Schindler 1971). Low Secchi transparency may indicate under-saturated oxygen conditions (Ruttner 1963, Wetzel 1983 p.175). In this study, transparency of 4 m predicts the existence of a minimum volume of suitable temperature and oxygen (see Estimation of missing data). In more productive lakes, lower Secchi transparency is indicative of higher particulate concentrations, especially phytoplankton (Wetzel 1983). Both under-saturation and high algal density predispose a lake to winterkill and/or summerkill oxygen conditions (Barica 1975, Barica and Mathias 1979, Liaw 1979). Hypoxia may limit survival of adults, fry, or eggs (Garside 1959).

Transparency may also be important for vision per se. There are several approaches to assessing the effects of light: general guidelines for fish vision, the sensitivity of visual pigments of lake trout to wavelengths of available light, the minimum angle subtended by a perceivable object, and the contrast between objects and the background.

The criterion of 4.2 m Secchi depth may be an index of general visibility. In field studies, several fish species require 0.001 to 1 meter-candle (abbreviated m.c., Blaxter 1975). "Light-controlled behaviour such as feeding and schooling, net avoidance and vertical migration seem to become extinct at light intensities near [0.1 meter-candle] equivalent to late dusk or early dawn..." (Blaxter 1975 p.770). If the Secchi depth represents about 10% of surface incident light (Wetzel 1983 p.66), the deepest visibility at 0.1 m.c. at mid-day is 18 m for lakes with Secchi depth of 3 m, and 62 m for 10 m (Figure 16). This assumes incident radiation of 6.3×10^4 uW/cm^2 (Ruttner 1963 p.139, Wetzel 1983 p.756) and a conversion of 1 uW/cm^2 = 2.5 m.c. (Blaxter 1970 p.213). Visibility occurs only at shallower depths if 1.0 m.c. is required.

By the sensitivity hypothesis, visual pigments of fish should have maximal absorption at the wavelength of ambient light (Dartnall 1975 p.557). Water transmits wavelengths

Figure 16. The depth of visibility (from corresponding Secchi depth) against the maximum depth of 15°C, separately for lakes with lake trout present (panel A) and absent (panel B). Solid circles represent lakes with suitable temperature and oxygen (see text) and open circles, those without suitability. Lines represent depths of 1.0 and 0.1 meter-candle intensity, and light of sensible wavelength for lake trout.


SECCHI DEPTH (m)
2
4
6
8
10
12
14
A
5
10
15
20
25
30
0.1
1
sensible
DEPTH (m)
B
0.1
1
sensible

from 450 to 700 nm preferentially and narrows the bandwidth with increasing depth towards 470 to 580 nm in very clear and slightly coloured water, respectively (Wetzel 1983, Dartnall 1975). The two visual pigments of lake trout are reasonably adapted to clear water, having maximal reception at 510 and 540 nm (Ali and Wagner 1975, McFarland and Munz 1965).

The clearest known water (Secchi depth about 70 m) retains sufficient light of 510 nm for photopic or daylight-type vision down to 500 m, and water of Secchi depth about 35 m does so to 180 m. Water of Secchi depth about 5 m does so for 540 nm light to only 20 m (from Figure 4 in Dartnall 1975). The depth at which light of sensible wavelength disappears is related to Secchi depth:

$$\log(\text{sensitive depth}) = 0.450 + 1.200 \log(\text{Secchi depth}),$$
$n = 3$, $r^2 = 0.996$.

This implies that lake trout have vision to depths of 180 m in very clear lakes, but would be limited visually to less than 20 m in less transparent lakes.

The sensitivity hypothesis appears to be relevant to lake trout presence. In addition to a minimum volume of suitable temperature and oxygen, sensible light below the observed depth of 15^{o}C seems a necessity (Figure 16). For example, the 3 uppermost lakes in the figure have sensitive depths of 12 to 36 m (from corresponding Secchi of 3.3 to 8 m) and temperatures of 15^{o}C or cooler at the surface. Only lakes to the upper right of the line are predicted to have sufficient light below 15°C for lake trout. The one exception to the rule is Wierzycki Lake, which lies to the lower left but has lake trout. Its transparency was unusually low during its survey due to erosion caused by recent forest fires (Sawchyn and Kardash 1976). Most non-lake-trout lakes do not have suitable VOLT1506'. One exception has a deeper sensitive depth of about 11 m than the observed depth of 15°C at 6 m, which should allow lake trout by this hypothesis. The scarcity of surveyed lakes with 15°C near the surface and relatively low sensitive depth prevents confirmation of this trend.

The effects of minimum subtended angles and object contrasts relate to feeding behaviour. Lake trout are generally piscivorous and adults prey preferentially on ciscoes (Scott and Crossman 1973, Martin and Olver 1980). Lake trout may adapt to planktivory: greater numbers and more highly developed gill rakers are found (Martin and Sandercock 1967, Qadri 1967) and condition factors and natural mortality are similar (Kerr and Martin 1968) in such cases. Nonetheless, planktivorous populations have sufficiently different growth rates, ages at maturity, and lifespans (Martin 1966) and lower metabolic efficiency in spite of a larger forage base (Kerr and Martin 1968) to indicate that non-piscivory is unusual for the species.

The minimum subtended angle which is required to elicit visual response may vary with movement of an object, age of fish, and other factors (several references in Ali 1975). Kerr (1971a) used 0.55° in modelling growth, while Confer et al. (1978) reported about 0.85° for lake trout feeding on plankton. If 0.75° is reasonable, maximal visual range would be 3 m for ciscoes viewed posteriorly (i.e. 4 cm wide amplitude) and 11 m laterally (i.e. 15 cm main body length), which is not restrictive (Kerr 1971a). The significance of the contrast in brightness between an object (e.g. prey) and background water is limited to specific conditions (Lythgoe 1975 and others in Ali 1975). At shallow depths, light which is reflected from the object travels a shorter distance horizontally through water on average than the background light. Therefore, it undergoes less band-width narrowing and scattering, which causes the object to appear "coloured" and "brighter" against the background light (Lythgoe 1968). In clear water, this contrast is effective for larger objects up to 20 to 25 m distant under photopic conditions. However, the effect is only relevant up to 5 m distance for objects which are only slightly brighter inherently than background water (e.g. ciscoes?) and/or small (e.g. plankton?)(Lythgoe 1968 p.1010).

Another specific feeding requirement may arise from the importance of the crustacean Mysis to young lake trout (Scott and Crossman 1973). These are generally distributed in glaciated lakes across North America, typically selecting depths with minimum light, minimum temperature, and maximum dissolved oxygen (Dadswell 1974). Only light is relevant as 18°C and 2 $mg.L^{-1}$ oxygen were tolerated by mysids. The selected light ranged from 3 to 4 times Secchi depth, which lies between the lines marked "sensible" and "0.1" (Figure 16). A Secchi depth of 4.2 m implies that mysids will be available to trout at 12 to 16 m depth. Transparency of less than 4.2 m may be sufficient in early summer or small lakes since the thermocline is shallow. However, as the Secchi depth decreases in mid-summer and/or the thermocline deepens in mid-summer and in larger lakes, mysids may not be available at suitable depths in lakes with lower transparency.

Given a need for temperatures below 15°C, these visual requirements may restrict lake trout. Lake trout may require clearer water in lakes with deeper thermoclines than in lakes with shallower thermoclines. Predictions based on the volume of suitable temperature-and-visibility conditions (similar to temperature-oxygen criteria above) may be useful.

Shield and non-shield criteria

The evaluation of differences between these two arbitrary regions was particularly instructive. The 5 to 40-fold differences in water area, volume, and temperature-oxygen volume criteria remained essentially unexplained on the basis of possible anomalies in the lake set. Assessments of non-shield lake representativeness, small-sample criteria, latitudinal gradients within the shield area, and trends in temperature-oxygen restrictions were consistent. Results suggested collectively that differences in water area, volume, and temperature-oxygen criteria were not likely due to so-called anomalies of lakes in this study. The analyses are interpreted to indicate greater habitat variability in the non-shield area in recent or post-glacial periods, or lack of access to southern and central Saskatchewan during immigration of lake trout.

One notable anomaly was that the incidence of lake trout lakes in small samples influenced the supposedly robust criteria. The small-sample criteria shifted away from the characteristics of the over-represented class, sometimes considerably. A similar over-representation of "acidified" lakes caused Beggs et al. (1985) to predict more extinctions of lake trout in Ontario than a more representative data set suggested. This artifact re-emphasizes the importance of random lake surveys (Knoke 1983 p.192), particularly in the region of overlap between classes (see Validation and Extrapolation).

Recent habitat conditions

Drought conditions which may have caused differences between shield and non-shield lakes for lake trout, were only partially confirmed for available lakes. Furthermore, the process used by various agencies to select lakes for collection of both waterlevel data and lake morphometry is unknown and unquantifiable. Thus, it is uncertain that the results are representative for all lakes.

Increasing waterlevel variations with larger lake area and significant differences in the relationships of shield and non-shield lakes were both observed. A plausible explanation would be a general correlation between lake area and drainage basin area (see Gorham 1958, Brunskill and Schindler 1971, data in Demers 1974, and Minns 1984). This may expose larger lakes to greater and/or more prolonged regional climatic variations. Presumably this correlation or climatic variation differs between shield and non-shield areas.

Waterlevel variations do not appear sufficient by themselves to account for observed differences in lake trout criteria. Variations were typically less than 1.0 m in the last 100 years in both shield and non-shield lakes (Figure 6). Although non-shield lakes generally have greater variation, as hypothesized earlier, there is considerable overlap with shield lakes.

Morphometry likewise seems to play a minor role in the observed differences in lake trout criteria in shield and non-shield lakes. The hypothesized tendencies of more shallows in small and non-shield lakes are generally confirmed. This is interpreted to mean that a smaller average volume is needed in shield lakes to maintain lake trout populations during years of low waterlevel. The effects of combined waterlevel and morphometric differences seem smaller than necessary.

Shield and non-shield lakes of 10 to 100 km^2 area lose only 2 to 3 % and 3 to 6 % of volume during extreme low summer waterlevels, respectively (see Appendix F). This seems negligible since only 1.5-fold out of a total 6.4-fold difference in volume criteria can be explained on this basis.

The conclusion that waterlevel variations and morphometric differences had negligible effects on lake volumes is at odds with anecdotal and survey records in some non-shield lakes. In saline lakes of south-central Saskatchewan (i.e. 50^o to 54^oN), salinity increased 1.7 to 3.7 % annually from pre-drought 1920-1925 to drought 1937-1941 periods (Rawson and Moore 1944). Assuming that these changes reflect solely decreases in lake volume, it appears that volumes declined 19.6 to 49.4 % in two decades.

The discrepancies between estimates from salinity and from the present study arise for several reasons. Firstly, few waterlevel data were available from pre-1950, so that climatic extremes of the late 1930s may not be well represented in this study. Nonetheless, the common perception of the 1930s drought as unique is based largely on the socio-economic upheavals. Actual hydrological conditions have been as severe in more recent periods (Findlay 1981) and the mid-1960s specifically were relatively dry (Environment Canada 1986, Rutherford 1970). Secondly, the assumption of direct correlation between lake volume and salinity is simplistic. Increases in dissolved solids depend on precipitation, evaporation, ratio of lake volume to area, concentrations in inflowing water, and rate of water exchange (Rawson and Moore 1944). A widespread correlation between higher TDS and lower-than-average streamflow, as found by Rutherford (1970), inflates estimates of changes in volumes. Thirdly, the lakes cited by Rawson and Moore (1944) were noteworthy partly because of their large changes. These were primarily lakes of internal drainage basins, all with salinities over 5,000 $mg.L^{-1}$ (Rawson and Moore 1944, Rutherford 1970, Liaw and Atton 1980). They may reflect conditions in the 30 % of Saskatchewan south of 54^{o} which is internal drainage (Last and Schweyen 1983), but not other non-shield lakes. Freshwater lakes in central forested areas were much less variable in salinity, although waterlevels changed considerably (Rawson 1957a, 1958).

Post-glacial conditions

Lake trout migrated into Saskatchewan following deglaciation from a Mississippi refugium between 12,000 and 9,500 years ago (Stewart and Lindsey 1983, Teller *et al.* 1980), contemporaneously with Phases 4 and 8 of Christiansen (1979) although his dates differ. Evidence from post-glacial vegetational patterns show serious climatic changes, particularly warmer and drier conditions farther north than today (Ritchie 1976). "Prairie" conditions reached their maximum extent about 6,500 years ago and moved southerly to their present position by 2,500 years ago (Ritchie 1976). Direct paleolimnological information is more limited (Ritchie 1983, Wilson 1981), but indicates that over a large part of the prairies "probably only the largest and deepest lakes retained water" (Delorme 1965 p.109).

If lake trout immigrated earlier, they had access to most of the study area *via* ice-marginal lakes (see Christiansen 1979) and pro-glacial water, but faced extirpation in many of the smaller lakes. If they immigrated later, dispersal was limited to a much smaller part of the study area, but climate remained more favourable. Later immigration may have led to more frequent colonization of larger lakes than smaller, if water connections to smaller lakes were no longer extant.

The differences between shield and non-shield lake criteria strongly suggest that immigration and/or climate were important factors of lake trout status. Evaluation of the relative importance of these post-glacial factors would be difficult for several reasons. (1) The regions of immigration and climate are highly correlated. Very few lakes show either earlier deglaciation and less severe climate or later deglaciation and more severe climate. (2) Climatic effects show local anomalies due to site-specific factors. A uniform shift in vegetation zones " ... seems overly simplistic [in light of] local variations in topography, relief aspects, elevation, hydrogeology, and soils" (Vance *et al*. 1983 p.374). The paleolimnology of lakes would be at least as sensitive to specifics such as depths, winds, and seasonal temperatures. (3) Dispersal routes depend on glacial re-advances, spillway connections (Stewart and Lindsey 1983), and intermittent headwater connections (Legendre and Legendre 1984). Only major examples of these have been mapped in central Saskatchewan (Christiansen 1979).

Multivariate criteria

Depth and water area The 86 % accuracy of the sedimentation model of Hilton (1985) in predicting lake trout was very impressive. Both the model and my assessment used idealized conical lake basins rather than individual lake morphometries and used fetch derived from lake area rather than actual "effective fetch" (Smith and Sinclair 1972). This undoubtedly reduced the precision of the criterion to some degree.

Wave action in large deep lakes (model PWA of Hilton 1985) occurs periodically during open water and predicts a negative accumulation of sediments in shallower areas. Autumn overturn in small deep lakes (model ICM) occurs annually about the time of lake trout spawning, and removes sediments at least temporarily (Hilton 1985). The cleaning of spawning sites is an important factor in lake trout egg survival (e.g. Machniak 1975, Sly 1984, Nester and Poe 1984), perhaps more important in small lakes than stratification. Most lakes in the ICM zone did not have lake trout present and yet most were "moderately" or "strongly" stratified (Figure 9). The absence of clean spawning sites in lakes under 5 km^2 may be limiting in spite of acceptable thermal conditions. Confirmation would require data on lake bottom slopes, presence or absence of sedimentation, and minimal amounts of spawning area needed by lake trout populations. This may not disprove the alternative explanation of a required minimum number of mature lake trout, which cannot be met in very small lakes (see Temperature - Oxygen above). The low incidence of walleye in small lakes may similarly be due to lack of cleaning action (Johnson et al. 1977) but remains unproven.

As wave action is shallower in lakes with shorter fetches

(Wetzel 1983, Smith 1979), this model predicts that spawning may range over a greater proportion of lake depth in larger lakes and be more restricted proportionally in smaller lakes. Wave action extends to 9.0 m in a 50-km^2 and 4.5 m in a 5-km^2 lake (from Figure 4 in Smith and Sinclair 1972), or possibly 18 m and 9 m if sediments are very soft (Hilton 1985). In practice, the depth of the thermocline averages 16.5 m and 10.2 m in 50-km^2 and 5-km^2 shield lakes (Cruikshank 1984). Machniak (1975) suggested that larger, deeper lakes contain more area suitable for spawning due to greater currents and wave action. Martin (1957) noted that "In general, spawning becomes deeper with increasing lake size probably because of deeper shoals and greater wave action". The prediction of potential spawning sites from wave models and depth contours could follow the example of Smith and Sinclair (1972 p.395). Spawning sites are known for Lac la Ronge, Hunter Bay, Whelan Bay, Crean, and other lakes.

Multiple discriminant analysis Stepwise rankings of variables in discriminant analyses showed that Secchi transparency (SECCHI) and minimum volume of suitable temperature (VOLT15T6) were consistently useful (Table 19). When both were available, no other depth, volume, or temperature-oxygen index was selected. VOLT15T6 was ranked more highly than volumes of suitable oxygen or temperature-oxygen in direct comparisons.

Using discriminant analysis, Hamilton et al. (1980) suggested that mean depth and morphoedaphic index (i.e. MEI = TDS / ZBAR) were more important than Secchi transparency or lake volume in 389 Ontario shield lakes. Nonetheless, higher MEI was associated with lake trout presence, which suggested that other factors should be considered (Hamilton et al. 1980) and that caution is in order in any comparison. The dominance of Secchi transparency and mean depth in the large-scale study of Johnson et al. (1977) has been discussed. Neither of these studies used temperature-oxygen volumetric data comparable to VOLT15T6 or VOLT15O6.

The accuracy of classification by MDA was good at 88 to 98 % (Table 20), but lower than expected and typically no better than univariate criteria. The reason may be partly the unmet statistical requirements of MDA. The requirements of normality of variables, equal covariances of classes, known class status, and random observations are all violated to some degree, as in many studies (Lachenbruch 1975, Dillon 1979, Solberg 1978, Johnson et al. 1977). The collective effect has not been evaluated statistically in this study.

A more interesting consideration is that some variables (e.g. VOLT15T6) may singly represent the suitability of lakes for lake trout. This can be seen in terms of both the statistical behaviour of variables and limnological behaviour. In multivariate data sets with low to moderate correlation, each additional variable frequently contributes negligible additional separation of classes (Lachenbruch 1975). The correlations must be large and positive (or negative) to overcome this effect. The moderately to highly correlated variables in this study should succeed, but the lack of improved predictions indicates otherwise. Limnologically, the volume of suitable temperature and oxygen is inter-related with depth, water area, fetch, and others. These factors determine the total lake volume, the influence of river inflows on incipient stratification, and the persistence and depth of any thermocline (see Estimation of missing data), for which VOLT15T6 is the final index.

Non-parametric MDA has fewer of the above restrictions, but did not clearly predict lake trout presence or absence more accurately. The use of fewer or more than five nearest neighbours was not examined, although this may show *ad hoc* improvements in accuracy (SAS 1987). One major disadvantage of non-parametric MDA is that the entire initial data set must typically be used to classify new observations. However, if the multi-dimensional surface which delineates the classes is expressed polynomially, it can be used (Lachenbruch 1975).

Estimation of missing data

The estimation of useful predictors from more-or-less correlated variables was more complex and less successful than planned. Even clear-cut relationships such as that between TDS and specific conductivity required adjustments for different methodologies.

The advantage of some estimations may not be obvious in the present data set: SPCON is available in fewer lakes than its correlate TDS. Yet SPCON can be measured electronically in the field rather than gravimetrically later in the lab, with the attendant problems of preservation. Others simply delimit certain behaviour: Estimated TMAXS shows that very few lakes are expected to have maximum surface temperatures below 15°C. Other estimations are relatively complex: Estimations of VOLT15T6 and VOLT15O6 were complicated by the uncertainty of thermal stratification and the complexity of oxygen behaviour.

The advantage of others is obvious: Secchi transparency is an excellent predictor of lake trout presence. Furthermore, it is easily measured in the field or is estimable from remotely sensed LANDSAT satellite data (Middleton and Munday 1980). Correlation of actual and remotely sensed Secchi depth has been excellent in some studies (Chagarlamudi _et al_.

1978 cited in Alfoldi 1982). A large-scale project to estimate Secchi depth and other water-quality indices in lakes over 8 ha in Wisconsin was successful (Scarpace et al. 1978). The seasonal nature of Secchi readings (Scarpace et al. 1978), the number of data needed for required precision, and methods of calibrating satellite data using multiple dates within the data set itself (Alfoldi 1982) have been addressed. Still, water-quality indices tax not only the technology but also present analytical approaches of remote sensing (Alfoldi 1982).

TDS from SPCON Correlation of TDS with SPCON was well defined, as expected. Results were similar to published regressions:

log TDS = 0.17 + 0.88 log SPCON (present shield lakes),
= −0.09 + 0.96 log SPCON (present non-shield lakes),
= −0.18 + 1.00 log SPCON
(Schlesinger and McCombie 1983), and
= −0.35 + 1.05 log SPCON (Wetzel 1983 at 20°C).

Caution is advised if these regressions are extrapolated beyond 20 to 32,000 uS, particularly into more saline waters. The stoichiometry of major ions (e.g. carbonates, sulfates, calcium, and magnesium) may change at 200 $mg.L^{-1}$ (Ryder et al. 1974). Saskatchewan lakes change from carbonate-type to sulfate-type at TDS about 700 $mg.L^{-1}$ (Rawson and Moore 1944) and exceed 100,000 $mg.L^{-1}$ in areas (e.g. Last and Schweyen 1983, Liaw and Atton 1980).

SHODEV and RLOGSHOD The original use of SHODEV was as an index of the "potential effect of littoral processes on the lake, area being constant" (Hutchinson 1957). SHODEV is used in this study as an index of shoreline extent, depth, and wind protection. The stipulation of equal area has been frequently forgotten, although Koshinsky (1968 p.251, 1970) showed that SHODEV increases with increasing WAREA in Saskatchewan shield lakes. The regression for 152 shield lakes was similar to earlier studies:

log SHODEV = 0.384 + 0.250 log WAREA (present study)

= 0.408 + 0.237 log WAREA (Koshinsky 1970).

RLOGSHOD, the ratio of actual to expected SHODEV, appears to be a better index of shoreline extent than SHODEV itself, as suggested by Koshinsky (1970). This ratio contributed to predictions of maximum depth, volume of suitable temperature, and maximum surface temperatures. Lakes with many islands and/or particularly sinuous shorelines are shallower, less voluminous, and more sheltered from wind than other lakes of similar area (see Appendix G). A disadvantage of RLOGSHOD is that the measurement of shoreline length on most lakes is more difficult than many other morphometric variables, such as FETCH or ORINW. It does not appear in selected regressions only for this reason (Table 21).

ZMAX and ZBAR Maximum depth (ZMAX) is related to water area in Saskatchewan lakes (Liaw and Atton 1980, 1981; Koshinsky 1970), mean depth (ZBAR), and other morphometric factors (Zimmerman et al. 1983). The present estimates based on log WAREA and log FETCH, with or without RLOGSHOD and ORINW, were certainly significant (Table 21).

Several indices based on surficial geology (e.g. rocky, morainal, glaciofluvial, and organic material prevalence) did not improve estimations significantly (see Appendix G). This is counter-intuitive as lakes situated on organic plains ought to be shallower than those on moraine or glacially scoured rock. It may be that simplifications (e.g. condensing detailed map data) or errors (e.g. relative depth-potentials assigned to rock, morainal, and other materials) have obscured this effect. One alternative approach that merits attention would be to estimate depth from surrounding terrestrial topographic contours, using land areas proportional to lake areas. In this case, ZBAR may be a more stable index of topography than ZMAX. Koshinsky (1970) indicated that the observed higher ratio of ZMAX to ZBAR in larger shield lakes results from greater probability of anomalously deep spots in a region of generally low relief.

ZMAX affects sedimentation and stratification in relatively well defined ways (Hilton 1985, Gorham 1980). However, assessment of spawning substrate conditions and the presence of a hypolimnion requires, at the least, a field survey of each lake to determine maximum depth. ZMAX cannot be estimated with the precision required to reliably predict sedimentation and stratification.

STRAFN The prediction of stratification using ZMAX and WAREA or FETCH considers only morphometry and wind-generated turbulence. The existence of a thermocline affects the transfer of heat, maximum surface temperatures, and heat storage capacity of a lake (Ragotzkie 1978, Zimmerman *et al*. 1983).

Stratification is also dependent on the rate of water exchange in more-or-less "riverine" situations. The Froud index of relative flow-through (Orlob 1983) explains the observed non-stratification of several lakes which morphometrically ought to stratify. The sequential use of both Froud and morphometric criteria not only improves the accuracy of predictions, but is presumably suitable to a wider range of lake conditions. Hydrological models relating seasonal discharge to watershed area, regional precipitation, and other conditions (e.g. Rochelle *et al*. 1988), would be particularly useful for extrapolation. There are only about 36 active and discontinued streamflow gauging stations in the shield region of Saskatchewan (Environment Canada 1983). The need for actual ZMAX in both Froud and morphometric criteria is also a definite constraint in assessing unsurveyed lakes.

The behaviour of the maximum depth of 15°C was similar to that of the thermocline in other studies. The present explanation of 74 % of variation compares to explanations of 36 to 85 % (Shuter et al. 1983, Patalas 1984, Cruikshank 1984) of thermocline or epilimnion depth using morphometry. The influence of fetch and the notable contribution of the NW-component of fetch (Appendix G), imply a dependence on wind-driven mixing as in thermocline formation. Greater fetch, which tends to be correlated with water area, volume, and maximum and mean depths, allows for greater mixing depth by wind-generated waves (Smith and Sinclair 1972). Other factors such as surface water temperature, wind speeds, local topography, and patterns of stratification are also relevant (Arai 1981, Patalas 1984, Zimmerman et al. 1983).

In stratified lakes, log WAREA and TMAXS were necessary for predictive-quality equations; most other regressions were only marginally acceptable (Hocking 1976)(Appendix G). Surface water temperatures may modify the thermocline depth by 10 to 30 % (Patalas 1984). Higher temperatures increase stability of the metalimnion and reduce the mixing depth (Arai 1981).

The depth of 15°C in non-stratified lakes is less predictable and few studies address non-stratified lakes successfully. In his review of temperature simulation in single-lake studies, Orlob (1983 p.269) noted that "for larger water bodies [and] for those that are not strongly stratified, ... we shall require more realistic models". For these situations, multi-dimensional models which assess the longitudinal and lateral gradients as well as the vertical profile of temperature are needed (Watanabe *et al.* 1983).

VOLT15T6 Predictions of lake trout presence or absence were 88 % accurate on the basis of VOLT15T6' or minimum volume of suitable temperature (Table 11). It appeared that this criterion might be estimable from water area, fetch, and air temperature (Arai 1981, Patalas 1984), but this was complex.

Regressions of log VOLT15T6 on morphometry and climate were excellent for non-riverine lakes with non-zero volume of 6 to 15°C water (Table 21). This class of lakes can be defined if ZMAX and June discharge (i.e. for the Froud index) are known. Regressions using WAREA, SECCHI, RLOGSHOD, and/or TMAXS were marginally acceptable for prediction. This implies that estimation is acceptable for lakes similar to this data set, but is not suitable for outlier lakes with unusual conditions (Hocking 1976). Estimations using only WAREA and FETCH were not acceptable statistically in comparison to other regressions using more variables (see Appendix G), but use easily available data. Non-zero VOLT15T6 was estimable in all lakes, even without knowledge of ZMAX or June discharge.

VOLT15T6 was poorly predictable based on status of stratification. This is perplexing as stratification creates a major dichotomy in thermal behaviour. The poor predictability may arise because "stratification" in this study was a subjective evaluation of the entire lake during mid-summer. By contrast, "VOLT15T6" was objectively based on conditions at the point of deepest known depth over the open-water survey period.

VOLT15O6 VOLT15O6 is a better predictor than VOLT15T6, but estimation of the magnitude of VOLT15O6 was not attempted as studies have shown that modelling is far more complex for oxygen than temperatures (e.g. Lasenby 1975, Watanabe et al. 1983). "Unlike temperature, variation in [dissolved oxygen] concentration within the water column may be brought about by an array of factors, not all of which are forced from the surface, and many of which are difficult to describe in a complete way" (Patterson et al. 1985).

Secchi transparency was a good predictor of the existence of suitable temperature and oxygen. In shield lakes, Secchi depth may be generally related to under-saturated oxygen conditions (Wetzel 1983 p.175). The best estimation of suitable VOLT15O6 may be Secchi depth (Appendix G), but the SECCHI criterion of lake trout status is more accurate (Table 11). This suggests that transparency used directly is the best predictor which does not require a detailed survey. Thus we have come full circle from the proximate cause, which is believed to be temperature and oxygen, to reliance on transparency if we wish to minimize actual fieldwork or use auxiliary data from remote sensing.

Marginal habitat and abundance

The difficulty with assessing marginal habitat stems from defining what seems very clear intuitively. Two definitions emerged as useful: (1) Minor errors within ± 10 % of the criterion indicate marginal habitat, so that lake trout may reasonably be lacking or present. These errors also allow for statistical imprecision of the criterion itself in a general way. (2) Major errors indicated poor accuracy by specific habitat variables, a need for further fish collections (Dadswell 1974), and/or anomalies such as lack of post-glacial immigration routes, presence of transients in unsuitable habitat, or population extinction in suitable habitat.

Some lakes must be deemed marginally suitable for trout if one accepts that clarity, cool temperatures, and/or abundant oxygen are requisite. These include Lac Ile-a-la-Crosse, Nemeiben, and Namew lakes. Lac Ile-a-la-Crosse has restricted area of suitable depth, low transparency, high benthic fauna, and only minor commercial harvests of lake trout (Saylor 1972). Nemeiben Lake is suitable over a small proportion of its area, in which all harvests by survey nets and all known lake trout fishing occurs (Koshinsky 1964). Namew Lake is similar, with the few, large lake trout which are frequently notable in extreme or variable environments (Reed 1959). Some intuitively suitable lakes have no natural lake trout. The most notable is Whelan Bay, for which all criteria predict lake trout and which presently supports a self-reproducing population and an intensive sport fishery based on only 4 years of moderate stocking of fry (Murray 1979).

Nonetheless, it appears that presence/absence data and/or the definitions used do not delineate a group of lakes in which habitat is distinctly distinguishable as marginal. Rather, habitat seems to form a continuum of suitability. Data on relative species compositions or lake trout abundance specifically may confirm this indication.

Validation and extrapolation

The accuracy of most criteria on the 68 test lakes was acceptable. Final criteria for all 330 lakes were within ± 10 % of preliminary ones, which suggests that most were stable predictors at least in shield lakes in Saskatchewan. Some authors reserve "validation" for tests on independent sets of data (Beck 1983). The reserved test lakes are independent, and an additional 50 or more lakes are available in provincial and consultant studies since 1982. Predictions of lake trout presence/absence in sets of 9,000 lakes in Ontario (Beamish et al. 1976, Minns 1986), about 80 lakes in the Northwest Territories (Falk 1979, Moshenko et al. 1980), 91 lakes in the Yukon (Lindsey et al. 1980), or elsewhere would be interesting.

Validation on lakes which are more representative of small and very small lakes and their species compositions would be more useful. By their nature, environmental baseline or impact assessment studies for mine, road, or powerline development (Koshinsky 1968, Beak 1979, Beak 1980) can be less selective than most resource management surveys. The adjustment of lake sets for incomplete and preferential surveys is essential for extrapolation, yet difficult. Random selection of lakes without regard for species composition would include many non-inhabited lakes. Surveys complete with detailed morphometry and seasonal trends in temperature and oxygen profiles are demanding of staff and time. They will likely remain unrepresentative of very small lakes, particularly those lacking preferred species, as noted elsewhere (Minns 1986).

One technique to reduce bias involves assigning lake trout status in lakes with unknown species. The initial classification rule is used, and then a new rule is estimated for the new, larger set. McLachlan (1975) showed that the second rule produces a lower error rate, and that one iteration usually suffices. This approach has been recommended but seldom used (Solberg 1978), and might be effective in cases of non-random sampling of lake trout status.

The presumed preferences for lake trout of 6, 4, and 2-fold are much less than reported in the only known study. Preferences were estimated at 32-fold for lake trout and 16-fold for walleye in 8,900 Ontario lakes (Minns 1986), assuming (i) that lake surveys mimicked a selective predation model, and (ii) an "exhaustive search" revealed all lake trout and walleye lakes. However, the converse approach of estimating the number of lake trout lakes was not suitable since this number was sensitive to the approximation (Minns 1986) in the model. The present study uses conservative, subjective preferences to estimate the number of lake trout lakes. More objective preferences might be possible from independent opinions of resource managers who proposed or selected Saskatchewan lakes for surveying since 1930.

Extrapolation relies on the joint probability of habitat x and the presence of trout given habitat x. The probability of lake area or log VOLT15T6 is essentially a numerical exercise, but the probability curves of lake trout are open to interpretation. Using the frequency distribution of log VOLT15T6 and zero to 6,4,2-fold preferences towards lake trout lakes, the total number of lake trout lakes in the shield region of Saskatchewan is about 320 to 160 lakes over 6.6 km^2. There are fewer than 1460 to 180 smaller lake trout lakes. The total number of lake trout lakes represents between 2 and 0.4 % of shield lakes in Saskatchewan. This is similar to the assumed 1 % occurrence in Ontario (Minns 1986), the only known comparison.

CONCLUSIONS

1. Lakes with and without lake trout differed significantly in 42 of 50 habitat variables available from lake surveys. Within the shield and non-shield regions, these classes differed in 35 and 31 traits, respectively.

2. Prediction of lake trout status was correct for 75 % or more of the lakes for 27 variables. In the shield region, many good criteria were temperature and oxygen indices; two variables achieved 90 % or better accuracy. In the non-shield region, good criteria related to location, morphometry, and temperature and oxygen; three variables achieved 90 % or better accuracy.

3. Non-shield lakes appeared to require 5 to 40-fold greater minimum area, volume, and volumes of suitable temperature and oxygen than shield lakes in order to have lake trout.

(a) Some of this difference was due to the effects of small sample sizes and non-random selection of lakes.

(b) Some may be due to greater variability of lake volume in non-shield lakes than shield lakes in the last 100 years. Greater waterlevel variations and generally shallower depths of non-shield lakes result in significantly less habitat during low-water periods than shield lakes.

(c) Effects of post-glacial immigration and/or climate are thought to be considerable in the non-shield region. Later immigration by lake trout may have, and the warmer and drier post-glacial climate would have, caused fewer occurrences of lake trout in smaller lakes in the southern part of the study area. The northern shield region per se coincides with the area which was least affected by either factor.

4. In shield lakes, lake trout need a minimum of (i) 2.2 hm^3 water below 15°C and above 6 $mg.L^{-1}$ oxygen (96 % accuracy of classification), or (ii) 10.3 hm^3 water between 6 and 15°C (88 % accuracy), during summer. The available volume is believed to determine population survival during a critical period, which may be relatively brief.

5. The minimum volumes of water of suitable temperature and/or oxygen may relate observed densities of lake trout to a maximum density during a critical period, and to a presumed minimum number of lake trout for population survival. The few shield lakes for which data are available have a maximum of 300 mature lake trout per hm^3; the threshold volumes indicate about 600 to 900 mature lake trout per lake.

6. In shield lakes, maximum depth of 31.2 m or greater predicts lake trout status with 92 % accuracy. However, its importance is believed to be due to its influence on temperature, oxygen, or sediment distribution. Clearing of

spawning areas by periodic wave action is essential, and is predictable from simple wave models using depth and fetch. The effect of depth on winter oxygen conditions was not evaluated.

7. In shield lakes, mean summer Secchi transparency of 4.2 m or greater predicts status with 88 % accuracy. More specifically, lake trout may depend on light sufficient for vision (about 1.0 meter-candle) or light sensible to lake trout visual pigments (i.e. 510-540 nm wavelength) extending into the zone of suitable temperature. The lower boundary of vision by lake trout is theoretically:
log (sensible depth) = 0.450 + 1.200 log (Secchi depth).

8. Multiple discriminant analysis showed that Secchi transparency and minimum volume of water of 6 to 15°C (VOLT15T6) contributed strongly and consistently to predictions, more so than all other criteria. Other studies have shown the importance of transparency, but have not evaluated volumetric temperature (or temperature and oxygen) indices in relation to presence and absence.

9. Several good criteria of lake trout status can be estimated from easily available data.
(a) maximum depth (ZMAX): Reasonable predictions from water area (WAREA) and fetch, but these are unreliable for use in

sedimentation or stratification models.

(b) stratification (STRAFN): Good predictions using morphometric and river flow-through concepts. These required ZMAX and FETCH and Froud index (FETCH, ZBAR, VOLUME, and river discharge) data, respectively.

(c) minimum volume of 6-15^{o}C (VOLT15T6): Good to excellent predictions in lakes with non-zero VOLT15T6. Good to excellent predictions if riverine lakes are excluded by Froud index and if non-zero VOLT15T6 is assumed, which leads to over-estimation of suitability of some lakes.

10. Lake surveys are generally not representative of water areas or TDS of Saskatchewan lakes, particularly very small (<10 km^2) or low-TDS (<50 mg.L^{-1}) lakes. Corrections for preferential surveying of larger lakes and lakes with lake trout present are essential for extrapolation to the total number of lake trout lakes.

11. There are an estimated 320 to 160 lake trout lakes over 6.6 km^2 in the shield region of Saskatchewan. Numbers of smaller lake trout lakes are less precisely known (1480 to 180 lakes).

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Appendix A

LAKE NAMES, LOCATIONS, AND DATA REFERENCES

Table A1. Names, locations, general descriptions, and sources of data for lakes in this study.

Lake name	Location °N	Location °W	Lake trout	Water area (km^2)	TDS ($mg.L^{-1}$)	References	
ALTHOUSE	5530	10450	X	0	.	2	.
AMISK	5435	10215	LT	321	94	22	23
AMISKOWAN	5353	10608	X	0	145	95	101
AMYOT	5342	10638	X	4	1201	95	.
ANNABEL	5450	10210	X	12	70	18	.
ATHABASCA	5915	10915	LT	7899	.	21	22
ATTITTI	5532	10228	LT	27	.	24	.
BALDHEAD	5526	10452	X	0	.	2	.
BALDY	5406	10438	X	0	.	98	.
BALLANTYNE BAY	5440	10324	X	271	94	72	.
BARTLETT	5530	10459	LT	5	.	2	.
BEAVERLODGE	5930	10835	LT	48	186	96	.
BEETLE	5357	10626	X	0	65	95	.
BELCHER	5515	10232	LT	18	.	24	.
BESNARD	5525	10600	X	177	60	39	.
BEWLEY	5349	10212	X	8	215	41	.
BIELBY	5532	10448	X	1	.	2	.
BIG	5352	10215	X	10	260	41	.
BIG PETER POND	5555	10844	X	552	137	3	.
BIG SANDY	5427	10505	X	80	190	18	.
BIGSTONE	5504	10524	X	19	142	90	100
BIRCHBARK	5338	10219	X	3	4060	41	.
BIRCHBARK	5333	10507	X	12	495	58	.
BITTERN	5358	10550	X	31	.	8	.
BLACK	5449	10201	X	0	95	18	.
BLACK	5912	10515	LT	445	10	19	20
BLACK	5712	10542	X	.	26	68	.
BLACK FOREST	5710	10538		.	26	68	.
BLOODSUCKER	5352	10233	X	15	245	41	.
BOG	5346	10210	X	10	255	41	.
BRABANT	5600	10343	X	52	58	25	.
BROACH	5743	10922	LT	10	31	1	.
C1	5819	10402	X	1	23	74	.
CABIN	5356	10644	X	0	154	95	.
CAMP ONE	5341	10613	X	0	279	95	.
CANDLE	5350	10520	X	129	235	30	.

continued

Table A1. continued.

Lake name	Location °N	Location °W	Lake trout	Water area (km^2)	TDS (mg.L^{-1})	References	
CANOE	5510	10815	X	211	175	26	.
CARSWELL	5837	10920	LT	36	144	42	43
CHEESEMAN	5350	10217	X	2	225	41	.
CHEEYAS	5423	10604	X	3	52	70	.
CHURCHILL	5555	10820	X	433	136	3	.
CLAM	5519	10543	X	42	51	28	.
CLEARSAND	5350	10534	X	9	.	8	88
CLUFF	5822	10934	LT	3	84	42	43
COLD	5433	11000	LT	348	.	36	37
CONTACT	5525	10452	LT	4	55	13	.
COSTIGAN	5657	10555	LT	57	47	38	.
COTE	5527	10453	X	0	.	2	.
COW	5350	10229	X	2	305	41	.
COWAN	5400	10715	X	32	412	33	.
CREAN	5405	10609	LT	104	.	8	10
CREE	5730	10630	LT	1155	.	4	.
CROSS	5400	10204	X	2	.	41	.
CUMBERLAND	5405	10218	X	246	190	40	.
CUT BEAVER	5347	10239	X	33	215	41	.
CYCLOID	5515	10516	X	0	.	2	.
DAN	5707	10546		.	20	68	.
DAVIN	5650	10340	LT	64	33	29	.
DAVIS	5552	10420	LT	12	30	25	.
DEEP	5350	10234	X	6	235	41	.
DELARONDE	5358	10658	X	135	221	31	.
DES ILES	5426	10925	X	46	.	35	.
DESCHAMBAULT	5442	10334	X	267	109	72	.
DICKENS	5544	10437	LT	7	39	25	.
DIETER	5713	10539		0	22	68	.
DORE	5446	10717	X	616	190	7	.
DOUGLAS	5712	10541	X	0	28	68	.
DOWNTON	5508	10514	X	0	.	34	.
DRINKING	5524	10412	X	16	126	44	.
DROPE	5526	10428	X	10	.	75	.
DUCK	5522	10456	X	0	.	2	.
DUPUEIS	5420	10432	X	1	.	98	.
EAST TROUT	5422	10505	LT	25	130	45	.
EGG	5353	10220	X	15	265	41	.
ELAINE	5427	10621	X	6	157	49	.
ELK	5341	10617		0	141	95	.
ELM	5344	10153	X	5	1360	41	.
FAFARD	5613	10306	X	14	34	94	.
FAIRY GLEN	5405	10446	X	0	.	98	.
FISH	5340	10610	X	1	462	95	101
FIVE FINGERS	5526	10457	X	1	.	2	.

continued

Table A1. continued.

Lake name	Location °N	°W	Lake trout	Water area (km²)	TDS (mg.L⁻¹)	References	
FLOTTEN	5437	10832	X	24	210	79	.
FONTAINE	5942	10627	LT	67	22	48	.
FRANK	5714	10539		.	25	68	.
FRED	5714	10536		0	.	68	.
FREDETTE	5937	10832	LT	6	111	96	.
FROBISHER	5625	10830	X	313	79	3	.
GEDAK	5743	10926	X	2	40	1	.
GERALD	5713	10541	X	.	54	68	.
GERMAINE	5819	10935	X	0	.	43	.
GILES	5855	10548	X	33	.	19	20
GILLINGHAM	5448	10251	X	1	70	18	.
GOOSE	5336	10230	X	13	29440	41	.
GRACE	5358	10431	X	0	.	98	.
GRANITE	5455	10232	X	12	.	55	.
GREEN	5410	10743	X	29	256	52	.
GREIG	5427	10843	X	16	300	15	.
HACKETT	5405	10657	X	9	218	53	.
HALKETT	5339	10608	X	10	276	8	87
HAMELL	5448	10157	X	2	80	18	.
HAMMER	5711	10538		0	.	68	.
HANNAH	5906	10335	LT	45	21	69	.
HANSON	5442	10250	LT	42	90	55	.
HARBO	5744	10925	LT	3	27	1	.
HARRISON	5749	10929	LT	6	24	1	.
HATCHET	5830	10340	LT	134	23	51	.
HAUGEN	5532	10450	LT	1	.	2	.
HEART	5359	10611	X	1	168	95	101
HEBDEN	5528	10448	LT	5	45	13	.
HENDAY	5819	10413	LT	.	17	74	.
HIGHBANK	5352	10227	X	8	265	41	.
HIGHROCK	5704	10530	LT	89	21	54	.
HINE	5531	10449	X	1	.	2	.
HIRTZ	5429	10949	X	2	335	79	.
HODGE	5748	10924	LT	5	29	1	.
HORSEFLY	5712	10537		0	.	68	.
HOURGLASS	5712	10540	X	0	37	68	.
HUNTER BAY	5510	10430	LT	129	112	5	60
ILE A LA CROSSE	5541	10745	X	414	180	56	.
ISKWATAM	5534	10304	X	20	92	94	.
ISLAND	5821	10939	X	2	52	42	43
ISPUCHAW	5400	10441	X	1	.	98	.
JACKFISH	5304	10824	X	75	1735	61	.
JAN	5455	10253	X	114	90	72	.
JEANNETTE	5433	10832	X	4	195	79	.
JEEP	5356	10633	X	0	84	95	.

continued

Table A1. continued.

Lake name	Location °N	Location °W	Lake trout	Water area (km²)	TDS (mg.L⁻¹)	References
JOHNSON	5452	10215	X	7	85	18	.
JUNCTION	5349	10227	X	4	245	41	.
KARL ERNST	5713	10539	X	0	.	68	.
KATHY	5714	10537		0	30	68	.
KEELEY	5455	10808	X	90	160	65	.
KEG	5524	10403	X	24	110	44	.
KENNEDY	5335	10255	X	18	300	41	.
KEWEN	5811	10351	X	3	.	74	.
KEY	5713	10537	X	2	23	68	.
KIMBALL	5425	10849	X	3	345	16	.
KINGSMERE	5406	10627	LT	47	.	8	10
KINIKINIK	5713	10538		0	.	68	.
KIRCHNER	5713	10539		.	25	68	.
KISTAPISKAW	5450	10243	X	3	80	18	.
KUSKAWAO	5527	10453	X	0	.	2	.
LA LOCHE	5628	10930	X	206	175	66	.
LA PLONGE	5510	10725	LT	197	92	27	.
LA RONGE	5510	10500	LT	1178	130	5	60
LAVALLEE	5417	10634	X	24	.	8	88
LEADLEY	5421	10604		1	.	70	.
LEPINE	5428	10937	X	3	145	79	.
LIMESTONE	5438	10313	X	36	140	18	.
LINDSTROM	5522	10327	X	11	61	99	.
LITTLE AMYOT	5511	10750	X	3	83	57	.
LITTLE BEAR	5420	10435	LT	15	144	64	.
LITTLE DEER	5524	10455	X	4	55	13	.
LITTLE MCDONALD	5711	10537		0	.	68	.
LITTLE PETER POND	5555	10844	X	189	144	3	.
LITTLE RASPBERRY	5424	10848	X	1	435	79	.
LITTLE SANDY	5356	10509	X	3	185	58	.
LOBSTICK	5340	10207	X	4	420	41	.
LOST	5402	10609	X	2	.	95	101
LOST ECHO	5408	10445	X	1	.	98	.
LOWER FISHING	5403	10439	X	3	215	50	.
LOWER FOSTER	5635	10520	LT	41	23	47	.
LOWER KEY	5714	10537		0	25	68	.
LOWER SEAHORSE	5712	10541	X	1	26	68	.
LUSSIER	5535	10448	X	0	.	2	.
LYNX	5521	10458	X	2	.	2	.
MACKAY	5527	10456	LT	8	60	13	.
MACLENNAN	5427	10619	X	2	91	70	.
MANAWAN	5524	10314	X	66	48	99	.
MARTIN	5720	10538	X	6	19	68	.
MATHESON	5425	10856	X	3	235	79	.
MCBRIDE	5451	10205	X	2	80	18	.

continued

Table A1. continued.

Lake name	Location °N	°W	Lake trout	Water area (km^2)	TDS ($mg.L^{-1}$)		References
MCCLEAN	5815	10353	X	2	23	74	.
MCCOMB	5532	10449	X	0	.	2	.
MCDONALD	5712	10535	LT	3	22	68	.
MCINTOSH	5545	10510	LT	61	40	81	.
MCLENNAN	5554	10420	LT	21	34	25	.
MCMAHON	5820	10404	X	2	17	74	.
MCNICHOL	5529	10440	X	1	.	2	.
MEADOW	5333	10245	X	11	265	41	.
MEKEWAP	5524	10452	X	0	.	2	.
MID	5450	10238	X	0	85	18	.
MIDDLE FOSTER	5640	10525	LT	30	20	47	.
MIDWAY	5515	10520	X	1	.	2	.
MIDWEST	5820	10403	X	4	21	74	.
MILE 109E (CLUFF)	5747	10926		1	27	71	.
MILE 109W (CLUFF)	5747	10927	X	0	20	71	.
MILE 11(SMOOTHSTO	5422	10613		0	.	70	.
MILE 110 (CLUFF)	5748	10926		0	28	71	.
MILE 119 (CLUFF)	5754	10925		1	24	71	.
MILE 3 (SMOOTHSTO	5417	10559		0	.	70	.
MILE 8 (SMOOTHSTO	5422	10607		0	.	70	.
MILL	5822	10935		0	64	42	43
MILLIKEN	5927	10845	LT	10	117	96	.
MINTO	5753	10920	X	11	18	1	.
MIROND	5510	10249	X	108	90	72	.
MISTOHAY	5427	10905	X	6	235	79	.
MONTREAL	5420	10540	X	440	229	90	100
MOOSE JAW	5351	10237	X	1	280	41	.
MOUNTAIN	5529	10430	X	54	140	75	.
MULLOCK	5528	10452	X	0	.	2	.
MURISON	5752	10925	LT	9	14	1	.
MURPHY	5713	10540		.	17	68	.
MURRAY	5303	10818	X	12	940	61	.
MUSKEG	5349	10234	X	2	235	41	.
MUSTUS 1ST	5426	10849	X	4	230	79	.
MUSTUS 2ND	5426	10852	X	1	205	79	.
MUSTUS 3RD	5427	10853	X	3	200	79	.
NAMEKUS	5347	10601	X	7	180	8	12
NAMEW	5410	10157	LT	186	105	40	.
NANISKAK EAST	5526	10456	X	0	.	2	.
NANISKAK WEST	5526	10456	X	0	.	2	.
NEMEIBEN	5520	10525	LT	155	45	73	.
NESOOTAO EAST	5450	10204	X	1	70	18	.
NESOOTAO WEST	5450	10204	X	1	80	18	.
NIPEKAMEW	5424	10458	X	15	165	45	.
NISTOWIAK	5525	10420	X	28	.	75	.

continued

Table A1. continued.

Lake name	Location °N	°W	Lake trout	Water area (km^2)	TDS ($mg.L^{-1}$)	References	
NORDBYE	5904	10330	LT	42	30	69	.
NORTHEAST	5715	10533		.	21	68	.
NORTHWEST	5715	10542		.	18	68	.
O'LEARY	5351	10628	X	1	157	95	.
OTTER	5535	10439	X	53	146	75	.
OUROM	5536	10312	X	9	125	44	.
OWAA	5341	10610	X	1	338	95	.
PANP 1052	5354	10602		0	96	95	.
PANP 1069	5355	10630	X	0	40	95	101
PANP 1103	5356	10630	X	0	39	95	.
PANP 1138	5357	10615		0	213	95	.
PANP 1149	5358	10609		0	186	95	.
PANP 180	5337	10611		0	213	95	.
PANP 207	5337	10606	X	0	363	95	101
PANP 300	5342	10604		0	176	95	.
PANP 301	5342	10605		0	190	95	.
PANP 453	5349	10644		0	1513	95	.
PANP 601	5356	10633	X	0	139	95	.
PANP 785	5348	10604		0	208	95	.
PANP 841	5350	10629	X	0	132	95	101
PANTER	5356	10636	X	0	75	95	.
PAUL	5347	10234	X	1	250	41	.
PECHEY	5523	10454	X	1	.	2	.
PEITAHIGAN	5427	10857	X	3	295	79	.
PELICAN	5506	10301	X	100	95	72	.
PETABEC	5344	10211	X	4	280	41	.
PIERCE	5430	10942	LT	26	160	79	.
PIG 1ST	5817	10406		.	.	74	.
PIG 2ND	5817	10407		.	.	74	.
PIG 3RD	5817	10407		.	.	74	.
PINKNEY	5403	10505	X	2	70	58	.
PIPRELL	5409	10454	X	1	.	76	.
PITA	5533	10243	X	31	89	94	.
POTATO	5342	10207	X	9	1370	41	.
POULTON	5527	10454	X	0	.	2	.
PREVIEW	5525	10448	X	1	.	2	.
RANDALL	5436	10615	X	2	57	70	.
RAT NORTH	5344	10213	X	2	230	41	.
RAT SOUTH	5354	10213	X	3	245	41	.
REDEARTH	5331	10253	X	15	220	41	.
REINDEER	5715	10215	LT	5297	21	84	.
RICHTER	5526	10454	X	0	.	2	.
RIOU	5907	10625	LT	181	63	77	.
ROUND	5713	10538		0	.	68	.
ROYAL	5603	10307	X	19	33	94	.

continued

Table A1. continued.

Lake name	Location °N	Location °W	Lake trout	Water area (km²)	TDS (mg.L⁻¹)	References	
RUSSELL	5726	10520	LT	34	.	68	.
RUSTY	5425	10846	X	2	195	79	.
SAHLI	5505	10255	LT	5	35	78	.
SANDY	5819	10947	X	2	118	43	.
SARGINSON	5443	10310	X	3	105	18	.
SCYTHES	5524	10455	X	0	.	2	.
SEALEY	5416	10436	X	1	.	98	.
SHAGWENAW	5554	10741	X	42	224	80	.
SHALLOW	5817	10407	X	1	26	74	.
SHANNON	5401	10441	X	0	.	98	.
SIM	5527	10442	X	2	.	2	.
SNAKE	5821	10938	X	0	60	42	43
STEEPHILL	5558	10309	X	44	48	94	.
STICKLEY	5406	10440	X	1	.	98	.
STURGEON	5325	10605	X	6	353	90	100
SULPHIDE	5522	10454	X	4	55	13	.
TENEYCKE	5526	10455	X	0	.	2	.
THE TWO RIVERS	5548	10309	X	52	31	94	.
TIBISKA	5416	10608	LT	7	.	8	88
TIE	5350	10649	X	2	405	93	.
TOBIN	5335	10330	X	228	245	83	.
TOO SMALL	5818	10403	X	0	20	74	.
TORCH	5343	10516	X	11	.	30	.
TRADE	5522	10344	X	69	106	44	.
TRAPPERS	5348	10602	X	2	161	95	101
TRIVEET	5525	10600	X	14	63	28	.
TROUT	5537	10517	X	32	130	81	.
TULABI	5446	10300	X	8	90	18	.
TURNOR	5635	10835	X	232	69	82	.
TURTLE	5336	10838	X	64	340	92	.
TYRRELL	5454	10207	X	6	90	18	.
UNSER	5442	10312	X	1	110	18	.
UPISES	5526	10454	X	0	.	2	.
UPPER FISHING	5403	10437	X	1	225	50	.
UPPER FOSTER	5647	10520	LT	102	38	46	.
UPPER SEAHORSE	5712	10541	X	1	31	68	.
USKIK	5532	10317	X	23	102	44	.
UTIKUMAK	5450	10814	X	3	150	65	.
VIVIAN	5425	10854	X	1	190	79	.
W1	5817	10410	X	1	15	74	.
WABENO	5419	10624	X	8	189	95	101
WAPATA	5851	10544	X	64	20	19	20
WAPAWEKKA	5450	10450	X	238	93	91	.
WAPISEW	5347	10228	X	21	250	41	.
WAPUMON	5534	10255	X	6	84	94	.

continued

Table A1. continued.

Lake name	Location °N	°W	Lake trout	Water area (km^2)	TDS ($mg.L^{-1}$)	References	
WASEKAMIO	5645	10845	X	134	70	82	.
WASKESIU	5358	10612	X	70	181	8	9
WASSEGAM	5416	10614	LT	9	.	8	10
WATERHEN	5428	10825	X	69	220	17	.
WATERHEN	5354	10225	X	8	270	41	.
WATHAMAN	5655	10343	X	73	41	29	.
WEYAKWIN	5430	10600	X	76	106	86	.
WHELAN BAY	5405	10510	X	19	155	59	.
WHITE GULL	5356	10504	X	15	470	58	.
WHITESWAN	5405	10510	X	.	.	58	59
WIERZYCKI	5601	10356	LT	7	55	25	.
WILDNEST	5500	10220	X	46	65	55	.
WILLOW AB	5350	10206	X	16	220	41	.
WILLOW C	5348	10206	X	14	220	41	.
WILLOW D	5347	10206	X	6	.	41	.
WILLOW E	5346	10206	X	7	.	41	.
WINTEGO	5533	10252	X	18	91	94	.
WINTERINGHAM	5448	10252	X	1	65	18	.
WITSUKITSHAK	5340	10611	X	1	251	95	.
WOLLASTON	5815	10315	LT	2062	40	4	.
WOOD	5517	10317	X	93	51	99	.
WROBEL	5712	10541		.	18	68	.
ZEDEN	5359	10440	X	0	.	98	.
ZIMMER	5710	10545	LT	3	29	68	.

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Appendix B

DESCRIPTION OF LAKE SURVEY METHODS AND HABITAT VARIABLES USED IN PRESENT STUDY

Habitat variables are described and physical and chemical methods are cited as necessary.

LOCATION

Lake Name (abbreviated LKNAME) - Reported name or gazetteer name (if necessary) or best known common name. "Lake" or "lac" excluded from name.

Lake Number (LKNO) - Arbitrary identifier of lake.

Latitude (LAT, or LATD for decimal ^{o}N) - As reported or gazetteered, or estimated from topographic 1:50,000 maps.

Longitude (LONG, or LONGD for decimal ^{o}W) - See LAT.

Nordicity (NORD) - Isolines defined as NORD = 4(LATD) - LONGD - 114. Related to climatic and vegetational zones in Saskatchewan (Richards and Fung 1969).

Geological Zone (GEOZONE) - Bedrock geology (i.e. sedimentary SE, boundary BD, Precambrian shield SH, Athabasca sandstone AT, and boundary Athabasca BA) from map by Saskatchewan Dept. Mineral Resources and Saskatchewan Research Council (1972). Determined from lake outline (not watershed) on topographic 1:50,000 maps or consultant studies, if necessary. Descriptions BD and BA took precedence over either contiguous zone overlain by lake.

Altitude (ALT) - For mean summer water surface as reported in survey. Units m.

References (REF1 and REF2) - Primary and secondary lake survey reports used as source for habitat and fish species data. Earliest survey was given preference, unless seriously incomplete.

Random Lake (RANDOM) - One of about 20% of lakes which were selected randomly for later validation of criteria.

MORPHOMETRY

Water Area (WAREA) - Lake water area as reported. Determined from dot grids in early surveys and small lakes and from polar planimetry in later surveys. Units km^2 .

Volume (VOLUME) - Water volume as reported (from truncated-cone method, see Wetzel 1983) or determined from water area and mean depth. Units hm^3 or million m^3.

Mean Depth (ZBAR) - As reported, infrequently a simple mean of numerous depth soundings (Koshinsky 1970). Units m.

Maximum Depth (ZMAX) - Maximum known depth from handline soundings or echo sounder transects. Units m.

Shoreline Length (SHOLEN) - As reported. Determined from suitably-scaled maps, including island shorelines. Units km.

Shoreline Development (SHODEV) - As reported or calculated as SHODEV = SHOLEN/2 x 3.1416 x WAREA (Hutchinson 1957).

Fetch (FETCH) - Longest straight line distance over water (disregarding only islands too small to be mapped), as defined by Hutchinson (1957). Units km.

Orientation (ORIENT) - Compass degrees between map north and fetch direction, restricted to 0^{o} to 180^{o}. Units ^{o}.

Flushing Time (FLUSH) - Theoretical time for complete water exchange. Earlier surveys used regional precipitation to estimate inflows (Rawson 1957b). Later surveys used actual outflows, although muskeg and groundwater seepage remained largely intractable (Koshinsky 1968). Units years.

Area Strata - Percent of water area between adjacent depth contours (i.e. hypsographic data). As reported, with a maximum of ten strata. Estimated by dot grid or polar planimetry (see WAREA). Abbreviated SA1, SA2,...SA10 for area and DA1, DA2,...DA10 for depth contours. Units % and m, respectively.

Volume Strata - Percent of water volume between adjacent depth contours. As reported, or calculated from area strata, depth of strata, and mean depth by a modified truncated-cone method (Wetzel 1983):

% volume in stratum Z1 to Z2

$= (Z2 - Z1)\ (\%A1 + \%A2 + (((\%A1)(\%A2))^{0.5}/(3 \times ZBAR)))$.

Strata were considered imprecise if the sum of calculated volume strata was not between 80 and 120 % of lake volume (see Temperature-Oxygen section). Abbreviated SV1, SV2,...SV10 for volume and DV1, DV2,...DV10 for depth contours. Units % and m, respectively.

PHYSICOCHEMISTRY

Secchi Depth (SECCHI) - Summer average of all open-water limnological stations. Secchi disc was white-and-black or all-white, 20 or 25 cm diameter, and read in shade during midday. No reading was used if Secchi transparency extended to ZMAX. Units m.

Photo Depth (PHOTOZ) - Same as above, except may equal ZMAX. This variable estimates light transmission for photosynthesis (Wetzel 1983 p.66), rather than water clarity *per se*. Units m.

Generally, surface water samples were collected periodically over the field season (i.e. late spring to early fall). Water chemistry samples were usually filtered through plankton net material (68 meshes.cm-1) to remove settleable material (Atton and Johnson 1970). Typically, data from a single sample in open water at the station of maximum depth and the mid-summer period (i.e. late June to early August) were used. Late July or early August samples are most indicative of mean annual total dissolved solids (Ryder *et al*. 1974). Readings below detection levels were generally shown at this limit (e.g. SO4 less than 1.0 was shown as 1.0). Early surveys occurred in southern and central regions where TDS, salinity, and constituents were moderate to very high. Detection limits improved as recent surveys were conducted in more northerly, more dilute lakes.

Methods of collection, storage, and analysis have varied between years, personnel, and agencies. In a similar retrospective study of TDS and TOTALK, Liaw and Atton (1980) noted that "the accuracy of the reported individual values should not be over-emphasized".

Colour (COLOUR) - Mid-summer surface sample, usually filtered. Field analyses by U. S. Geological Survey colorimetric method. Units Pt (= USGS = Hazen units).

Surface pH (PHMINS) - Minimum summer surface pH. Almost all surveys used the colorimetric Hellige pH comparator in the field; most recently electronic pH meters were used.

Bottom pH (PHMINB) - Minimum summer bottom pH.

Total Dissolved Solids (TDS) - Mid-summer surface sample. Analysis by weighing residue after filtration and drying to constant weight at 105 or 110°C (Liaw and Atton 1980). Some early analyses used drying 1 hr at 180°C (Rawson and Moore 1944), which may decompose bicarbonates and organic matter (Rawson 1951, Ryder et al. 1974). Some surveys used "sum of constituents" for total dissolved solids (Mayhood et al. 1973). Units $mg.L^{-1}$.

Total Alkalinity (TOTALK) - Mid-summer surface sample. Most analyses by titration with standard acid solution, using methyl orange as indicator (Rawson 1936, APHA 1955 p.35, Liaw and Atton 1980) or recently to inflection point (APHA 1971). No adjustment was made for any over-estimation of true alkalinity in dilute waters, unlike Liaw and Atton (1981). Units $mg.L^{-1}$ CaCO3.

Specific Conductivity (SPCON) - Mid-summer surface sample. Analyses by standard conductivity cell (Atton and Johnson 1970) or electronic meters (APHA 1971), corrected to 25°C. Units uS (= umhos.cm^{-1}).

Loss on Ignition (LOSSIG) - Mid-summer filtered surface sample. Earliest analyses by ignition at 950°C of residue from TDS analysis (Rawson 1936, APHA 1925 p. 25); most analyses by ignition at 500 or 550°C for 1 hr (APHA 1955, 1971). Loss of ignition represents organic matter in the residue and volatilization of carbonates, nitrates, and other components (APHA 1925). Loss of carbonates (and others?) is reduced by ignition below 600°C (Golterman 1975 p.215).

Cations and Anions - Mid-summer surface sample. Analyses for calcium (CA), magnesium (MG), sodium (NA), potassium (K), bicarbonate (HCO3), carbonate (CO3), sulfate (SO4) and chloride (CL) have followed the standard methods of the day (APHA 1955, 1971). Units mg.L^{-1}.

CA in early surveys by gravimetric or permanganate titration method; for many years by EDTA titration. MG in early surveys by gravimetric or photometric method; for many years by modified EDTA titration of hardness and subtraction of CA; some recently by atomic absorption spectrometry (e.g. Tones 1979). NA and K in early surveys were not differentiated in analyses "by difference" (i.e. TDS minus known CA, MG, HCO3, CO3, SO4, and CL). By 1957, it was clear that NA (including K) levels by this method were misleadingly high, usually "by at least 30 percent" and occasionally 3 to 5 times more than by direct analyses (Rawson 1957a). For many years, NA by gravimetric and K by colorimetric or volumetric standard methods; both recently by flame photometry.

HCO3 and CO3 for many years by nomographic calculation from methyl orange alkalinity and phenolphthalein alkalinity; more recently pH meters have replaced indicators. Hydroxide alkalinity was rarely found in these lakes. SO4 for many years by gravimetric barium method; some recently by ion chromatography. CL for many years by silver nitrate titration; some recently by ion chromatography, especially in dilute waters.

TEMPERATURE-OXYGEN

Generally temperature and oxygen readings were taken periodically over the field season at the deepest station of the lake. In this study, preference was given to this station, although other stations were also frequently available in larger or multi-basin lakes.

Some early surveys used reversing thermometers and bathythermographs for intermediate and bottom temperatures; recent surveys used electrical telethermometers for temperature profiles. All surface temperatures and calibrations were by standard rod thermometers. Dissolved oxygen determinations used the modified Miller method (Miller

1914, Ellis and Kanamori 1973) for decades for convenience in field analyses (Rawson 1936, Atton and Johnson 1970). Some recent surveys used Winkler's method or electronic oxygen-electrode meters. The Winkler method is generally more precise, although the Miller method is effective in high-carbonate waters (Walker et al. 1970, Ellis and Kanamori 1973).

Temperature, Maximum Surface (TMAXS) - Summer maximum temperature was used only if rise-and-fall of temperatures was reported or if at least several mid-July to mid-August temperatures were available. Units ^{o}C.

Temperature, Maximum Bottom (TMAXB) - As above, for the deepest limnological station reported. Units ^{o}C.

Stratification (STRAFN) - Degree of thermal stratification. Based on survey author's description of one to several summers' temperature profiles, with minor modifications imposed for consistency between authors and/or lakes. Criteria were primarily sharpness and persistence of thermocline. Five subjective classes: 0 = non-stratified, 1 = weak, 2 = moderate, 3 = strong, 4 = very strong.

Oxygen, Minimum Surface (OMINS) - Summer minimum was used only if several readings throughout the field season were available. Units $mg.L^{-1}$.

Oxygen, Minimum Bottom (OMINB) - As above. Few studies attempted to delineate microstratification at the lake bottom

(Rawson 1936), so readings were for "near bottom". Units mg.L^{-1}.

Depth of shallowest 6 mg.L^{-1} oxygen (HIGH6MG) - Shallowest open-water depth below which oxygen was less than 6 mg.L^{-1} (4.2 cm^3.L^{-1}) at least temporarily. Used only if several readings throughout the summer and at useful intermediate depths were available. Units m.

Minimum volume of water at or above 6 mg.L^{-1} oxygen (VOL6MG) - Minimum volume of surface water with acceptable oxygen levels, calculated from HIGH6MG depth and volume strata (see above) as described in VOLT15T6 below. Units hm^3.

Depths of deepest 15^{o}C and same-day 6^{o}C (T15T6U and T15T6L) -See similar variables in Table 1. Deepest open-water depth below which temperature was acceptable (i.e. T15T6U, T15O6U, etc.) and same-day depth above which temperature or oxygen was acceptable (i.e. T15T6L, T15O6L, etc.) for lake trout. Available under similar conditions as OMINS and HIGH6MG. Units m.

Minimum volume of 6-15^{o}C water (VOLT15T6) - See similar variables in Table 1. Minimum volume of water with temperature or temperature and oxygen acceptable for lake trout. Calculated as volume between upper criterion (e.g. T15T6U, T15O6U, etc.) and lower criterion (e.g. T15T6L, T1506L, etc). Interpolated from area strata (as necessary) by a truncated-cone approximation:

% volume from Z1 to Za, which is between Z1 and Z2

= (%A2) x (Za - Z1)/ZBAR + ((%A1 - %A2) x (Za - Z1) x [1 + (Z2 - Za)/(Z2 - Z1) + $(Z2 - Za)^2/(Z2 - Z1)^2$] / (3 x ZBAR)).

BIOTA

Net plankton samples were taken periodically over the field season at the deepest station on the lake, and usually at auxiliary stations in larger or multi-basin lakes. A large Wisconsin net (mouth diameter 25 cm) with a straining cone of 68 meshes.cm^{-1} was hauled vertically from near bottom (typically 2 m above bottom) to surface at 1.0 m.s^{-1}. Net efficiency was usually averaged from beginning, middle, and end-of-field-season comparisons with vertical series of 10-L trap samples (Rawson 1953, Atton and Johnson 1970). Identification and relative abundance by taxa were usually reported, but not considered in this study.

Net plankton dry weight (NETDRY) - Above samples were dried at 52 to 60°C for 48-72 hr to constant weight. Dry weight was averaged over the season and stations reported. Units kg.ha^{-1}.

Net plankton organic weight (NETORG) - Above dried samples were ashed over open flame and then at 600°C for 15 minutes. See LOSSIG above. Units kg.ha^{-1}.

Benthic fauna were typically sampled once or more per summer to represent proportionally all depths and bottom types of each basin. Ekman dredges (225-500 cm^2) and Peterson dredges (675 cm^2) were used on softer and harder substrates, respectively. Rocky areas were assumed to contain no benthic fauna (Atton and Johnson 1970). Dredgings were washed through three screens (finest 11 $meshes.cm^{-1}$, occasionally 15) and specimens preserved in 70 % ethanol.

Benthic Fauna Numbers (BENNOA) - Numbers per unit area were averaged by proportional sampling or by weighted depth zone areas for the summer. Units $numbers.m^{-2}$.

Benthic Fauna Categories - Numerical composition of faunal taxa were averaged for the lake, as above. Abbreviated BC1, BC2,...for taxa and BC1%, BC2%,...for numerical composition. Units taxon codes and %, respectively.

Benthic Fauna Dry Weight (BENDRY) - Wet weights of specimens were determined after (partial) drying on absorbent paper; crayfish, large clams, and mollusc shells (estimated as 1/3 of mollusc wet weights) were excluded. Dry weights were reported as 12 to 15 % (largely chironomid or amphipod benthos, respectively) of wet weight (Rawson 1953, Atton and Johnson 1970).

WINTER PHYSICOCHEMISTRY

Winter water chemistry was available infrequently, usually from a single sample at a mid-lake station. Surface (i.e.

immediately below ice cover) and bottom samples were analyzed as described for summer physicochemistry. Preference was given to readings from March, the generally critical period for oxygen (Barica and Mathias 1979), or to lowest observed oxygen conditions.

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Appendix C

FISH SPECIES COMPOSITIONS:

NOMENCLATURE, DEFINITIONS, AND METHODS USED

FISH SPECIES COMPOSITION

Surveys were generally planned to determine the presence and relative abundances of all fish species in all areas and depths of the lake throughout the field season. Standard gillnets were used predominantly, augmented frequently by shoreline seining and occasionally by poisoning, angling, stomach analysis, or other methods.

Each standard gillnet consisted of 46 m each of six different meshes (Table C1) fished as one gang in order of mesh size. Sets were made with the smallest mesh alternately furthest from shore and nearest shore, and in the deepest area and shallowest area, to reduce obvious bias (Atton and Johnson 1970). Gillnets were typically fished on the bottom for 24 hr, with longer sets usually adjusted to 24 hr using Kennedy (1951). From one to tens of net sets were made on each lake, depending on lake area, the number of basins, the survey objectives, and available staffing. The seine used was typically 9 m long, 2 m deep in the centre and 1 m at each end, bagged in the centre, and constructed of 13-mm stretched mesh (Atton and Johnson 1970). Seining was usually done in several locations, limited primarily by available staff and time and by nearshore suitability.

Table C1. Specifications of the standard gillnet used in provincial lake surveys.

Mesh size[a] (mm)	Length (m)	Depth[b] (meshes)	Material[c]
38	46	60	210/2 nylon
51	46	45	210/2 nylon
76	46	30	210/2 nylon
102	46	22	210/3 nylon
127	46	16	210/3 nylon
140	46	16	210/3 nylon

a Stretched measure.

b Approximately 1.8 m.

c Multifilament nylon replaced cotton about 1953 (Atton 1955, Novakowski 1955).

No criterion was established for a minimum number of gillnet sets or seine hauls which would be sufficient. A tautology was implicit since an author's judgement of reasonable success in catching specimens of the (expected) fish species was accepted. Additions to the species lists by later surveys demonstrated the incompleteness of some surveys, particularly for smaller or less preferred species (e.g. cyprinids, catostomids, and cottids).

"Regular" fish species were those species found by lake survey methods and which were permanent residents of the lake

(Atton and Merkowsky 1983). "Auxiliary" species were found by surveys but believed to be transients (T), were presumed or known to be extirpated (E), were known to be introduced whether self-sustaining or not (I), were reported in commercial (C) or sport (S) fishing records, or were reported by other means (R). Fish species nomenclature followed Scott and Crossman (1973), with minor exceptions.

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Appendix D

SAMPLE SIZES, MEANS, AND FREQUENCY DISTRIBUTIONS OF HABITAT VARIABLES

Table D1. Sample sizes, means, and frequency distributions of all habitat variables in the random subset of 262 lakes.

Variable[a] Bedrock geology	Number of lakes	Mean	Standard deviation	Minimum	Quartiles 25 %	50 %	75 %	Maximum
Location:								
LATD	262	55.43	1.588	53.05	54.08	55.17	56.70	59.70
LONGD	262	105.38	2.172	101.88	103.73	105.28	106.36	109.82
NORD	262	2.35	6.170	-10.13	-2.70	2.36	7.45	18.77
ALT	119	455.7	114.56	265.0	340.0	490.0	527.0	697.0
Morphometry:								
WAREA	248	73.073	380.191	0.006	0.642	5.445	29.67	5296.5
VOLUME	216	1100.0	7105.88	0.085	3.628	30.22	257.91	95250
ZBAR	215	6.818	5.409	0.4	2.6	5.6	8.8	30
ZMAX	247	19.519	21.805	0.8	5	13.4	27.1	215
SHOLEN	189	163.55	722.30	0.76	7.05	23.34	111.65	9245.66
SHODEV	189	4.11	3.97	1.05	1.66	2.3	5.85	35.8
FETCH	197	8.39	12.29	0.14	1.60	4.30	9.89	107

continued

Table D1. continued

Variable Bedrock geology	Number of lakes	Mean	Standard deviation	Minimum	Quartiles 25 %	50 %	75 %	Maximum
ORIENT	183	78.32	54.51	0	35	65	121	179
FLUSH	58	7.73	23.53	0.1	0.25	1.95	5.75	175
Physicochemistry:								
SECCHI	176	3.60	2.33	0.3	2.12	3	4.38	13.9
PHOTOZ	183	3.51	2.33	0.3	2	2.9	4.3	13.9
COLOUR	90	24.9	23.5	0	9	20	37	130
PHMINS	168	7.36	0.61	6	7	7.2	7.9	8.9
PHMINB	161	6.94	0.65	5.6	6.4	6.9	7.3	8.9
TDS	197	329.26	2115.35	10	39.5	105	213	29440
TOTALK	159	70.02	79.07	1.5	13	26	124	396
SPCON	169	470.19	3100.98	8	38.5	117	321	40000
LOSSIG	88	98.75	237.42	0	29.5	50	75	1885
CA	195	24.04	50.43	0.39	4	16.3	33	662
MG	194	15.91	39.70	0.11	1.48	6	16.3	438
NA	185	67.58	701.21	0.3	1.3	2.9	9.55	9500

continued

Table D1. continued

Variable Bedrock geology	Number of lakes	Mean	Standard deviation	Minimum	Quartiles 25 %	50 %	75 %	Maximum
K	174	3.81	12.90	0	0.8	1.8	3.4	165
CO3	173	2.75	8.69	0	0	0	0	54.8
HCO3	175	114.97	107.55	1	23.2	85	173	591
SO4	184	18.83	98.02	0	0	1	2.85	857
CL	189	107.03	1172.65	0	0.5	1	4	16000
Temperature-Oxygen:								
TMAXS	208	20.40	2.28	13	19	20.5	22	27.4
TMAXB	184	13.48	5.66	4	7.58	14.2	18.98	23.1
OMINS	176	7.73	0.89	3.43	7.14	7.75	8.38	9.85
OMINB	173	4.42	3.06	0	1.14	4.85	7.21	9.71
HIGH6MG	171	15.97	18.1	0	4	9	20	97
VOL6MG	148	1383.88	8082.63	0	3.74	36.81	278.82	89242
T15T6U	185	10.52	8.08	0	5	9	13	46
T15T6L	184	18.92	15.55	1	6	16	28.8	74

continued

Table D1. continued

Variable Bedrock geology	Number of lakes	Mean	Standard deviation	Minimum	Quartiles 25 %	50 %	75 %	Maximum
VOLT15T6	157	712.26	5458.58	0	0	0.19	24.00	58174.5
T1606U	179	10.39	8.18	0	4	9	13	46
T1506L	170	16.61	18.18	0	5	10	21.2	90
VOLT1506	146	735.32	5668.29	-1064.47	0	0	2.29	58174.5
T1504U	170	10.39	8.30	0	4	9	13	46
T1504L	163	19.19	19.21	0	6	12	26	97
VOLT1504	142	779.55	5742.15	-108.97	0	·0	13.13	58174.5
T1206U	169	12.54	9.49	1	5.5	11	18	46
T1206L	164	17.11	17.99	0	5	10	23.75	90
VOLT1206	143	297.46	2334.23	-492.37	-0.01	0	0.73	26083.4
Biota:								
NETDRY	143	53.08	40.21	3.7	24.4	42		
NETORG	113	36.65	28.92	0.9	19.55	59.6	46.45	217
BENNOA	152	1659.53	1542.26	...	751.8	1280.5	2054.5	13231
BENDRY	154	14.29	14.68	0.8	4.6	9.8	17.9	89

continued

Table D1. continued

Variable Bedrock geology	Number of lakes	Mean	Standard deviation	Minimum	Quartiles 25 %	50 %	75 %	Maximum
Winter:								
OWINS	60	7.78	4.45	0	4.33	8.71	11.42	13.99
TDSWINS	77	334.1	924.9	4	75.5	75	195	6390
SPCOWINS	66	133.2	160.4	10	51.2	73	163.2	803
CAWINS	53	17.46	24.58	0.39	3.2	8	22.05	110
MGWINS	53	6.08	9.49	0.24	1.25	2.1	4.7	45.5
NAWINS	53	2.80	2.34	0.73	1.5	2.2	2.8	12.6
KWINS	51	1.96	2.15	0.3	0.8	1.5	2.1	13.1
CLWINS	53	0.87	1.89	0	0	0	1	9.5

a Excludes variables which are available in fewer than 50 lakes.

Appendix E

UNIVARIATE PREDICTION OF LAKE TROUT PRESENCE

Table E1. Univariate prediction of lake trout presence or absence and sample sizes and error rates in 262 lakes.

Variable Bedrock geology	Number of lakes with lake trout: Present	Absent	Statistical difference $(P \le)$[a]	Criterion of presence[b]	Errors (%)[c]: All	Present /absent
Location:						
LATD	46	182	0.0001	≥ 56.52	20	50/13
shield	36	81	0.0001	≥ 57.21	31	53/21
non-shield	10	101	0.0118	≥ 54.95	14	80/8
LONGD	46	182	0.0930	≥ 107.10	31	76/19
shield	36	81	0.0120	≥ 105.38	33	56/23
non-shield	10	101	0.9221	< 102.19	16	90/9
NORD	46	182	0.0001	≥ 7.042	21	52/13
shield	36	81	0.0004	≥ 8.125	34	56/25
non-shield	10	101	0.2660	≥ 0.958	14	80/8
ALT	29	72	0.7355	≥ 523.5	47	74/34
shield	22	29	0.1482	≥ 444.0	47	55/41
non-shield	7	43	0.3071	< 266.4	20	86/9
Morphometry:						
WAREA	46	179	0.0001	≥ 46.7	24	59/15
shield	36	79	0.0001	≥ 26.8	31	50/23
non-shield	10	100	0.0010	≥ 201.4	16	90/9
VOLUME	44	157	0.0001	≥ 430.01	21	48/13
shield	34	77	0.0001	≥ 217.67	27	44/19
non-shield	10	80	0.0002	≥ 1400.00	16	70/9
ZBAR	44	156	0.0001	≥ 9.65	14	32/9
shield	34	77	0.0001	≥ 8.30	17	29/12
non-shield	10	79	0.0001	≥ 12.30	9	40/5
ZMAX	46	178	0.0001	≥ 32.65	11	26/7
shield	36	79	0.0001	≥ 31.15	16	25/11
non-shield	10	99	0.0001	≥ 36.50	7	40/4

continued

Table E1. continued

Variable / Bedrock geology	Number of lakes with lake trout: Present	Absent	Statistical difference (P≤)	Criterion of presence	Errors (%): All	Present /absent
SHOLEN	46	128	0.0001	≥ 118.1	31	59/21
shield	36	77	0.0001	≥ 109.1	34	53/25
non-shield	10	51	0.1018	≥ 130.4	23	70/14
SHODEV	46	128	0.0005	≥ 5.85	32	59/22
shield	36	77	0.0030	≥ 6.35	38	58/29
non-shield	10	51	0.8992	≥ 3.60	26	80/16
FETCH	44	128	0.0001	≥ 11.67	29	57/18
shield	36	73	0.0001	≥ 7.40	31	47/23
non-shield	8	65	0.0075	≥ 25.10	19	88/11
ORIENT	42	126	0.3024	≥ 124.5	42	83/28
shield	35	66	0.9602	< 38.5	48	69/36
non-shield	7	60	0.9265	≥ 172.0	18	86/10
Physicochemistry:						
SECCHI	42	131	0.0001	≥ 4.54	14	29/9
shield	36	69	0.0001	≥ 4.15	12	19/9
non-shield	6	62	0.0011	≥ 4.95	12	67/6
PHOTOZ	42	138	0.0001	≥ 4.54	13	29/9
shield	36	71	0.0001	≥ 4.15	11	17/8
non-shield	6	67	0.0008	≥ 4.95	11	67/6
COLOUR	9	62	0.0021	< 6.0	18	78/10
shield	9	41	0.0059	< 7.5	28	78/17
non-shield	0	21	...	...	..	...
PHMINS	39	127	0.0062	< 7.0[d]	30	64/20
shield	33	74	0.8802	< 7.0[d]	39	64/28
non-shield	6	53	0.1125	< 7.1	19	100/9
PHMINB	40	119	0.0006	< 6.4	31	60/21
shield	32	72	0.0379	< 6.4	41	72/28
non-shield	8	47	0.1003	< 7.0[d]	25	88/15

Table E1. continued

Variable Bedrock geology	Number of lakes with lake trout Present	Absent	Statistical difference (P≤)	Criterion of presence	Errors (%) All	Present /absent
TDS	38	137	0.0001	< 40.5	21	47/14
shield	32	53	0.0345	< 38.5	35	47/28
non-shield	6	84	0.0032	< 86.5	13	100/7
TOTALK	32	105	0.0001	< 14.5	30	66/19
shield	30	57	0.3278	< 14.5	45	63/35
non-shield	2	48	0.1247	< 37.0	8	100/4
SPCON	32	118	0.0001	< 41.0	21	50/14
shield	27	50	0.0711	< 31.5	39	56/30
non-shield	5	68	0.0206	< 96.0	14	100/7
CA	37	136	0.0001	< 4.30	22	51/14
shield	31	52	0.1023	< 3.80	39	52/31
non-shield	6	84	0.0466	< 13.70	11	83/6
MG	36	136	0.0001	< 1.55	22	53/14
shield	31	52	0.5978	< 1.33	41	55/33
non-shield	5	84	0.0093	< 3.85	9	80/5
NA	35	131	0.0001	< 1.28	22	54/14
shield	31	51	0.0718	< 1.28	35	48/27
non-shield	4	80	0.1201	< 1.10	10	100/5
K	33	122	0.0001	< 0.90	27	64/17
shield	30	49	0.0848	< 0.90	44	60/35
non-shield	3	73	0.0716	< 0.20	8	100/4
CO3	28	126	0.0053	< 0.0[d]	30	82/18
shield	23	50	0.4976	< 0.0[d]	44	70/32
non-shield	5	76	0.1054	< 0.0[d]	12	100/7
HCO3	29	127	0.0001	< 21.0	21	55/13
shield	23	48	0.3195	< 16.5	44	65/33
non-shield	6	79	0.0429	< 62.0	14	100/8

continued

Table E1. continued

Variable Bedrock geology	Number of lakes with lake trout: Present	Absent	Statistical difference (P≤)	Criterion of presence	Errors (%): All	Present /absent
SO4	35	130	0.8883	< 0.0[d]	29	69/18
shield	30	46	0.1955	≥ 1.0[d]	32	40/26
non-shield	5	84	0.4308	< 0.0[d]	11	100/6
CL	36	134	0.6544	< 0.05	32	72/21
shield	31	53	0.0121	≥ 1.05	30	42/23
non-shield	5	81	0.0159	< 0.0[d]	9	80/5
Temperature-Oxygen:						
TMAXS	43	158	0.0002	< 18.85	26	58/17
shield	33	80	0.0002	< 18.85	27	45/19
non-shield	10	78	0.8229	< 18.60	23	100/13
TMAXB	43	139	0.0001	< 7.45	19	42/12
shield	33	77	0.0001	< 7.70	19	30/14
non-shield	10	62	0.0017	< 7.45	17	60/10
OMINS	41	133	0.0001	≥ 8.35	24	49/17
shield	33	74	0.0001	≥ 8.17	24	39/18
non-shield	8	59	0.3472	≥ 8.92	18	75/10
OMINB	40	131	0.0063	≥ 7.21	32	65/22
shield	30	75	0.0063	≥ 6.92	30	53/21
non-shield	10	56	0.4156	≥ 7.93	26	90/14
HIGH6MG	39	130	0.0001	≥ 23.0	17	36/11
shield	31	73	0.0001	≥ 26.5	19	32/14
non-shield	8	57	0.0001	≥ 18.0	6	25/4
VOL6MG'[e]	36	110	0.0001	≥ 317.65	26	53/17
shield	29	62	0.0001	≥ 150.90	29	45/21
non-shield	7	48	0.0017	≥ 1583.50	15	57/8
T15T6U	43	140	0.0704	≥ 13.5	38	79/25
shield	33	75	0.5039	≥ 11.5	46	73/35
non-shield	10	65	0.0010	≥ 16.5	17	70/9

Table E1. continued

Variable Bedrock geology	Number of lakes with lake trout		Statistical difference (P≤)	Criterion of presence	Errors (%)	
	Present	Absent			All	Present /absent
T15T6L	43	139	0.0001	≥ 29.5	19	40/12
shield	33	74	0.0001	≥ 28.5	25	42/18
non-shield	10	65	0.0001	≥ 32.5	5	20/3
VOLT15T6'[e]	39	116	0.0001	≥ 24.00	14	28/9
shield	30	62	0.0001	≥ 10.33	12	17/10
non-shield	9	54	0.0001	≥ 204.21	6	22/4
T15O6U	39	131	0.0738	≥ 13.5	39	85/25
shield	33	74	0.4290	≥ 11.5	46	73/34
non-shield	6	57	0.0016	≥ 16.5	16	83/9
T15O6L	36	127	0.0001	≥ 24.5	17	39/10
shield	31	72	0.0001	≥ 26.5	20	32/15
non-shield	5	55	0.0007	≥ 15.5	7	40/4
VOLT15O6'[e]	34	110	0.0001	≥ 3.29	7	15/5
shield	29	61	0.0001	≥ 2.15	4	7/3
non-shield	5	49	0.0116	≥ 69.05	7	40/4
T15O4U	39	129	0.1167	≥ 13.5	38	85/24
shield	33	72	0.4467	≥ 11.5	47	73/35
non-shield	6	57	0.0058	≥ 17.5	11	50/7
T15O4L	36	125	0.0001	≥ 29.5	14	31/10
shield	31	70	0.0001	≥ 29.5	21	32/16
non-shield	5	55	0.0003	≥ 33.0	3	20/2
VOLT15O4'[e]	34	106	0.0001	≥ 16.29	10	21/7
shield	29	59	0.0001	≥ 7.39	9	14/7
non-shield	5	47	0.0001	≥ 202.90	4	20/2
T12O6U	39	128	0.0001	≥ 18.5	34	72/22
shield	33	71	0.0124	≥ 17.0	45	70/34
non-shield	6	57	0.0038	≥ 19.5	14	67/9

continued

Table E1. continued

Variable Bedrock geology	Number of lakes with lake trout		Statistical difference (P≤)	Criterion of presence	Errors (%)	
	Present	Absent			All	Present /absent
T1206L	36	126	0.0001	≥ 26.5	17	36/11
shield	31	71	0.0001	≥ 28.5	20	32/14
non-shield	5	55	0.0019	≥ 19.5	7	40/4
VOLT1206'[e]	34	107	0.0001	≥ 1.04	9	18/6
shield	29	60	0.0001	≥ 0.84	11	17/8
non-shield	5	47	0.0107	≥ 35.74	8	40/4
Biota:						
NETDRY	37	104	0.0005	< 25.8	33	62/22
shield	31	68	0.0231	< 24.2	40	65/29
non-shield	6	36	0.4084	< 40.6	19	67/11
NETORG	33	79	0.0020	< 23.2	33	54/24
shield	27	51	0.0380	< 22.2	41	59/31
non-shield	6	28	0.3428	< 29.0	24	67/14
BENNOA	36	116	0.0001	< 720	24	50/16
shield	30	67	0.0013	< 758	25	40/18
non-shield	6	49	0.0402	< 554	15	67/8
BENDRY	38	116	0.0001	< 4.6	19	37/13
shield	32	67	0.0001	< 4.6	21	31/16
non-shield	6	49	0.0163	< 4.8	15	67/8

a Difference by Mann-Whitney test.
b Midpoint of delineation is shown.
c Apparent error rate for all lakes when numbers of errors were (approximately) equal for true presences and true absences, followed by those with and without lake trout, respectively.
d Numerous tied rankings for this criterion were classified randomly.
e Only lakes with total water volumes estimable within ± 20 % are shown (see Appendix B).

Appendix F

SHIELD AND NON-SHIELD LAKE WATERLEVEL VARIATIONS, MORPHOMETRY, AND RESIDUAL VOLUMES

INTRODUCTION

This appendix is basically a repository for the mathematical and other analyses of the differences between shield and non-shield lakes in recent habitat conditions.

METHODS

RECENT CONDITIONS

Waterlevels The minimum daily waterlevel for each month with at least 3 days' data was obtained (Environment Canada 1983; Water Survey of Canada, Regina, Calgary, and Winnipeg Regions, November 1983 microfiches). Two or more periods-of-record on a lake were tied to a common elevation by the principle of "water level transfer" (L. Heinze, Water Survey of Canada, Regina, pers. comm.). Monthly mean waterlevels were preferable to daily, but were not readily available for all months. Fluctuations due to "wind set-up" or seiches were excluded, if reported or observed. As July and August are critical months for temperature-and-oxygen volumes, the lower minimum daily waterlevel was used to represent the summer minimum.

Typical and extreme low waterlevels were estimated from polynomial regressions of the probability of observed waterlevels. Polynomials were fitted by stepwise linear regression:

$$Yi = a_0 + a_1 Xi + a_2 Xi^2 + a_3 Xi^3 + \ldots + a_9 Xi^9 \quad \text{(equation F1)}$$

where Yi was the predicted waterlevel (m) corresponding to a given cumulative probability Xi, and Xi was the observed probability of the ith or lower waterlevel (m) from:

$$Xi = Ri / (n+1) \quad \text{(equation F2)}$$

where Ri was the rank-order of the ith waterlevel when the lowest observed waterlevel was ranked 1, and n was the number of observations. Linear regression required the re-definitions:

$$Z_1 = Xi,\ Z_{2i} = Xi^2,\ Z_{3i} = Xi^3,\ \ldots\ Z_{9i} = Xi^9 \quad \text{(equation F3)}$$

(Freund and Minton 1979 p.161).

Variables were added to regression equation F1 stepwise using significance levels of 0.25 for entry and 0.25 for removal (SAS 1982). Equation F2 above provides probabilities which are "correct on the average" for replicate 20-year periods representing actual 2000-year conditions (Hjelmfelt and Cassidy 1975 p.34).

An alternate method, that of maximizing the multiple coefficient of determination (R^2) to the best 1-variable, 2-

variable, ... 9-variable equations and selecting by the Cp statistic (SAS 1982), had been rejected. Theoretically, selection by Cp produces the best regression for a minimal subset of variables. The selection requires that 2p-t-1 <= Cp <= 2p-t (equation F4) for extrapolation and parameter estimation, Cp <= p (equation F5) for prediction, and Cp <= t+1 (equation F6) for marginally acceptable prediction (Hocking 1976 p.18). Here p variables are a subset of the t variables comprising the full equation, with the intercept making p+1 and t+1 terms. By this method, most regressions satisfied equation F4 and some equations F5 or F6; a few lakes required the full 9-variable model. Nonetheless, Cp statistics led to high-degree polynomial regressions and predicted waterlevels clearly out of line with recorded fluctuations, occasionally with disconcerting inflections at very low or high probability. Extrapolation to 100-year predictions appeared inadvisable, even when parameter estimation was good (see Hocking 1976 p.15, Freund and Minton 1979 p.161).

Differences between predicted low summer waterlevels for typical years (i. e. cumulative 50 % probability or median) and extreme years (i. e. cumulative 1 % probability, or nominally 1 in 100 years) represented recent waterlevel variations. The effects of bedrock geology on these variations were tested by the step-down method of linear regression and analysis of covariance (Freund and Minton 1979 p.224, SAS 1982 p.139). Prediction intervals for 95 % of single observations were calculated.

Morphometry Effects of waterlevel variations were interpolated from volume-at-depth data for surveyed lakes in the present study. Most lakes with waterlevel data did not have morphometric data available.

Residual volumes Residual volumes were estimated using the two separate lake sets. Waterlevel variations were predicted from water area, and residual volumes from waterlevel variations and morphometry. The confidence limits of residual volumes assumed that the effects of waterlevel variation and morphometry were multiplicative and independent. The standard error (Sr) of the residual volume at any water area was calculated as:

$$Sr/\bar{r} = (Sw^2/\bar{w} + Sm^2/\bar{m})^{0.5}$$

where r, w, and m denote residual volume, waterlevel variation, and morphometric depth (from Meyer 1975 p.40, Sokal and Rohlf 1969 p.422). The 95 % confidence limits used n=10 shield lakes and n=23 non-shield lakes from the waterlevel lake set, which was the smaller set.

RESULTS

RECENT CONDITIONS

Waterlevels Summer waterlevel data were available for 33 lakes in central and northern Saskatchewan, Manitoba, and Alberta (Table F1). Usually 15 to 20 years of data were available on one lake, with the longest 51 years. Some short periods-of-record on the same lake were unusable since a common elevation could not be established.

The chosen stepwise method produced polynomial regressions of good to excellent correlation and lower degree than the alternative (Table F2). Inflections were infrequently seen and predicted waterlevels were seemingly credible (Table F3) although the problem of extrapolation remained in principle.

Predicted waterlevel variations ranged from 0.070 m for Little Bear (non-shield, small lake) to 1.862 m for Winnipegosis (non-shield, very large lake). Regressions showed increasing waterlevel variations with larger lake areas which were significantly different for shield and non-shield lakes (Table F4).

Table F1. Lakes with a minimum of 10 years of July or August waterlevels for 1982 and earlier.

Lake	Water area (km^2)	Station[a] Number	Lat °N	Long °W	Years of data[b]
Shield lakes:					
Athabasca[c]	7850	07MC003	59°23	108°53	17 (1937...67)[d]
Cree	1230	07LD001	57°21	107°08	15 (1965...82)
Deschambault	267	05KF003	54°40	103°24	11 (1965-82)
Footprint	27	05TF001	55°48	98°51	14 (1961-75)[e]
Jan	114	05KG010	54°54	102°50	16 (1965-81)
Nemeiben	154	06CB003	55°16	105°22	16 (1965-82)
Reed	190	05TA001	54°35	100°29	20 (1963-82)
Schist	18	05KG004	54°45	101°50	33 (1950-82)
Wintering	106	05TD002	55°19	97°41	33 (1949-82)
Wollaston[f]	2290	06DA003	58°29	103°17	31 (1952-82)
Non-shield lakes:					
Amisk	347	05KG003	54°39	102°05	23 (1960-82)
Big Quill	255	05MA010	51°47	104°19	14 (1969-82)
Brightsand	32	05EG010	53°39	108°51	15 (1966-82)
Chitek	34	06AD012	53°45	107°44	19 (1964-82)
Churchill	544	06BA001	55°51	108°29	28 (1955-82)
Clearwater[g]	59	05KK009	53°59	101°10	22 (1959-82)
Cold	365	06AF002	54°28	110°10	24 (1955-82)
Des Iles	46	06AF009	54°26	109°19	15 (1967-82)
Dore	642	06AG003	54°38	107°24	15 (1965...82)
Greig	12	06AF010	54°27	108°42	17 (1965-82)
La Biche	234	07CA004	54°46	111°58	51 (1930-82)
La Ronge	1178	06CB001	55°06	105°18	35 (1930-67)[h]

continued

Table F1. continued.

Lake	Water area (km²)	Station Number	Lat °N	Long °W	Years of data
Little Bear	15	05KF002	54°18	104°41	18 (1965-82)
Little Quill	112	05MA002	51°53	104°08	10 (1919...82)
Makwa	30	06AD014	54°05	109°12	17 (1963-82)
Red Deer	252	05LC003	52°54	101°28	19 (1963-82)
Redberry	64	05GD003	52°42	107°06	14 (1966-82)
Simonhouse	82	05TA002	54°32	101°08	19 (1963-82)
Swan	313	05LE007	52°32	100°52	22 (1952...82)
Turtle	64	05EG009	53°37	108°35	18 (1964-82)
Waskesiu	70	06CA002	53°55	106°05	24 (1954-79)
Waterhen	73	06AF007	54°28	108°31	17 (1965-82)
Winnipegosis	5150	05LD002	52°58	100°58	20 (1963-82)

a Water Survey of Canada waterlevel station (Environment Canada (1983)).

b " - " designates most years and " ... " sporadic years.

c Includes station 07MC002 data adjusted by -2.220 m.

d Regulated in 1968 (see Bennett 1970).

e Apparently regulated in 1976.

f Includes station 06DA001 data adjusted by +0.008 m.

g Includes station 05KK003 data with no adjustment required.

h Regulated in 1968.

Table F2. Predictive polynomial equations for low daily waterlevel in July or August.

Lake	Best equation by stepwise regression[a] (Number of years, multiple R^2)
Shield lakes:	
Athabasca	$Y = 208.524 + 1.464X + 0.384X^2$ (n=17, R^2=0.98)
Cree	$Y = 486.592 + 0.779X - 0.737X^2 + 0.428X^5$ (n=15, R^2=0.98)
Deschambault	$Y = 324.469 + 1.728X - 1.445X^2 + 1.118X^9$ (n=11, R^2=0.98)
Footprint	$Y = 237.984 + 1.411X^2$ (n=14, R^2=0.92)
Jan	$Y = 28.705 + 0.729X + 2.761X^8 - 2.122X^9$ (n=16, R^2=0.99)
Nemeiben	$Y = 370.220 + 2.043X^2 - 2.309X^3 + 3.028X^8 - 2.311X^9$ (n=16, R^2=0.99)
Reed	$Y = 278.656 + 1.116X - 0.744X^2 + 0.758X^9$ (n=20, R^2=0.97)
Schist	$Y = 291.649 + 0.475X - 0.145X^2 + 0.277X^6$ (n=33, R^2=0.99)
Wintering	$Y = 181.104 + 0.840X - 135.776X^6 + 473.378X^7 - 559.475X^8 + 222.975X^9$ (n=33, R^2=0.98)
Wollaston	$Y = 27.835 + 1.224X - 0.923X^2 + 0.872X^9$ (n=31, R^2=0.98)
Non-shield lakes:	
Amisk	$Y = 0.805 + 0.247X + 0.541X^2$ (n=23, R^2=0.99)
Big Quill	$Y = 514.278 + 1.848X - 0.218X^9$ (n=14, R^2=0.99)
Brightsand	$Y = 663.014 + 0.502X - 2.937X^8 + 3.146X^9$ (n=15, R^2=0.98)
Chitek	$Y = 565.900 + 1.794X - 3.522X^2 + 2.501X^3$ (n=19, R^2=0.98)
Churchill	$Y = 29.989 + 4.336X - 6.701X^2 + 119.708X^7 - 231.219X^8 + 116.506X^9$ (n=28, R^2=0.99)
Clearwater	$Y = 259.823 + 0.779X - 0.384X^2 + 0.093X^8$ (n=22, R^2=0.99)
Cold	$Y = 534.768 + 0.946X - 0.870X^2 + 6.685X^8 - 6.169X^9$ (n=24, R^2=0.99)

Table F2. continued.

Lake	Best equation by stepwise regression (Number of years, multiple R^2)
Des Iles	$Y = 26.185 + 0.831X - 0.542X^3 + 1.271X^9$ ($n=15$, $R^2=0.98$)
Dore	$Y = 27.879 + 2.303X - 2.448X^2 + 7.402X^8 - 5.916X^9$ ($n=15$, $R^2=0.97$)
Greig	$Y = 475.542 + 0.324X + 0.110X^5$ ($n=17$, $R^2=0.95$)
La Biche	$Y = 543.080 + 1.744X - 5.300X^2 + 9.588X^3 - 7.585X^5 + 3.077X^8$ ($n=51$, $R^2=0.99$)
La Ronge	$Y = 362.366 + 4.840X - 6.183X^2 + 3.987X^4 - 0.413X^9$ ($n=35$, $R^2=0.99$)
Little Bear	$Y = 620.042 + 0.120X + 0.090X^3$ ($n=18$, $R^2=0.99$)
Little Quill	$Y = 517.744 + 1.185X$ ($n=10$, $R^2=0.97$)
Makwa	$Y = 523.805 + 0.553X - 0.418X^4 + 0.642X^9$ ($n=17$, $R^2=0.98$)
Red Deer	$Y = 261.317 + 1.588X - 1.378X^3 + 1.816X^9$ ($n=19$, $R^2=0.99$)
Redberry	$Y = 504.570 + 2.698X - 1.139X^2 + 0.496X^9$ ($n=14$, $R^2=0.98$)
Simonhouse	$Y = 295.071 + 2.599X - 1.732X^2 + 0.774X^9$ ($n=19$, $R^2=0.99$)
Swan	$Y = 258.330 + 1.056X - 1.790X^5 + 2.402X^9$ ($n=22$, $R^2=0.98$)
Turtle	$Y = 654.206 + 0.930X$ ($n=18$, $R^2=0.96$)
Waskesiu	$Y = 532.156 + 0.876X - 2.104X^2 + 1.762X^3 - 0.272X^9$ ($n=24$, $R^2=0.98$)
Waterhen	$Y = 472.031 + 3.620X - 5.543X^2 + 4.291X^4$ ($n=17$, $R^2=0.98$)
Winnipegosis	$Y = 250.738 + 29.587X - 208.186X^2 + 803.055X^3 - 1760.390X^4 + 2193.718X^5 - 1443.675X^6 + 388.674X^7$ ($n=20$, $R^2=0.99$)

a Y is predicted waterlevel (m from arbitrary elevation of station) and X is cumulative probability of lower daily July or August waterlevel (see text).

Table F3. Predicted low daily waterlevels in July or August for typical and extremely low years.

Lake	Predicted waterlevel (m)		
	Typical	Extreme	Variation
Shield lakes:			
Athabasca	209.351	208.538	0.813
Cree	486.811	486.600	0.211
Deschambault	324.974	324.486	0.488
Footprint	238.337	237.984	0.353
Jan	29.076	28.713	0.363
Nemeiben	370.450	370.220	0.230
Reed	279.030	278.668	0.362
Schist	291.855	291.654	0.201
Wintering	181.351	181.112	0.239
Wollaston	28.218	27.847	0.371
Non-shield lakes:			
Amisk	1.064	0.808	0.256
Big Quill	515.201	514.297	0.904
Brightsand	663.260	663.020	0.240
Chitek	566.229	565.918	0.311
Churchill	30.741	30.031	0.710
Clearwater	260.116	259.830	0.286
Cold	535.038	534.778	0.260
Des Iles	26.535	26.193	0.342
Dore	28.436	27.902	0.534
Greig	475.708	475.546	0.162
La Biche	543.600	543.097	0.503
La Ronge	363.488	362.413	1.075
Little Bear	620.114	620.044	0.070
Little Quill	518.336	517.756	0.580
Makwa	524.057	523.811	0.246

continued

Table F3. continued.

Lake	Predicted waterlevel (m)		
	Typical	Extreme	Variation
Red Deer	261.942	261.333	0.609
Redberry	505.635	504.597	1.038
Simonhouse	295.939	295.097	0.842
Swan	258.807	258.341	0.466
Turtle	654.671	654.216	0.455
Waskesiu	532.287	532.164	0.123
Waterhen	472.723	472.067	0.656
Winnipegosis	252.875	251.013	1.862

Morphometry The 209 lakes showed greater relative volume changes in small lakes than in larger ones as a result of waterlevel variations. Regressions were similar for 0.5 m in shield and non-shield lakes, but significantly different at 2 m (Table F5). Note that equations under "added intercepts" are not statistically unique solutions and probably biased (Freund and Minton 1979, SAS 1982).

Table F4. Regressions of low waterlevel variations (m) on log water area (km^2).

Source and regressions	df	SS	MS	F-statistic
Total	32	4.128	...	
One regression:	1	1.271	1.271	F1=13.82 ***
Y=-0.137 + 0.285X (r^2=0.31)				
Residual	31	2.857	0.092	
Added intercept:	1	0.504	0.504	F2=6.42 **
Shield Y=-0.4058 + 0.3203X				
Non-shield Y=-0.1318 + 0.3203X				
Residual	30	2.354	0.078	
Added coefficient:	1	0.355	0.355	F3=5.14 **
Shield Y=0.0344 + 0.1369X (r^2=0.39)				
Non-shield Y=-0.4030 + 0.4487X (r^2=0.50)				
Residual	29	1.999	0.069	

** significant at $0.01<P<0.05$ *** significant at $P<0.01$

Table F5. Regressions of relative volume above 2 m (%) on log water area (km^2).

Source and regressions	df	SS	MS	F-statistic
Total	209	70510.40	...	
One regression:	1	16072.18	16072.18	F1=61.409***
Y=37.629 - 7.659X (r^2=0.23, n=210)				
Residual	208	54438.22	261.72	
Added intercept:	1	222.53	222.53	F2=0.850 NS
Shield Y=36.946 - 7.887X (r^2=0.32, n=124)				
Non-shield Y=39.105 - 7.887X (r^2=0.09, n=86)				
Residual	207	54215.69	261.91	
Added coefficient:	1	846.94	846.94	F3=3.269*
Shield Y=37.755 - 9.136X				
Non-shield Y=35.894 - 5.252X				
Residual	206	53368.75	259.07	

NS not significant at P=0.10 * significant at 0.05<P<0.10
*** significant at P<0.01

Waterlevel variations of 2 m affected the volume of shield lakes over 100 km^2 less than comparable non-shield lakes (Table F5). Larger non-shield lakes tended to fall near or above the upper 95 % prediction limits of the regression. Absolute volume below 2 m was greater in larger lakes than smaller, as expected. The regression of absolute volume below 2 m depth on water area was again significantly different for shield and non-shield lakes.

Residual volumes Residual volume increased with increasing water area in spite of greater waterlevel variation. Residual volumes predicted from expected waterlevel variations (Table F6) and corresponding water area (Table F7) showed statistical differences between shield and non-shield lakes.

The effect of waterlevel variation on volume of lakes, however, was negligible. Certainly no major reduction from typical water volumes found in lake surveys were predicted for the lowest waterlevels expected 1 in 100 years (see Tables F7 and F8).

Table F6. Regressions of log residual volume (hm^3) on predicted waterlevel variation (m).

Source and regressions	df	SS	MS	F-statistic
Total	208	345.88	...	
One regression:	1	230.32	230.32	F1=412.55***
Y=0.7333 + 4.7122X (r^2=0.66, n=209)				
Residual	207	115.56	0.558	
Added intercept:	1	0.12	0.120	F2=0.21 NS
Shield Y=0.7477 + 4.7437X				
Non-shield Y=0.6970 + 4.7437X				
Residual	206	115.44	0.560	
Added coefficient:	1	69.52	69.516	F3=310.34 ***
Shield Y=0.0562 + 9.5562X (r^2=0.90, n=124)				
Non-shield Y=1.1076 + 3.2311X (r^2=0.76, n=85)				
Residual	205	45.92	0.224	

NS not significant at P=0.10 *** significant at P<0.01

Table F7. Regressions of log residual volume (hm^3) on log water area (km^2).

Source and regressions	df	SS	MS	F-statistic
Total	208	345.883	...	
One regression:	1	330.040	330.040	F1=4286.2 ***
Y=0.6883 + 1.0976X (r^2=0.95, n=209)				
Residual	207	15.843	0.077	
Added intercept:	1	0.286	0.286	F2=3.76 *
Shield Y=0.7127 + 1.1058X				
Non-shield Y=0.6350 + 1.1058X				
Residual	206	15.557	0.076	
Added coefficient:	1	0.359	0.359	F3=4.851 **
Shield Y=0.6961 + 1.1315X (r^2=0.97, n=124)				
Non-shield Y=0.7013 + 1.0515X (r^2=0.92, n=85)				
Residual	205	15.198	0.074	

NS not significant at P=0.10 ** significant at 0.01<P<0.05
*** significant at P<0.01

Table F8. Regressions of log total water volume (hm^3) on log water area (km^2).

Source and regressions	df	SS	MS	F-statistic
Total	208	350.359	...	
One regression:	1	335.223	335.223	F1=4586.8***
Y=0.6924 + 1.1062X (r^2=0.96, n=209)				
Residual	207	15.136	0.073	
Added intercept:	1	0.262	0.262	F2=3.63*
Shield Y=0.7158 + 1.1140X				
Non-shield Y=0.6414 + 1.1140X				
Residual	206	14.874	0.072	
Added coefficient:	1	0.278	0.278	F3=3.91**
Shield Y=0.7011 + 1.1366X (r^2=0.97, n=124)				
Non-shield Y=0.6997 + 1.0662X (r^2=0.92, n=85)				
Residual	205	14.595	0.071	

* significant at 0.05<P<0.10

** significant at 0.01<P<0.05 *** significant at P<0.01

DISCUSSION

RECENT CONDITIONS

Waterlevels The polynomial regressions used were preferable to other approaches to hydrological prediction. Pearson Type III curves are well established for prediction of water discharges as minimum values are bounded by zero flow (Hjelmfelt and Cassidy 1975). Waterlevels may resemble a Pearson Type IV curve (Elderton and Johnson 1969) but have not been modelled in this way.

The predictions of waterlevels in this study agree reasonably with the few available predictions by hydrologists for the same lakes. Retrospective studies by other agencies show variations for pre-regulated Lake Athabasca of 1.5 m (1 in 40 years) compared to 0.8 m from the present regressions, for Cree Lake of 0.5 m by prediction and 1.2 m by local residents (1 in 37 years) compared to 0.6 m from this study, and for pre-regulated Cumberland Lake of 2.9 m (1 in 49 years) (Bennett 1970, Canada 1970, 1977).

Lakes with long-term waterlevel data may or may not represent all lakes of similar size and location or allow direct comparisons between periods of drought and wet. Some lakes have been described as representative of the region hydrologically (e.g. Big Quill by Whiting 1972). Some were selected for monitoring under the International Hydrological Decade program and are assumed to be representative. Some were studied during hydro-electric use (e.g. Lac Ile-a-la-Crosse and Churchill) or for hydro-electric potential (e.g. Cree Lake by Canada 1970). It is assumed that the monitored lakes are more useful socio-economically and possibly larger than others nearby, and may represent the shield and non-shield regions reasonably.

Individual lake waterlevels were not adjusted to regional trends, so that lakes monitored since 1930 may or may not be comparable to those monitored since only 1960. Twelve of the 33 lakes analysed had data for 20 or more years, but only 3 lakes had data prior to 1950 (Table F1). Predictions of components of the hydrologic cycle (or "water balance") are available for 1925 to 1980 for Saskatchewan, Manitoba, and Alberta (Environment Canada 1986). In particular, smoothed data on precipitation, runoff, evapotranspiration, and water storage are available for 10-day periods for 100 grids between 49-60^{O}N and 92-120^{O}W (Environment Canada 1986). Correlation of lake waterlevels with hydrologic components has been demonstrated (e.g. Laycock 1973). Trends in these indicators may allow better comparability between lakes with dissimilar periods-of-record of waterlevels.

Morphometry The 209 lakes showed the anticipated differences: a greater proportion of the lake volume above 0.5 and 2 m depth in smaller lakes, and above 2 m in non-shield lakes. Absolute volume below 2 m shows corresponding trends: shield and non-shield lakes about 10 km^2 area are similar, but larger shield lakes have greater volume than non-shield lakes. The large variability in data, however, means that the relationships do not reliably diverge at common lake areas. This variability reflects differences in lake substrate or origin in some regions: many non-shield lakes near Cumberland Lake lie in glaciolacustrine sediments and are essentially cylindrical in cross-section, compared to others in river or former river valleys which are distinctly V-shaped.

Residual volumes The conclusion is that changes in summer lake volumes within the last 100 years have been generally small in the study area. The effects of climate on deep-water temperature conditions via changes in fetch and maximum depth (see Estimation of missing data) are assumed to be similar. Changes in volumes of suitable temperature-and-oxygen, TDS, spawning habitat, and other factors influenced by climatic conditions cannot be assessed with available data.

Clearly several factors have weakened this analysis. The uncertain representation by lakes with long-term waterlevel data hinders the extrapolation of results to other lakes in the study area. The lack of morphometric data on many lakes which were monitored for waterlevel prevents direct estimates of volume changes. For example, greater fluctuations of waterlevels due to high precipitation/evaporation potential and greater relative volume changes are expected in lakes with low volume to area ratios . The mathematical coalition of two data sets to assess the combined effects of waterlevel variation and morphometry may mask these inter-related factors. In addition, the non-linearities of some relationships (e.g. Figure 8 in text) and the lack of very shallow, small non-shield lakes may be relatively unimportant.

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Appendix G

ESTIMATION OF MISSING DATA AND BIAS USING OTHER HABITAT VARIABLES

INTRODUCTION

Some lakes in this study lack one or more variables which are available for most other lakes. The estimation of missing variables from correlated variables allows for a larger sample size. More importantly, it also reduces bias if smaller or non-lake-trout lakes are surveyed less frequently, yet differ in habitat traits (see text). Furthermore, criteria which predict lake trout presence or absence accurately can sometimes be estimated from more easily available variables.

METHODS

General methods of all-subset and stepwise regression and associated tests are described in the text.

Three surficial geology indices and their logarithmic transformations were examined for potential contribution to predictions of ZMAX. Maps in Schreiner (1984) showed types of materials (i.e. Rock, Morainal, GlacioFluvial, GlacioLacustrine, Eolian, Organic, Alluvial, and Lacustrine) and their relative proportions (i.e. >60 / <40 / <15 %). These were collated and condensed, if necessary, into three or fewer zones for each lake and assigned type-proportions:

A / B / C was assigned 70 / 25 / 5 %,

A / B / . was assigned 75 / 25 / 0 %,

A / . / C was assigned 95 / 0 / 5 %,

A / . / . was assigned 100 / 0 / 0 %.

Each zone was weighted by its proportion of the applicable lake basin. Potential for greater depth for each type of material was arbitrarily set at: R=10, M=5, GF=2, GL or E=1, and O or A or L=0.

The first index (GEO1) was an average of type-potentials, weighted by type-proportions and zone-proportions. The second index (GEO2) was simply the weighted proportion of rock in the lake basin. The third index (GEO3) was the absolute area of rock available in the lake basin (i.e. GEO2 times the water area (km^2)).

The Froud index (Orlob 1983) predicts stratification of lakes from water-exchange rates. This index is:

$$F = \frac{l}{d}\frac{Q}{V} (r_0 / g r)^{0.5}$$

where l, d, and V are the length (m), average depth (m), and volume (m^3) of the lake, Q is the flow-through discharge ($m^3.s^{-1}$), g is the acceleration of gravity ($9.8 m.s^{-2}$), and r_0 and r are the reference density and the density difference of the water over depth d ($g.cm^{-3}$). Incipient stratification of $10^{o}C$ surface and $4^{o}C$ bottom or reference water was assumed for June conditions, implying $r_0 = 1$ and $r = 0.0003$. The modified equation was then:

$$F = \frac{(1000*FETCH)(June\ discharge)}{(ZBAR)(1000000*VOLUME)} (d / 0.00294)^{0.5}$$

Average June discharges were available for lakes with streamflow stations (Environment Canada 1983), lakes with EIA studies, and connected lakes for single or three-year periods.

RESULTS AND DISCUSSION

About 67 % of the pairs of morphometric variables were correlated significantly (Table G1). The highest correlations were between fetch and water area (r^2=0.96), volume and area (r^2=0.92), volume and fetch (r^2=0.90), and maximum and mean depths (r^2=0.86). The ratio of actual to expected log SHODEV (i.e. RLOGSHOD) was uncorrelated in 12 of 15 comparisons, which made it noteworthy in this highly collinear set of variables.

TDS from SPCON Correlation of TDS with SPCON was well defined. However, initial regressions showed higher TDS than predicted at SPCON below 20 uS in many shield lakes from two

Table G1. Pairwise Pearson correlations (r) of habitat variables and numbers of lakes. Statistical significance is P<0.01 unless indicated otherwise.

	Log$_{10}$ of															
	WAREA	VOLUME	ZMAX	ZBAR	FETCH	FETDEV	SHODEV	VOLT15T6	VOLT1506	VOL6MG	RLOGSHOD	OMINB	STRAFN[a]	TMAXS	TMAXB	T15T6U
Log$_{10}$ of: WAREA	...	0.96 275	0.51 312	0.43 274	0.98 249	-0.12 249	0.61 237	0.18 194**	0.31 183	0.66 204	-0.01 219NS	0.17 218**	-0.04 225NS	-0.16 266	-0.01 237NS	0.48 231
VOLUME		...	0.66 275	0.66 274	0.95 230	-0.18 230	0.64 231	0.36 194	0.33 183	0.71 204	-0.01 216NS	0.08 212NS	0.16 211**	-0.19 241	-0.18 227	0.56 228
ZMAX			...	0.93 274	0.59 250	-0.18 249	0.49 236	0.67 194	0.26 183	0.55 204	0.05 219NS	-0.12 218*	0.56 225	-0.22 266	-0.60 237	0.57 231
ZBAR				...	0.51 229	-0.16 229**	0.32 230	0.68 194	0.20 183	0.54 204	-0.02 215NS	-0.15 212**	0.62 210	-0.15 240**	-0.59 226	0.50 227
FETCH					...	0.06 249NS	0.64 219	0.16 166**	0.31 156	0.76 172	-0.02 219NS	0.18 187**	-0.05 199NS	-0.14 217**	0.01 204NS	0.48 194
FETDEV						...	-0.15 219**	-0.03 166NS	-0.12 156NS	-0.23 172	0.13 219*	-0.03 187NS	-0.07 199NS	0.19 217	0.03 204NS	-0.29 194
SHODEV							...	0.22 170	0.34 161	0.50 178	0.27 219	0.11 195NS	0.07 196NS	-0.08 208NS	-0.05 204NS	0.44 201
VOLT15T6								...	0.26 181	0.33 181	-0.01 162NS	-0.20 179	0.83 170	-0.25 193	-0.87 185	-0.07 194NS
VOLT1506									...	0.23 180	-0.00 154NS	0.18 171**	0.06 159NS	-0.26 183	-0.15 173**	-0.08 183NS

Table G1. continued.

	Log$_{10}$ of															
	WAREA	VOLUME	ZMAX	ZBAR	FETCH	FETDEV	SHODEV	VOLT15T6	VOLT1506	VOL6MG	RLOGSHOD	OMINB	STRAFN[a]	TMAXS	TMAXB	T15T6U
RLOGSHOD											...	-0.06 183NS	0.04 181NS	0.32 193	0.06 189NS	0.04 189NS
OMINB												...	-0.47 189	-0.32 218	0.30 213	-0.08 214NS
STRAFN													...	-0.02 215NS	-0.87 206	-0.11 197NS
TMAXS														...	0.22 239	0.02 230NS
TMAXB															...	0.17 219**

a Categorical variables are more suited to non-parametric correlation, rather than Pearson's as shown.
NS not significant at P > 0.10 * significant at 0.05 < P < 0.10 ** significant at 0.01 < P < 0.05

studies (see Figure 10 in text). Provincial survey procedures included filtering water samples with plankton netting of 80-um mesh, conductivity readings in the field, and TDS analysis in the lab (Atton and Johnson 1970). These problem samples were not filtered or otherwise treated in the field, but were filtered during lab analysis (Beak 1979 Volume 1 p.5-60 and Volume 2 p.5A-13). Field readings of specific conductivity were assumed to be accurate, but decomposition of non-ionic suspended solids may have contributed to anomalously high dissolved solids during later analysis (W.K. Liaw, Fisheries Branch, pers. comm.). When these two studies were excluded, regressions became more linear and more similar in slope to non-shield lakes. Separate regressions were indicated for shield and non-shield lakes (Table G2).

<u>SHODEV and RLOGSHOD</u> In this study, SHODEV was a potential indicator of depth, wind-protection, and other habitat conditions. Separate regressions of log SHODEV on log WAREA were indicated for shield and non-shield lakes (Table G3). Non-shield lakes had greater residuals at larger log WAREA, suggesting greater variability in lake outline.

Table G2. Regressions of log TDS ($mg.L^{-1}$) on log SPCON (uS) over the range 20 to 32,000 uS.

Source and regressions	df	SS	MS	F-statistic
Total	185	35.217	...	
One regression:	1	33.418	33.418	F1=3418 ***
Y=0.142 + 0.880 X (R^2=0.95,n=186)				
Residual	184	1.799	0.010	
Separate regressions:	2	0.172	0.086	F3=9.56 ***
Shield Y=0.167 + 0.878 X (R^2=0.79,n=77)				
Non-shield Y=-0.087 + 0.956 X)R^2=0.96,n=109)				
Residual	182	1.627	0.009	

*** significant at P<0.01

Deviation of actual SHODEV of any lake from that predicted by water area (Koshinsky 1970) was represented in this study by the ratio of actual log SHODEV to predicted log SHODEV (based on shield and non-shield regressions in Table G3). The use of a ratio reduced the correlation with log SHODEV (r=0.27, see Table G1) from that observed using a difference between actual and predicted (r=0.57), but clearly did not obviate the confounding effect of lake area. This ratio was later assessed as a predictor of maximum and mean depth, volume, and maximum surface temperatures.

Table G3. Regressions of log SHODEV on log WAREA (km^2).

Source and regressions	df	SS	MS	F-statistic	
Total	236	23.819	...		
One regression:	1	9.632	9.632	F1=160	***
$Y=0.318 + 0.184 X$ ($R^2=0.40$, n=237)					
Residual	235	14.187	0.060		
Separate regressions:	2	6.175	3.088	F3=91	***
Shield $Y=0.384 + 0.250 X$ ($R^2=0.73$, n=152)					
Non-shield $Y=0.188 + 0.130 X$ ($R^2=0.25$, n=85)					
Residual	233	8.012	0.034		

*** significant at $P<0.01$

Elongation of lakes was thought to be more important than shoreline sinuosity in causing high SHODEV values (Koshinsky 1970, Hutchinson 1957). Elongation was defined as the ratio of actual FETCH to the fetch of a circle of the same area (called FETDEV, cf. shoreline development). The term "sinuous" is subjective (except implicitly in the definition of SHODEV) and cannot be assessed directly. However, elongation was relatively minor compared to WAREA and FETCH, and was not selected in stepwise regressions (Table G4). Shield lakes showed a statistically significant regression, but the correlation was unimpressive for practical purposes; non-shield lakes showed non-significant correlation.

Table G4. Regressions of log SHODEV on log WAREA (km^2), log FETCH (km), and log FETDEV.

Number of variables	Equations (multiple R^2, Cp-reliability)a
All lakes (n=219):	
1	$Y=0.325 + 0.190 \log WAREA$ (R^2=0.44 M)
2	$Y=0.353 + 0.243 \log WAREA - 0.109 \log FETCH$ (R^2=0.44 M)
3b	$Y=0.240 + 0.186 \log WAREA + 0.002\ ORINW$ (R^2=0.46 M)
Shield lakes (n=144):	
1	$Y=0.387 + 0.250 \log WAREA$ (R^2=0.74 M)
2	$Y=0.429 + 0.329 \log WAREA - 0.164 \log FETCH$ (R^2=0.74 M)
Non-shield lakes (n=75):	
1	$Y=0.105 + 0.296 \log FETCH$ (R^2=0.32 U)
2	$Y=0.036 + 0.141 \log WAREA - 0.574 \log FETCH$ (R^2=0.33 M)

a Reliability of equations according to Cp-statistics is: E is suitable for extrapolation, P is suitable for prediction, M is marginally acceptable for prediction, and U is unacceptable.

b Variable ORINW (° from NW orientation) was available for selection and n differed slightly.

<u>ZMAX and ZBAR</u> Regressions of log ZMAX on subsets of morphometric variables showed that log WAREA and log FETCH were important, explaining 37 % of total variation (Table G5). Minor increases in R^2 were possible using orientation as lakes oriented more northeasterly have greater maximum depth. Separate regressions explained about 50 and 20 % of variation in shield and non-shield lakes, respectively.

Surficial geology indices were determined for about 135 shield lakes. Index GEO1 was bi-modally non-normally distributed, and ranged from 0.6 to 9.8 on the theoretical 0 to 10 range. GEO2 was positively skewed (median 0.005) and ranged from 0 to 0.95 on the theoretical 0 to 1 range. GEO3 was positively skewed (median 0.08) and ranged from 0 to 187 km^2, in a set in which the largest lake was 1156 km^2. LogGEO2 and logGEO3 were bi-modal as a result of adding the small constant 10^{-3} to zero data.

The three indices rated different lakes as very high or very low in depth potential (Table G6). GEO1 and GEO2 rated some of the same lakes very highly since both indices are weighted towards rock materials. GEO2 and GEO3 rated lakes without rock as very low on proportional and areal bases.

Table G5. Regressions of log ZMAX (m) on other morphometric variables.

Lake set	Equations (multiple R2, n, Cp-reliability)
<u>All lakes (n=219):</u>	
1	Y=1.034 + 0.213 log WAREA (R2=0.35 U)
2	Y=1.172 + 0.471 log WAREA - 0.534 log FETCH (R2=0.37 M)
3	Y=1.151 + 0.490 log WAREA - 0.572 log FETCH + 0.032 RLOGSHOD (R2=0.37 M)
4b	Y=1.017 + 0.452 log WAREA - 0.515 log FETCH + 0.003 ORINW (R2=0.40 M)
<u>Shield lakes (n=144):</u>	
1	Y=1.065 + 0.252 log WAREA (R2=0.47 U)
2	Y=1.236 + 0.576 log WAREA - 0.674 log FETCH (R2=0.50 M)
3	Y=1.186 + 0.595 log WAREA - 0.704 log FETCH + 0.052 RLOGSHOD (R2=0.50 M)
4b	Y=1.119 + 0.594 log WAREA - 0.743 log FETCH + 0.003 ORINW (R2=0.53 M)
<u>Non-shield lakes (n=75):</u>	
1	Y=0.895 + 0.333 log FETCH (R2=0.19 P)
1b	Y=0.980 + 0.167 log WAREA (R2=0.20 P)
2	Y=0.959 + 0.130 log WAREA + 0.076 log FETCH (R2=0.20 M)
2	Y=0.969 + 0.161 log WAREA + 0.020 RLOGSHOD (R2=0.20 P)
2b	Y=0.825 + 0.348 log FETCH + 0.001 ORINW (R2=0.22 P)

a Log WAREA (km^2), log FETCH, log FETDEV, ratio of log SHODEV, and ORINW (^{o} from NW orientation) were available.

b Reliability according to Cp is: E is suitable for extrapolation, P is suitable for prediction, M is marginally acceptable for prediction, and U is unacceptable.

c Variable ORINW was available for selection and n differed slightly.

Table G6. Lakes which are rated very high and very low by three surficial geological indices of depth.

Ranking	Index: GEO1	GEO2	GEO3
Highest	Milliken	Milliken	Deschambault
2nd highest	Beaverlodge	Fontaine	Jan
3rd highest	Tyrrell	Beaverlodge	Nemeiben
4th highest	Fontaine	Island	Black
5th highest	Trout	Snake	Pelican
...			
5th lowest	Costigan	Riou[a,b]	Riou[b]
4th lowest	Broach	Drope[b]	Drope[b]
3rd lowest	Mid	Henday[b]	Kewen[b]
2nd lowest	Kewen	Kewen[b]	Martin[b]
Lowest	Germaine	Gerald[b]	Russell[b]

a Vertical symbols group lakes with the same index value.
b All of these lakes lack rock material.

In all-subset regressions, none of the indices improved predictions of log ZMAX notably. In two trials, no index added significantly to regressions based on other morphometry (Table G7). GEO2 was the simplest index and was preferred marginally over the other indices. GEO1, which weighted potential according to both type and prevalence of materials, was the most general index. Therefore, it was most

Table G7. Regressions of log ZMAX on three surficial geological indices and other morphometric variables.

Lake set	Equations (multiple R^2, n, Cp-reliability)
Shield lakes:	
log ZMAX =	1.293 + 0.649 log WAREA - 0.850 log FETCH (R^2=0.48, n=111, M)[a]
log ZMAX =	1.310 + 0.658 log WAREA - 0.851 log FETCH - 0.115 GEO2 (R^2=0.48, n=111, M)[a]
log ZMAX =	1.071 + 0.242 log WAREA (R^2=0.43, n=111, M)[b]
log ZMAX =	1.088 + 0.250 log WAREA - 0.113 GEO2 (R^2=0.43, n=111, M)[b]

a Available variables included GEO1, GEO2, GEO3, log GEO2, log GEO3, log WAREA, log FETCH, RLOGSHOD, and ORINW.

[b] Available variables included GEO1, GEO2, GEO3, log GEO2, log GEO3, log WAREA, log FETCH, log FETDEV, and ORIFET.

susceptible to mis-assignment of potential to various types: rock may not be 10 in relation to moraine at 5 and lacustrine material at 0. The term "rock" assimilates Precambrian igneous material with pronounced "topographic trends" and late Precambrian sediment on the "relatively flat lying" Athabasca basin (Schreiner 1984 p.6). Ground moraine is composed of (1) sandy till in the Precambrian region, which contains "an abundance of large, angular ... boulders which commonly dominate the deposit" and (2) very sandy till in the Athabasca basin, which "commonly contains subangular to subrounded boulders of varying sizes" (Schreiner 1984 p.30). Yet the coarsest glaciofluvial material generally comprises cobbles and pebbles, so that the ordination of other types appears correct.

Mean depth (ZBAR) was less predictable than maximum depth. Regressions showed that log WAREA was most important, followed by log FETCH in shield lakes and log FETDEV in non-shield lakes (Table G8). Minor improvements in R^2 due to orientation of lakes were observed again. Liaw and Atton (1981) reported 33 % correlation for ZBAR and WAREA in Saskatchewan lakes.

STRAFN and T15T6U The degree of stratification (STRAFN) was simplified to "no" (none or weak) or "yes" (moderate, strong, very strong) for this analysis. The boundary condition for stratification according to Gorham (1980 cited in Cruikshank 1984):

$$\log ZMAX\ (m) \geq 0.60 + 0.25\ (2 + \log WAREA)\ (km^2)$$

correctly classified 77 % of 225 lakes (i.e. 68 % of 125 shield lakes and 88 % of non-shield lakes). This improved to 82 % when all lakes with log ZMAX over 26 m were assumed to stratify. An alternate boundary condition using FETCH was derived in the present study:

$$\log ZMAX\ (m) \geq 0.78 + 0.42 \log FETCH\ (km)$$

and correctly classified 82 % of 199 lakes (i.e. 82 % of 119 shield lakes and 84 % of 80 non-shield lakes).

Table G8. Regressions of log ZBAR (m) on log WAREA (km^2), log FETCH (km), log FETDEV, ratio of log SHODEV, and ORINW (^{o} from NW orientation).

Number of variables	Equations (multiple R^2, Cp-reliability)
<u>All lakes (n=215):</u>	
1	Y=0.636 + 0.2151 log WAREA (R^2=0.28 U)
2	Y=0.716 + 0.301 log WAREA - 0.308 log FETCH (R^2=0.29 P)
3	Y=0.717 + 0.300 log WAREA - 0.306 log FETCH - 0.001 RLOGSHOD (R^2=0.29 M)
4b	Y=0.598 + 0.271 log WAREA - 0.274 log FETCH + 0.003 ORINW (R^2=0.31 P)
<u>Shield lakes (n=142):</u>	
1	Y=0.649 + 0.158 log WAREA (R^2=0.31 P)
2	Y=0.701 + 0.256 log WAREA - 0.204 log FETCH (R^2=0.31 P)
3	Y=0.699 + 0.257 log WAREA - 0.206 log FETCH + 0.003 RLOGSHOD (R^2=0.31 M)
4b	Y=0.590 + 0.247 log WAREA - 0.227 log FETCH + 0.002 ORINW (R^2=0.34 M)
<u>Non-shield lakes (n=75):</u>	
1	Y=0.602 + 0.152 log WAREA (R^2=0.22 M)
2	Y=0.704 + 0.146 log WAREA - 0.473 log FETDEV (R^2=0.25 P)
3	Y=0.704 + 0.147 log WAREA + 0.463 log FETDEV - 0.003 RLOGSHOD (R^2=0.25 M)
4b	Y=0.611 + 0.322 log WAREA - 0.345 log FETCH + 0.002 ORINW (R^2=0.27 P)

a Reliability of equations according to Cp are: E is suitable for extrapolation, P is suitable for prediction, M is marginally acceptable for prediction, and U is unacceptable.

b Variable ORINW was available for selection and n differed slightly.

Fetch has been measured in several different ways (Arai 1981, Patalas 1984), the best of which may be "effective fetch" or a weighted mean of 15 individual lines upwind from any given point (Smith and Sinclair 1972). This definition, however, characterises a single point for sedimentation and other site-specific purposes, rather than the entire lake as required for vertical temperature profiling. Fetch in the present study is essentially "axial length", which over-estimates the effects of wind in long narrow lakes (Smith 1979).

The Froud index was available for 46 lakes and correctly predicted non-stratification for lakes with $F > 0.03$. This index compares the inertial force of moving surface water in an impoundment or lake to the stability induced by density differences between the surface and bottom layers in the waterbody. The present criterion is different than recommended: F for non-stratified lakes > 0.1 and F for stratified lakes $<< 0.32$ (Orlob 1983).

The present modification simplifies several factors: (1) Fetch was used for length since no other datum was easily available, but "length along flow-through" is intended; (2) Discharges were based on June data, although Orlob (1983) did not specify monthly or annual discharges; (3) The assumption of $10^{o}C$ surface and $4^{o}C$ bottom water seemed reasonable for early summer, and r varies little within feasible limits for this region (Wetzel 1983, CRC 1968).

Although maximum depth was itself predictable from water area, fetch, and other morphometric variables, attempts to use estimated depth in a boundary condition were unsuccessful. The individuality of lakes was lost in the estimation of ZMAX by linear regressions, so that stratified and non-stratified lakes intermingled in plots. Similarly, pairs of variables (e.g. log FETCH and log WAREA, log FETCH and ORINW, and RLOGSHOD and log WAREA) showed no delineation of stratification.

Regressions of log T15T6U on subsets of variables showed that log WAREA and log FETCH were important, explaining about 47 % of total variation (Table G9). TMAXS was a relatively unimportant variable when stratified and non-stratified lakes were combined in this regional study.

In 86 stratified lakes, log WAREA and log FETCH explained 74 % of variation (Table G9). Other studies on stratified lakes have explained 66 to 72 % (Shuter et al. 1983), 85 % (Patalas 1984), and 36 to 79 % (Cruikshank 1984) of thermocline or epilimnion depth using area, fetch, or other morphometry. The maximum depth of 15°C behaves similarly to the thermocline, and is apparently also dependent on wind-driven mixing. The NW-component of fetch was necessary for predictive purposes, presumably due to wind-mixing. Log WAREA and TMAXS explained 77 % of variation. Furthermore, use of TMAXS produced equations which were suitable for prediction according to the Cp-statistic (Hocking 1976).

Table G9. Regressions of log T15T6U (maximum depth of 15°C, m) on log WAREA (km^2), TMAXS (°C), log FETCH, log FETDEV, ratio of log SHODEV, ORINW (° from NW orientation), and ORIFET (NW-component of log fetch, km) for lakes with TMAXS above 15°C.

Number of variables	Equations (multiple R^2, Cp-reliability)
All lakes (n=171):	
1	Y=0.787 + 0.186 log WAREA (R^2=0.44 M)
2	Y=0.925 + 0.418 log WAREA - 0.491 log FETCH (R^2=0.47 P)
3	Y=0.927 + 0.421 log WAREA + 0.508 log FETCH + 0.021 ORIFET (R^2=0.47 P)
3	Y=0.909 + 0.421 log WAREA + 0.496 log FETCH + 0.016 RLOGSHOD (R^2=0.47 P)
4	Y=0.841 + 0.297 log FETCH - 0.848 log FETDEV + 0.001 ORINW + 0.084 ORIFET (R^2=0.47 P)
Stratified lakes (n=86):	
1b	Y=0.809 + 0.179 log WAREA (R^2=0.74 M)
2b	Y=0.843 + 0.239 log WAREA - 0.126 log FETCH (R^2=0.74 M)
2	Y=1.168 + 0.168 log WAREA - 0.017 TMAXS (R^2=0.77 M)
3	Y=1.224 + 0.169 log WAREA - 0.018 TMAXS - 0.001 ORINW (R^2=0.77 M)
3	Y=1.191 + 0.153 log WAREA - 0.018 TMAXS - 0.066 ORIFET (R^2=0.77 M)
4	Y=1.223 + 0.220 log WAREA - 0.018 TMAXS - 0.147 log FETCH + 0.081 ORIFET (R^2=0.78 P)
4	Y=1.200 - 0.018 TMAXS + 0.293 log FETCH - 0.439 log FETDEV + 0.081 ORIFET (R^2=0.78 P)
Non-stratified lakes (n=74):	
2	Y=1.024 + 0.709 log WAREA - 1.005 log FETCH (R^2=0.49 M)
3	Y=1.023 + 0.719 log WAREA - 0.899 log FETCH - 0.191 ORIFET (R^2=0.50 M)
3	Y=0.921 + 0.732 log WAREA - 1.037 log FETCH + 0.100 RLOGSHOD (R^2=0.51 M)
4	Y=0.925 + 0.740 log WAREA - 0.937 log FETCH + 0.095 RLOGSHOD - 0.178 ORIFET (R^2=0.52P)

a Reliability of equations according to Cp are: E is suitable for extrapolation, P is suitable for prediction, M is marginally acceptable for prediction, and U is unacceptable.

b Variable TMAXS was not available for selection and n differed slightly.

Arai (1981) and Patalas (1984) noted that the effect of higher surface temperatures was to increase stability of the metalimnion and reduce the mixing depth. Shield and non-shield lakes have statistically different regressions on log WAREA and TMAXS (Table G10), but the reason was not evident.

VOLT15T6 Attempts to estimate VOLT15T6 were complex. Six northern lakes were entirely below 15°C, ranging from Midwest at 4 km^2 to Wollaston at 2062 km^2. These lakes were near others which reached 15.8 to 21.0°C surface temperatures and no explanation for these lower temperatures was obvious (Table G11). Deletion of lakes with TMAXS below 15°C was only partially useful. Secondly, two distinct classes of lakes occurred: those with some predictable VOLT15T6 and those with none. It appeared that stratification caused non-linear behaviour of the depth of 15°C. Stratification forces a thermocline at least 2 m but seldom more than 20 m deep regardless of lake size (Patalas 1984).

Table G10. Regressions of log T15T6U (m) on log WAREA (km^2) and TMAXS (^{o}C) in stratified lakes.

Source and regressions	df	SS	MS	F-statistic
Total	90	4.398	...	
One regression:	2	3.372	1.686	F1=140.5 ***
Y=1.171 + 0.169 logWAREA - 0.017 TMAXS (R^2=0.77, n=91)				
Residual	88	1.026	0.012	
Separate regressions:	3	0.117	0.039	F3=3.54 **
Shield Y=1.126 + 0.167 logWAREA - 0.016 TMAXS (R^2=0.76,n=65)				
Non-shield Y=1.268+0.136 logWAREA-0.017 TMAXS (R^2=0.76,n=26)				
Residual	85	0.909	0.011	

** significant at 0.01<P<0.05 *** significant at P<0.01

Table G11. Lakes with TMAXS of 15°C or lower.

Lake	TMAXS	WAREA (km^2)	FETCH (km)	ZMAX (m)
Wollaston	14.3	2062	...	97
Upper Foster	14.0	102	...	24
Fontaine	14.3	67	...	72
Douglas	14.4a	36	1	11
Karl Ernst	15.0a	10	0.5	15
Midwest	13.0b	4	...	6

a Another ten lakes in the Key Lake area had temperatures between 15.8 and 19.0°C.

b Another seven lakes in the Midwest Lake area were between 16.0 and 21.0°C.

Initial regressions of log VOLT15T6 on morphometry and climate did not reveal strong correlations. The best equations explained about 37 % of variation in 87 stratified lakes and only 18 % in 59 non-stratified lakes (Table G12). Similarly, regressions explained only 15 % of variation in 96 lakes predicted to stratify by the fetch-boundary condition (see STRAFN), and 54 % in 50 lakes predicted not to stratify. Known and predicted stratification produced generally similar equations, which suggested common mechanisms. However, the low correlations did not allow useful predictions of VOLT15T6.

Table G12. Regressions of log VOLT15T6 (hm^3)[a] on log WAREA (km^2), log FETCH, log FETDEV, ratio of log SHODEV, ORIFET (NW component of log fetch, km), and TMAXS (°C).

Number of variables	Equations (multiple R^2, Cp-reliability)
	Stratified lakes (n=87):
	Y=-0.111 + 0.956 log WAREA (R^2=0.29 M)[c]
	Y=-0.657 + 2.024 log FETCH (R^2=0.30 M)[c]
	Y=-0.805 - 0.290 log WAREA + 2.612 log FETCH (R^2=0.31 M)[c]
	Y=3.545 - 0.935 log WAREA + 3.641 log FETCH - 0.219 TMAXS (R^2=0.37 P)
	Non-stratified lakes (n=59):
	Y=-5.926 + 1.385 log FETCH - 1.831 ORIFET (R^2=0.13 M)[c]
	Y=-5.411 + 0.641 log WAREA - 0.132 RLOGSHOD - 1.805 ORIFET (R^2=0.14 P)[c]
	Y=-2.414 + 0.605 log WAREA - 1.812 ORIFET - 0.148 TMAXS (R^2=0.18 P)
	Predicted stratification (n=96):
	Y=-2.288 + 2.436 log FETCH (R^2=0.11 P)[c]
	Y=-1.424 + 2.333 log FETCH - 0.766 RLOGSHOD (R^2=0.12 P)[c]
	Y=3.456 + 2.066 log FETCH - 0.268 TMAXS (R^2=0.15 P)
	Y=3.469 - 0.590 log WAREA + 3.214 log FETCH - 0.282 TMAXS (R^2=0.15 P)

continued

Table G12. continued.

Number of variables	Equations (multiple R^2, Cp-reliability)
	Predicted non-stratification (n=50):
	Y=-7.525 + 7.403 log FETCH - 6.711 ORIFET (R^2=0.53 P)[c]
	Y=-7.525 + 7.403 log FETCH - 6.711 ORIFET (R^2=0.53 P)
	Y=-5.985 + 3.339 log WAREA + 0.656 RLOGSHOD - 6.529 ORIFET (R^2=0.53 P)[c]
	Y=-3.706 + 7.177 log FETCH - 6.614 ORIFET - 0.178 TMAXS (R^2=0.54 P)
	Lakes with non-zero VOLT15T6 (n=88):
	log VOLT15T6 = -0.008 + 1.080 log WAREA + 0.188 log FETCH (R^2=0.84 U)[c]
	log VOLT15T6 = -0.799 + 1.097 log WAREA + 1.428 log SECCHI (R^2=0.88 M)[c]
	log VOLT15T6 = -0.858 + 1.027 log WAREA + 1.480 log SECCHI + 0.291 log ORIFET (R^2=0.88 M)[c]
	log VOLT15T6 = 1.392 + 1.114 log WAREA - 0.264 RLOGSHOD -0.050 TMAXS (R^2=0.86 M)
	Non-riverine lakes with non-zero VOLT15T6 (n=75):
	log VOLT15T6 = -0.025 + 1.070 log WAREA + 0.397 log FETCH (R^2=0.90 U)[c]
	log VOLT15T6 = -0.288 + 1.193 log WAREA + 0.888 log SECCHI -0.154 RLOGSHOD (R^2=0.91 M)[c]
	log VOLT15T6 = 1.113 + 0.840 log WAREA + 0.741 log FETCH - 0.058 TMAXS (R^2=0.91 M)

a The small constant 10^{-6} was added before log transformation.

b Reliability of equations according to Cp are: E is suitable for extrapolation, P is suitable for prediction, M is marginally acceptable for prediction, and U is unacceptable.

c Variable TMAXS was not available for selection and n may have differed slightly.

Further analyses showed that lakes which were assumed to have non-zero VOLT15T6 were well predicted at 84 to 88 % of variation (Table G13). If only non-riverine lakes were considered, this improved further.

<u>TMAXS</u> The effect of TMAXS on maximum depth of 15°C has been shown, but data are frequently not available. A sinusoidal trend of seasonal surface temperature has been observed (Rawson 1936, Shuter et al. 1983). Freeze-up and break-up of lakes lag seasonal air temperatures, and summer water temperatures approach mean annual air temperatures (Ragotzkie 1978, Schindler 1971, Shuter et al. 1983). Mean air temperature (Shuter et al. 1983) was represented by the variable NORD (see Appendix B) or its square, NORD2. The correlation of NORD with temperature was reasonable for exploratory purposes (Figure G1).

In lakes of known stratification status, about 29 % of variation in TMAXS was explained (Table G13). RLOGSHOD and either NORD or $NORD^2$ were common in useful equations: higher TMAXS was predicted for more sinuous shorelines and higher air temperatures, respectively. In stratified lakes, log WAREA and ORINW were added: higher TMAXS was predicted for smaller lakes and those oriented more northwesterly. In non-stratified lakes, ORINW was added: higher TMAXS was predicted for northeasterly orientations (Table G13). Similar

Figure G1. Relationship between mean annual air temperature (solid lines) and NORD (hatched lines, see Appendix B).

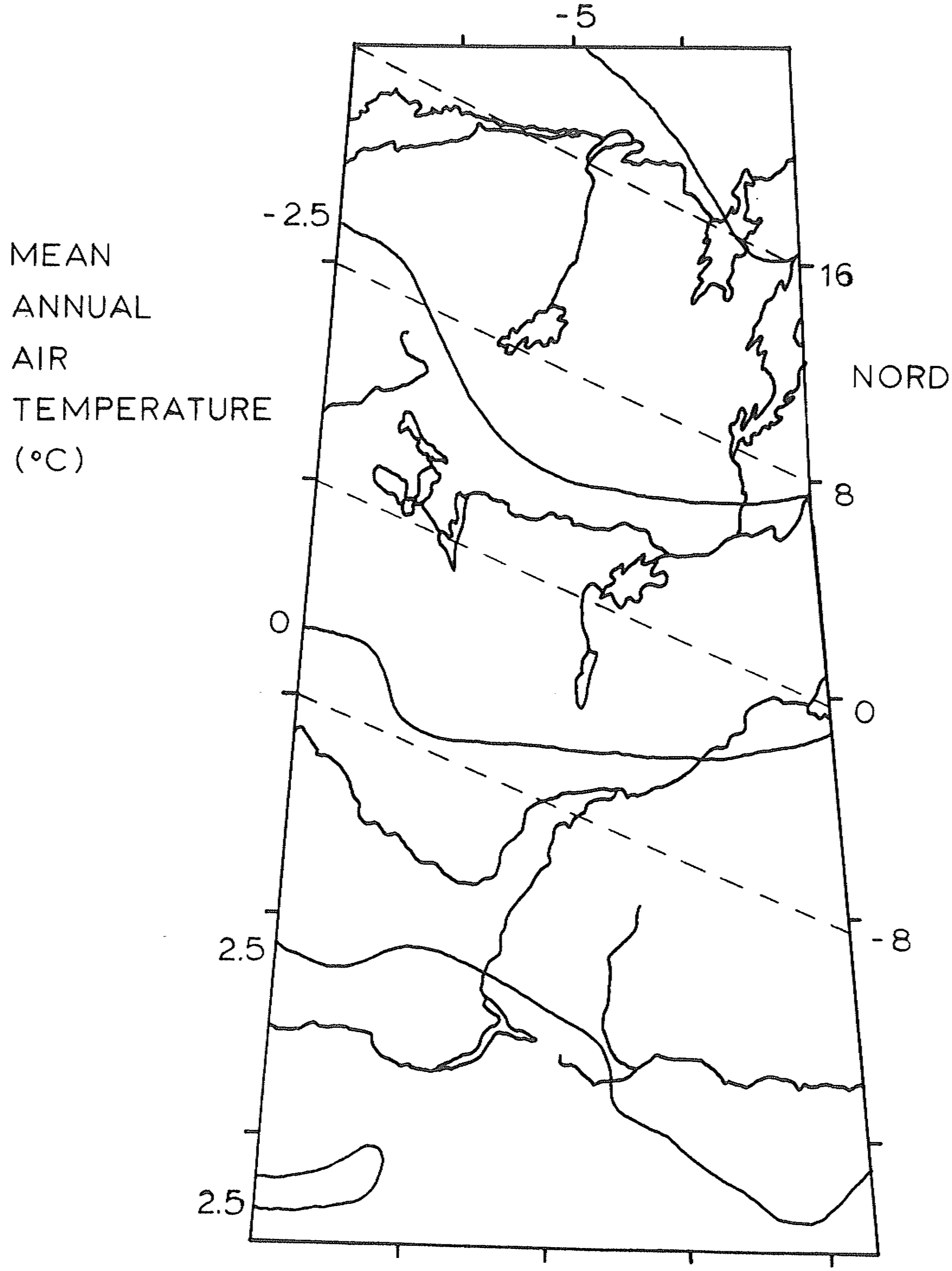
MEAN
ANNUAL
AIR
TEMPERATURE
(°C)
-5
-2.5
0
2.5
2.5
16
NORD
8
0
-8

Table G13. Regressions of TMAXS (°C) on log WAREA (km^2), log FETCH, log FETDEV, ratio of log SHODEV, ORINW (° from NW orientation), ORIFET (NW-component of log fetch, km), NORD, and NORD2.

Number of variables	Equations (multiple R^2, Cp-reliability)
All lakes (n=164):	
2	Y=19.604 + 1.475 RLOGSHOD (R^2=0.27 M)
3	Y=19.659 - 0.430 log WAREA + 1.720 RLOGSHOD - 0.153 NORD (R^2=0.27 M)
4	Y=19.361 - 1.208 log WAREA + 1.907 log FETCH + 1.428 RLOGSHOD - 0.015 NORD2 (R^2=0.29P)
4	Y=19.896 - 0.348 log WAREA + 1.524 RLOGSHOD - 0.070 NORD - 0.011 NORD2 (R^2=0.29 P)
Stratified lakes (n=86):	
1b	Y=20.885 - 0.019 NORD2 (R^2=0.26 M)
2	Y=19.806 + 1.344 RLOGSHOD - 0.020 NORD2 (R^2=0.31 M)
2b	Y=19.817 + 0.974 RLOGSHOD - 0.017 NORD2 (R^2=0.28 P)
3	Y=20.069 - 0.463 log WAREA + 1.400 RLOGSHOD - 0.018 NORD2 (R^2=0.35 M)
3b	Y=20.436 + 1.007 RLOGSHOD - 0.011 ORINW - 0.017 NORD2 (R^2=0.30 P)
4	Y=20.964 - 0.452 log WAREA + 1.453 RLOGSHOD - 0.016 ORINW - 0.017 NORD2 (R^2=0.37 P)
Non-stratified lakes (n=74):	
1	Y=19.062 + 1.677 RLOGSHOD (R^2=0.20 M)
1b	Y=19.303 + 1.892 RLOGSHOD (R^2=0.24 M)
2	Y=19.194 + 1.712 RLOGSHOD - 0.083 NORD (R^2=0.23 M)
2b	Y=19.733 - 0.379 log WAREA + 1.745 RLOGSHOD (R^2=0.28 P)
2b	Y=19.960 + 1.736 RLOGSHOD - 1.202 log FETCH (R^2=0.30 P)
3	Y=18.316 + 1.747 RLOGSHOD + 0.019 ORINW - 0.119 NORD (R^2=0.28 P)

a Reliability of equations according to Cp are: E is suitable for extrapolation, P is suitable for prediction, M is marginally acceptable for prediction, and U is unacceptable.
b Stratification was estimated from the WAREA boundary condition, including stratification of lakes over 26 m deep (see text).

equations resulted when these 164 lakes were classed as stratified or non-stratified by area or fetch boundary conditions (see STRAFN above).

The prediction of TMAXS using log ZBAR, log T15T6U, NORD, and $NORD^2$ was much less successful than the 80 to 90 % reported by Shuter et al. (1983). For 92 stratified lakes, up to 41 % of variation was explained, but for 77 non-stratified lakes only 15 %, and the use of additional variables log WAREA and/or log FETCH was necessary. Shuter et al. (1983) used the thermocline depth and mean depth to indicate the heat storage volume of stratified and non-stratified lakes, respectively. However, the best equations including only one measure of depth were always considerably less useful in this study.

VOLT1506 The Secchi depth criterion of 4 m predicted suitable conditions with 84 % accuracy in 86 shield lakes. Transparency was a good predictor of the existence of suitable temperature and oxygen (VOLT1506), but the magnitude of VOLT1506 was not assessed.

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