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Assessment of the Capability to Compute Evaporation from Okanagan Lake, other Mainstem Lakes and Basin Lakes and Reservoirs using the Existing Database

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Final Report

Report to the Okanagan Water Supply and Demand Study on Lake Evaporation

Assessment of the Capability to Compute Evaporation from Okanagan Lake, Other Mainstem Lakes and Basin Lakes and Reservoirs using the Existing Database

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Abstract: *Daily lake evaporation is computed for 6 of the largest Okanagan Basin Lakes over the period 1996-2006 through application of 19 models grouped according to input data requirements. Evaluation of the selected models was limited because of a lack of over-lake observations or lake-representative data for crucial required inputs. The models were forced with "existing" land-based meteorology, modeled water surface temperature, and 1971 heat content interpolations extended over all years. A mass transfer model (Trivett, 1984) based on eddy correlation (designated here as ETR) was used as a "Reference" for comparing evaporation model outputs since it was the only approach derived from direct observations on Okanagan Lake. In all years and lakes, this study found a large range in the cumulative daily evaporation totals (~ 350 mm/yr to 1000+ mm/yr) reminiscent of the earlier findings of Trivett (1984). In general, the mass transfer formulations consistently had lower annual evaporation totals than other methods such as energy budget or combination models, however, the cumulative evaporation curves were rather monotonic compared to 1971 eddy correlation evaporation indicating that application of the shore-based meteorology was not fully capable of capturing the increased lake evaporation which occurs during the summer months. Models that included heat content (Energy Budget and Combination Models) generally showed an exaggerated summertime evaporation response. Based on an 11-year average and using the ETR model, the water loss from Lake Okanagan is 169.8 x 10^6 m^3 yr^{-1} which is similar to the evaporation from the Quinn model (EQN) at 149.98 x10^6 m^3 yr^{-1}. Lakes Kalamalka, Skaha, and Osoyoos have water losses are in the order 6.78, 8.82, and 5.53 x10^6 m^3 yr^{-1} respectively. The smaller lakes Wood and Vaseux Lakes had average evaporative losses of 2.63 and 1.01 x10^6 m^3 yr^{-1} respectively.*

Database limitations, assumptions and possible limitations on empirical coefficients precluded recommendation of most of the tested methods on the Okanagan lakes at this time – further research is required when representative lake data are available. Consequently, the ETR model (Trivett, 1984) is recommended for application to Okanagan Lake and mainstem lakes using the existing database. Since there is far less data available in other parts of the Basin, only models with limited data inputs (e.g. such as in the Mass Transfer, Solar Radiation-Temperature, or Temperature and Daylength Groups) could be considered. However, many of these models generated long-term mean and ranges of lake evaporation significantly greater than the "Reference" evaporation *using the existing database. Consequently, an alternative approach involving regression of long-term (11-year) averaged evaporation (ETR) was regressed against air temperature for each of the 6 lakes. Results of the 2nd order polynomials for all lakes were very encouraging with explained variation* $R^2 = 0.54 – 0.90$*. Considering only "smaller" lakes as the most likely lake size to occur over the Basin, results indicated* $R^2 = 0.63 – 0.90$ *with correlation coefficients ranging from* $r = 0.79 – 0.95$*. Since air temperature has been extrapolated over the Basin grid and considering the strength of the regression relationship for small lakes, the regression approach is recommended as the first approximation to evaporation from Basin lakes.*

Recommendations are also provided for enhancement of the meteorological, radiation, and limnological databases for the Okanagan Lakes. Intensive multi-year in-lake investigations are required on all of the 6 lakes in order to determine which model provides the "optimal" response in the Okanagan environment. An intensive investigation can be designed to provide quality data from which to derive lake to land transformations which can enable more efficient use of the land-based meteorology as well as further refinement of surface temperature models.

Résumé

L'évaporation quotidienne des lacs a été calculée pour six des plus grands lacs du bassin de l'Okanagan pendant la période s'échelonnant entre 1996 et 2006, en appliquant 19 modèles groupés selon les exigences relatives aux données d'entrée. L'évaluation des modèles choisis était limitée en raison du manque d'observations au-dessus des lacs ou de données représentatives sur les lacs qui permettent d'obtenir les données essentielles nécessaires. Les modèles ont été créés à l'aide de la météorologie terrestre « existante », de la température de la surface de l'eau modélisée et des interpolations de l'enthalpie de 1971 appliquées à toutes les années. Un modèle de transfert de masse (Trivett, 1984) fondé sur la technique de corrélation de tourbillons (désignée ici par ETR, pour eddy correlation technique) a servi de « référence » pour comparer les extrants du modèle d'évaporation étant donné que c'était la seule méthode dérivée d'observations directes sur le lac Okanagan. Pendant toutes les années et dans tous les lacs, on a noté au cours de cette étude un grand intervalle dans les totaux cumulatifs de l'évaporation quotidienne (de ~ 350 mm/an à 1 000+ mm/an), ce qui rappelait les résultats antérieurs de Trivett (1984). En général, les formulations de transfert de masse comportaient de façon constante des totaux annuels d'évaporation inférieurs que les autres méthodes comme le bilan énergétique ou les modèles de combinaison. Toutefois, les courbes de l'évaporation cumulative étaient plutôt monotones comparativement à l'évaporation selon l'ETR de 1971, ce qui révèle que l'application de la météorologie terrestre n'a pas été entièrement à même de saisir l'évaporation accrue des lacs qui se produit au cours des mois d'été. Les modèles qui comprenaient l'enthalpie (bilan énergétique et modèles de combinaison) ont en général révélé une réaction exagérée d'évaporation estivale. En fonction d'une moyenne de 11 ans et à l'aide du modèle ETR, la perte d'eau du lac Okanagan est de $169{,}8 \times 10^6\ m^3\ an^{-1}$*, ce qui est similaire à l'évaporation selon le modèle Quinn (EQN) se chiffrant à* $149{,}98 \times 10^6\ m^3\ an^{-1}$*. Les lacs Kalamalka, Skaha et Osoyoos affichent des pertes en eau de l'ordre de 6,78, 8,82 et* $5{,}53 \times 10^6\ m^3\ an^{-1}$ *respectivement. On a noté dans les plus petits lacs Wood et Vaseux des pertes moyennes dues à l'évaporation de 2,63 et* $1{,}01 \times 10^6\ m^3\ an^{-1}$ *respectivement.*

Les limites des bases de données, les hypothèses et les limites possibles des coefficients empiriques ont empêché de recommander pour le moment la plupart des méthodes mises à l'essai dans les lacs de l'Okanagan – il faudra mener d'autres recherches quand les données représentatives sur les lacs seront disponibles. Par conséquent, (Trivett, 1984) on recommande d'appliquer le modèle ETR pour le lac Okanagan et les lacs fluviaux quand on utilise la base de données actuelle. Comme il existe beaucoup moins de données dans d'autres parties du bassin, seuls les modèles à entrées de données limitées (p. ex. comme dans les groupes transfert de masse, rayonnement solaire-température ou température et durée du jour) doivent être envisagés. Toutefois, bon nombre de ces modèles ont produit à long terme une moyenne et des intervalles sur l'évaporation des lacs considérablement plus élevés que l'évaporation de « référence » à l'aide de la base de données existante. Par conséquent, une autre méthode comportant la régression de l'évaporation moyenne à long terme (11 ans) (ETR) a été établie par régression par rapport à la température de l'air pour chacun des six lacs. Les résultats de ces polynômes d'ordre 2 pour tous les lacs ont été très encourageants avec une variation expliquée R^2= 0.54 – 0.90. Compte tenu que seuls les lacs de petite taille se trouveront vraisemblablement dans le bassin, les résultats ont donné R^2 = 0,63 – 0,90 avec des coefficients de corrélation allant de r = 0,79 – 0,95. Compte tenu de la température de l'air extrapolée par rapport à la grille du bassin et de la force de la relation de régression pour tous les petits lacs, on recommande la méthode de la régression comme la première approximation de l'évaporation à partir des lacs du bassin.

Les recommandations contenaient aussi une amélioration des bases de données sur la météo, les radiations et la limnologie pour les lacs de l'Okanagan. Il faudra mener des analyses intensives pluriannuelles pour les six lacs afin de déterminer quel modèle procure une réponse optimale dans l'environnement de l'Okanagan. On peut concevoir une analyse intensive pour fournir des données de qualité à partir desquelles calculer des transformations du sol pouvant donner lieu à une utilisation plus efficace de la météorologie terrestre et un plus grand raffinement des modèles sur la température de la surface.

1. Introduction

The Okanagan valley lies in a dry region of British Columbia in which there are gradual changes in climate between the south and north of Okanagan Lake. The replenishment of water to the Okanagan lakes is irregular. This is the result of large inter-annual variations in basin runoff. Water quantity and quality resource issues are of increasing concern as a consequence of increased water demands from a growing population and from agriculture and industry (Schertzer et al., 2004). The economy of the basin is heavily dependent on water based tourism and recreational activities.

The Basin has 6 main lakes consisting of Okanagan Lake and 5 other mainstem lakes (Fig. 1). A number of early investigations focused on these lakes, provided information on the baseline physical conditions (e.g. Coulthard and Stein, 1967). As part of the

Canada-British Columbia Okanagan Agreement (1974), a comprehensive program was initiated during 1971 (April – October) to provide data on the trophic status of each lake and the effect of physical factors which affect the lake chemistry and biota. The collected data were intended to provide a basis to understand the lake systems and to provide a knowledge base for determining probable future states of the water resources in the Okanagan valley under different management options. The investigation provided important information on the lake chemistry (e.g. Williams, 1971) and on the lake physics (e.g. Blanton and Ng, 1971; 1972). The physical limnological results for each of the Okanagan lakes pertaining to air temperature cycle, wind regimes, lake morphometry, light transparency and thermal structure are pertinent to the current research relating to computation of lake evaporation. A summary of the limnology of the Okanagan lakes was prepared by Pinsent and Stockner (1974).

An important component in the evaluation of water supply and demand within the Okanagan is the water loss through lake evaporation. In the 1974 Okanagan Basin investigation, mean monthly values of evaporation were derived for Okanagan Lake based on corrected pan evaporation from the Summerland CDA climate station (C-BC OBA, 1974) which was modified by elevation and latitude for application over the Okanagan Basin. Using eddy correlation observations located at Penticton Marina, Trivett (1984) concluded that Okanagan Lake evaporation was significantly over-estimated in the 1974 study. In the intervening years since the 1984 results, the lake evaporation issue has not been resolved.

In 2004, the Province of British Columbia (BC) initiated a study to determine the current supply and demand for water in the Okanagan Basin. Phase I of the study identified and catalogued relevant data sources, identified gaps, and developed a strategy for future studies (SEC, 2005). Through partnership between the Okanagan Basin Water Board (OBWB), Environment Canada, Agriculture Canada and the First Nations, a Phase II study was initiated with 3 broad goals to (a) determine the current supply of and demand for water throughout the Okanagan Basin; (b) to develop or select a model that routes water from tributaries in to main valley lakes and downstream into Lake Osoyoos that can be used to examine water management alternatives, and (c) to identify future changes in both supply and demand and to run the model for several realistic future scenarios. A Work Scope was developed to investigate lake evaporation as one of the critical hydrological components in this assessment.

1.1 Terms of Reference

Specific terms of reference with regard to the current investigation of evaporation from the Okanagan Lakes can be found in the *Work Scope for Phase II Lake Evaporation Study (Task 5.4).* The Terms of Reference includes a listing of tasks, such as, to evaluate evapotranspiration from two previous studies and ongoing work by Environment Canada and Agriculture Canada; to compute evaporation for four reference periods: base case (1971-2000), mid 2020s, mid-2050s, and mid-2080s; to estimate monthly lake evaporation for each of those five lakes for each of the four reference periods in dry years with return periods 1:5, 1:10, and 1:25 years, and wet years with return periods 1:5, 1:10, and 1:25 years (relative to the period 1971-2000); and others. The tasks outlined under the Terms of Reference may be addressed in future through the ongoing Okanagan investigation. This study is focussed on estimating lake evaporation and Objectives have been formulated as listed below.

1.2 Objectives

The Objectives of this investigation have been developed with reference to the *Work Scope for Phase II Lake Evaporation Study,* however, are formulated in recognition of database limitations. The primary objectives addressed in this report are the following:

- to provide an evaluation of the existing database for evaporation calculations
- to consider a range of lake evaporation methods for possible application to the Okanagan Basin
- to compute evaporation for Okanagan Lake and the 5 other mainstem lakes (Kalamalka, Wood, Skaha, Vaseux and Osoyoos) using existing meteorological, radiation and limnological data over the period 1996-2006.
- to evaluate the performance of the selected lake evaporation models on daily, annual and long-term means
- to outline the limitations in computing evaporation on the Okanagan lakes based on the current existing database with respect to data availability and reliability
- to recommend an optimum method or combination of methods from which evaporation can be computed from Okanagan Lake and other mainstem lakes
- to recommend a method for computing lake evaporation from other water bodies in the Okanagan Basin such as upland reservoirs
- to identify the data requirements suggest enhancements to the existing database and to suggest a plan for future intensive investigation of lake evaporation.
- to evaluate the uncertainty in the computed evaporation estimates and to assign Data Source codes and Data Error estimates to the weekly lake evaporation data set.
- to provide computer-based output files of lake evaporation computations to ESSA's Okanagan Water Database for WUAM pre-processing

2. Lakes and Measurement Sites

The Okanagan Basin is a long north-south trench in the Interior plateau of British Columbia (Zaremba *et al.,* 2005). Lake Okanagan lies within the Okanagan Valley (Fig. 1). It is a long and narrow lake approximately 120 km in length and ranges from 1.5 to 5 km in width. The lake has a complex bathymetry which divides it into three main basins. The Okanagan Basin also includes 5 mainstem lakes (Kalamalka, Wood, Skaha, Vaseux and Osoyoos Lakes). The main physiographic characteristics of the six lakes are given in Table 1.

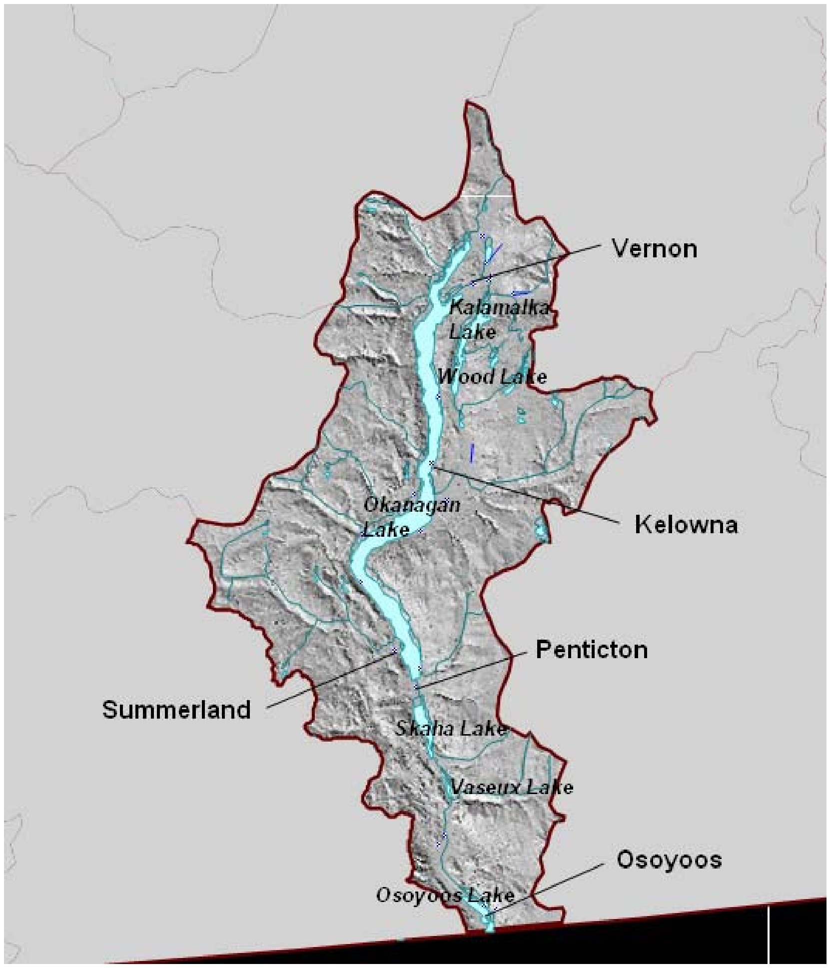


Figure 1. Okanagan Basin and location of the 6 main lakes and primary meteorological stations.

Table 1. ***Physiographic characteristics of the six Okanagan lakes (based on C-BCOBA, 1974)***.

	Kalamalka	Wood	Okanagan	Skaha	Vaseux	Osoyoos
A ($x10^6 m^2$)	25.9	9.3	348.0	20.1	2.75	15.0
V ($x10^6 m^3$)	1,520	200	26,200	558	17.7	254
D (m)	59	22	76	26	6.5	15
Dmax (m)	142	34	242	57	27.0	63
R (yr)	65	30	60	1.2	0.03	0.7

A is surface area, V is volume, D is mean depth, Dmax is maximum depth, R is water residence time

3. Lake Evaporation Models

There are numerous methodologies that have been developed for determining evaporation from lakes. The available methods include, for example, the water budget, Bowen-ratio energy budget method (BREB), eddy correlation, mass-transfer / aerodynamic technique, combination method and less data intensive techniques that utilize solar radiation, temperature, daylength or evaporation pans. Each methodology has its area of application and limitations. For example, the eddy correlation method is considered a direct method of determining lake evaporation but is not widely used routinely due to cost limitations. The mass transfer method is commonly used on large deep lakes such as the Laurentian Great Lakes because the input data are readily available and it is applicable on hourly to daily time scales, however, the approach does not consider the lake heat storage. Combination methods consider both the energy input to the lake and the mass transfer concept; however, it is a data intensive method. For a large lake the water budget is typically valid for longer time scales such as a month since errors in the input-output components may be of similar magnitude as the storage change on smaller time scales.

Lake evaporation studies are typically biased to large lakes (e.g. Schertzer, 1978; 1987; Schertzer *et al.* 1987; 2000, 2004) and often form part of the boundary condition for other studies investigating lake water quality (e.g. Lam and Schertzer, 1999). With respect to the assessment of the applicability of different evaporation methodologies to various lakes, there have been a number of investigations that have compared results from different techniques. Rassmussen *et al.* (1995) compared seven empirical methods applied to Minnesota lakes. Singh and Xu (1997) compared thirteen mass transfer methods to lakes in Ontario. Recently, Rosenberry *et al*. (2007) compared fifteen methods to evaluate evaporation from Mirror Lake which is a small lake in New England. The latter investigation evaluated 15 evaporation formulae grouped as belonging to the Combination Group, Solar Radiation-Temperature Group, Temperature – Daylength Group, Temperature Group, Mass Transfer Group, and the BREB method.

This investigation follows the general design of the previous studies which evaluated multiple evaporation methods. In particular, this study includes many of the methods tested by Rosenberry *et al*. (2007) with the addition of several other techniques which are either used in the Okanagan Basin or which may be applicable in other parts of the basin which have a paucity of observations. The following are the evaporation methodologies used in this investigation.

3.1 Energy Budget Group

EEB: Bowen Ratio-Energy Budget *(e.g. Harbeck, 1962; Harbeck et al., 1958)*

The Bowen Ratio-Energy Budget (BREB) method (e.g. Schertzer, 1987; Rosenberry *et al.*, 2007) for a lake involves solving for the component radiative fluxes, change in heat storage, advective components and partitioning of the turbulent heat fluxes through the Bowen ratio. The BREB method can be written as follows:

$$E = \frac{Q_s - Q_r + Q_a - Q_{bs} - Q_x + Q_V - Q_b}{\rho(L(1+\beta) + cT_o)}$$

where:

E	= lake evaporation from Energy Budget approach (m s^{-1}) Multiply "E" by 8.64 x 10^7 to convert to mm d^{-1}
Q_S	= incoming solar radiation (W m^{-2})
Q_r	= reflected shortwave radiation (W m^{-2})
Q_a	= incoming longwave radiation (W m^{-2})
Q_{ar}	= reflected longwave radiation (W m^{-2})
Q_{bs}	= emitted longwave radiation from the water surface (W m^{-2})
Q_x	= change in heat storage (W m^{-2})
Q_v	= net advected energy (W m^{-2})
Q_b	= net energy conducted from lake to sediments (W m^{-2})
ρ	= density of water (assume 998 kg m^{-3})
L	= latent heat of vaporization (J kg^{-1})
β	= Bowen ratio (dimensionless)
c	= specific heat capacity of water (4186 J kg^{-1} $^{o}C^{-1}$)
T_0	= water surface temperature (^{o}C)

In general, for a large lake, the heat loss through the lake bottom is small compared to the surface radiative exchanges and the net advective components due to hydrological inputs and losses are also considered to be relatively small. These terms may become more important for a smaller lake. In the absence of supporting data, these components are not considered in this investigation. Computing the partial energy budget is common in many energy budget investigations of lakes often due to database limitations.

Methods used to derive the radiative flux components, and heat storage of the lakes are discussed below.

The Bowen Ratio (Bowen, 1926) is the ratio between sensible to latent heat and can be written as the following:

$$\beta = c_B P \left[\frac{T_0 - T_a}{e_0 - e_a} \right]$$

where:

c_B	= empirical constant Bowen (1926), 0.61 ($^{o}C^{-1}$)
P	= standard pressure at specific altitude (kPa)

T_a = air temperature (^oC unless indicated otherwise)
e_0 = saturation vapor pressure at the water surface temperature (Pa)
e_a = atmospheric vapor pressure (Pa)

The traditional method of computing the Bowen Ratio ignores any covariance between wind speed, vapour pressure or temperature differences which can potentially introduce additional errors in the BREB method. Rosenberry *et al.* (2007) report that Lenters *et al.* (2005) determined that neglecting the potential covariance with wind speed could result in a mean bias error of 1% in the BREB method. This study computed the Bowen Ratio in the traditional approach. An intensive energy budget study was conducted on Lake Ontario in 1971-72 through the International Field Year for the Great Lakes (IFYGL, 1981). The IFYGL research indicated that β was particularly difficult to determine for very stable spring and early summer periods. In addition, as β approaches -1, the term $1/(1+\beta)$ approaches infinity. In order to avoid this problem, in the Okanagan lakes computations, a preliminary test was conducted to iterate through values of β to eliminate occurrences of B = -1 and also high evaporation values associated with values approaching -1. The following two constraints were placed on the computed value of the Bowen Ratio:

$$if\ (\beta \le -1.0\ and\ \beta \ge -1.5)\ then\ \beta = -1.5$$
$$if\ (\beta \le -0.25\ and\ \beta > -1.0)\ then\ \beta = -0.25$$

These constraints were applied uniformly for all of the Okanagan lakes studied.

3.2 Combination Group

Combination methods generally include an available energy term and an aerodynamic component. The combination models are amongst the most data intensive of the evaporation techniques. For practical applications, the formulations require direct over-lake observations of the radiative fluxes, water surface temperature and supporting meteorological data such as wind speed, air temperature, relative humidity or dew point temperature.

EPT: Priestly-Taylor *(e.g. Stewart and Rouse, 1976)*

$$E = \alpha \frac{\Delta}{\Delta + \gamma} \frac{Q* - Q_x}{L\rho} \times 86.4$$

where, E = lake evaporation, multiplier 86.4 to convert output to mm d^{-1}
α = 1.26, Priestley-Taylor empirically derived constant, dimensionless
Δ = slope saturated vapour pressure-temp. curve at mean air temp.(Pa $^oC^{-1}$)
γ = psychrometric constant (depends on temp. & atmos. pressure) (Pa $^oC^{-1}$)

Q^* = net radiation (W m^{-2})
Q_x = change in lake heat storage (W m^{-2})
L = latent heat of vaporization (MJ kg^{-1})
ρ = density of water (998 kg m^{-3} at 20^{o}C)

EBR: deBruin-Keijman *(e.g. deBruin and Keijman, 1979)*

$$E = \frac{\Delta}{0.85\Delta + 0.63\gamma} \frac{(Q^* - Q_x)}{L\rho} \times 86.4$$

where, E = lake evaporation, multiplier 86.4 to convert output to mm d^{-1}
Δ = slope saturated vapour pressure-temp. curve at mean air temp.(Pa ^{o}C^{-1})
γ = psychrometric constant (depends on temp. & atmos. pressure) (Pa ^{o}C^{-1})
Q^* = net radiation (W m^{-2})
Q_x = change in lake heat storage (W m^{-2})
L = latent heat of vaporization (MJ kg^{-1})
ρ = density of water (998 kg m^{-3} at 20^{o}C)

EPM: FAO Penman-Monteith *(e.g. Allan et al., 1998)*

$$E = \frac{0.408\Delta\left(Q^* - Q_x\right) + \gamma \frac{900}{T + 273} U_2 vpd}{\Delta + \gamma\left(1 + 0.34U_2\right)}$$

where, E = lake evaporation (mm d^{-1})
α = 1.26, Priestley-Taylor empirically derived constant, dimensionless
Δ = slope saturated vapour pressure-temp. curve at mean air temp. (Pa ^{o}C^{-1})
γ = psychrometric constant (depends on temp. & atmos. pressure) (Pa ^{o}C^{-1})
Q^* = net radiation (W m^{-2})
Q_x = change in lake heat storage (W m^{-2})
L = latent heat of vaporization (MJ kg^{-1})
ρ = density of water (998 kg m^{-3} at 20^{o}C)
U_2 = wind speed at 2 m above the surface (m s^{-1})
vpd = vapour pressure deficit ($e_s - e_a$) (mb)

EPN: Penman *(e.g. Brutseart, 1982)*

$$E = \frac{\Delta}{\Delta + \gamma} \frac{(Q^* - Q_x)}{L\rho} \times 86.4 + \frac{\gamma}{\Delta + \gamma}(0.26(0.5 + 0.54U_2)(e_s - e_a))$$

where, E = lake evaporation, multiplier 86.4 to convert to (mm d^{-1})
α = 1.26, Priestley-Taylor empirically derived constant, dimensionless
Δ = slope saturated vapour pressure-temp. curve at mean air temp. (Pa $^oC^{-1}$)
γ = psychrometric constant (depends on temp. & atmos. pressure) (Pa $^oC^{-1}$)
$Q*$ = net radiation (W m^{-2})
Q_x = change in lake heat storage (W m^{-2})
L = latent heat of vaporization (MJ kg^{-1})
ρ = density of water (998 kg m^{-3} at 20^oC)
U_2 = wind speed at 2 m above the surface (m s^{-1})
e_0 = saturated vapor pressure at water surface temperature (mb)
e_s = saturated vapor pressure at mean air temperature (mb)
e_a = vapor pressure at temperature and relative humidity of the air (mb)

EPK: Penman-Kimberly *(e.g. Maidment, 1992)*

$$E = \frac{\Delta}{\Delta+\gamma}\left(Q*-Q_x\right)+\frac{\gamma}{\Delta+\gamma}\frac{6.43W_f\,vpd}{\lambda}$$

$$W_f = a_w + b_w U_2$$

$$a_w = 0.4+1.4\exp\left\{\left[\left(j-173\right)/58\right]^2\right\}$$

$$b_w = 0.605+0.345\exp\left\{-\left[\left(j-243\right)/80\right]^2\right\}$$

where, α = 1.26 = Priestley-Taylor empirically derived constant, dimensionless
Δ = slope saturated vapour pressure-temp. curve at mean air temp. (Pa $^oC^{-1}$)
γ = psychrometric constant (depends on temp. & atmos. pressure) (Pa $^oC^{-1}$)
$Q*$ = net radiation (W m^{-2})
Q_x = change in lake heat storage (W m^{-2})
L = latent heat of vaporization (MJ kg^{-1})
ρ = density of water (998 kg m^{-3} at 20^oC)
U_2 = wind speed at 2 m above the surface (m s^{-1})
vpd = vapour pressure deficit ($e_s - e_a$) (mb)
W_f = wind function
j = day of the year

EBS: Brutsaert-Stricker *(e.g. Brutsaert and Stricker, 1979)*

$$E = (2\alpha - 1)\left(\frac{\Delta}{\Delta + \gamma}\right)\left(\frac{Q^* - Q_x)}{L\rho}\right) \times 86.4 - \frac{\gamma}{\Delta + \gamma} 0.26(0.5 + 0.54U_2)(e_s - e_a)$$

where, E = lake evaporation, multiplier 86.4 to convert to (mm d^{-1})
α = 1.26 = Priestley-Taylor empirically derived constant, dimensionless
Δ = slope saturated vapour pressure-temp. curve at mean air temp. (Pa $^oC^{-1}$)
γ = psychrometric constant (depends on temp. & atmos. pressure) (Pa $^oC^{-1}$)
Q^* = net radiation (W m^{-2})
Q_x = change in lake heat storage (W m^{-2})
L = latent heat of vaporization (MJ kg^{-1})
ρ = density of water (998 kg m^{-3} at 20^{o}C)
U_2 = wind speed at 2 m above the surface (m s^{-1})
e_0 = saturated vapor pressure at water surface temperature (mb)
e_s = saturated vapor pressure at mean air temperature (mb)
e_a = vapor pressure at temperature and relative humidity of the air (mb)

EDB: deBruin *(e.g. deBruin, 1978)*

$$E = 1.192\left(\frac{\alpha}{\alpha - 1}\right)\left(\frac{\gamma}{\Delta + \gamma}\right)\frac{(2.9 + 2.1U_2)(e_s - e_a)}{L\rho} \times 86.4$$

where, E = lake evaporation, multiplier 86.4 to convert to (mm d^{-1})
α = 1.26 = Priestley-Taylor empirically derived constant, dimensionless
Δ = slope saturated vapour pressure-temp. curve at mean air temp. (Pa $^oC^{-1}$)
γ = psychrometric constant (depends on temp. & atmos. pressure) (Pa $^oC^{-1}$)
L = latent heat of vaporization (MJ kg^{-1})
ρ = density of water (998 kg m^{-3} at 20^{o}C)
U_2 = wind speed at 2 m above the surface (m s^{-1})
e_s = saturated vapor pressure at water surface temperature (mb)
e_a = ambient vapour pressure of the air at dew point temperature (mb)

Rosenberry *et al*. (2007) defines the term e_s as saturated vapour pressure at temperature of the air. This definition was used in the computation of the evaporation from the deBruin formulation.

3.3 Solar Radiation, Temperature Group

EJH: Jensen-Haise *(e.g. McGuinness and Bordne, 1972)*

$$E = (0.014T_a - 0.37)(Q_s \times 3.523 \times 10^{-2})$$

where, E = lake evaporation (mm d^{-1})
Q_s = solar radiation (W m^{-2})
T_a = air temperature (^oF)

***EMK: Makkink** (e.g. McGuinness and Bordne, 1972; Makkink, 1957)*

$$E = \left(\left(52.6 \frac{\Delta}{\Delta + \gamma} \frac{Q_s}{L\rho} \right) - 0.12 \right)$$

where, E = lake evaporation (mm d^{-1})
Δ = slope saturated vapour pressure-temp. curve at mean air temp.(Pa $^oC^{-1}$)
γ = psychrometric constant (depends on temp. & atmos. pressure) (Pa $^oC^{-1}$)
Q_s = solar radiation (W m^{-2})
L = latent heat of vaporization (MJ kg^{-1})
ρ = density of water (998 kg m^{-3} at 20^oC)

***ESS: Stephens-Stewart** (e.g. McGuinness and Bordne, 1972)*

$$E = (0.0082T_a - 0.19)(Q_s \times 3.495 \times 10^{-2})$$

where, E = lake evaporation (mm d^{-1})
Q_s = solar radiation (W m^{-2})
T_a = air temperature (^oF)

***ETU: Turc** (e.g. Turc, 1961)*

$$RH < 50\%: \qquad E = 0.013\left(\frac{T_a}{T_a + 15}\right)\left(Q_s + 50\right)\left(1 + \frac{50 - RH}{70}\right) \cdot 86.4$$

$$RH > 50\%: \qquad E = 0.013\left(\frac{T_a}{T_a + 15}\right)\left(Q_s + 50\right) \cdot 86.4$$

where, E = lake evaporation, multiplier 86.4 to convert to (mm d^{-1})
T_a = air temperature (^oC)
RH = relative humidity (percent)

Q_s = solar radiation (Wm^{-2})

3.4 Temperature, Daylength Group

***EHM:* Hamon** *(e.g. Hamon, 1981)*

$$E = 0.55\left(\frac{D}{12}\right)^2 \frac{SVD}{100}\left(25.4\right)$$

where, E = lake evaporation, multiplier 25.4 to convert to (mm d^{-1})
SVD = saturated vapor density at mean air temperature (g m^{-3})
D = hours of daylight

***EBC:* Blaney-Criddle** *(e.g. McGuinness and Bordne, 1972)*

$$E = (0.0173T_a - 0.314)\times T_a \times (\frac{D}{D_{TA}})\times 25.4$$

where, E = lake evaporation, multiplier 25.4 to convert to (mm d^{-1})
T_a = air temperature (^{o}F).
D = hours of daylight
D_{TA} = total annual hours of daylight for a specific latitude

3.5 Temperature Group

***EPA:* Papadakis** *(e.g. McGuinness and Bordne, 1972)*

$$E = 0.5625(e_s \max - (e_s \min - 2))\left(\frac{10}{d}\right)$$

where, E = lake evaporation (mm d^{-1})
e_s max = saturated vapor pressure at daily max.air temperature (Pa)
e_s min = saturated vapor pressure at daily min.air temperature (Pa)
d = number of days in the month

***EHS:* Hargreaves-Samani** *(e.g. Hargreaves and Samani, 1985)*

$$E = 0.0023\left(T_a \max - T_a \min\right)^{\frac{1}{2}} \left(T_a + 17.8\right) * R_a$$

where, E = lake evaporation (mm d^{-1})
T_a max = daily maximum air temperature (^oC)
T_a min = daily minimum air temperature (^oC)
R_a = extraterrestrial radiation (MJ m^{-2} d^{-1} / 2.43 = mm/d)

3.6 Mass Transfer Group

ERH: Ryan-Harleman *(e.g. Rassmussen et al., 1995)*

$$E = \frac{(2.7(\Delta\theta_v)^{0.333} + 3.1U_2)(e_s - e_a)}{L\rho} \times 86.4$$

where, E = lake evaporation, multiplier 86.4 to convert to (mm d^{-1})
L = latent heat of vaporization (MJ kg^{-1})
ρ = density of water (998 kg m^{-3} at 20^oC)
U_2 = wind speed at 2m above the surface (m s^{-1})
e_s = saturated vapor pressure at water surface temperature (mb)
e_a = vapor pressure at temperature and relative humidity of the air (mb)
$\Delta\theta_v$ = the difference in virtual air temperatures (^oC) between the water surface and the ambient air (Rassmussen *et al.*, 1995; Ryan and Harleman, 1973)

ETR: Trivett *(e.g. Trivett, 1984)*

$$E = 0.024(e_s - e_a)U_2$$

where, E = lake evaporation (mm d^{-1})
U_2 = wind speed at 2 m above the surface (km hr^{-1})
e_s = saturated vapor pressure at surface water temperature (mb)
e_a = ambient vapour pressure of the air at dew point temperature (mb)

EQN: Quinn *(e.g. Quinn, 1978)*

$$E = (0.052 + 0.0066U_3)(e_s - e_a)U_3$$

where, E = lake evaporation (mm d^{-1})

U_3 = wind speed at 3 m above the surface (m s^{-1})

e_s = saturated vapor pressure at water surface temperature (mb)

e_a = ambient vapour pressure of the air at dew point temperature (mb)

Table 2. Comparison between model central principle of evaporation and general data requirements.

		Data Requirements				
MODEL	CENTRAL PRINCIPLE of EVAPORATION	Tair	Vapour pressure deficit, Wind	Twater	Solar or Net radiation (Q*)	Heat storage change (Q_x)
Energy Budget Group	Energy Partitioning					
Bowen Ratio		X	X	X	X	X
Combination Group	Heat flux and water vapour flux					
Priestly-Taylor				X	X	X
deBruin-Keijman				X	X	X
Penman-Monteith			X	X	X	X
Penman			X	X	X	X
Penman Kimberly			X	X	X	X
Brutsaert-Striker			X	X	X	X
deBruin			X			
Solar Radiation-Temp	Air temp and solar radiation as proxies for energy inputs					
Jensen-Haise		X			X	
Makkink					X	
Stephens-Stewart		X			X	
Turc		X			X	
Temp-Day-length	Air temp and day-length as proxies for energy inputs					
Hamon			X			
Blaney-Criddle		X				
Temperature	Air temperature diurnal range as proxy for energy inputs					
Papadakis		X		X		
Hargreaves-Samani		X				
Mass Transfer Group	Water vapour flux					
Ryan-Harleman		X	X	X		
Trivett			X	X		
Quinn			X	X		

3.7 Supporting Data and Computations

The following formulations were used in computation of some of the common terms in the evaporation formulas listed above.

3.7.1 Elevation and Latitude and Longitude: In formulations requiring elevation, and latitude and longitude, we used the following information for each of the primary meteorological stations.

Table 3. Elevation, latitude and longitude of the 5 primary meteorological stations.

	Elevation (m, asl)	Latitude (deg, min.)	Longitude (deg, min.)
Vernon	482.2	50 13.2	119 12.0
Kelowna	429.5	49 57.6	119 22.8
Summerland	454.2	49 34.2	119 39.0
Penticton	344.1	49 27.6	119 36.0
Osoyoos	297.2	49 1.8	119 264

***3.7.2 Atmospheric Pressure*:** Atmospheric pressure at each station was computed as the following:

$$P = 101.3 - 0.01055(EL)$$

where: P = atmospheric pressure (kPa)
EL = station elevation (m, asl)

***3.7.3 Specific Heat*:** Specific heat was taken as a constant

$$cp = 0.001013 \qquad (\text{MJ kg}^{-1}\ {}^{o}\text{C}^{-1})$$

***3.7.4 Latent Heat of Vaporization*:** Latent heat of vaporization was computed as the following:

$$\lambda = 2.50025 - (0.9002365\, T_a)$$

where: λ = latent heat of vaporization (MJ kg^{-1})
T_a = daily mean air temperature (^{o}C)

3.7.5 Psychrometric Constant: The psychrometric constant was computed as the following:

$$\gamma = (cp \cdot P)/(0.622 \cdot \lambda)$$

where: γ = psychrometric constant (kPa $^{o}C^{-1}$)

***3.7.6 Slope of the Saturation Vapour Pressure Gradient*:** The slope of the saturation vapour pressure gradient is the following:

$$\Delta = 0.61121((17.368 \cdot 238.88)/(T_a + 238.88)^2) \cdot \exp((T_a \cdot 17.368)/(T_a + 238.88))$$

where: Δ = slope of the saturation vapour pressure gradient (kPa $^{o}C^{-1}$)
T_a = air temperature (^{o}C)

***3.7.7 Vapour Pressures*:** Vapour pressures for es, e_a, and saturated vapour pressures at T_a, $T_a \max$, and $T_a \min$ were computed based on Prupappacher and Klett (1980) which is valid over the range -50 ^{o}C to + 50 ^{o}C. The general form of the formula is given below for saturation vapour pressure at surface water temperature:

A0 = 6.107799961 E0
A1 = 4.436518521 E-1
A2 = 1.428945805 E-2
A3 = 2.650648471 E-4
A4 = 3.031240396 E-6
A5 = 2.034080948 E-8
A6 = 6.136820929 E-11

$$e_s = A_0 + T_s \cdot (A_1 + T_S \cdot (A_2 + T_s \cdot (A_3 + T_S \cdot (A_4 + T_s \cdot (A_5 + A_6 \cdot T_S)))))$$

where: e_s = saturated vapour pressure at surface water temperature (mb)

***3.7.8 Saturated Vapour Density*:** The Hamon model specifically defines computation of the saturated vapour pressure and the saturated vapour density at air temperature which are computed as the following:

$$ESAT = 6.108 \cdot \exp((17.26939\, T_a)/(T_a + 237.3))$$
$$RHOSAT = (216.7 \cdot esat)/(T_a + 273.3)$$

where, $ESAT$ = saturated vapour pressure at air temperature (mb)
$RHOSAT$ = saturated vapour density at air temperature (g m^{-3})

3.7.9 Wind Height Adjustment: Evaporation formulae are sensitive to wind height. We have assumed that all wind height observations from the main stations are at 10m. The evaporation model of Quinn (EQN) requires wind height to be adjusted to 3m height. All other evaporation models in this study have been formulated for a 2 m height. The wind height adjustment formula used here is the 1/7 power law relationship:

$$U_2 = U_1 \cdot \left(\frac{Z_2}{Z_1} \right)^{1/7}$$

where:

U_2 = wind speed at height level 2

U_1 = wind speed at height level 1

Z_2 = measurement height level 2

Z_1 = measurement height level 1

The wind height adjustment used here conforms to the U.S. Army Corps of Engineers (1984) guidelines. In general, the formulation is applicable in neutral to near-neutral conditions (Schertzer *et al.,* 2003). However, since there were no over-lake observations from which to compute Richardson Number, the over-lake stability could not be evaluated and wind height adjustment is done without reference to a stability correction (e.g. Oke, 1987). In practical application over the Great Lakes with a lack of spatial data representation, the above formulation is applied without stability correction.

4.0 Selection of a Reference Evaporation for Comparing Models

Comparison between multiple evaporation formulae is often done through use of a "Reference" evaporation. Ideally the "Reference" evaporation would be determined from an approach such as the eddy correlation method which is considered a direct technique or from a method from which evaporation can be computed with lake-representative input values. Rosenberry *et al*. (2007) used the BREB method as the "Reference" from which to compare evaporation amounts from all other methods. In this investigation, a lack of over-lake meteorological or limnological observations and the application of various assumptions (see below), precludes selection of the BREB method or others listed above as a directly applied Reference. An alternative approach for defining a Reference evaporation was used in this study. The criteria used to select a Reference evaporation was that the evaporation should be derived from a direct method such as eddy correlation or from a model using lake-representative Okanagan Lake data. The only model output that satisfied this criteria was the mass transfer approach (Trivett, 1984) in which the transfer coefficient was based on eddy correlation observations near the lake at Penticton. Consequently, evaporation computed through the mass transfer model (ETR: Trivett, 1984) is used throughout this report as the Reference evaporation from which results of other methods are compared. Consequently, methods that produce lake evaporation equal to or in similar ranges to the Reference evaporation could be considered as potential methods to be recommended for application to Okanagan lakes. Alternatively, methods that diverge significantly from the Reference evaporation would not be considered for potential application using the existing database. Rejection of a method does not necessarily mean that the method does not apply. Rather, future research with intensive over-lake observations may be required for further testing of such methods.

4.1 Okanagan Mass Transfer Model (ETR: Trivett, 1984)

Trivett (1984) derived a mass transfer formulation for Lake Okanagan based on eddy correlation measurements at Penticton Marina in close proximity to Okanagan Lake. The mass transfer formulation that was derived from the eddy correlation observations had a constant transfer coefficient (M = 0.024) which agreed well with other studies of large lakes (see Helferty, 1981; Kohler, 1954; Harbeck, 1962). Figure 2 shows a comparison between the derived cumulative daily evaporation from the Trivett (1984) mass transfer technique and the evaporation from the modified Class A Pan, Temperature Index approach and the Morton model (Morton *et al.*, 1980). The original computations were done over the period May 1980 to end-April, 1981. The estimated annual evaporation loss using the mass transfer method (350 mm/yr) was less than half of the annual total from any of the other three methods which ranged from approximately 700 to 1000 mm/yr. In addition, the cumulative evaporation derived from the mass transfer approach also differed significantly in the seasonal shape compared to the other methods.

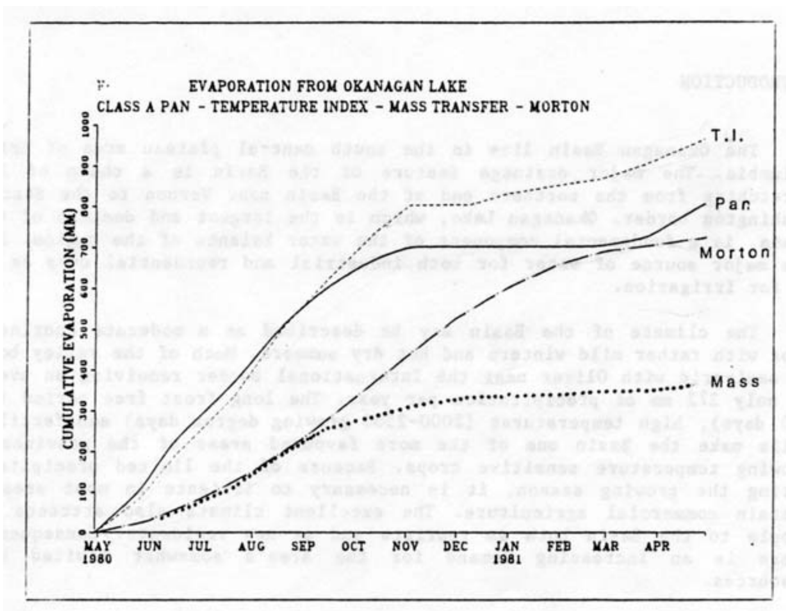


Figure 2. Comparison between evaporation computed by the mass transfer technique Trivett (1984) and the modified Class A pan, Temperature Index approach and the Morton model. Evaporation was computed from May 1980 to end-April, 1981. (based on Trivett, 1994)

Since the computations in this study are reported for the annual period (Jan – Dec), the cumulative evaporation results listed in Fig. 2 have been re-integrated to provide an indication of the shape of the cumulative daily evaporation curve. Figure 3 shows the Trivett (1984) curve reintegrated combining periods Jan-April (based on 1981 values), and May-Dec (based on 1980 evaporation). The total evaporation in the reintegrated curve matches the annual evaporation in the original Trivett (1984) study.

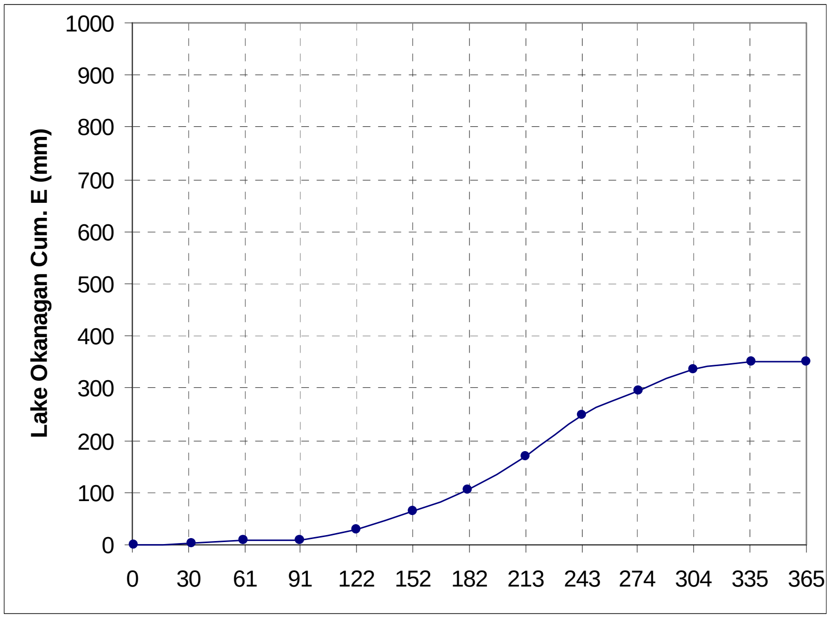


Figure 3. Approximation to the annual evaporation curve of Lake Okanagan for an annual period (Jan. – Dec.) based on re-integration of the Trivett (1984) mass transfer curve shown in Fig. 2.

4.2 Application of the Reference Evaporation (ETR: Trivett, 1984)

The evaporation computed in this study from the 19 methods listed above are not compared directly to the 1980-81 evaporation of Trivett (1984) shown in Fig. 3. The 1980-81 evaporation results are only used as a guide as to the annual evaporation amount and shape of the cumulative evaporation curve for Lake Okanagan. Rather, the evaporation from each model and model group are inter-compared and also compared with respect to a "Reference" evaporation. The Reference is the ETR evaporation determined in each of the years 1996 to 2006 for each lake.

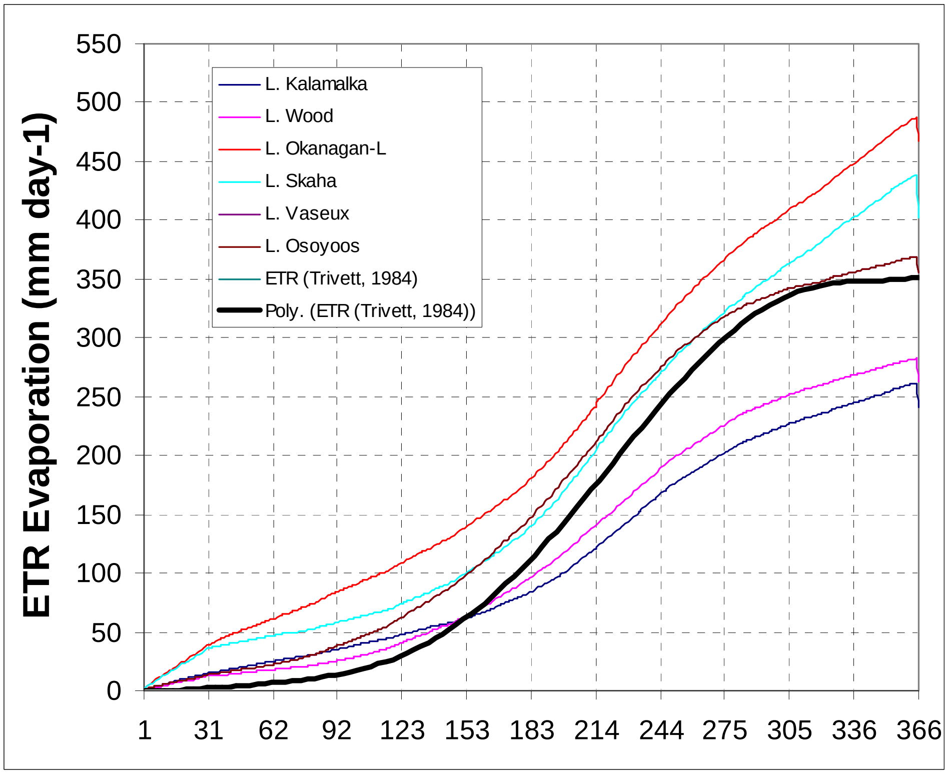


Figure 4. Comparison between Lake Okanagan evaporation computed by mass transfer formula (ETR: Trivett, 1984) and the 11-year average evaporation computed from ETR for all 6 Okanagan lakes. Black polynomial curve represents the Trivett (1984) run on 1980-81 data.

Figure 4 shows a comparison between the evaporation computed for Okanagan Lake from the mass transfer formula (Trivett, 1984) based on 1980-81 data (thick curve) and the longterm 11-year average ETR curves derived for each of the 6 Okanagan lakes. As expected, there are differences in the evaporation rates between the Okanagan lakes, partly due to differing weather conditions over the large latitudinal range of the basin. Other contributing factors are related to the limitations of the existing meteorological and limnological database. Figure 4 shows that evaporation from Kalamalka and Wood Lakes is less than from ETR Trivett (1984) while Skaha and Osoyoos lakes have a similar seasonal shape to ETR Trivett (1984). Figure 4 also shows that the ETR model using existing data, generates higher cumulative evaporation in the January to April period than the evaporation curve for 1980/81.

There was no ice information incorporated in the current runs. It was assumed that if computed surface temperature was equal to or less than $0^{o}C$, then there is complete ice cover on the lake and evaporation is set to zero for that day. In general, there were few such occurrences and future computations should require some information on ice conditions.

5. Databases

5.1 Meteorological Stations

In the absence of direct observations of lake evaporation, this study applied evaporation formulations described in Section 3 that utilize surface meteorological and climate records. The accuracy of the computed evaporation from these formulations depends on many factors. Three of the key factors include the following:

- how representative the meteorological, hydrological and limnological data are to over-lake conditions,
- the assumptions used to apply the data, and
- the quality and completeness of the climate record.

What follows is an assessment of these factors relative to the six main lakes in the Okanagan Basin.

The types of weather observations required to estimate lake evaporation are specified by the particular formulations used to calculate these estimates. For example, the mass transfer approach requires daily values of wind speed and vapour pressure deficit. Wind speeds are recorded hourly and the vapour pressure deficit is obtained from dew point temperatures and the temperature of the water surface. Other approaches require observations or estimates of air temperature, relative humidity, solar radiation and net radiation, cloud amount and cloud opacity, and sunshine hours etc. While temperature and relative humidity are routine observations at automatic stations, sunshine, radiation and cloud cover are typically observed only at one of two airports in the Okanagan - Penticton and Kelowna.

For Okanagan Lake, there is no single climate station that represents conditions along the entire 120 km length of the lake. Ideally, several lake-representative stations would be used with the required measurements observed and recorded at all sites. However, it is more often the case that perhaps only one particular site provides the required suite of observations even though the location might not be representative of conditions everywhere along the lake. The remaining lakes are small relative to Okanagan Lake, so typically the closest climate station to the lake is chosen for the smaller lakes.

5.1.1 Penticton Airport. Penticton Airport is staffed by human weather observers and has a long record of hourly synoptic observations dating back to 1953. Penticton Airport is located at the north end of Skaha Lake giving it very good exposure to weather conditions over the lake. A full suite of hourly synoptic meteorological parameters is observed there and the record is nearly 100 percent complete.

5.1.2 Kelowna Airport. Meteorological measurements began at Kelowna Airport in the late 1950s operating with a full suite of hourly weather observations. Human observers were replaced in 2005 with a fully automatic weather observing station (AWOS). The record is fairly complete with only a few missing days. Kelowna Airport is separated from Okanagan Lake by two high ridges with a valley in between. For this reason, weather conditions at Kelowna Airport, particularly wind, are not representative of those over the lake. Between 1971 and 1976, there was an anemometer on the Kelowna Bridge reporting hourly wind distances. While this is a different measurement than the two-minute average wind speeds recorded at Kelowna Airport, it was possible to calculate a regression equation between the two sites and use that to adjust Kelowna Airport winds upward by 64% so that the airport winds could be used as a proxy measure of winds over the lake.

5.1.3 Summerland CS. The Summerland climate station has supported research at Agriculture and Agri-Food Canada's Summerland research station since 1916. The climate station is on a bench at 455 metres and roughly 120 metres above the lake. In the early 1990s the human observing program was discontinued and replaced by an automatic station. Summerland was one of the few locations in British Columbia where solar radiation and net radiation measurements were taken. Unfortunately, this program was terminated in 1995 as a cost cutting measure. While radiation measurements continued to be made, the data were not entered into the climate archive. Recently, there have been efforts to rescue and archive the radiation data, however, the record appears to be incomplete and spotty.

5.1.4 Osoyoos CS. This site is an automatic climate station with hourly data going back to 1991. The site is roughly 1 km east of Osoyoos Lake. A full suite of hourly meteorological measurements exist. The record is fairly complete with only a few missing observations.

5.1.5 Vernon CS. This automatic station was originally sited at the upper air site in Vernon at 566 metres. On 27 March 1997 the site was relocated to Vernon Coldstream Ranch at a much lower elevation of 482 metres and situated 5 kilometres east of Kalamalka Lake. Several generations of the family that owned the ranch had been taking daily climate observations since 1900 and this ended in 1997 with the installation of the auto-station. The relocation of the station should have triggered a new climate station number since differences in elevation at the two sites produces quite different climatic regimes. Daily averaged wind speeds at the upper air site are 32% higher than at Coldstream Ranch. The small valley in which the station is located is oriented east-west which runs perpendicular to the main valley, so wind measurements will not be representative of the lake. There are also more than one thousand missing hourly values which when added to the station relocation problems and siting issues suggest this site is of limited value.

The locations of these 5 sites are shown in Fig. 1. The completeness of the data at these sites is listed in Table 4.

Table 4. Completeness of daily meteorological records at five stations.

	Penticton A	Kelowna A	Summerland	Osoyoos CS	Vernon CS
Temperature	100%	100%	96%	100%	97%
Dew Point	96%	100%	88%	96%	85%

Wind	100%	100%	97%	97%	96%
Relative Humidity	100%	99%	93%	96%	85%
Sunshine	32%	75%	0%	0%	0%
Cloud Conditions	100%	100%	0%	0%	0%

5.2 Characteristics of the Primary Meteorological Variables

The key meteorological variables required in the selected evaporation models include air temperature, dewpoint temperature, wind speed, relative humidity and cloud amount. Additional observations such as cloud opacity and sunshine would be useful for more rigorous models of some of the radiation flux components, however, limitations in terms of the length of the record or distribution over the Okanagan basin did not allow using these variables in such computations, however, available statistics are provided for future reference. Daily-averaged meteorological values used in this study were computed from hourly observations from each station.

***5.2.1 Air Temperature*:** Records of air temperature are nearly complete at all stations except for Summerland and Vernon (Table 4). Table 5 provides statistics on the observed daily averaged air temperatures between stations. Lowest daily-averaged air temperatures (~ 8°C) are observed at the northernmost stations Vernon and Kelowna while the highest average air temperature occurs at the southernmost station of Osoyoos (10.5 °C). As expected, the highest maximum temperature is also observed at Osoyoos (16.4°C). The lowest daily averaged air temperature over the 1996-2006 period occurred at Kelowna at 1.8°C which is nearly half of that observed at the other stations.

Table 5. Daily-averaged air temperature statistics at the primary meteorological stations.

	Daily Average Air Temperature (°C)			
	Min	**Max**	**Mean**	**Stdev**
Penticton A	-17.6	29.7	9.7	8.47
Kelowna A	-24.1	29.0	8.1	8.64
Summerland CS	-19.3	30.4	9.4	8.92
Osoyoos CS	-16.6	31.0	10.5	9.00
Vernon CS	-25.0	29.3	8.0	9.00

	Daily Average Maximum Temp (*C)			
	Min	**Max**	**Mean**	**Stdev**
Penticton A	-15.4	38.6	15.1	10.40
Kelowna A	-17.6	38.9	14.1	10.68
Summerland CS	-17.4	38.4	14.2	10.47
Osoyoos CS	-14.8	40.9	16.4	11.17
Vernon CS	-20.0	38.5	13.4	10.99

	Daily Average Minimum Temp (*C)			
	Min	**Max**	**Mean**	**Stdev**
Penticton A	-19.8	22.4	4.2	7.05
Kelowna A	-30.3	20.5	1.8	7.23
Summerland CS	-21.6	24.4	4.7	7.49
Osoyoos CS	-20.6	25.5	4.7	7.47
Vernon CS	-30.5	21.2	3.2	7.59

***5.2.2 DewPoint Temperature*:** Records of dewpoint temperature over the 1996-2006 period are complete only for Kelowna (Table 4). Penticton and Osoyoos records are 96% complete, however, records at Summerland and Vernon are less than 90% complete. Table 6 provides statistics on the observed daily averaged dewpoint temperature between stations. Lowest daily-averaged dewpoint temperature (1.6 ^{o}C) occurs at Kelowna while the highest value occurred at both the most southerly site Osoyoos (3.0 ^{o}C) and the northernmost station Vernon (3.1 ^{o}C).

Table 6. Daily-averaged dewpoint temperature statistics at the primary meteorological stations.

	Daily Avg Dew Point Temp (^{o}C)			
	Min	**Max**	**Mean**	**Stdev**
Penticton A	-26.4	16.6	2.2	6.21
Kelowna A	-28.8	15.5	1.6	6.59
Summerland CS	-25.4	16.5	2.1	6.19
Osoyoos CS	-24.2	18.8	3.0	6.70
Vernon CS	-27.0	16.5	3.1	6.44

***5.2.3 Wind Speed*:** Wind speed is a critical variable for computation of lake evaporation, especially in the mass transfer formulations. Fortunately, records of wind speed over the 1996-2006 period are nearly complete for all stations with Penticton and Kelowna at 100% and other stations greater than 96% complete (Table 4). Table 7 provides statistics on the observed daily averaged wind speed between stations. Lowest daily-averaged wind speed occurs at Kelowna (5.9 km/hr) as opposed to that recorded at Penticton (10.8 km/hr). As discussed in this Report, the earlier investigation by Trivett (1984) highlighted that the Kelowna Airport wind speeds are not representative of over lake values (significantly lower) based on a comparison with observations with Kelowna Bridge data. Conversely, the Penticton Airport winds are more exposed to then lake condition, however, they also differ considerably from Penticton Marina winds especially during the summer period when higher lake evaporation rates are expected (see Trivett, 1984). As indicated in this Report, Kelowna winds have been adjusted based on regression results between Kelowna A and Kelowna Bridge values.

Table 7. Daily-averaged wind speed statistics at the primary meteorological stations.

	Daily Average Wind Speed (km/hr)			
	Min	**Max**	**Mean**	**Stdev**
Penticton A	0.0	45.8	10.8	6.48
Kelowna A	0.0	26.0	5.9	3.52
Summerland CS	1.9	33.6	8.6	3.26
Osoyoos CS	0.0	28.4	7.0	3.38
Vernon CS	0.6	31.0	6.4	2.68

***5.2.4 Relative Humidity*:** Representative values of relative humidity are required as a direct input to some of the listed evaporation formulas and in others it can be used in the computation of ambient vapour pressure in the absence of dewpoint temperature. Records of relative humidity over the 1996-2006 period are compete only for Penticton (100%) and nearly complete at Kelowna (Table 4). Records at Vernon are only 85% complete. Table 8 provides statistics on the observed daily averaged relative humidity between stations. Lowest daily-averaged relative humidity (62.7%) occurs at Penticton while the highest value occurs at Vernon at 73% which also has the highest maximum and minimum values.

Table 8. Daily-averaged relative humidity statistics at the primary meteorological stations.

	Daily Average Relative Humidity (%)			
	Min	**Max**	**Mean**	**Stdev**
Penticton A	23.8	97.9	62.7	15.12
Kelowna A	25.5	99.5	67.8	14.55
Summerland CS	17.0	100.0	64.3	18.30
Osoyoos CS	26.1	98.0	65.3	15.20
Vernon CS	25.2	100.0	73.7	16.98
	Daily Average Maximum RH (%)			
	Min	**Max**	**Mean**	**Stdev**
Penticton A	32.0	100.0	80.9	12.26
Kelowna A	41.0	100.0	88.9	9.67
Summerland CS	33.0	100.0	81.3	15.98
Osoyoos CS	37.0	99.0	87.2	10.49
Vernon CS	43.0	100.0	91.5	10.40
	Daily Average Minimum RH (%)			
	Min	**Max**	**Mean**	**Stdev**
Penticton A	12.0	96.0	45.3	18.14
Kelowna A	10.0	98.0	46.3	19.03
Summerland CS	5.0	100.0	46.9	20.83
Osoyoos CS	10.0	98.0	43.4	20.10
Vernon CS	9.0	100.0	51.6	23.31

***5.2.5 Cloud Amount*:** Knowledge of cloud amount, cloud layers and cloud type are crucial for application of physically based solar radiation models (e.g. Davies *et al*., 1975) and for application of radiative transfer models (e.g. Schertzer and Sawchuk, 1990). Cloud type is also an important consideration in computation of the longwave radiative flux in non-clear sky periods. Unfortunately, in the Okanagan Basin, cloudiness details are limited to cloud amount (Table 4). Based on Penticton A, the mean daily cloudiness over the 1996-2006 period was 6.4 tenths (Table 9). In the absence of cloud amounts at the other stations, cloud amount from Penticton has been extended to all stations to facilitate computations requiring cloudiness.

Table 9. Daily-averaged cloud amount statistics at the primary meteorological stations.

	Daily Average Cloud Amount (tenths)			
	Min	**Max**	**Mean**	**Stdev**
Penticton A	0.0	10.0	6.4	2.83
Kelowna A	n/a	n/a	n/a	n/a
Summerland CS	n/a	n/a	n/a	n/a
Osoyoos CS	n/a	n/a	n/a	n/a
Vernon CS	n/a	n/a	n/a	n/a

***5.2.6 Cloud Opacity*:** Cloud opacity is observed only at Penticton and Kelowna (Table 4). The average opacity at Penticton is nearly a tenth higher than that at Kelowna (Table 10). Cloud opacity is not used in this current study.

Table 10. Daily-averaged cloud opacity statistics at the primary meteorological stations.

	Daily Average Cloud Opacity (tenths)			
	Min	**Max**	**Mean**	**Stdev**
Penticton A	0.0	10.0	5.7	3.03
Kelowna A	0.0	10.0	4.9	2.95
Summerland CS	n/a	n/a	n/a	n/a
Osoyoos CS	n/a	n/a	n/a	n/a
Vernon CS	n/a	n/a	n/a	n/a

***5.2.7 Sunshine Hours*:** Bright sunshine is only observed at Penticton and Kelowna, however, over the 1996-2006 period the record is only 32% complete at Penticton and 75% complete at Kelowna (Table 4). The high missing data precluded application of simple empirical relationships involving computed extraterrestrial radiation and sunshine to estimate daily total of incoming global solar radiation or for applying it as a predictand for cloud amount. Sunshine records are not used in this study.

Table 11. Daily-averaged sunshine statistics at the primary meteorological stations.

	Daily Average Sunshine (hrs)			
	Min	**Max**	**Mean**	**Stdev**
Penticton A	0.0	14.6	5.3	4.55
Kelowna A	0.0	15.1	5.5	4.62
Summerland CS	n/a	n/a	n/a	n/a
Osoyoos CS	n/a	n/a	n/a	n/a
Vernon CS	n/a	n/a	n/a	n/a

5.3 Radiation Fluxes

Evaporation computed through the BREB method, combination techniques and several of the less intensive formulations require daily values of the extraterrestrial radiation, net radiation (Q^*), solar radiation (Q_s), and/or daylength.

5.3.1 Extraterrestrial Radiation (R_a) is the energy received at the top of the atmosphere. Computation of R_a requires information on the station latitude and longitude (see Table 3) for computation of the geometric components of the extraterrestrial radiation. Computation of the extraterrestrial radiation for daily periods is as follows:

$$R_a = \frac{24(60)}{\pi} G_{SC} d_r \left[\omega_s \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_s) \right]$$

where:

R_a = extraterrestrial radiation (MJ/m^2/d)
G_{sc} = solar constant (0.0820 MJ/m^2/min)
d_r = inverse relative distance Earth-Sun
ω_s = sunset hour angle [rad]
φ = latitude [rad]
δ = solar declination [rad]

$$d_r = 1 + 0.033\cos\left(\frac{2\pi}{365} JD\right), \qquad \delta = 0.409\sin\left(\frac{2\pi}{365} JD - 1.39\right)$$

where: JD = day of the year (1 to 365 or 366)

$$\omega_s = \arccos\left(-\tan(\varphi)\tan(\delta)\right)$$

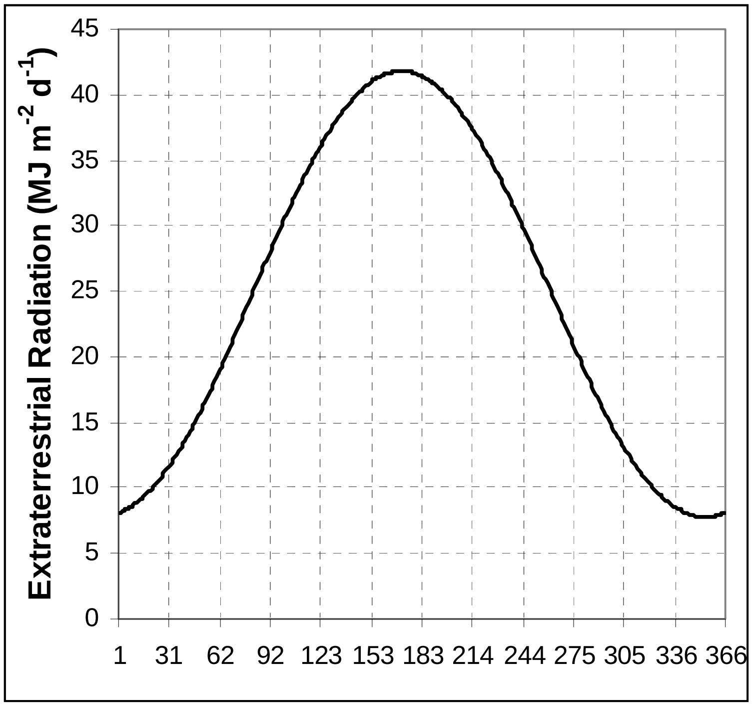


Figure 5. Example of the computed extraterrestrial radiation (Ra) for Lake Okanagan-L in 1996.

Figure 5 shows an example of the computed extraterrestrial radiation (Ra) for Lake Okanagan-L based on the latitude of the primary meteorological station Penticton in 1996. Lowest values occur in winter with a minimum of 7.76 MJ m^{-2} d^{-1} occurring in mid-December. The maximum value of Ra was 41.8 MJ m^{-2} d^{-1} occurring in mid-June.

5.3.2 Net Radiation is a principal component of the BREB method and is required for most of the selected Combination models. The net radiation ($Q*$) represents the algebraic sum of the radiative heat gains and losses at the water surface as follows:

$$Q* = Q_s - Q_r + Q_a - Q_{ar} - Q_{bs}$$

where:

$Q*$	= net radiation
Q_s	= incoming global solar radiation
Q_r	= reflected global solar radiation
Q_a	= incoming longwave radiation
Q_{ar}	= reflected longwave radiation
Q_{bs}	= emitted longwave radiation

In the Okanagan Basin, net radiation measurements have been taken associated with agricultural research (Denise Neilsen, per com.), however, these observations are not conducted over the lake surface. Consequently, the net radiative exchange across the lake surface is approximated in this investigation by computation of the individual radiative flux components.

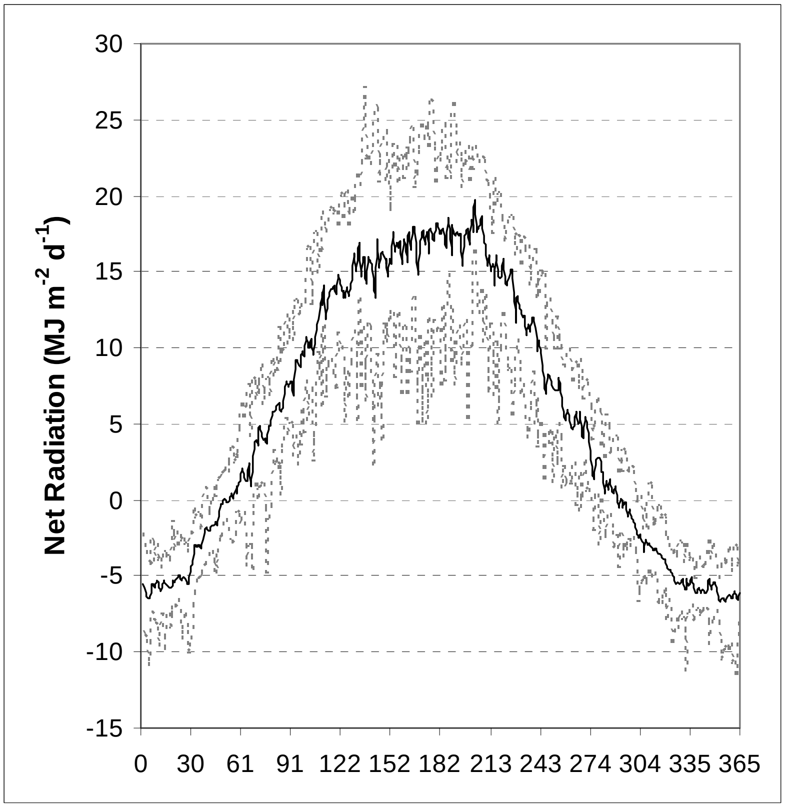


Figure 6. Variation of the long-term (1996-2006) mean and range of net radiation ($Q*$) for Lake Okanagan-L.

Figure 6 shows the daily net radiation computed for Lake Okanagan-L (L refers to Lake using Penticton meteorology). The net radiation flux is negative for most days in the winter months Jan., Feb., Oct., Nov., Dec. indicating a net heat loss from the lake and a net heat gain in other months. Minimum net radiation occurred in mid-December (-11.05 MJ m^{-2} d^{-1}) and the maximum occurred in mid-July (24.5 MJ m^{-2} d^{-1}).

5.3.3 Incoming Global Solar Radiation has been measured at Summerland over the 1996-2006 period, however, the observations have not been processed in time for this report and they are not continuous observations. Sunshine hours have also been measured, however, do not extend over the 1996-2006 period of this study. Davies et al. (1988) describe the primary models available from which to compute solar radiation.

These include radiative transfer methods (e.g. Sawchuk and Schertzer, 1988), physically-based models (Davies *et al.*, 1975; Davies and Hay, 1980), and empirical formulations based on cloud amount or sunshine (e.g. Kimball, 1928; Neumann, 1954; Laevastu, 1960; Mateer, 1963, etc.). These types of radiation models require information on cloudiness, often both cloud type and amount and some require cloud layers for parameterization of radiation transfer. Consequently, without direct measurements or observations of cloudiness or sunshine from which to apply empirical techniques, solar radiation has been computed based on Hargreaves and Allen (2003) which used computed values of extraterrestrial radiation and the difference between maximum and minimum air temperatures as a predictand of ambient conditions.

$$Q_s = 0.16 R_a \sqrt{T_a \max - T_a \min}$$

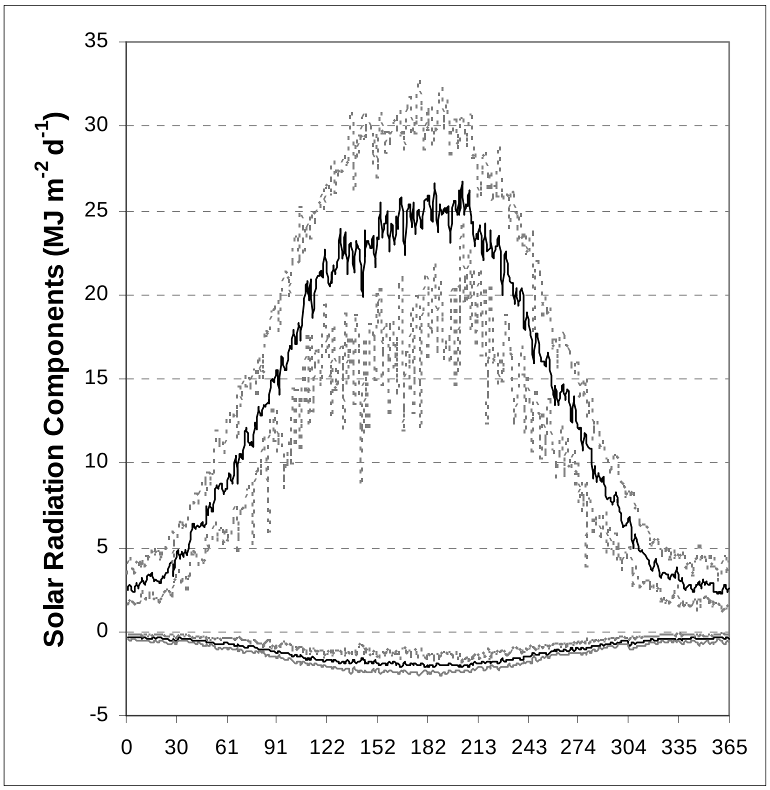


Figure 7. Variation of the long-term (1996-2006) mean and range of the incoming solar radiation and reflected solar radiation for Lake Okanagan-L based on the primary meteorological station at Penticton Airport.

Figure 7 shows the variation of the longterm (1996-2006) mean and range of the incoming solar radiation for Lake Okanagan-L based on the primary meteorological station of Penticton Airport. Minimum solar radiation income occurs in the winter months with minimums approaching 1.6 MJ m^{-2} d^{-1}. Maximum solar radiation income occurs in June-July with maximum values approaching 32 MJ m^{-2} d^{-1}. Net solar radiation Q_s^* is computed as $Q_s^* = Q_s - Q_r$ *(not plotted)* and is slightly less than the incoming solar radiation.

5.3.4 Reflected Solar Radiation can be observed using upright and inverted pyranometers, however, there are no direct observations of reflected solar radiation over the Okanagan lakes. Reflected solar radiation is a function of the surface albedo. Nunez *et al*. (1971) examined surface albedo on Lake Ontario as part of the International Field Year for the Great Lakes (IFYGL, 1981). They determined that under cloudless conditions and for zenith angles less than 70-deg, measured albedo values are higher than the theoretical Fresnel reflection by about 2 percent. The albedo of diffuse radiation and wave effects tend to be the dominant processes for zenith angles larger than 70-deg so that large scatter may result. Under overcast conditions (totally diffuse incoming solar radiation) an albedo of between 7 – 8 % was obtained. This was in reasonable agreement with a theoretical estimate of 6.6% for diffuse isotropic radiation plus a backscatter term which was observed to be less than 2%. There is an increasing dependence of albedo on zenith angle for decreasing cloud amount. In energy budget analyses for Lake Ontario, Davies and Schertzer (1974) generalized the IFYGL albedo studies and applied monthly means of albedo. In this investigation, this concept is followed and daily albedo is assigned as indicated in Table 12. Future research is required to quantify the mean and range of surface albedo for the Okanagan case.

As depicted in the 1996 example for Lake Okanagan-L (Fig. 7), the computed daily values of reflected solar radiation ranged from 0.2 to 2.54 MJ m^{-2} d^{-1}.

$$Q_r = \alpha_s Q_s$$

where:

α_s = surface albedo

Table 12. Monthly mean values of albedo for a lake surface (based on Davies and Schertzer, 1974; 1975).

	J	F	M	A	M	J	J	A	S	O	N	D
Albedo (%)	13	9	8	8	8	8	8	8	8	9	13	16

5.3.5 Incoming Longwave Radiation is not measured at the Okanagan lakes, consequently, it must be computed based on the existing meteorological database. Under clear skies, with temperature and dewpoint atmospheric soundings at short time intervals, computational methods exist from which atmospheric emissivity can be computed by stepwise evaluation. In the Okanagan basin, such observations are not available, consequently, the evaluation of the atmospheric emissivity must be based on measurements near the ground. Numerous empirical formulas have been developed for the computation of incoming longwave radiation from air temperature and water vapour pressure near the ground (e.g. Angstrom, 1916; Anderson, 1954; Brunt 1932; Swinbank, 1964; Idso, 1981; Idso and Jackson, 1969). In this application, atmospheric emissivity was evaluated based on Idso (1981) and incoming clear sky longwave radiation ($L_c \downarrow$) is computed below.

$$Q_{ld} = \varepsilon \sigma T_a^4 ,$$

Under cloudy sky conditions, additional radiation is emitted from water and ice particles at the bottom of the clouds which is evaluated based on a factor based on type of cloud and cloud height (A) and the cloud amount (C). Table 13 provides values for the coefficient A.

$$Q_a = Q_{ldc} + (Q_{ldc} \cdot A \cdot C^2)$$

where:

T_a = air temperature in ^oK

σ = 4.903E-9

ε_a = atmospheric emissivity

$\varepsilon_a = 0.70 + (5.95E - 5 \cdot e_a \cdot \exp(1500/T_a)$ based on Idso (1981)

A = coefficient based on cloud type

C = cloud amount

Table 13. Values for coefficient A for evaluation of incoming longwave radiation. (based on Boltz, 1949; Oke, 1987)

Cloud Type	Height (km)	A
Cirrus	12.20	0.04
Cirostratus	8.39	0.08
Altocumulus	3.66	0.17
Altostratus	2.14	0.20
Cumulus	low	0.20
Stratocumulus	1.22	0.22
Stratus	0.46	0.24
Fog	0.00	0.25

In most practical applications, detailed cloud information on cloud type, cloud layers and cloud amount are not readily available. Reliable cloud amount was only available for Penticton Airport, however, since Okanagan Lake is 120 km long, cloud amount was not extended from this station over the basin. Incoming longwave radiation was approximated by assuming an average cloud amount of 0.3 which is at the low end of the longterm mean cloud amount for Penticton, and a coefficient value of A=0.3 was assigned. These values imply generally low cloud amounts in the Okanagan Basin and cloud types ranging from altocumulus to stratocumulus (Table 13). These are broad assumptions and it is suggested that cloudiness be recorded at additional sites for future research.

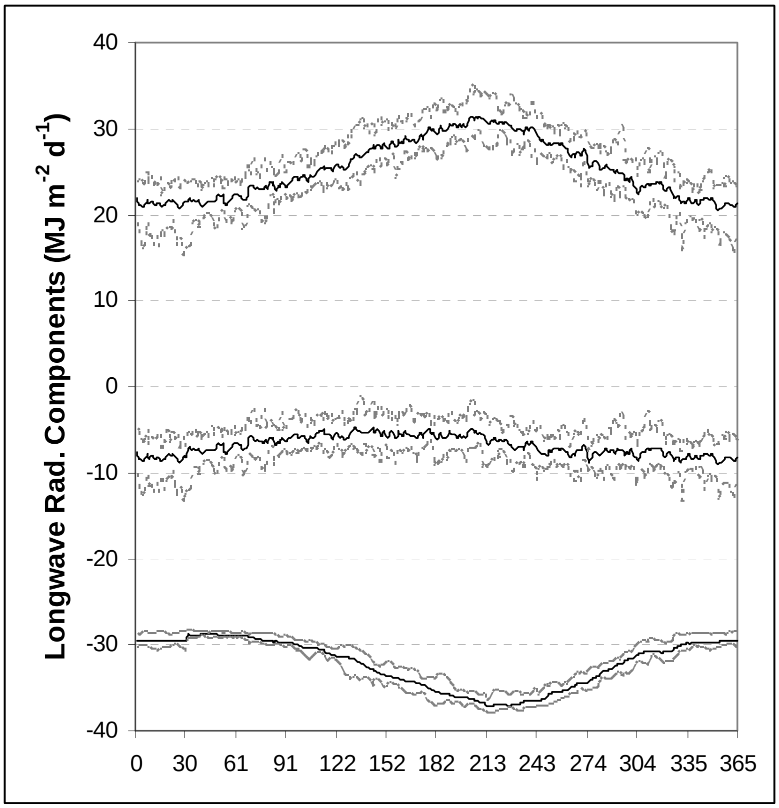


Figure 8. Variation of the longterm (1996-2006) mean and range for computed incoming longwave radiation, outgoing longwave radiation and net longwave radiation for Lake Okanagan-L.

Figure 8 shows an example of the computed daily incoming longwave radiation for Lake Okanagan-L. The incoming longwave is related to air temperature and cloudiness and the flux varies from lower values in winter (~ 15.9 MJ m^{-2} d^{-1}) to a maximum of (34.1 MJ m^{-2} d^{-1}) .

5.3.6 Reflected Longwave Radiation is not measured over the Okanagan Lakes. The reflected longwave radiation was assumed to be 3 percent of the incoming longwave radiation (Anderson, 1954).

$$Q_{ar} = 0.03 Q_a$$

Figure 8 shows the sum of reflected longwave radiation and longwave radiation emitted from the water surface in 1996. Actual values of reflected longwave radiation are small relative to the emitted flux and range from lower values in winter (min. 0.46 MJ m^{-2} d^{-1}) to a maximum of (1.03 MJ m^{-2} d^{-1}) at the end of July.

5.3.7 Emitted Longwave Radiation is not measured over the Okanagan lakes. The emitted longwave flux is a function of the surface water temperature as given below. Ideally, surface water temperature is measured from a meteorological buoy or through temperature moorings, however, there are no direct observations of the lake surface temperature in the Okanagan lakes. Surface water temperature is computed based on the Hyatt Logistical Model (Hyatt *et al.*, 2005) described under Limnological Variables (Section 5.4.1). The logistical model provides daily surface temperature estimates as a function of hysteresis between air temperature and water temperature. The emitted longwave radiation is computed as the following:

$$Q_{bs} = \varepsilon \sigma T_s^4$$

where:

T_s = water surface temperature in ^oK

σ = Stefan-Boltzman constant (5.67 x 10^{-8} W m^{-2} K^{-4} s^{-1})

ε = emissivity of water (0.97)

Figure 8 shows the longterm mean and range of the outgoing longwave radiation which is the sum of the reflected and emitted longwave radiation, shown for Lake Okanagan-L. The emitted longwave radiation ranged from -28.92 to -36.76 MJ m^{-2} d^{-1} .

The net longwave radiation is computed as $Q_L^* = Q_a - Q_{ar} - Q_{bs}$. The daily net longwave radiation is negative throughout the year with values ranging from – 2.49 to -13.31 MJ m^{-2} d^{-1}).

5.3.8 Relative Comparison Between Radiative Fluxes: Figure 9 shows an example composite of the longterm means of the radiative fluxes computed in this study for Lake Okanagan-L. Differences in flux values for each of the Okanagan lakes is expected and are related to the differences in meteorological data values between selected primary meteorological stations, the different heat contents and differences in surface water temperatures.

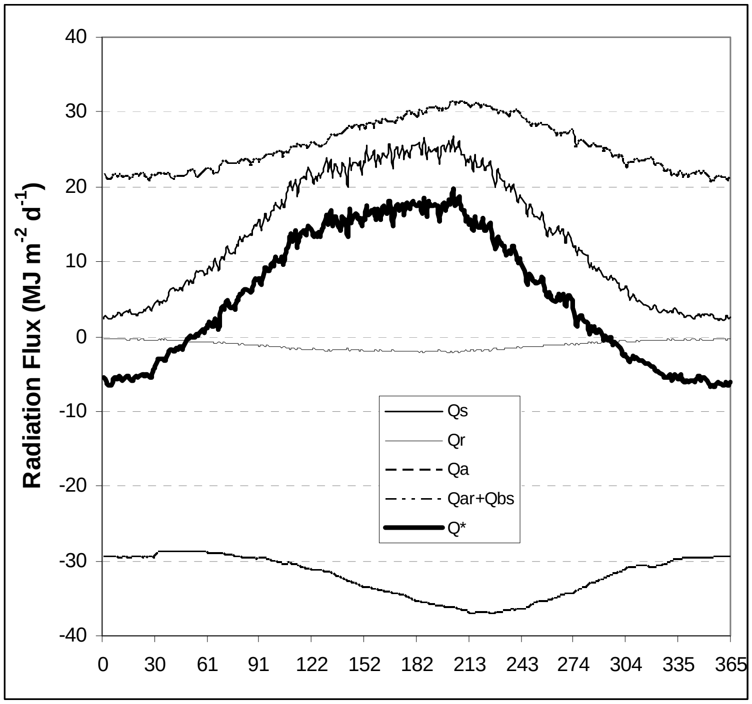


Figure 9. Variation of the long-term (1996-2006) mean computed radiative flux components for Lake Okanagan-L. For plotting purposes, the incoming fluxes are positive and the energy lost from the lake is negative.

5.3.9 Daylength: Daylength is required for the Blaney-Criddle and Hamon methods and was computed based on the following relationship,

$$N = \frac{24}{\pi}\omega_s$$

where:

N = daylight hours (hrs)

π = pi (3.14159)

ω_s = arcos(-tan(φ)tan(δ)) as defined earlier for Extraterrestrial Radiation

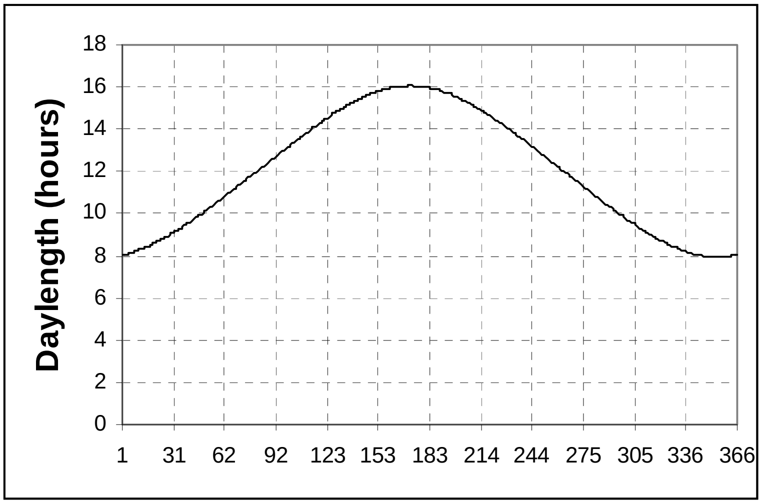


Figure 10. Example of the computed daylight hours for Lake Okanagan-L referenced to the primary station Penticton for 1996.

Figure 10 shows an example of the computed daylight hours for Lake Okanagan-L in 1996. In this example, computations are referenced to the primary station Penticton. Daylight hours range from a minimum of 7.94 hours in December to a maximum of 16.06 hours in June.

5.4 Limnological Variables

5.4.1 Water Surface Temperature**:** Water temperature is a fundamental limnological variable required for analysis of physical, chemical and biological processes in the aquatic ecosystem. In the selected lake evaporation formulas, water temperature is used directly or in component values for estimation of the net radiation and saturation vapour pressure etc. Unfortunately, there are no long-term continuous records of daily water surface temperatures for the 6 main Okanagan lakes (Hyatt *et al*., 2005; Stockwell *et al*., 2001). Past records include observations from specific lake studies (e.g. Blanton and Ng, 1971; 1972) and from short-term resource studies lasting weeks, months but rarely over annual periods (Hyatt *et al.*, 2005). Beginning in 2002, the Canadian Water Survey installed thermistors at three sites in south and central Okanagan to record hourly water temperatures: Okanagan Lake at Kelowna Bridge (08NM083), Okanagan Falls Dam (08NM002) which is representative of surface temperatures for Skaha Lake immediately upstream, and Okanagan River at Oliver which, at some times of year, is representative of surface temperatures in Vaseux or Osoyoos lakes (08NM085). Hyatt (pers. comm.) found that the latter station (08NM085) has not been providing very useful records of water temperature. The BC Ministry of Environment has been collecting spot water temperature measurements mostly in spring and fall in support of its environmental quality program going back to the early 1970s (V. Jensen, pers. comm.). Without water surface observations or estimates, most of the evaporation formulations selected in this investigation would not be able to be applied.

Recently, Hyatt *et al*. (2005) has developed a logistical model approach for Okanagan Lake based on hysteresis function between 10-day mean air temperature and water surface temperature adapted from Mohseni *et al*. (1998). The air-to-water temperature relationship is described below with a continuous non-linear four parameter logistic model of the general form,

$$T_s = \mu_h + (\alpha_h - \mu_h) / 1 + e^{\gamma_h(\beta_h - T_a)}$$

where:

- T_s = estimated water surface temperature (^oC)
- T_a = measured air temperature (^oC)
- α_h = estimated maximum water temperature (^oC)
- μ_h = minimum water surface temperature (^oC)
- β_h = air temperature at inflection of S-shaped function
- γ_h = maximum slope of the function

The logistical model accounts for heat storage effects (hysteresis) through consideration of both warming and cooling cycles. The logistic model was originally developed for Okanagan Lake. For this investigation, the model was extended to all of the 6 Okanagan lakes by use of nearest station air temperatures and available water surface temperatures from the Water Survey of Canada and the BC Ministry of Environment. Table 14 provides coefficients used for each of the 6 lakes in this analysis to derive representative water surface temperatures.

Table 14. Coefficient values used in the Hyatt et al. logistical model to generate water surface temperature for the 6 Okanagan lakes for (a) Heating Cycle, and (b) Cooling Cycle periods.

A. Heating

	Kalamalka	Wood	Okanagan	Skaha	Vaseux	Osoyoos
α_h	24	24	25	25	27	27
μ_h	3.0	0.0	3.5	0.0	0.0	0.0
β_h	14.7	11.8	13.9	14.4	13.5	13.5
γ_h	0.300	0.288	0.227	0.235	0.199	0.199

B. Cooling

	Kalamalka	Wood	Okanagan	Skaha	Vaseux	Osoyoos
α_h	25	25	25	26	28	28
μ_h	3.0	0.0	3.5	0.0	0.0	0.0
β_h	9.5	7.4	9.6	9.9	12.6	12.6
γ_h	0.151	0.148	0.180	0.135	0.160	0.160

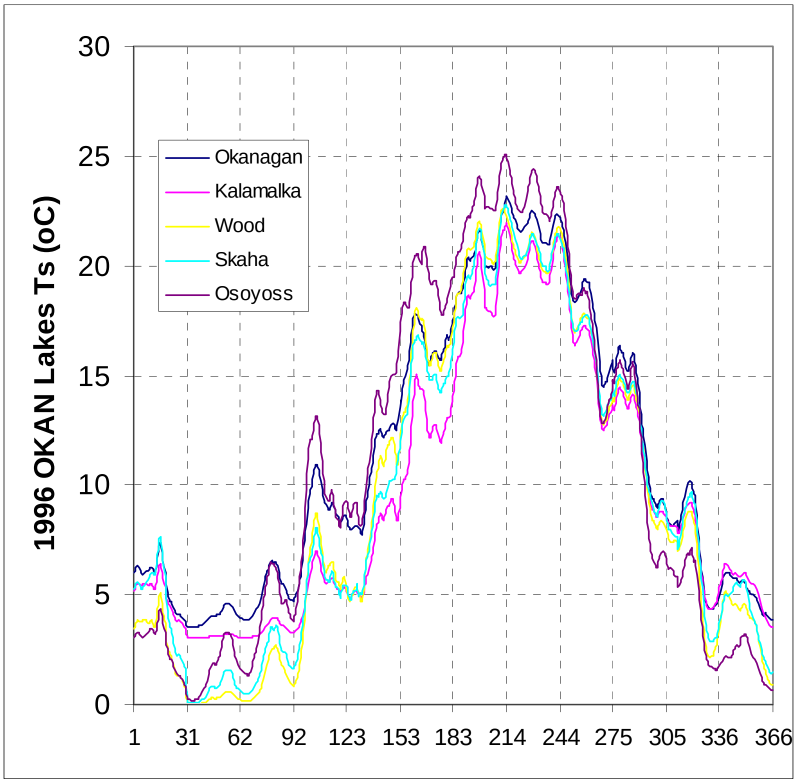


Figure 11. Example of the computed water surface temperature for the 6 Okanagan Lakes for 1996 using the Hyatt Logistical Model approach.

Figure 11 shows an example of the computed water surface temperature for Lake Okanagan-L based on the Hyatt Logistical Model approach. There was insufficient data to develop coefficients for Vaseux Lake and, as indicated in Table 14, Vaseux Lake surface water characteristics were assumed to be the same as Osoyoos Lake.

During the winter period, (Jan – Mar.), Okanagan Lake has a larger heat content than the smaller lakes. Minimum surface water temperatures that are equal to, or approach 0^oC are computed for Lakes Wood, Skaha and Osoyoos. In the absence of ice information, we have assumed ice cover if the computed surface temperature is $0^{o}C$, however, based on Fig. 11 for 1996, there are few occasions at which the surface temperature is at $0^{o}C$. During the heating phase, there are larger differences between lake temperature than in the cooling phase. During the warming to the peak temperature in July-August, some of the highest temperatures are computed for Osoyoos Lake and the lowest for Kalamalka Lake. Peak temperatures in 1996 are computed in the range 22 – 25 ^{o}C depending on lake. In the cooling phase, from August – December the lakes have a nearly 3-month period in which surface temperatures are very similar.

The curves of Fig. 11 show oscillation in the surface water temperature which are generally in phase for all lakes. Large deep lakes have a high heat capacity and do not generally have large changes in the surface temperature unless there are other factors such as passage of storms etc. which may mix warmer surface water with deeper cooler water. The pattern computed in Fig. 11 may be related to weather, however, we note that the model uses 10-day mean air temperature as the predictand which is applied to dampen the larger daily air temperature changes compared to the water surface. Future research is required in order to do a comparison between computed and observed water temperature for all of the lakes.

***5.4.2 Lake Heat Storage*:** Heat storage change is required in the combination group of evaporation models (Schertzer, 1997). Blanton and Ng (1971; 1972) used limited temperature survey data collected in 1971 over the months April to October to derive an estimate of heat content for each of the 6 Okanagan lakes. No other data were available from which to make such heat storage estimates. Consequently, the existing heat content estimations from the 1971 experiment were combined with subjective approximation of heat contents for remaining months to provide an annual cycle of the lake heat storage. Table 15 provides the measured heat content and subjective values used to derive the annual heat content cycle for each lake. Interpolation between heat content estimations were completed by applying cubic spline technique (Fig. 12).

Table 15. Measured heat content for the 6 Okanagan lakes based on lake surveys conducted by Blanton and Ng (1971; 1972).

	JD	Date	Heat Content (cal / cm^2)	Heat Content (MJ / m^2)
Wood	114	24-Apr-71	2500	104.7
	148	28-May-71	10300	431.2
	171	20-Jun-71	13800	577.7
	209	28-Jul-71	16200	678.1
	237	25-Aug-71	18100	757.7
	278	5-Oct-71	13500	565.1
Kalamalka	115	25-Apr-71	2000	83.7
	149	27-May-71	11500	481.4
	172	21-Jun-71	14800	619.5
	237	25-Aug-71	25100	1050.7
	278	5-Oct-71	13500	565.1
Okanagan	120	30-Apr-71	4000	167.4
	155	4-Jun-71	19100	799.5
	173	22-Jun-71	19800	828.8
	206	25-Jul-71	22250	931.4
	242	30-Aug-71	33300	1393.9
	276	3-Oct-71	23000	962.8
Skaha	120	30-Apr-71	1900	79.5
	145	25-May-71	10100	422.8
	167	16-Jun-71	14000	586.0
	202	21-Jul-71	19950	835.1
	236	25-Aug-71	22200	929.3
	281	8-Oct-71	17500	732.6
Vaseux	171	20-Jun-71	6250	261.6
	285	5-Oct-71	6600	276.3
Osoyoos	112	22-Apr-71	3900	163.3
	140	20-May-71	10900	456.3
	166	15-Jun-71	14500	607.0
	200	19-Jul-71	20100	841.4
	234	22-Aug-71	21900	916.7
	285	12-Oct-71	15500	648.8

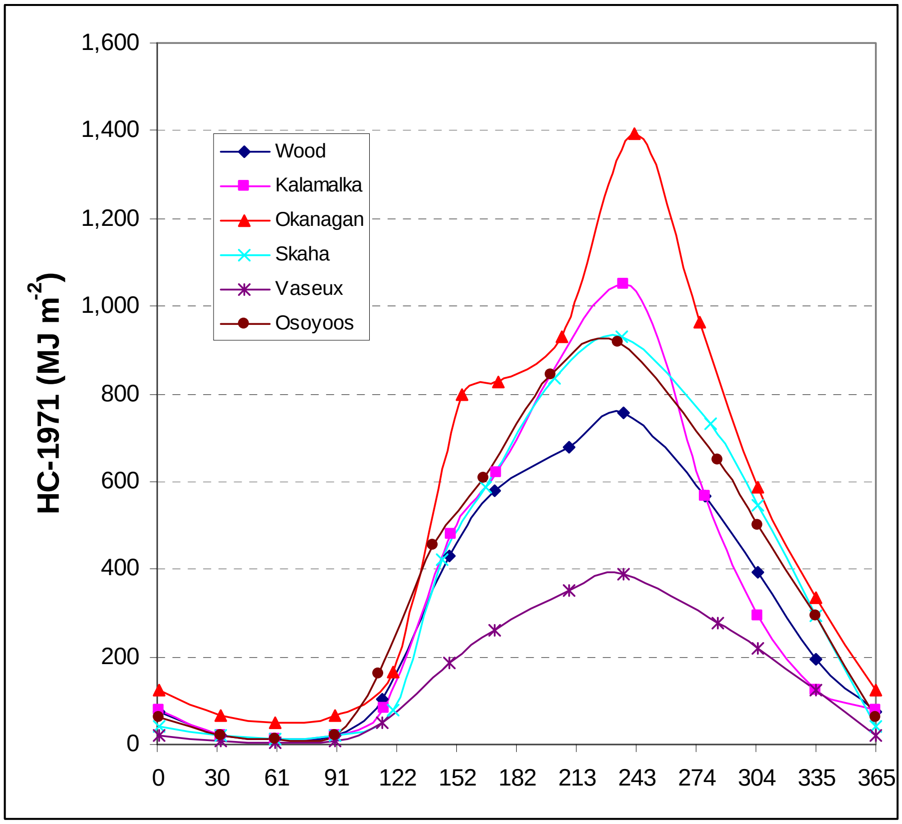


Figure 12. Heat content (HC) of Lakes Okanagan, Kalamalka, Wood, Skaha, Vaseux and Osoyoos based on Blanton and Ng (1971;1972. Annual curves are subjectively interpolated based on measured values in Table 15. Symbols represent both measured values from Table 15 and subjective values used in the cubic spline interpolation.

The heat stored in a lake is related to the energy gains and losses through radiative and turbulent exchanges and the bathymetric characteristics such as surface area and volume. The temperature of maximum density in freshwater is 4°C and a dimictic lake is a lake that passes through the temperature of maximum density once in the spring and again in the fall. The spring heating is the period between the lowest heat content in the lake (~ February) and the date at which the lake passes the temperature of maximum density. The summer heat gain is the period from the temperature of maximum density to the date of maximum heat content. The magnitude of the heat content at the minimum is related to the volume of water and the lake volume is also responsible for observed lags between lakes. With respect to Fig. 12 , Vaseux Lake has the lowest total heat content (~ 400 MJ m^{-2}) compared to Okanagan Lake (~ 1,400 MJ m^{-2}). In general, the slopes of the lake heat content curves during the heating cycle are less steep than in the cooling phase (after maximum heat content. Based on the limited data from 1971, Kalamalka Lake has a net heat loss at a similar rate as Okanagan Lake while Lakes Skaha, Osoyoos, and Wood have similar rates of heat gains and loss although they have different magnitudes of maximum heat content.

In the absence of spatially representative lake temperature profile observations for the Okanagan lakes during 1996-2006, the heat content curves of Fig. 12 generated from 1971 observations (Blanton and Ng, 1972), are assumed to apply for computation of the heat content change (Q_x) for all years of computation 1996-2006. This is a broad assumption since weather conditions vary from year to year and consequently the magnitude and timing of lake heat gains and losses can be affected.

5.4.3 Heat Storage Change

Ideally, the heat storage in a lake (H) is computed from detailed information on the lake bathymetry and spatially representative vertical temperature profiles to derive the lake heat content, for example, from Schertzer *et al.* (2003; 2008),

$$H = \iiint_V \rho_w c p T_w dxdydx ,$$

Using heat content curves (Fig. 12) based on Blanton and Ng (1971), the daily heat storage change (Q_x) is computed as the following:

$$Q_x = dH / dt .$$

Figure 13 shows a comparison between the magnitude and variability of the heat storage change computed for each of the 6 Okanagan lakes. As expected heat storage change is small during the winter period January – March compared to other times of the year for all lakes.

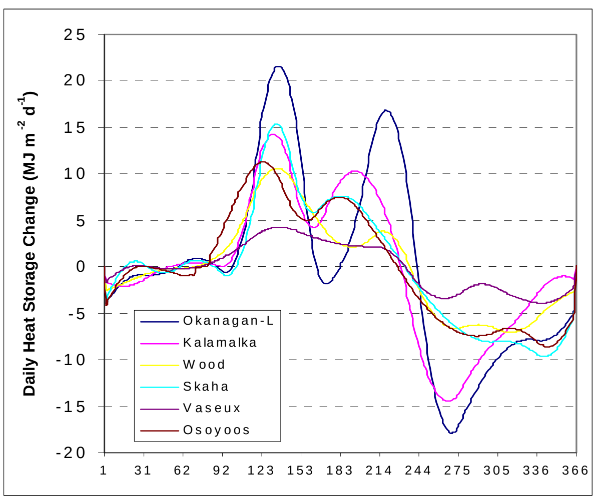


Figure 13. Comparison between the daily heat storage change computed for the Okanagan lakes based on heat content curves in Fig. 12 constructed from limited lake data reported by Blanton and Ng (1971; 1972).

Maximum heat storage for all of the lakes occurs approximately in August (Fig. 12). Vaseux Lake has the smallest amplitude change in both the heating and cooling phases. In comparison, the largest changes in the daily heat storage occurs for Okanagan Lake followed by Kalamalka Lake.

As indicated previously, the heat storage and heat storage change for all of the Okanagan lakes is based on Blanton and Ng (1971; 1972). Since there are no further investigations or data of sufficient spatial and temporal resolution to compute the lake heat content, the computed heat storage change for 1971 has been applied to all years in this study.

***5.4.4 Ice Extent*:** Ice cover on a lake is an important component influencing the air-water heat exchange. For example, the presence of an ice cover on a lake will result in decoupling the lake from the overlying atmosphere effectively negating evaporation from the water surface. Most of the main valley lakes are ice-covered in winter, generally from late December to the middle of March (Pinsent and Stockner, 1974). Lake Okanagan seldom has a complete ice cover, but the bays and shallow inlets are often frozen over long periods. Okanagan Centre and the entire lake have only had complete ice cover 3 to 4 years in the past 100 years. As a result the lake stratifies in spring and mixes throughout the winter. Partial freezing of sheltered areas such as Vernon Arm can occur, i.e. Vernon Arm is dimictic during cold winters but monomictic during warm winters.

There are no longterm continuous records of ice extent for the 6 Okanagan lakes. A lack of lake data precludes the application a 1-dimensional ice model to estimate the ice on these lakes. Consequently, it is assumed that if the logistical model (Hyatt *et al.* …) generates a negative surface temperature, the lake is considered to be ice covered and lake evaporation is assigned a value of 0 mm/day.

6. Computational Procedure

6.1 Handling of Missing Data

The meteorological data record for Okanagan Basin meteorological stations is not complete for all of the required input variables in the evaporation models. As described in more detail below, rather than terminating a computation of evaporation on a particular day with a missing data value(s) we have adopted a procedure of designating a Primary station, a Secondary station and if a missing value still remains then we apply a long-term mean value from a selected meteorological station. The station assignments are listed in Table 16 pertaining to each lake.

Table 16. Listing of primary and secondary stations used to compute evaporation from each Okanagan lake.

Lake	Primary	Secondary	Mean (1996-06)
Kalamalka	Vernon	Kelowna	Vernon
Wood	Vernon	Kelowna	Vernon
Okanagan-L	Penticton	Summerland	Penticton
Okanagan-S	Summerland	Penticton	Summerland
Okanagan-C	Kelowna	Penticton	Kelowna
Okanagan-N	Vernon	Kelowna	Vernon
Skaha	Penticton	Osoyoos	Penticton
Vaseux	Osoyoos	Penticton	Osoyoos
Osoyoos	Osoyoos	Penticton	Osoyoos

6.2 Generating Longterm Means

As indicated in Section 5, there are periods of missing data at the 5 primary meteorological stations. The evaporation models listed in Section 3 each have their required set of meteorological and radiation input requirements. One option for computing evaporation is to terminate the computation for a day if any of the required data input values are missing. The alternative is to apply techniques to provide an appropriate value or values to replace the missing variables to allow computation of the daily evaporation total from the respective model. Methodologies to approximate values to replace missing values include such approaches as interpolation. Each method will involve limitations. In this study, we have opted to designate a Primary meteorological station for each lake and a "nearest neighbour" site as a Secondary meteorological data source to replace a missing data field(s) (Table 16). This assumes that the Secondary station has a similar statistical data distribution. Even with designating a Primary and Secondary meteorological station, it is still possible that there could be a missing data field(s). We solve this problem by recourse to a long-term mean value.

Ideally, the long-term mean would be a climate normal of 30 years record, however, climate normals are usually monthly mean values. In this application, it is more realistic to generate a continuous mean daily time-series for a variable rather than having a monthly climate normal. We use the available 1996-2006 data record to generate a scattergram of daily values for each required meteorological variable. For a variable with no missing daily-averaged data, the scattergram would contain 4,015 values over the 11 year period. For each variable, we generated a 2^{nd} polynomial curve to provide a first approximation of the longterm mean fit through the data. An example of the scatter in the long-term (1996-2006) daily-averaged data and the 2^{nd} order polynomial fit representing the long-term mean for selected variables are shown in Fig. 14 for Penticton Airport.

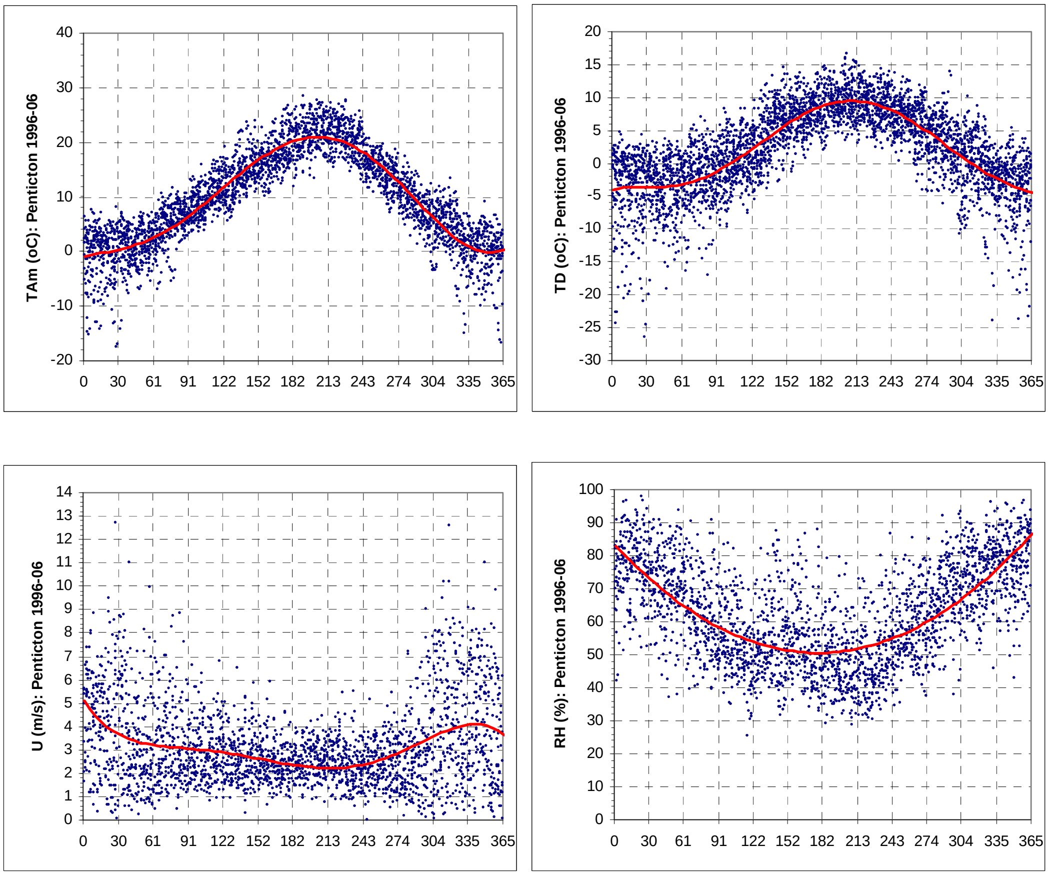


Figure 14. Example of longterm daily data (1996-2006) and 2nd order polynomial curves representing long-term mean for Penticton A. data (a) air temperature, (b)dewpoint temperature, (c) wind speed, and (d) relative humidity.

6.3 Substitution of Data

The preceding section described the procedures adopted to handle the occurrence of a missing meteorological data value(s) so that computation of the daily evaporation can proceed. The procedure adopted is invoked mainly in the case of randomly occurring missing data and often the data will be available from the Secondary station. Substitution of the daily long-term mean for missing meteorological data in the evaporation computations is generally more realistic than substituting long-term monthly mean values and allows proceeding to approximate an evaporation amount. One disadvantage in substituting long-term means is that the long-term mean may not be consistent with other data values on a particular weather day which will introduce error into the computation.

7. Daily Evaporation Results

7.1 Cumulative Daily Evaporation

Daily lake evaporation (mm/d) was computed based on evaporation formulae representative of the BREB Group, Combination Group, Solar Radiation – Temperature Group, Temperature-Daylength Group, Temperature Group, and Mass Transfer Group. The daily evaporation estimates from each model for the period 1996-2006 were used to generate long-term mean cumulative evaporation curves for each model and lake.

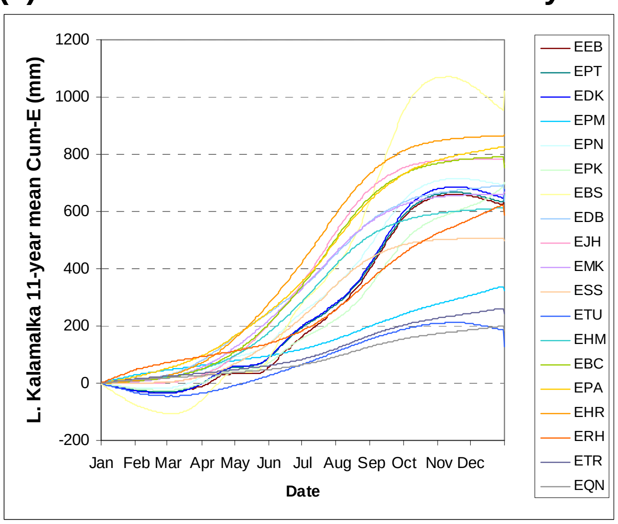
Figures 15 shows a comparison between long-term averaged (11-year mean) cumulative daily evaporation curves from each model determined over the period 1 January to 31 December for each lake. The annual total evaporation from each model was compared to the evaporation generated from the Trivett (1984) mass transfer formula through use of a simple rank order,

$$Rank = [(E_{(Model)} - E_{(ETR\ Model)}) / E_{(ETR\ Model)}]x100.$$

where,

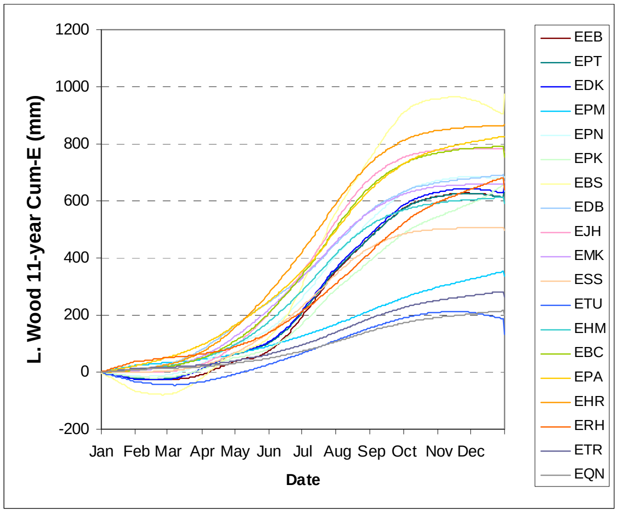
Rank	= model rank compared to the ETR model
$E_{(model)}$	= evaporation from a model
$E_{(ETR\ model)}$	= evaporation from the Trivett (1984) model

(a) Lake Kalamalka Cumulative Daily Evaporation



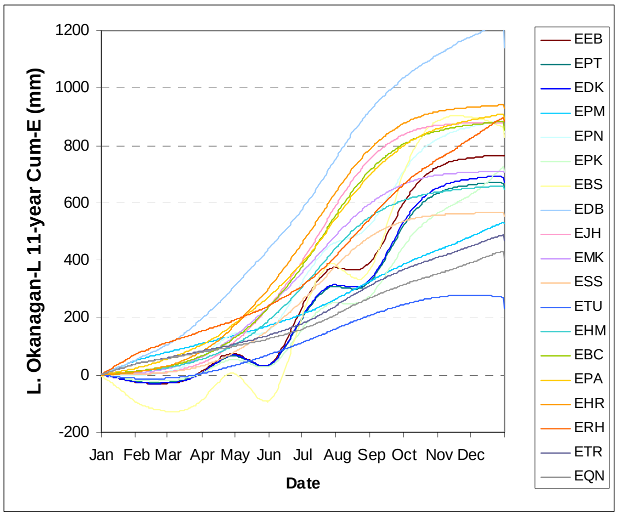
Rank	Model	Model Group	% diff from ETR
1	ETR	MT	0
2	EQN	MT	-24
3	EPM	C	30
4	ETU	S-T	-30
5	ESS	S-T	94
6	EHM	T-D	134
7	ERH	MT	139
8	EPT	C	143
9	EDK	C	149
10	EEB	C	153
11	EMK	S-T	154
12	EDB	C	164
13	EPK	C	165
14	EPN	C	166
15	EJH	S-T	200
16	EBC	T-D	203
17	EPA	T	217
18	EHR	T	232
19	EBS	C	246

(b) Lake Wood Cumulative Daily Evaporation



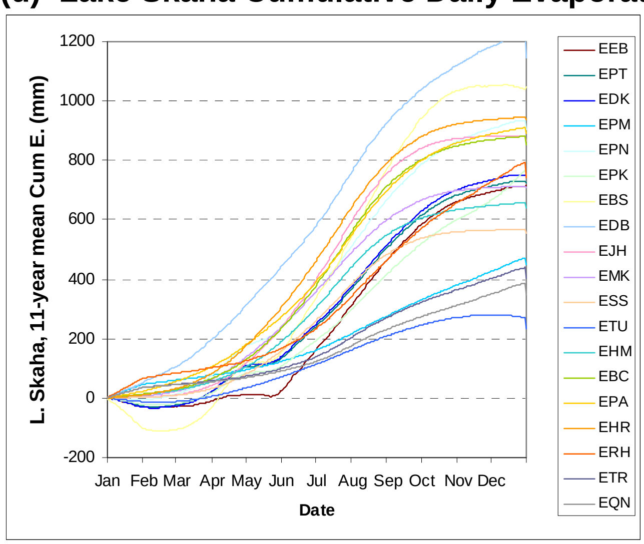
L=3 Rank	Model	Model Group	% Diff from ETR
1	**ETR**	MT	0
2	**EQN**	MT	-24
3	**EPM**	C	25
4	**ETU**	S-T	-35
5	**ESS**	S-T	79
6	**EHM**	T-D	117
7	**EPT**	C	118
8	**EEB**	C	120
9	**EDK**	C	123
10	**EPK**	C	134
11	**EMK**	S-T	135
12	**EPN**	C	141
13	**ERH**	MT	141
14	**EDB**	C	145
15	**EJH**	S-T	177
16	**EBC**	T-D	180
17	**EPA**	T	193
18	**EHR**	T	207
19	**EBS**	C	212

(c) Lake Okanagan Cumulative Daily Evaporation Results



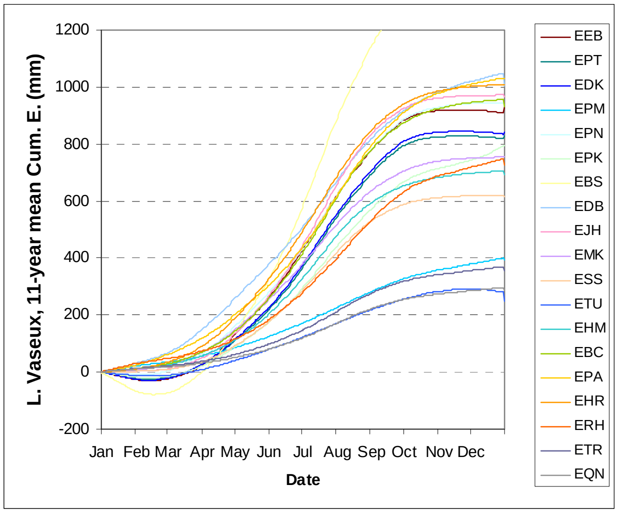
Rank	Model	Model Group	% diff from ETR
1	**ETR**	MT	0
2	**EPM**	C	9
3	**EQN**	MT	-12
4	**ESS**	S-T	16
5	**EHM**	T-D	36
6	**EPT**	C	38
7	**EDK**	C	42
8	**ETU**	S-T	-45
9	**EMK**	S-T	46
10	**EPK**	C	50
11	**EBS**	C	54
12	**EEB**	C	56
13	**EJH**	S-T	81
14	**EPN**	C	82
15	**EBC**	T-D	82
16	**ERH**	MT	84
17	**EPA**	T	87
18	**EHR**	T	94
19	**EDB**	C	151

(d) Lake Skaha Cumulative Daily Evaporation



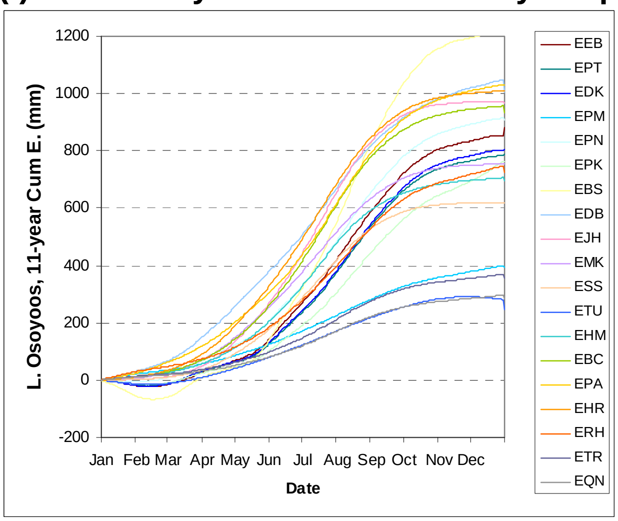
L=4 Rank	Model	Model Group	% Diff from ETR
1	**ETR**	MT	0
2	**EPM**	C	8
3	**EQN**	MT	-12
4	**ESS**	S-T	31
5	**ETU**	S-T	-38
6	**EHM**	T-D	51
7	**EMK**	S-T	64
8	**EPT**	C	68
9	**EEB**	C	72
10	**EDK**	C	73
11	**EPK**	C	76
12	**ERH**	MT	81
13	**EBC**	T-D	103
14	**EJH**	S-T	103
15	**EPA**	T	109
16	**EPN**	C	114
17	**EHR**	T	118
18	**EBS**	C	136
19	**EDB**	C	181

(e) Lake Vaseux Cumulative Daily Evaporation



L=5 Rank	Model	Model Group	% Diff. from ETR
1	**ETR**	MT	0
2	**EPM**	C	9
3	**EQN**	MT	-20
4	**ETU**	S-T	-23
5	**ESS**	S-T	70
6	**EHM**	T-D	93
7	**ERH**	MT	103
8	**EMK**	S-T	107
9	**EPK**	C	117
10	**EPT**	C	124
11	**EDK**	C	129
12	**EEB**	C	153
13	**EPN**	C	158
14	**EBC**	T-D	162
15	**EJH**	S-T	166
16	**EHR**	T	176
17	**EPA**	T	182
18	**EDB**	C	184
19	**EBS**	C	223

(f) Lake Osoyoos Cumulative Daily Evaporation



L=6 Rank	Model	Model Group	% Diff. From ETR
1	**ETR**	MT	0
2	**EPM**	C	9
3	**EQN**	MT	-20
4	**ETU**	S-T	-23
5	**ESS**	S-T	70
6	**EHM**	T-D	93
7	**ERH**	MT	103
8	**EMK**	S-T	107
9	**EPK**	C	109
10	**EPT**	C	115
11	**EDK**	C	120
12	**EEB**	C	136
13	**EPN**	C	150
14	**EBC**	T-D	162
15	**EJH**	S-T	166
16	**EHR**	T	176
17	**EPA**	T	182
18	**EDB**	C	184
19	**EBS**	C	216

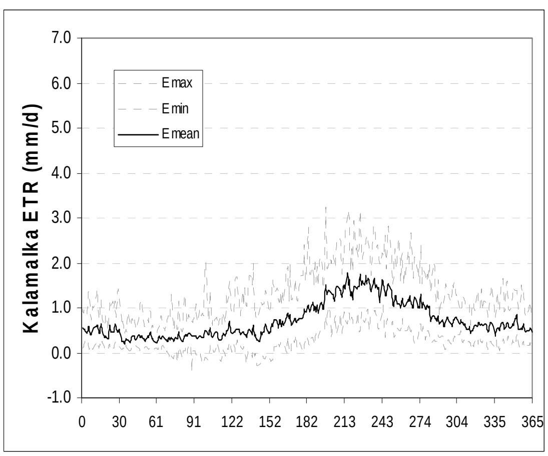
Figure 15. A composite of the longterm-averaged (1996-2006) cumulative daily evaporation curves for all 19 evaporation methods for Okanagan lakes, (a) Kalamalka, (b) Wood), (c) Okanagan, (d) Skaha, (e) Vaseaux, and (f) Osoyoos.. The associated table provides a rank order based on the % difference from the reference evaporation.

As indicated in Fig. 15 there is a significant difference in the cumulative evaporation total between models. In general, evaporation generated through the Trivett (1984) mass transfer relationship is significantly lower than that derived from other methodologies. This was also observed for 1980-81 eddy correlation (mass transfer) results in comparison to pan, temperature index and Morton's method (Trivett, 1984, Fig. 2). Differences of some model results compared to the Reference amount is very large in some cases exceeding 100 and 200 percent.

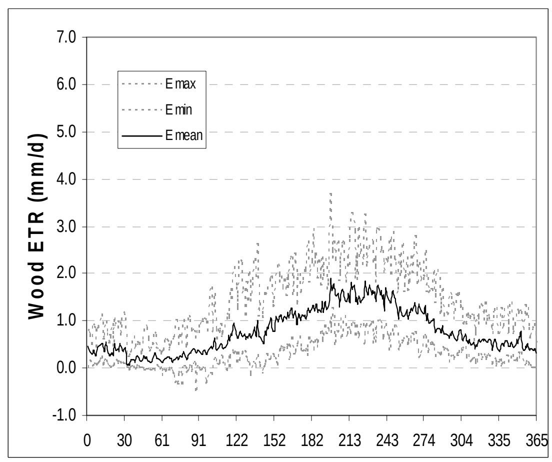
7.2 Longterm Daily Evaporation Based on the Trivett 1984 Model

Since Okanagan Lake and other mainstem lakes vary in size and latitudinal distribution, it could be expected that such differences will have an impact on the magnitude and phase of the lake evaporation. Figure 16 shows the long-term (11-year) mean and range of evaporation computed for the 6 lakes based on the ETR mass transfer approach (Trivett, 1984). What is immediately apparent is that the seasonal cycle of the evaporation is not similar to very large lakes such as the Laurentian Great Lakes. Large deep lakes such as the Laurentian Great Lakes have very large heat storage gained through the summer months. This heat gain is lost through radiative cooling as well as heat losses through turbulent exchanges mainly in the fall / early winter months. Consequently, in such systems, evaporation is low in the summer and high in the fall / early winter. As indicated in Fig. 16, the evaporation for Okanagan Lake and the mainstem lakes is maximal in the summer - early fall period. Considering the long-term mean evaporation curves, evaporation is lowest for the more northerly lakes compared to Okanagan Lake and the lakes situated towards the south.

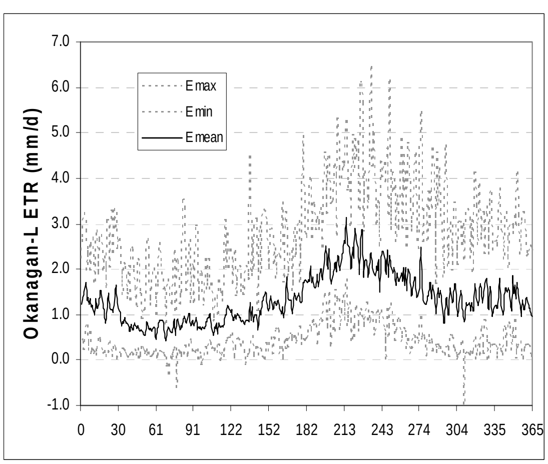
a. Kalamalka Lake



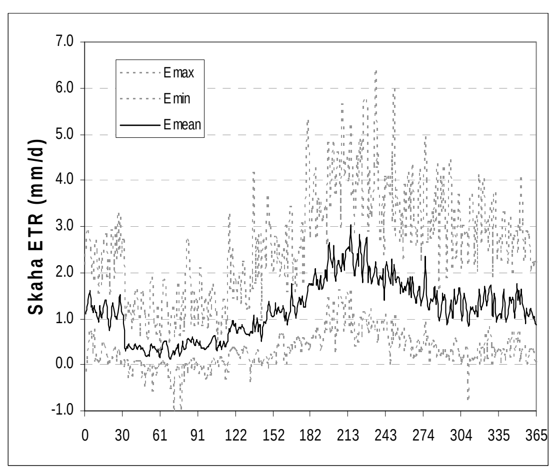
b. Wood Lake



c. Okanagan Lake



d. Skaha Lake



e. Vaseux Lake f. Osoyoos Lake

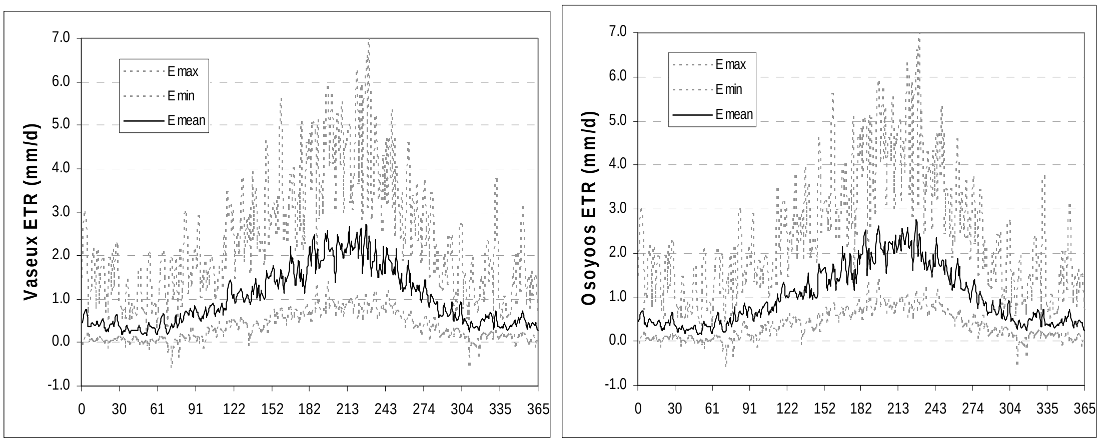


Figure 16. Daily longterm mean evaporation and range (1996-2006) based on the Trivett (1984) mass transfer evaporation formula for (a) Kalamalka Lake, (b) Wood Lake, (c) Okanagan-L Lake, (d) Skaha Lake, (e) Vaseux Lake, and (f) Osoyoos Lake.

7.3 Relationship Between Principal Variables of the Mass Balance Model

Figure 17 shows a time series of the relationship between critical meteorological and lake variables that affect the magnitude and phase of the evaporation in Okanagan lakes and are pri8mary input values to the mass transfer method.

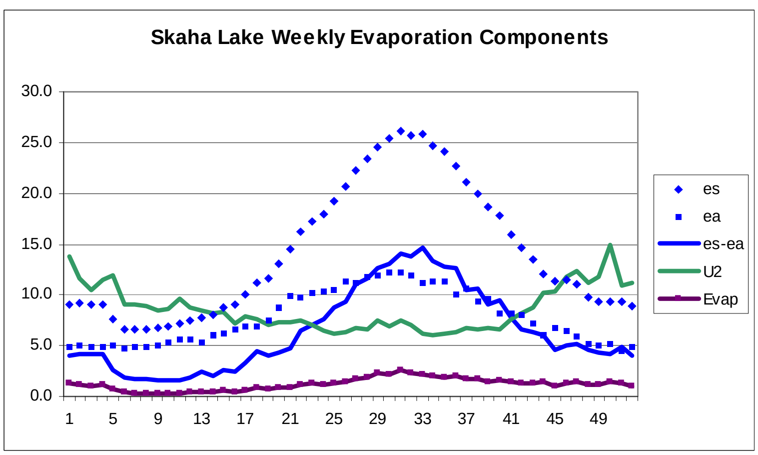


Figure 17. An example of the relationship between critical evaporation variables based on Skaha Lake.

Based on the example for Skaha Lake, it can be seen that the vapour pressure difference $(e_s - e_a)$ is maximal in the summer months. Consequently, even though wind speed is highest in the fall and winter, the combination of wind speed and vapour pressure results in higher evaporation during the summer months compared to other times of the year.

8. Annual Evaporation Results

8.1 Annual Evaporation (mm/yr)

A comparison between annual evaporation totals over a number of years can provide valuable insight on which methods consistently produce higher or lower annual evaporation totals compared to in-group formulations and between-groups. Table 17 provides a summary of the total annual evaporation (mm/yr) computed from all models over the period 1996-2006.

Table 17. Summary of the mean annual evaporation (mm/yr) from 6 Okanagan lakes for the period 1996-2006 based on 19 lake evaporation models.

Model Group	Kalamalka	Wood	Osoy-L	Skaha	Vaseux	Osoyoos
	E (mm/yr)	E (mm/yr)	E (mm/yr)	E (mm/yr)	E (mm/yr)	E (mm/yr)
Energy Budget						
EEB	657.4	616.8	759.5	746.7	923.0	861.8
Combination						
EPT	632.2	612.7	668.4	729.5	818.9	782.7
EDK	647.4	627.5	689.5	751.6	834.4	801.9
EPM	338.4	352.1	531.6	472.1	399.9	399.9
EPN	692.6	677.1	884.6	934.2	942.9	914.1
EPK	688.6	657.8	728.0	765.9	793.1	764.3
EBS	899.4	877.2	745.5	1023.6	1177.7	1150.6
EDB	691.6	691.6	1226.7	1230.9	1046.1	1046.1
Solar Rad - Temp.						
EJH	782.4	782.6	880.2	883.7	971.8	971.8
EMK	661.5	661.5	710.5	713.0	754.9	754.9
ESS	506.1	506.2	565.3	567.7	620.6	620.6
ETU	185.0	186.3	271.0	271.2	280.9	280.9
Temp. - Daylength						
EHM	612.4	612.4	660.1	657.6	706.3	706.3
EBC	791.4	791.5	883.0	881.5	956.6	956.6
Temperature						
EPA	826.4	826.1	910.2	910.4	1030.6	1030.6
EHR	866.0	865.9	941.1	945.8	1009.7	1009.7
Mass Transfer						
ERH	623.1	682.0	896.6	794.2	747.2	747.2
ETR	261.8	282.7	488.0	439.0	368.9	368.9
EQN	199.6	215.4	431.0	386.8	296.4	296.4

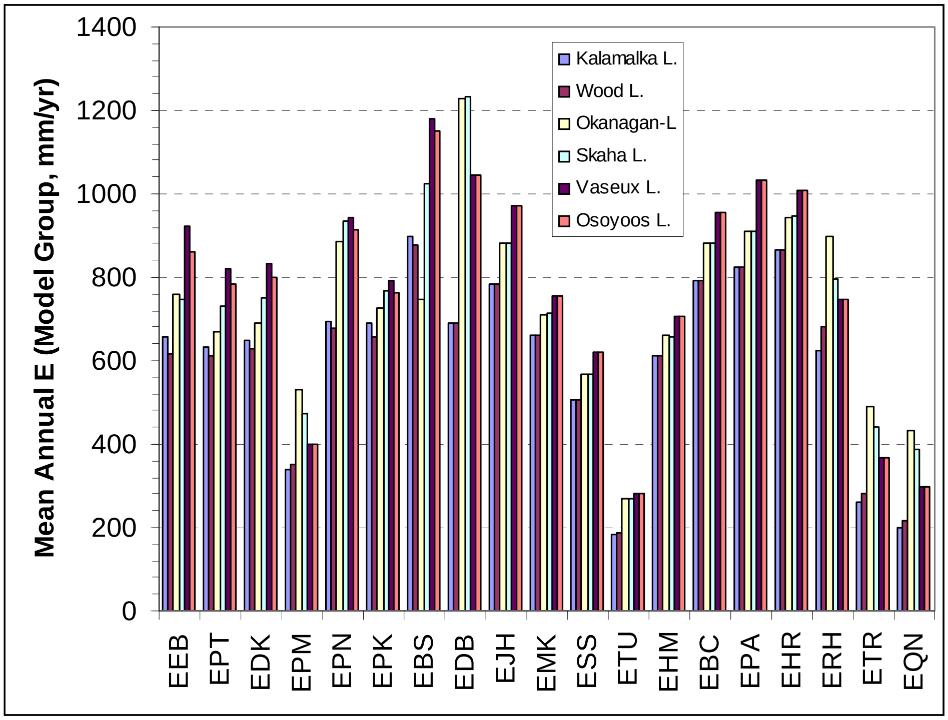


Figure 18. Comparison between 11-year mean evaporation computed from 19 evaporation methods for the 6 Okanagan lakes

Figure 18 shows a dramatic range in the computed evaporation for Okanagan lakes using the 19 different evaporation models. Based on the long-term annual computations, the lowest computed annual evaporation (generally < 450 mm/year) occurs with the models EPM (Combination Group), the ETU (Solar Radiation, Temperature Group), and the ETR and EQN (Mass Transfer Group). In contrast, very high evaporation totals (generally > 1000 mm/yr) occurs with the EBS and EDB models (Combination Group)

8.2 Volume of Water Evaporated (m^3/yr)

Knowledge of the volume of water evaporated is an important consideration. In the tabulations provided above, comparisons are made between the evaporation rates approximated for each lake. Each of the Okanagan lakes have different physical dimensions such as surface area, depth and volume. The differing morphometric conditions affect such factors as the lake heat storage and the effective surface area available for the surface evaporation process. Table 1 provides a listing of the surface areas used for each of the 6 Okanagan lakes.

Table 21 summarizes the computed 11-year averaged volume of water evaporated from each of the 6 Okanagan lakes based on each of the 19 selected evaporation models in units of (x 10^6 m^3 yr^{-1}). Graphical representation of the data in Table 21 is shown in Fig 19 for the 5 smaller lakes and in Fig. 20 for Lake Okanagan-L with respect to each of the models. What is immediately apparent is that the average volume of water evaporated from Lake Okanagan-L is significantly greater than the other mainstem lakes.

Table 18. Volume of water evaporated (x 10^6 m^3yr^{-1}) from each of 6 Okanagan lakes for 1996-2006 based on 19 lake evaporation models.

Model Group	Kalamalka (xE6 m^3/yr)	Wood (xE6 m^3/yr)	Okan-L (xE6 m^3/yr)	Skaha (xE6 m^3/yr)	Vaseux (xE6 m^3/yr)	Osoyoos (xE6 m^3/yr)
Energy Budget						
EEB	17.03	5.74	264.30	15.01	2.54	12.93
Combination						
EPT	16.37	5.70	232.61	14.66	2.25	11.74
EDK	16.77	5.84	239.96	15.11	2.30	12.03
EPM	8.76	3.28	185.01	9.49	1.10	6.00
EPN	17.94	6.30	307.83	18.78	2.59	13.71
EPK	17.83	6.12	253.33	15.40	2.18	11.46
EBS	23.29	8.16	259.43	20.57	3.24	17.26
EDB	17.91	6.43	426.91	24.74	2.88	15.69
Solar Rad. - Temp.						
EJH	20.26	7.28	306.30	17.76	2.67	14.58
EMK	17.13	6.15	247.24	14.33	2.08	11.32
ESS	13.11	4.71	196.73	11.41	1.71	9.31
ETU	4.79	1.73	94.31	5.45	0.77	4.21
Temp. - Daylength						
EHM	15.86	5.70	229.73	13.22	1.94	10.59
EBC	20.50	7.36	307.29	17.72	2.63	14.35
Temperature						
EPA	21.40	7.68	316.74	18.30	2.83	15.46
EHR	22.43	8.05	327.50	19.01	2.78	15.15
Mass Transfer						
ERH	16.14	6.34	312.01	15.96	2.05	11.21
ETR	6.78	2.63	169.81	8.82	1.01	5.53
EQN	5.17	2.00	149.98	7.78	0.81	4.45

Based on the results from model ETR (Trivett (1984), the average water evaporated from Lake Okanagan is 169.8 x 10^6 m^3 yr^{-1} which is similar to the evaporation from the Quinn model (EQN) at 149.98 x10^6 m^3 yr^{-1}. Lakes Kalamalka, Skaha, and Osoyoos have similar water losses, and also based on ETR their water losses are in the order 6.78 x10^6 m^3 yr^{-1}, 8.82 x10^6 m^3 yr^{-1}, and 5.53 x10^6 m^3 yr^{-1} respectively. As expected, the lowest water losses are from the smaller lakes, Wood and Vaseux Lakes. Based on model ETR, their average evaporative losses are 2.63 x10^6 m^3 $yr^{-1}$and 1.01 x10^6 m^3 yr^{-1}.

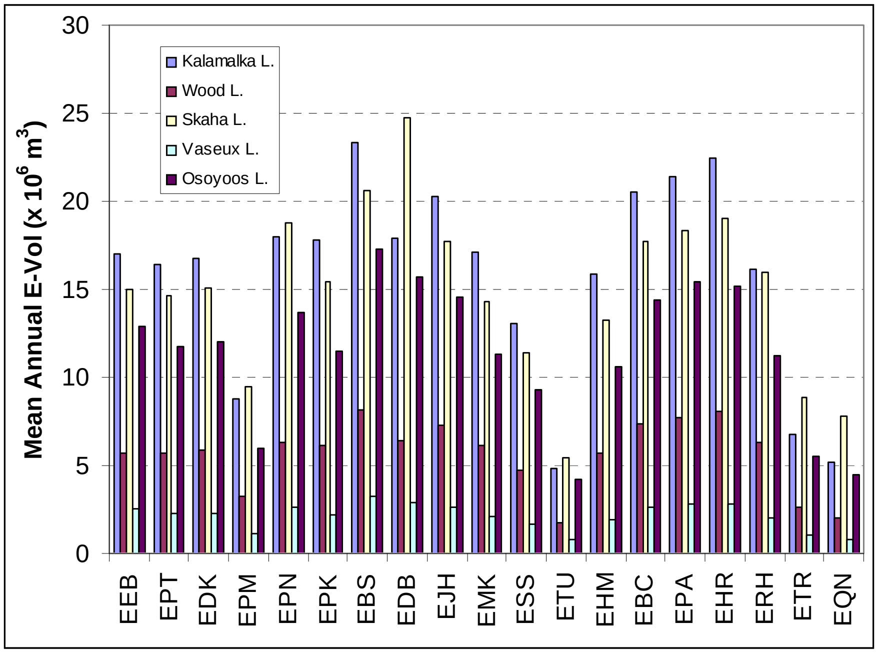


Figure 19. Comparison between 11-year mean annual volume of water evaporated from Lakes Kalamalka, Wood, Skaha, Vaseux, and Osoyoos from each of 19 selected evaporation models.

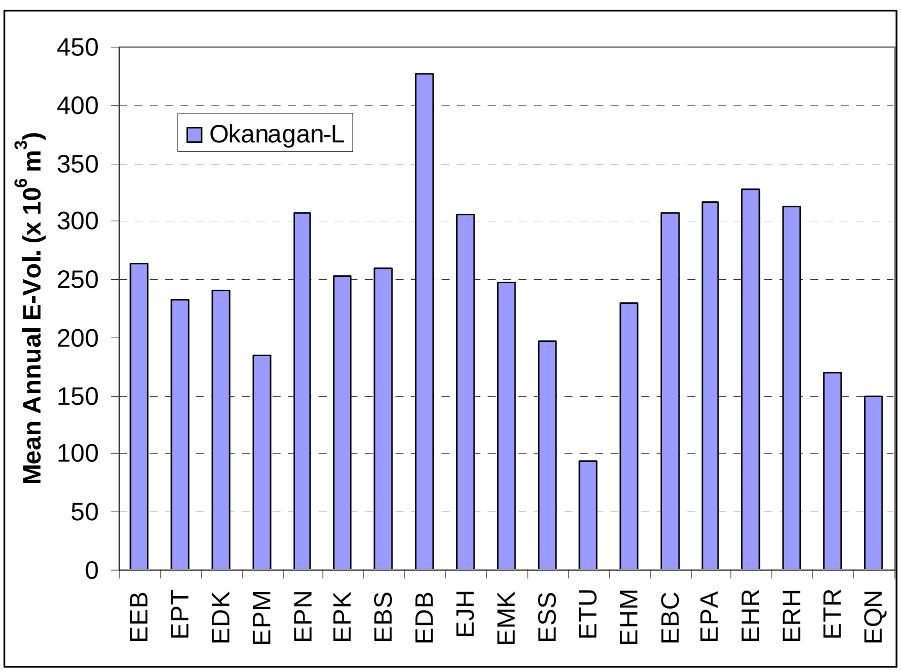


Figure 20. Comparison between 11-year mean annual volume of water evaporated from Lake Okanagan-L from each of 19 selected evaporation models.

9. Recommended Evaporation Approach for Okanagan Lake and Other Mainstem Lakes

This investigation examined the applicability of a range of models to determine evaporation from Okanagan Lake and other mainstem lakes using the existing database. A total of 19 evaporation models were examined which were representative of six methodologies, i.e. Energy Budget, Combination Method, Solar Radiation – Temperature Group, Temperature – Daylength Group, Temperature Group and Mass Transfer Group. The existing meteorological database consisted of observations from the primary stations of Penticton, Summerland, Kelowna, and Vernon. Lake data consisted primarily of data from historical investigations.

The recommendation of an evaporation approach for a particular lake(s) is usually related to an assessment of the accuracy of the tested model in comparison to a "Reference" evaporation result determined from a direct approach such as the eddy covariance or some method such as the energy budget forced with lake-representative data. Generally, the reference evaporation is derived through a well planned, and spatially representative experiment. This is not the case for the current investigation that must rely on an existing database which does not include detailed lake observations and in which land-based meteorological data is not representative of lake conditions (Trivett 1984). In the case of Okanagan Lake and the mainstem lakes, the recommendation of a model approach is heavily related to the limitations of the existing database and critical assumptions imposed in order to apply the tested model.

9.1 Database Limitations

9.1.1 Meteorology: The most severe limitations in this study centered on the lack of over-lake data. For example, many of the evaporation relationships require information on air temperature, dew point temperature / relative humidity and wind speed and water surface temperature. These data are critical for determination of the saturated vapour pressure and ambient vapour pressure as well as the mechanical energy required for the evaporation process. Trivett (1984) provided extensive analysis of the differences between data from land-based sites and over-lake conditions and recommended implementation of sites more representative of lake conditions. Recommendations from that study were largely not implemented. For example, in this investigation, wind speeds at Kelowna required to be increased by 64% to be representative of wind speeds taken at Kelowna Bridge. There were no data to determine transformations for other variables at Kelowna or the other primary stations. Consequently, all evaporation computations in this study are subject to the limitations imposed by a lack of over-lake data.

9.1.2 Radiative Fluxes: Determination of the lake heat flux is a critical requirement in the energy budget and combination approaches and methodologies requiring solar radiation. Unfortunately, in this study area, there were no measured values of the components of solar, longwave or net radiation (over-water). In addition, ancillary data such as cloudiness was measured at only one site at Penticton, surface water temperature and surface albedo was not measured. All of the heat flux components for these methods were determined largely from empirical relationships requiring extensive assumptions. Consequently, all evaporation computations in this study from methods requiring heat flux values are subject to the limitations imposed by a lack of direct over-lake measurements or limited support data. Other than for computations of extraterrestrial radiation and daylength, the radiative fluxes generated in this study have been unverified. Solar radiation collected at Summerland in the past is currently being processed, however, indications are that there is a high level of missing observations. Never-the-less, processing of these data will allow future verification of solar radiation computations.

9.1.3 Water Temperature: Water temperature is a critical variable in most of the evaporation methods and was not routinely measured in the lakes over the 1996-2006 period. Water temperature was approximated based on a hysteresis between water temperature and 10-day mean air temperature through the Hyatt Logistical Model. For the purposes of this study, the Hyatt Logistical Model was extended to the mainstem lakes and are therefore only preliminary results. Future research is required to verify the accuracy of the derived coefficients.

9.1.4 Heat Content: Lake heat content is a critical component in the energy budget, combination approaches. The only data available for approximating the heat content for these 6 lakes was collected in 1970-71 by Blanton and Ng (1971, 1972). Daily values of heat content were derived by cubic spline interpolation and an annual cycle for each lake was done subjectively. Lake heat content determined for 1970-1971 period was extended to all years (1996-2006). There were no data to assess the possible error in applying the heat content of one year equally to other years (1996-2006) has not been assessed. Heat content must be rigorously evaluated in order to support evaporation models such as energy budget and combination models.

9.1.5 Advected Heat: Precipitation, and inflows and outflows etc. are used to evaluate the net advection of heat into and out of lakes through hydrological processes. For large deep lakes such as the Laurentian Great Lakes heat gains and losses through hydrological components is small compared to the radiative exchange (Derecki, 1975; Schertzer and Sawchuk, 1990). In smaller lakes, these components may have greater importance. The advection due to hydrological components was not assessed in this analysis due to a lack of data.

9.2 Critical Assumptions

Based on the database limitations the following is a list of some of the assumptions that were invoked in order to proceed with the lake evaporation computations:

- evaporation could be approximated using the “existing” database
- some required variables not available at all stations could be transferred from those stations with measured values
- filling of missing data from a primary station could be done with a secondary site

- missing data from both primary and secondary meteorological stations could be solved by introducing long-term mean meteorology (1996-2006)
- water surface temperature could be approximated using the Hyatt Logistical model extended to all lakes.
- heat content derived from 1971 limited data could be spline interpolated and extended to all years (1996-2006) and derived change in heat storage are valid.
- Bowen Ratios computed from non-overlake data and water temperature assumptions are valid
- No data were available to test computed solar and longwave radiation fluxes. It is assumed that the computed values are applicable to the Okanagan lakes.

9.3 Performance of the Models with the Existing Database

The rationale for modelling evaporation based on a large number of approaches from representative model groups was to determine whether there was a discernable pattern to the computed lake evaporation or a central tendency for the annual evaporation amount and whether the model computations were in phase over the annual period. In this investigation, all model results were compared against a Reference Model. The Reference Model was the mass transfer approach of Trivett (1984) which was derived from eddy covariance observations (i.e. a direct evaporation approach). It should be noted that no other method met the criteria (i.e. based on direct evaporation approach or based on comprehensive lake observations) to be selected as a Reference model for intercomparison of the results. In this Section, comparison with the Reference evaporation is only reported for Okanagan Lake.

9.3.1 Performance of the Energy Budget Group: The Energy Budget Group consisted of only one method (EEB). The energy budget evaporation is based on a partial energy budget since it did not account for advected heat from hydrological inputs and outputs to the lake which can occur through major inflows, outflows, tributary inputs, runoff, groundwater or precipitation.

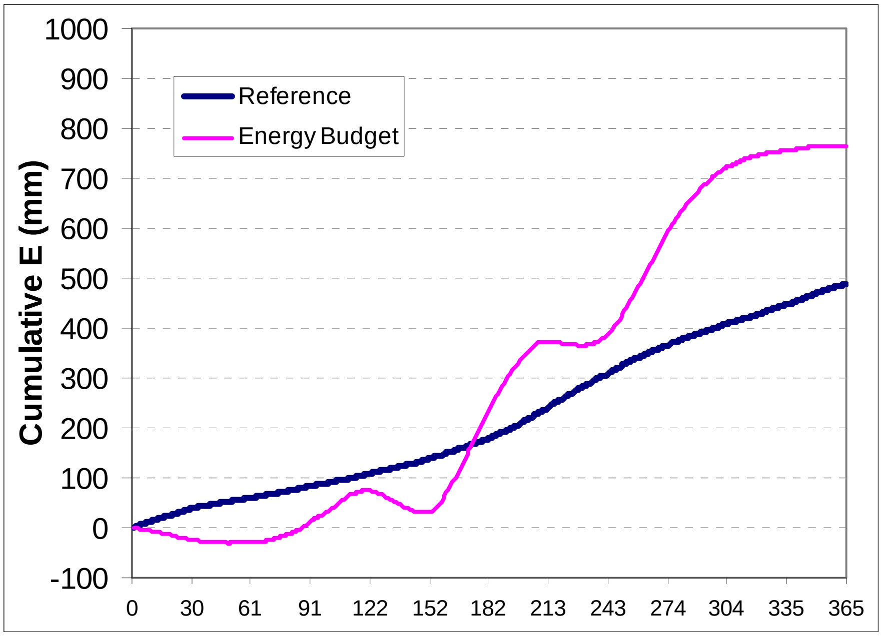


Figure 21. Comparison between 11-year average evaporation computed from the lumped Energy Budget Group and the Reference evaporation (ETR).

Figure 21 shows a comparison between 11-year average evaporation from the energy budget approach and from the Reference (ETR). The range of evaporation estimates from both approaches is not plotted. Immediately apparent is that evaporation from January through March is negative in the energy budget approach implying a heat gain to the lake. Oscillations in the energy budget evaporation are related to rapid heat gain in the spring and also timing of the maximum heat storage occurrence. As noted above, determination of evaporation through the energy budget method requires detailed lake data for computation of the net radiation (Q^*) and also detailed spatially representative vertical temperature observations from which to derive lake heat storage and heat storage change (Q_x). The existing database did not allow for comprehensive computation of the net radiation or lake heat storage. Further, heat content derived from 1971 observations was extended to all years 1996-2006. Based on the numerous assumptions required to "force" the energy budget approach using the existing data, the energy budget evaporation result can only be considered a preliminary result requiring future research with lake data. Consequently, the energy budget approach cannot be recommended at the present time for Okanagan Lake or the mainstem lakes. In similar investigations in which multiple lake evaporation models are assessed, the energy budget approach is often selected as the "Reference" evaporation method. The energy budget method should be considered in future investigations with appropriate data input.

9.3.2 Performance of the Combination Group: The Combination Group consisted of 7 methods (EPT, EBR, EPM, EPN, EPK, EBS, and EDB). Figure 22 compared the 11-year mean evaporation and range derived from the seven combinations methods with the Reference evaporation (ETR). As observed in the energy budget approach, the evaporation from the combination model approach is slightly negative in the January-February period. Oscillations in the evaporation in the spring and time of maximum heat content are also observed in Fig 22 (and Fig. 21) indicating that the heat storage change also has a strong effect on the seasonal evaporation pattern in this method – based on the existing databases.

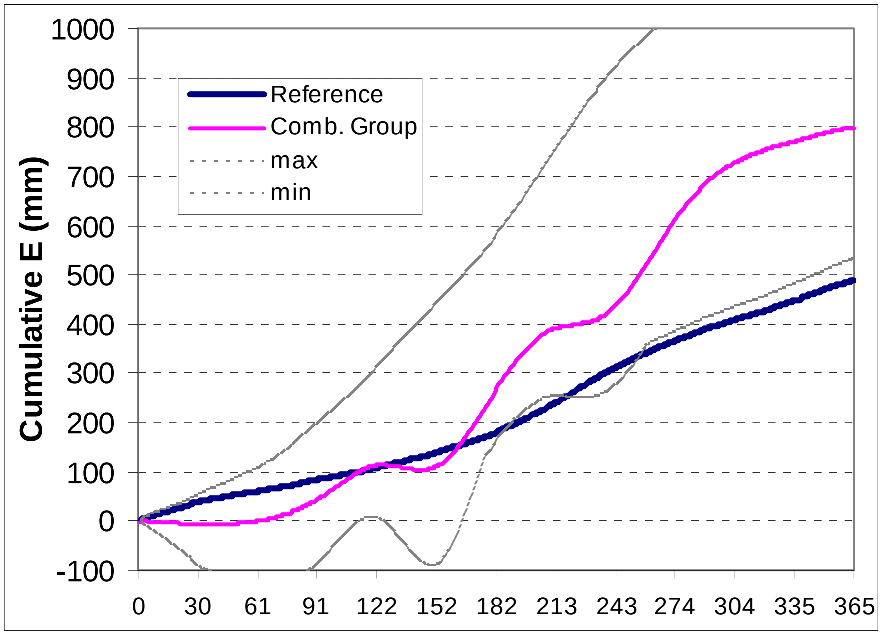


Figure 22. Comparison between 11-year average evaporation computed from the lumped Combination Model Group and the Reference evaporation (ETR).

Since the combination methods require information on the net radiation and lake heat storage change ($Q^* - Q_x$), the approach suffers from the same assumptions and limitations as indicated for the energy budget approach. Since the combination models include elements of mass transfer (vapour pressure gradient and wind function) the lack of over-lake data becomes an additional source of error in this methodology. Consequently, since the combination methods require intensive lake or lake representative data which is not available in the "existing" database the combination methods cannot be recommended at the present time for application to Okanagan Lake or its mainstem lakes. This methodology should be considered in future with appropriate data input.

9.3.3 Performance of the Solar Radiation-Temperature Group: The Solar Radiation – Temperature Group consisted of 4 models (EJH, EMK, ESS, and ETU). This group of models have the advantage of requiring minimal data input such as solar radiation, air temperature, atmospheric pressure, and relative humidity. However, as in all methods, it is important that the observations are representative of lake conditions.

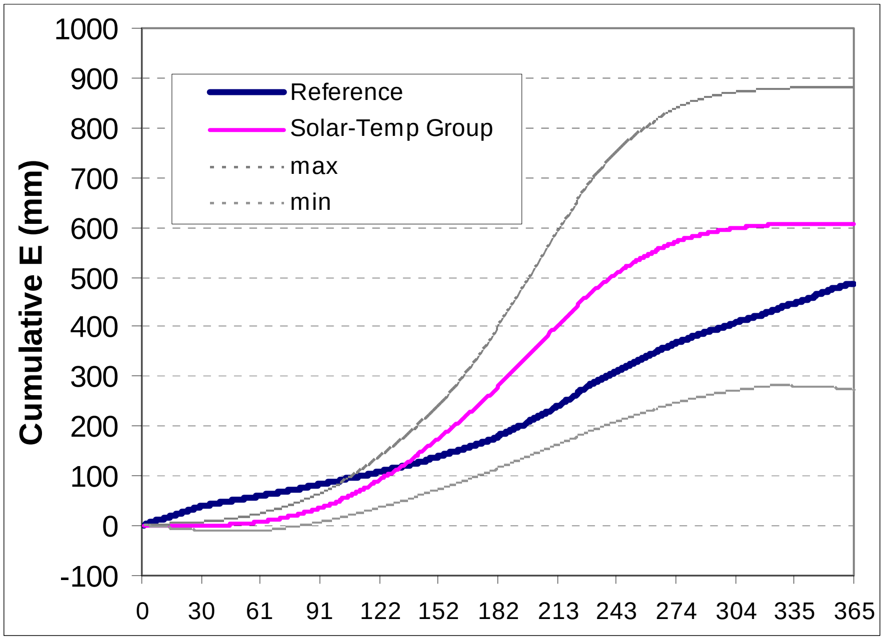


Figure 23. Comparison between 11-year average evaporation computed from the Solar Radiation-Temperature Group and the Reference evaporation (ETR).

Figure 23 shows a comparison between 11-year average evaporation and range computed from the Solar Radiation-Temperature Group of models against the reference evaporation. As indicated in Fig. 23, the group of models produce an annual cycle of evaporation similar to the energy budget and combination methods. The lower bound of the range encompasses the ETR mean evaporation curve. Since heat storage is not considered in this class of models, there are no oscillations associated with spring warming or at the time of maximum heat content. The mean curve indicates low and non-negative evaporation in the January to February period. Although the computed evaporation range for this Group of formulations is large, the ensemble mean has similar characteristics as the reference evaporation curve. Future research on the application of these models is required using over-lake observations of the required input variables to further assess the applicability of these approaches.

9.3.4 Performance of the Temperature-Daylength Group: The Temperature-Daylength Group consisted of two models (EHM and EBC). As in the Solar Radiation – Temperature Group, this group of formulations require less data input than in the energy budget or combination approaches. The primary inputs are hours of daylight and air temperature. Empirical formulations are often site specific, and consequently, may not be as transportable from one region to another. Although the daylength is computed based on latitude from astronomical parameters, other data inputs such as air temperature are required to be representative of the over-lake conditions.

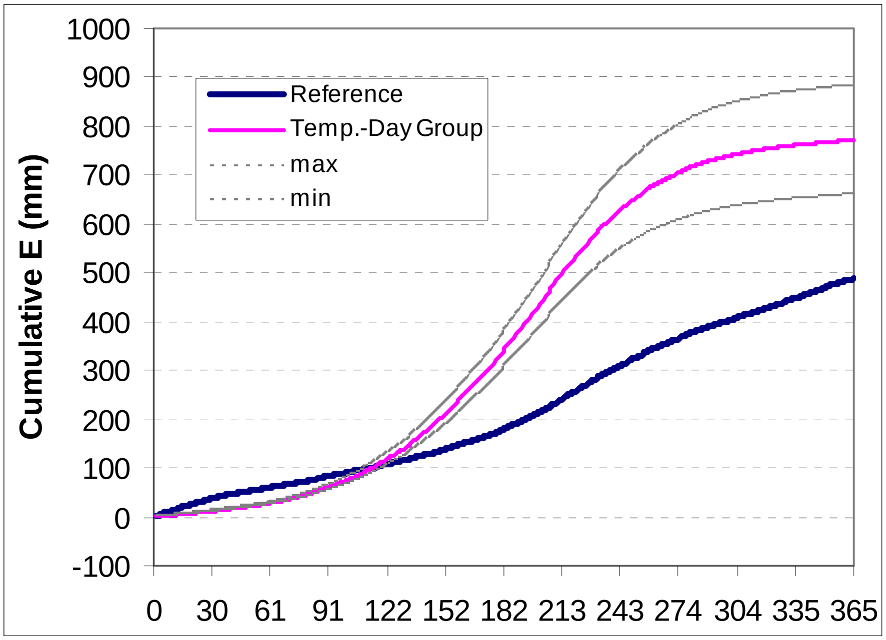


Figure 24. Comparison between 11-year average evaporation computed from the lumped Temperature-Daylength Group and the Reference evaporation (ETR).

Figure 24 shows a comparison between the 11-year mean and range of the temperature-daylength models compared to the reference evaporation. Although the cumulative evaporation over the January to April period corresponds well to the reference evaporation, the cumulative evaporation from May to December shows large divergence from the reference evaporation especially through the summer and fall period. Total evaporation from this group is similar to that from the energy budget and combination grouped average. Future analyses using these models requires comprehensive testing of the applicability of the empirical coefficients for the Okanagan lakes. The Temperature-Daylength methods cannot be recommended for application to the Okanagan lakes using the existing database at this time.

9.3.5 Performance of the Temperature Group: The Temperature Group consisted of two sample models (EPA and EHS). The advantage of these empirical models is that they require only maximum and minimum air temperature and extraterrestrial radiation which is easily computed. Again, coefficients for such empirical approaches may not be transferable from one region to another.

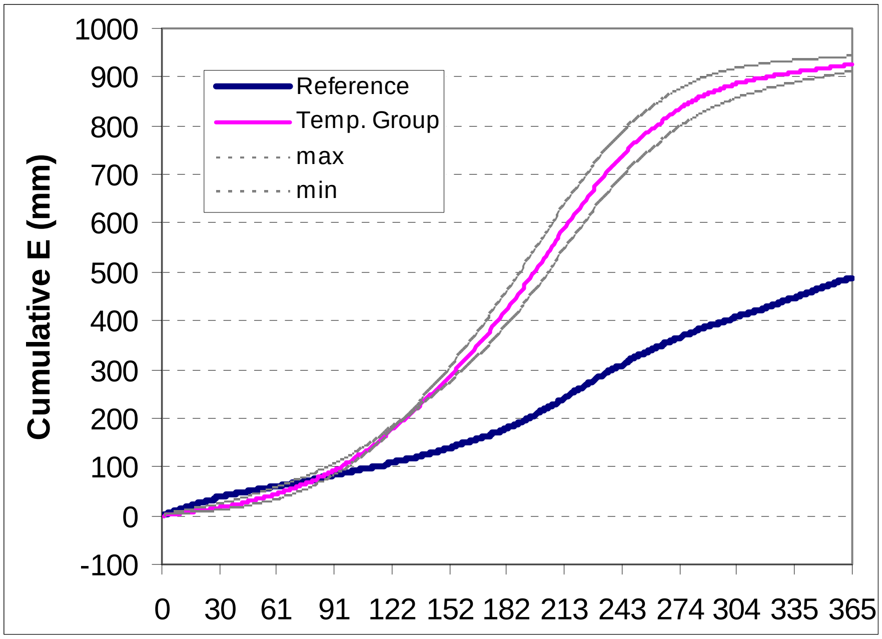


Figure 25. Comparison between 11-year average evaporation computed from the Temperature Group of models and the Reference evaporation (ETR).

Figure 25 shows a comparison between the mean and range of the Temperature Group of models and the Reference evaporation. As shown in the Temperature-Daylength Group, the Temperature Group of models also conforms to the reference evaporation during the winter. However, the divergence from the reference evaporation is very steep during the summer. This may be indicative of a lack of correspondence between maximum and minimum temperatures from the land-based meteorological stations and over-lake conditions. No data were available to develop lake-land transformations for air temperature. The Temperature Group of evaporation models cannot be recommended for the Okanagan lakes using the existing database without further research.

9.3.6 Performance of the Mass Transfer Group: The Mass Transfer Group consisted of 3 sample models (ERH, ETR, and EQN). The ETR model was chosen as the Reference evaporation since the mass transfer coefficient was based on direct observations through the eddy covariance methods conducted near Okanagan Lake at Penticton Marina (Trivett, 1984). Figure 26 shows a comparison of the 11-year mean evaporation derived from the Mass Transfer Group compared to the reference evaporation (ETR).

The mass transfer technique is based on physical principles (Munn, 1961). The evaporation computed from this method is considered proportional to a function of the average wind speed and the difference between vapour pressure of the air at the evaporating surface (e_s) and the vapour pressure of the air at some level above the surface (e_a). The difference between e_s and e_a is usually fairly large so that the requirement on the accuracy of the measuring instruments is not so severe as it is when trying to determine the vapour pressure profile in the free air stream (Williams, 1961). In general practice, e_s is determined as the saturation vapour pressure corresponding to the surface temperature. In this investigation, surface temperature is not measured but computed through the Hyatt Logistical Model and some inaccuracy is expected. Inaccuracy is also expected to occur through the use of land-based wind speed and air temperature.

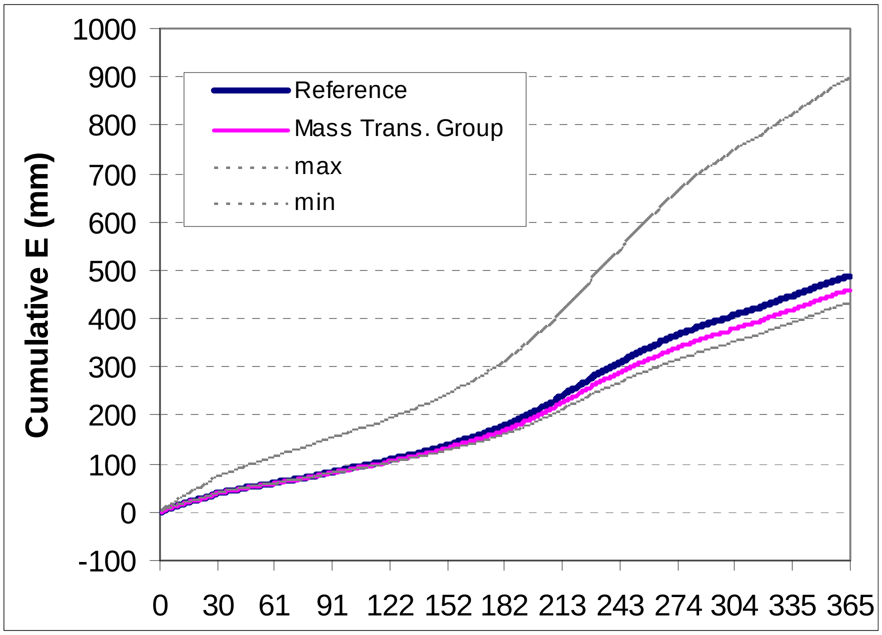


Figure 26. Comparison between 11-year average evaporation computed from the lumped Mass Transfer Group and the Reference evaporation (ETR).

The Ryan-Harleman formulation (ERH) requires determination of the difference in virtual temperatures between the water surface and the ambient air (Rassmussen *et al.*, 1995; Ryan and Harleman, 1973). Some error is expected in the determination of the virtual temperatures since there was no direct over-lake measurement of the air temperatures. The ERH method was found to provide the largest errors compared to 15 other methods applied at Mirror Lake, USA (Rosenberry *et al.*, 2007) and in Fig. 26, the upper bound of values are evaporation estimated from the ERH model. Consequently, the ERH method is not recommended for application to the Okanagan lakes using the existing database.

The EQN method is based on extensive research on Lake Ontario during the International Field Year for the Great Lakes (IFYGL). The formulation includes a variable mass transfer coefficient compared to the constant coefficient of Trivett (1984). In addition, the wind speed requirements in both ETR and EQN are different as well as the measurement height requirement. As indicated in the preceding comparisons, the correspondence between the reference evaporation (ETR) and the EQN model developed for Lake Ontario is excellent and the EQN model could be considered as an alternative approach for the Okanagan lake evaporation computations using the existing database.

Trivett (1984) provided a summary of methods used for calculating the mass transfer coefficient and provided a table comparing mass transfer functions and discussion relating to derivation of the coefficient for Lake Okanagan conditions. The coefficient derived for Lake Okanagan is (M=0.024). The mass transfer coefficient for Okanagan Lake is comparable to the range of values determined for other lakes (e.g. Sable Is. M=0.0233; Lake Superior M=0.0198 to 0.0239, Lake Ontario M=0.0262 to 0.0275 and Lake Hefner M=0.0269. This indicates that the mass transfer coefficient determined for Okanagan Lake is robust and independent of climate inputs.

9.4 Ranking Model Output Compared to the Reference Evaporation

On method for comparing the general performance of the individual models is to rank the model evaporation according to the correspondence with the reference evaporation. Table 19 provides a first order ranking based on the percentage difference between computed annual evaporation for each model compared to the reference evaporation (ETR) for each lake. The ranking is constrained to a maximum of 100% difference from the Reference evaporation and provides an indication of possible alternative models that may be applicable to the Okanagan lakes using the existing database.

Table 19. Rank order of the five best model outputs for each Okanagan lake. Rank order is based on the percentage difference between the volume of water evaporated from a particular model compared the reference evaporation (ETR, Trivett, 1984). Comparisons are done using 11-year averaged total evaporation from each model.

% Diff from ETR	Okanagan	Kalamalka	Wood	Skaha	Vaseux	Osoyoos
0	ETR	ETR	ETR	ETR	ETR	ETR
1 to 10	EPM	-	-	EPM	EPM	EPM
11 to 20	EQN	-	-	EQN	EQN	EQN
	ESS	-	-	-	-	-
21 to 30	-	EQN	EQN	-	ETU	ETU
	-	EPM	EPM	-	-	-
	-	ETU	-	-	-	-
31 to 40	EHM	-	ETU	ESS	-	-
	-	-	-	ETU	-	-
41 to 50	-	-	-	-	-	-
51 to 60	-	-	-	-	-	-
61 to 70	-	-	-	-	ESS	ESS
71 to 80	-	-	ESS	-	-	-
80 to 90	-	-	-	-	-	-
91 to 100	-	ESS	-	-	-	-

Based on this simple measure, Table 19 indicates that the Penman-Monteith Method (EPM), the Quinn method (EQN) and the Stephens-Stewart method (ESS) provided evaporation estimates within 20% of ETR for most lakes. As indicated above, the EPM method (Combination Group) requires extensive lake data which is not available in this study. The ESS method is indicated for Okanagan Lake but performed poorly for the other lakes. As indicated above, future research is required using measured solar radiation and data to verify the applicability of the model coefficients for this lake. The ETU method may be another alternative approach, however, it's correspondence with the reference evaporation is also poor and likely related to the problem of coefficients not applicable to the Okanagan lakes. Compared to the reference evaporation, the EQN method may be a viable alternative to the ETR Method.

9.5 Recommended Evaporation Model for Okanagan Lake and Mainstem Lakes Using the Existing Database

ETR Mass Transfer: Trivett (1984) $E = 0.024(e_s - e_a)U_2$

The proceeding sections provided details on the performance of 19 possible evaporation methods for application to Okanagan Lake and its mainstem lakes using the existing database. Evaporation from each method was generated for daily and annual periods and intercompared as cumulative evaporation amounts as well as annual totals. Since there were no detailed direct or indirect observations of evaporation over the 1996-2006 period, a Reference evaporation was selected from which each model result could be compared. The Reference chosen was the mass transfer model derived by Trivett (1984) which was developed based on actual measurements through eddy correlation conducted at Penticton Marina in 1980-1981.

Based on the analysis provided in this report, the mass transfer model derived by Trivett (1984) is recommended for application to Okanagan Lake and the mainstem lakes. The following is a summary of the main points leading to this recommendation:

- ***Validity of the Mass Transfer Coefficient (Trivett, 1984)***: The Trivett (1984) mass transfer formula incorporates a mass transfer coefficient derived from eddy covariance observations conducted in close proximity to Okanagan Lake in 1980-81. The eddy covariance observations are considered a direct measure of evaporation. One possible limitation is that the mass transfer coefficient is determined only at one location (at Penticton), however, other studies have indicated that this is not an important consideration (see below).

- ***Similarity of the Mass Transfer Coefficient Values in Other Lakes***: The Trivett (1984) derived mass transfer coefficient (M = 0.024) is very similar in magnitude to values derived for other lakes of varying sizes. The similarity in magnitude of the transfer coefficient strongly suggests that the mass transfer coefficient is largely independent of climatic differences and is applicable to the Okanagan lakes.

- ***Impact of the Lack of Over-lake Observations***: Large divergences in estimates of lake evaporation from a range of evaporation models used in this study is largely attributed to a lack of direct over-lake observations of data (e.g. lake temperature, meteorological variables, heat fluxes and heat content, etc.). While the mass transfer approach does require representative lake observations of wind speed, water surface temperature and air temperature as many other approaches, it has an important advantage in that it does not require heat fluxes or heat content observations – all of which do not exist over the 1996-2006 period.

- ***No Requirement for Heat Storage***: Assumptions were made in order to "force" application of many of the evaporation models considered in the study. With reference to heat content, the cumulative evaporation results strongly suggest that application of heat content from one year, such as 1971, over all years likely contributes to error in the energy budget and combination approaches since the heat storage change is a dominant term especially for Okanagan Lake. Again, the mass transfer method does not require lake heat storage change.

- ***No Requirement for Heat Flux Components***: The net radiation is required in the energy budget, combination methods and solar radiation is required in some of the empirical approaches. There were no direct observations of the net radiation over water, and no continuous measurements of solar or longwave radiation. These fluxes were difficult to compute in this investigation since required support data was largely missing. No data exist for verification of the accuracy of the computed heat fluxes. The advantage of the mass transfer method is that it does not require net radiation, solar or longwave radiation.

- ***Impact of Empirical Coefficients***: Unlike the mass transfer approach in which the mass transfer coefficient is derived from direct observations from the Okanagan Lake, other less data intensive empirical techniques such as those in the Solar Radiation-Temperature Group, Temperature-Daylength Group, or Temperature Group have coefficients developed elsewhere and may not be applicable to Okanagan Lake. These less data intensive techniques are appealing but require investigation to verify the empirical coefficients for application to the Okanagan lakes. In the mass transfer approach, the mass transfer coefficient compares well between lakes of different sizes in other parts of the world strongly indicating that the Trivett (1984) coefficient is applicable to the Okanagan lakes

- ***Alternative Methods***: Alternative methods to the mass transfer approach of Trivett (1984) would be advantageous especially for future investigations considering computations prior to 1996 which also has a limited database. The EPM, EQN, ESS are possible alternatives with computed evaporation within 20% of the reference evaporation (ETR). As indicated above, EPM is a data intensive approach, and ESS requires verification of empirical coefficients. The EQN is another mass transfer method developed for Lake Ontario. The good correspondence with the ETR method strengthens the argument that the mass transfer coefficient is not sensitive to climate differences. Further detailed investigation is required with over-lake meteorology, radiation and temperature data to determine if there is convergence between evaporation results if lake representative input data is used.

9.6 Sensitivity of the Recommended Evaporation Model (ETR) to Selected Input Data

Although the mass transfer model (e.g. Trivett, 1984) is based on near-lake observations using eddy covariance observations, the model has some limitations to consider. It is also subject to the same limitations of the existing database.

Okanagan Lake is 120 km in length, and consequently, there are differing meteorological as well as water temperature differences between the south and north parts of the lake. Such differences have the potential to impact on the accuracy of the evaporation estimate of this long lake regardless of the model recommended for this lake. The sensitivity of models for computing lake evaporation based on different meteorological inputs located along the length of Okanagan Lake is tested using different station assignments as listed in Table 20. The model outputs for Lake Okanagan in this study are reported as Okanagan-L (using Penticton meteorology).

Table 20. Primary and secondary station combinations used to assess the model sensitivity for computing evaporation using meteorological data along the 120 km length of Okanagan Lake. The indexes associated with Okanagan are used to designate the following L=lake, N=north, C=central, and S=south.

	Primary	Secondary	Mean (1996-06)
Okanagan-L	Penticton	Summerland	Penticton
Okanagan-N	Vernon	Kelowna	Vernon
Okanagan-C	Kelowna	Penticton	Kelowna
Okanagan-S	Summerland	Penticton	Summerland

Longterm-averaged (1996-2006) daily cumulative evaporation curves for all of the evaporation methods is shown in Fig. 27 (a) for Lake Okanagan-L, 27 (b) for Lake Okanagan-N, 27 (c) Lake Okanagan-C and 27 (d) for Lake Okanagan-S using primary, secondary and long-term mean assignments listed in Table 20.

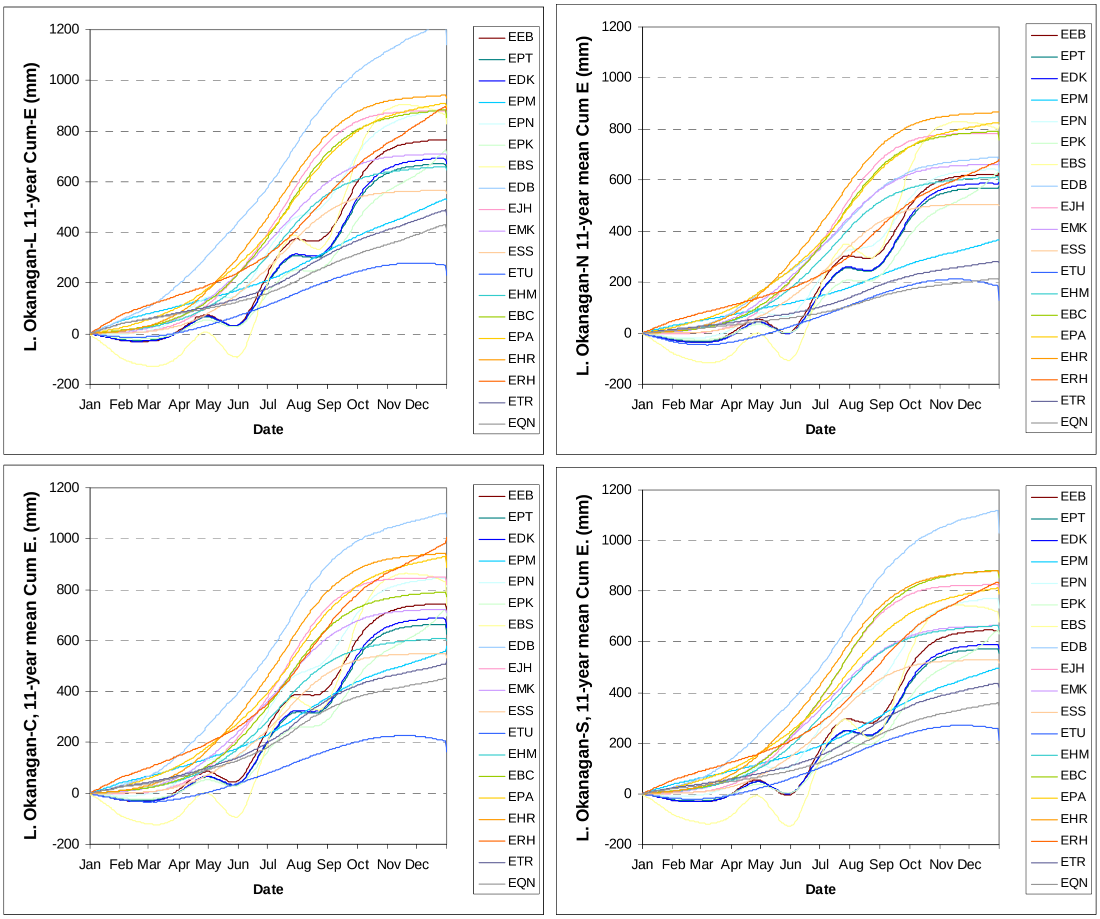


Figure 27. Comparison of longterm-averaged (1996-2006) cumulative daily evaporation curves for all evaporation methods for (a) Lake Okanagan-N, (b) Lake Okanagan-C, Lake Okanagan-S The curve ETR is used as the Reference evaporation curve.

A comparison between the 11-year averaged annual total evaporation for each of 4 the Okanagan runs is given in Table 21 for each of the 19 models. Figure 28 shows the difference in the estimated evaporation for each station combination compared to Okanagan-L.

Table 21. Comparison between 11-year averaged annual total evaporation (mm/yr) for Lake Okanagan using meteorological station assignments (Table …) as input data to 19 evaporation models. Okanagan-L is the evaporation based on the Penticton meteorological input data. Evaporation values of Okanagan-S, -C, and -N are used to test the sensitivity of the model output based on location on the input meteorological data.

	Model	Okan-L	Okan-S	Okan-C	Okan-N
1	**EEB**	759.5	646.7	737.8	617.2
2	**EPT**	668.4	571.7	661.8	566.3
3	**EDK**	689.5	588.3	684.9	584.2
4	**EPM**	531.6	496.6	558.0	364.2
5	**EPN**	884.6	772.4	844.6	640.4
6	**EPK**	728.0	651.0	726.8	633.1
7	**EBS**	745.5	627.9	730.9	702.2
8	**EDB**	1226.7	1117.8	1089.9	691.6
9	**EJH**	880.2	825.2	847.2	782.4
10	**EMK**	710.5	664.3	723.9	661.5
11	**ESS**	565.3	529.9	548.6	506.1
12	**ETU**	271.0	256.9	205.3	185.0
13	**EHM**	660.1	665.0	609.5	612.4
14	**EBC**	883.0	883.7	790.5	791.4
15	**EPA**	910.2	813.0	929.6	826.4
16	**EHR**	941.1	881.2	942.6	866.0
17	**ERH**	896.6	836.5	979.2	672.8
18	**ETR**	488.0	437.0	508.0	281.4
19	**EQN**	431.0	358.6	450.8	214.8

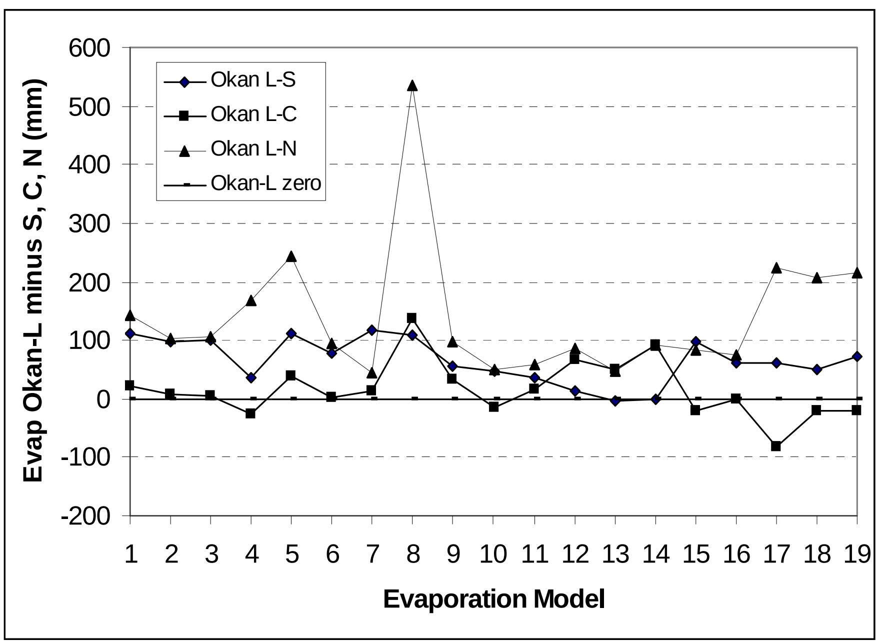


Figure 28. Illustration of the sensitivity of evaporation estimates computed for Okanagan Lake using meteorological station assignments (Table 20) for 19 models. Evaporation for each model represents the longterm-averaged (1996-2006) cumulative daily evaporation. The curves represent the magnitude of difference between Okanagan-L and Okanagan –N, -C, and –S for each model.

Figure 28 shows that in general, the evaporation computed using the southernmost meteorological station at Penticton as the primary meteorological data is higher than all of the other data assignments. On average, the difference Okanagan (L-S) indicates that Okanagan-L is 65.6 mm higher than Okanagan-S. In the case, Okanagan (L-C) the diference is +15.8 and the difference is +140.6 on average for Okanagan (L-N) due to the large change in model 8 (deBruin) and larger differences exhibited between the two runs for models 4 (EPM), 17 (ERH), 18 (ETR), 19 (EQN). This indicates that for a long lake such as Okanagan Lake, selection of the meteorological station data location can have a significant impact on the estimated lake evaporation. This is probably a lesser concern for the smaller lakes.

To account for the sensitivity in the evaporation estimates particularly for Okanagan Lake, computed daily evaporation from each meteorological station for Okanagan Lake have been forwarded to the ESSA Database, Consequently, the individual estimates can be averaged in various combinations for hydrological scenario testing.

10. Recommended Evaporation Approach for the Okanagan Basin Lakes

The Terms of Reference for this study has required selection of a model(s) or other technique(s) from which evaporation from the basin lakes can be approximated. Database limitations are much greater for determination of evaporation from basin lakes which precludes application of such techniques as the energy budget or combination approaches. Further, the above analysis indicates that many of the empirical relationships that have less input data demands may also require further research to verify that coefficients are applicable in the Okanagan basin. The mass transfer approach requires wind speed and data from which to determine the vapour pressure difference. These required data are not available outside the domain of Okanagan Lake and the mainstem lakes. Since a 500 x 500m grid has been established over the Okanagan Basin containing precipitation and air temperature data, we have explored the possibility of applying a regression approach using air temperature as a predictand for approximating evaporation from the basin lakes.

10.1 Lake Evaporation and Air Temperature

Examples of the annual cycle for long-term 11-year air temperature and computed evaporation are shown in Fig. 29 for Okanagan, Kalamalka, and Osoyoos Lakes. In a study of evaporation for Mirror Lake (Rosenberry *et al*., 2007), a regression between lake evaporation and air temperature was derived. Testing of the regression approach for that lake indicated that it was a viable alternative for computing evaporation in the absence of other approaches. The main advantage of such an approach is that it requires only air temperature. In the case of the Okanagan Basin, such data are available over the climate grid.

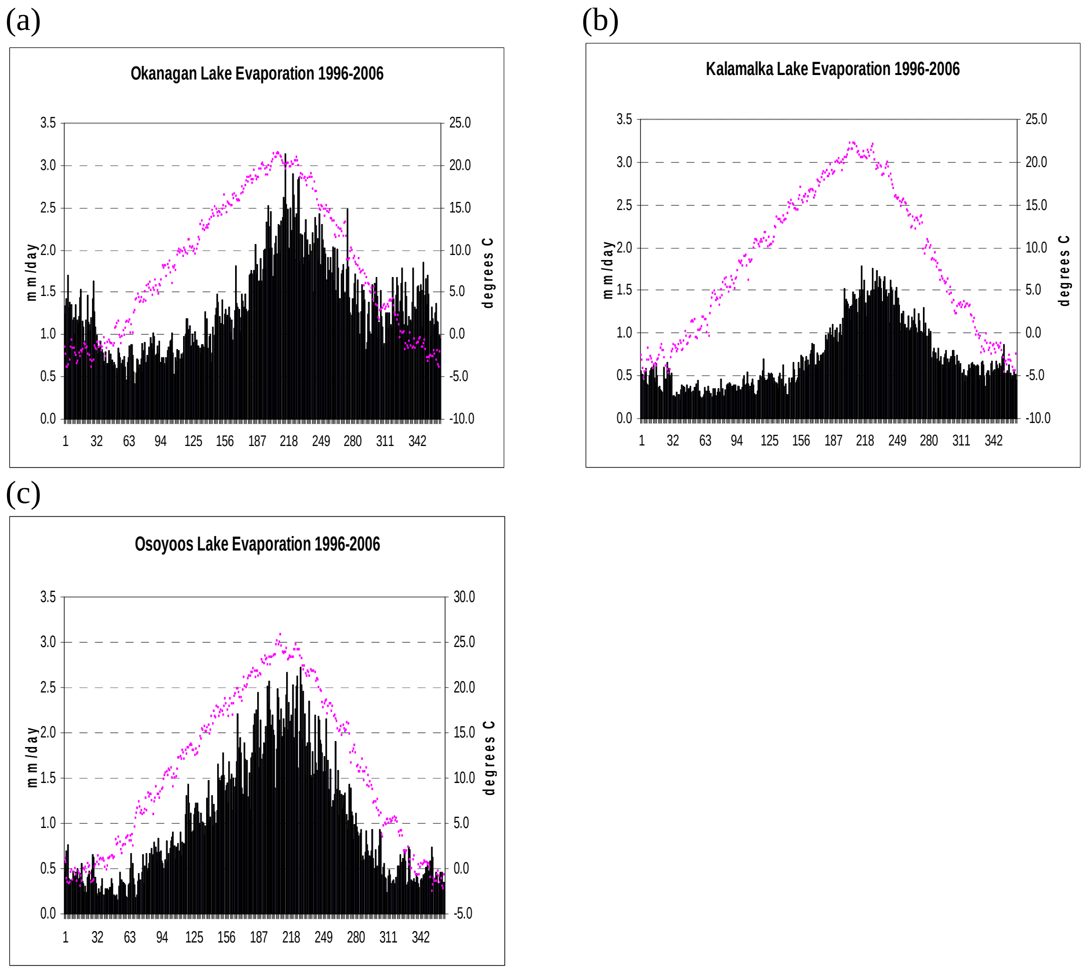


Figure 29. Examples showing a comparison between longterm (11-yr mean) evaporation from ETR models and air temperature from different meteorological stations (a) Okanagan-L Evaporation and Kelowna air temperature, (b) Kalamalka Lake Evaporation and Vernon air temperature, (c) Osoyoos Lake evaporation and Osoyoos air temperature..

10.2 Regression Between Lake Evaporation and Air Temperature

Figures 30a-e, show 2nd order polynomial regressions between longterm (11-year) mean evaporation versus air temperature. As indicated in the scattergrams, the relationship between evaporation and air temperature is quite good. For Okanagan Lake, the correlation coefficient is $r = 0.73$; Kalamalka Lake $r = 0.80$; Wood Lake $r = 0.90$; Skaha Lake $r = 0.74$; and Osoyoos/Vaseux Lakes $r = 0.95$.

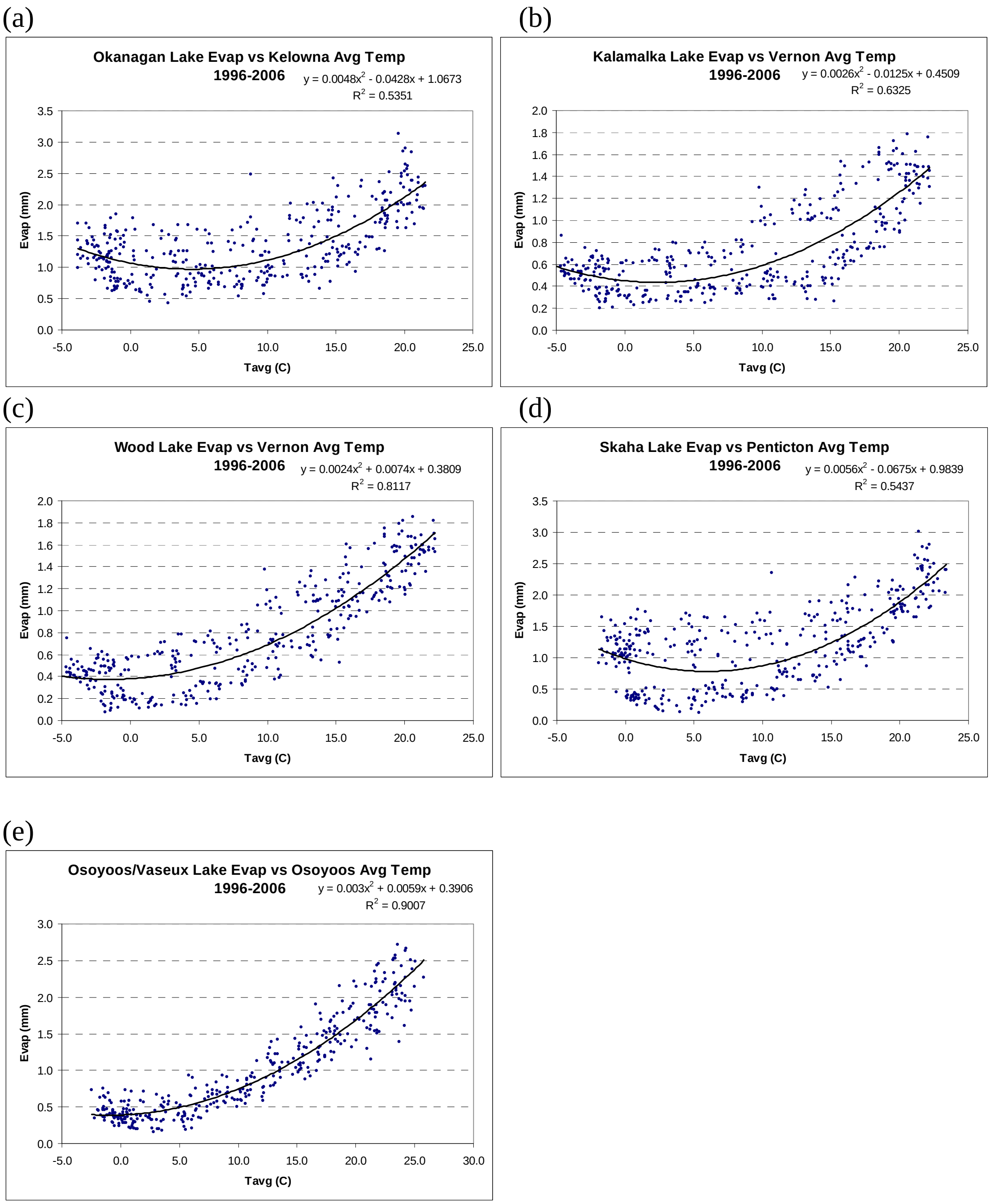


Figure 30. Scattergrams showing the relationship between 11-year means of evaporation (ETR: Trivett 1984) and air temperature for Okanagan Lake and mainstem lakes. Curves represent 2nd order polynomials.

10.3 Generalization of the Regression Curves

Figure 31 shows a comparison between the 2nd order polynomial curves from the longterm mean evaporation and air temperature for each of the lakes determined in Fig. 30. In general the shape of the curves is similar for all lakes showing lowest evaporation occurring in the air temperature range 0 to 10 ^{o}C and increasing evaporation in conditions of higher air temperatures.

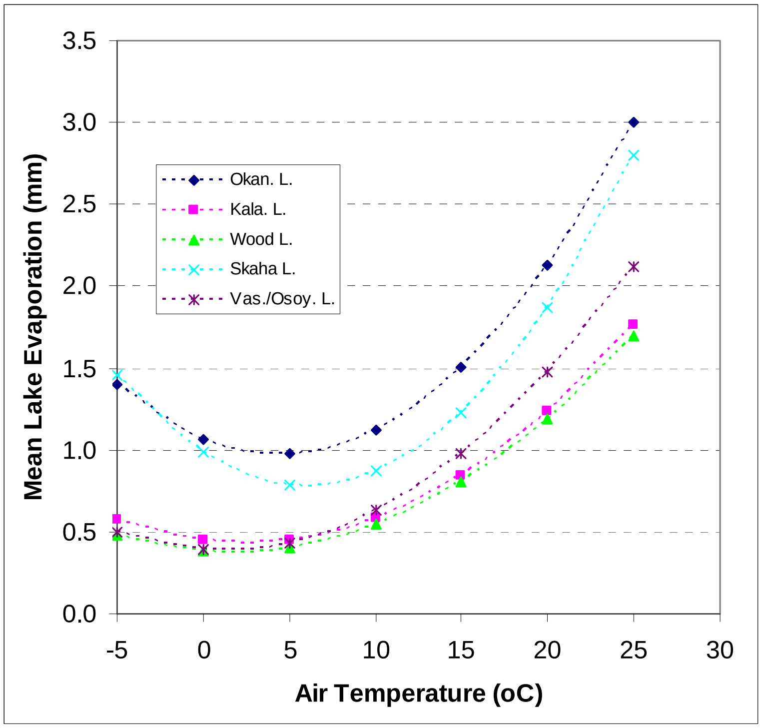


Figure 31. Composite of the 2nd order regression curves relating long-term mean (1996-2006) computed lake evaporation (ETR model, Trivett mass transfer) and station air temperature for each Okanagan lake.

In low air temperature ranges of -5 to 0 ^{o}C, the 2nd order polynomials suggest either low or decreasing evaporation, however, the shape of the curves in this range of air temperature may be an artifact of the regression analysis. Okanagan Lake generally does not have a significant ice cover and evaporation may still be expected at a low rate during the winter conditions. Skaha Lake is downstream of Okanagan Lake and it may respond similarly to Okanagan Lake. Other lakes in the system experience ice cover during winter. The effect of ice is to decouple the lake surface from the atmosphere and consequently in the presence of a complete ice cover, evaporation from the lake does not occur. As such, application of the polynomial relations for approximation of lake evaporation should be constrained at times when air temperature is < 0^{o}C in the presence of ice. In the case of Okanagan Lake and Skaha Lake with no ice cover, evaporation should be arbitrarily set at a low value such as indicated at 0^{o}C. In the case of lakes with ice cover at temperatures < 0 ^{o}C, the evaporation rate should be arbitrarily set to zero. Future research is required on these lakes to verify these assumptions.

10.4 Recommended Evaporation Formula for Okanagan Basin Lakes

Figure 32 shows a further generalization of the regressions of Fig. 31 by combining results for Okanagan Lake and Skaha Lake, by combining results for Kalamalka, Wood, Vaseux and Osoyoos Lake, and by deriving the average curve based on all lakes.

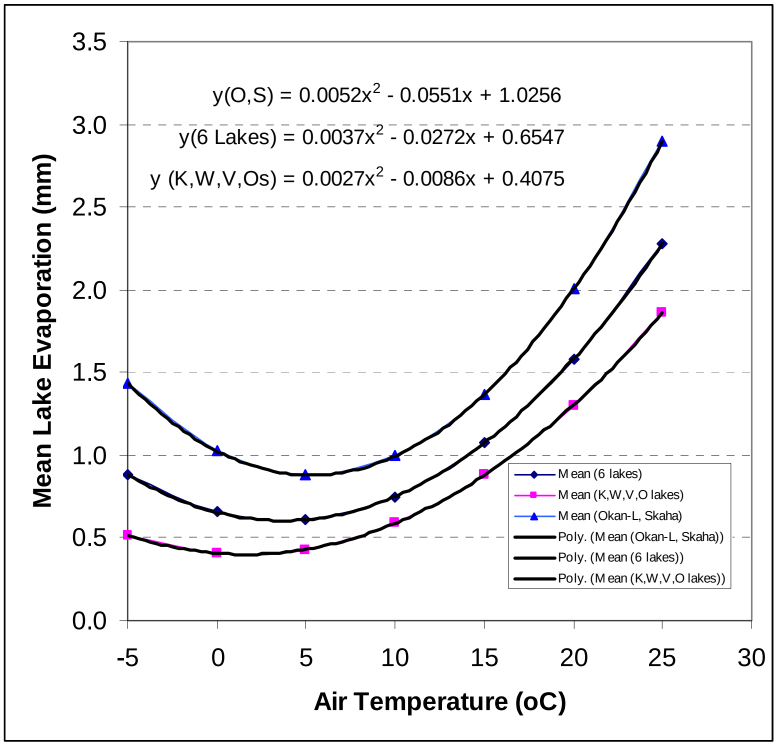


Figure 32. Generalized regression curves between computed lake evaporation (ETR model) and station air temperature based on 11-year means. Curve (diamonds) represents the average between Okanagan and Skaha Lake. Curve (squares) represents the average between Kalamalka, Wood Vaseux and Osoyoos Lakes. Curve (circle) represents the average of all 6 lakes.

Essentially this procedure yields a family of curves ranging from large lakes (Okanagan Lake) to the smaller lake sizes. Lakes located in the Basin are predominantly "smaller" size lakes (e.g. see Fig. 1). It is assumed here that the lake evaporation response for the Okanagan Basin smaller size lakes would be similar to the response computed for the ensemble averaged curve representing lakes such as Kalamalka, Wood, Vaseux and Osoyoos (Fig. 32).

Since the Basin lakes are likely to be "small" lakes, it is reasonable to assume that the regression curve built on the longterm ETR results for (Kalamalka + Wood + Vaseux + Osoyoos) would be applicable for computing a "first approximation" of the lake evaporation over the basin lakes ($E_{(BL)}$) as a function of air temperature (T_a), equation:

$$E_{(BL)} = 0.0027(T_a^2) - 0.0086(T_a) + 0.4075$$

Since the basin lakes can be represented by GIS, an inventory of the lake size distribution over the basin 500m x 500m grid can be established. Based on air temperature determined as the mean over the grid, the evaporation from each lake or aggregate average over each grid can be easily computed based on equation ($E_{(BL)}$).

There are a number of important advantages in applying the evaporation regression results to the Okanagan Basin lakes based on its existing database:

- the regression equation is not a data intensive procedure and can easily utilize the current air temperature data that has been developed over the 500km x 500km basin climate grid.
- the regression results indicate that for the small lakes, R^2 values range from 0.63 – 0.90 and the correlation coefficient ranges from r ~ 0.79 - 0.95 implying that there is an acceptable relationship between computed evaporation and associated air temperatures.
- the regression formulation can be applied over a given number of years from current climate (1996-2007)
- the regression formulation can be extended to year 2100 based on a given climate scenario(s).
- since $E_{(BL)}$ is based on long-term evaporation results from the Trivett (1984) model (ETR), the computed basin evaporation will have correspondence to the evaporation computed for Okanagan Lake and the mainstem lakes.

Since the regression approach is not a physically-based procedure, it is subject to limitations which are common among empirical methods. For example, it is expected that there would be some limitations in applying the relationship outside the data ranges used to construct the relationship. This problem is reduced somewhat since it is based on longterm (11-year) data.

11. Error Estimates and ESSA Database

11.1 Gross Error Estimates

Each component of the basin hydrology is requested to provide an error estimate and data error range based on the template in Table 25. The earlier investigation conducted by Trivett (1984) provided very detailed information and discussion on the characteristics between some of the critical meteorological data and general lack of representativeness to over lake conditions. This concern was also echoed in this study. For example, a comparison between the wind speed at Kelowna Airport required to be increased by 64% to be comparable to winds measured at the Kelowna Bridge location. This is a very significant difference. There is also evidence from past research to indicate that there are differences between Penticton Airport and Marina wind speeds. This investigation also draws caution to the use of the “existing” meteorological database which may not be representative of the over-lake conditions. Proper input data, or data that has been properly adjusted to over-lake conditions is required or there is a very great risk in high error in computations which are temperature and wind dependent. The lack of over-lake data precludes direct quantification of the representativeness and associated errors that exist between the land station and over-lake conditions.

Additional error was introduced into this study with respect to the limnological variables. For example, many of the formulas require information on the water surface temperature and the lake heat storage change. There were no lake-wide measurements from which to derive these values for the 1996-2006 period. These values were approximated from the Hyatt Logistical Model which was originally developed for Lake Okanagan but was extended over the other lakes in a preliminary effort to provide values of this critical variable as a function of 10-day mean air temperature. The daily heat storage change for every day in 1996-2006 was computed based on heat content curves constructed from limited temperature data in 1971. With no alternative, these curves were extended over the 1996-2006 period for all lakes. Higher or lower water levels combined with differences in solar income or hydrological flow-through in any particular year may differ from the 1971 values, however, this could not be evaluated.

Incoming solar radiation and longwave radiation was not measured, but approximated using first order methods. Cloudiness characteristics were approximated based on Penticton observations.

Table 22. Table of gross error estimates and data error ranges.

Data source:

Category	Value
Entirely from measurements at the node	a
Combination of measurements at the node and modelling	b
Modelled, based on other areas of the Okanagan Basin	c
Modelled, but with limited or questionable data	d
Expert judgment	e

Data error range:

Approximate value of the standard error	Value
< = 10%	1
>10% - 25%	2
>25% - 50%	3
>50% - 100%	4
>100%	5

each is a measure of data quality

With reference to Table 25 and based on our concerns of then lake-representativeness of the "existing" database, we suggest that the **"Lake Evaporation was Modeled with Limited or Questionable Data (Value = d)"**

We suggest that, "**Approximate Range of the Standard Error of the lake evaporation may be in the order (> 25% - 50%)".** Lower error is likely from the mass transfer formulations and for selected models from the groups of approaches based on comparison between 1971 evaporation totals and the current mass transfer totals (E ~ 350-450 mm/year). However, some models compute evaporation significantly higher than this range.

The large differences observed in the model groups may be more a function of the input data than the model structure. An intensive future study on these lakes would be required to resolve this issue.

11.2 Computer-based Files for ESSA's Okanagan Water Database for WUAM

This investigation has generated a large number of data files which may be of interest to the ESSA Okanagan Water Database. These data include the following:

11.2.1 Input data files: Input data files created include the following:

- Daily-averaged Meteorology (1996-2006) from Vernon, Kelowna, Penticton, Summerland and Osoyoos
- Computed surface temperature for 6 lakes based on the Hyatt Logistical model
- Interpolated heat content curves for each of 6 lakes based on 1971 limnological research (Blanton and Ng, 1971, 1972)

11.2.2 Output Data Files Generated: Output data files included the following:

- Daily radiation budget component output for each lake (MJ m^{-2} d^{-1})
- Daily lake evaporation for each of 6 lakes (mm/d) from 19 models

11.2.3 Files to be Transferred to ESSA's Okanagan Water Database: Based on the Terms of Reference the following data files are to be uploaded to ESSA's Okanagan Water database:

- Daily lake evaporation from the recommended evaporation model (Trivett 1984 mass transfer model) for Okanagan Lake and mainstem lakes for the period 1996-2006.
- Results of the Sensitivity Analysis providing a range of evaporation estimates from Okanagan-N, Okanagan-C and Okanagan-S. These data will provide options for combination of stations for evaporation estimates on Okanagan Lake under various scenarios.

12. Recommendations for Enhancing Observations and for Future Investigations

Lake evaporation is a critical component in the overall hydrology of the Okanagan Basin. As shown in this analysis, it is extremely difficult to make decisions as to the “optimal” evaporation model to apply to the 6 largest Okanagan lakes or to the other lakes within the basin. The major difficulty stems from limitations in the historical meteorological / radiation database which is not representative of the over-lake condition (Trivett, 1984) , and the paucity of lake observations from which to determine key components such as water surface temperature, radiative fluxes, and heat content which are required in the BREB and combination methodologies.

The lake evaporation issue has not been resolved since the initial research studies conducted in the 1970’s. Future research is required in order to conclusively determine the magnitude and seasonal distribution of the lake evaporation component of the six Okanagan lakes (Lakes Kalamalka, Wood, Okanagan, Skaha, Vaseux and Osoyoos).

12.1 Strengthening Existing Lake Databases

A major difficulty in the determination of evaporation from Okanagan Lake and Mainstem lakes in previous and current investigations is the lack of over-lake meteorological and limnological data required for all of the methods considered. In the short term, the following recommendations are suggested:

12.1.1 Meteorology: Standard meteorological observations including a minimum of air temperature, relative humidity, and wind speed and direction should be established at nearshore lake-representative locations for all lakes. Since Okanagan Lake is 120 km in length and it has been shown that there are considerable differences in the conditions along the north – south distance, it is recommended that 3 lake-representative locations be established for this lake.

12.1.2 Radiation Fluxes: Many methods for computing evaporation require solar radiation directly or net radiation. Net radiation observations related to lake studies are difficult to establish since they require over-water platforms. Alternatively, solar radiation can be easily measured. At minimum, two sites should be established, e.g. Summerland and at Vernon. Historical observations at Summerland should be processed in order to extend the database back in time. Solar radiation can also be computed, however, cloudiness is required.

12.1.3 Limnological Observations: Surface water temperature is a fundamental variable and is required in nearly all lake evaporation approaches. Two methods are possible for consideration in establishing a surface temperature database. In one approach, a time-series of near surface temperature (and temperature profile) can be derived through continuous observations from suitable lake platforms or single-point moorings. Instrumentation such as Stowaway Tidbit loggers are inexpensive and can provide an accuracy of ± 0.2 ^{o}C which is sufficient for most climatological-type investigations.

12.2 Development of an Intensive Lake Observation and Modelling Study:

If the objective is to determine the magnitude of the evaporation from the 6 main lakes and to recommend the "optimal" evaporation formulations that can be applied to each of the lakes (and Basin) then an intensive Lake Observation Investigation is required. As shown in this and previous investigations, there is a lack of over-lake observations in the Okanagan lakes. An intensive research program would involve the following minimal components:

- ***3 Meteorological Buoys*** strategically located along the length of Lake Okanagan. The buoy platform should include standard meteorology such as air temperature, wind speed and direction, relative humidity, atmospheric pressure. Two meteorological buoys should include observations of both solar and longwave radiation. This configuration would allow redundancy to avoid catastrophic failure of the instrument systems.
- ***Shoreline Meteorological Towers*** are required to support intensive computations from a range of evaporation formulae as used in this investigation
- ***8 Temperature Moorings*** are required in order to provide data on the surface water temperature and to derive heat storage of the lakes. There should be 3 temperature moorings associated with the meteorological buoy locations on Lake Okanagan. Each of the remaining 6 lakes should have at least one temperature mooring (e.g. Schertzer and Murthy, 1994).
- ***Hydrodynamic Observations*** such as currents (acoustic Doppler current meters) at the locations of the meteorological buoys would be advantageous since these measurements could support the development and verification of 3-dimensional hydrodynamic / thermal models of Lake Okanagan. Meteorological and limnological observations associated with the remaining 5 lakes can be used to drive 1-dimensional temperature models such as MYLAKE or DYRESM.
- ***Lake Surveys*** should be conducted at periodic intervals (e.g. monthly to take supporting observations such as light transmission.

12.2.1 Multi-Year Investigation: Multi-year investigation of the meteorological, radiation and limnological variables is recommended in order to derive annual cycles and to understand the variability in the over-lake components. The magnitude of the over-lake variables and seasonal patterns of the variables will likely be different than associated land-based stations removed from the lake. This needs to be quantified.

12.2.2 Development of Lake-Land Transformations: Multi-year intensive lake observations are required for the development of lake-land transformations. Development of lake-land transformations for key variables is essential when intensive lake observations are not available. Currently, the representativeness of the land-based meteorological data for over-lake applications (evaporation computations) has not been quantified and needs to be done. The intent here would be to have techniques available for utilizing the historical data from the primary land-based meteorological stations which require adjustment for over-lake computations.

12.2.3 Periodic Lake Sampling Plan: The hydrology of the Okanagan lakes (including evaporation) is an important consideration in the Basin hydrologic budget. Periodic observations of important lake variables should be done on the Okanagan lakes to support longer-term assessments of the lake hydrology.

12.2.4 Climate Change Impacts Assessments: The hydrology and evaporation of the Okanagan basin and lakes may be sensitive to climate variability and change - which needs to be evaluated. Assessments of impacts requires a combination of reliable time-series observations which can be assessed to understand the current variability of key variables and interannual variability of fluxes, thermal structure, (e.g. Schertzer and Croley 1997; 1999; Schertzer and Sawchuk, 1990), and aquatic ecosystem components (e.g. Lam and Schertzer, 1999). The database is also important for verification of and selection of appropriate models to apply in climate impacts analyses.

13. Concluding Remarks

This investigation provides an assessment of the capability to compute evaporation from Okanagan Lake, other mainstem lakes and Basin lakes with the proviso of using the existing database of meteorological, radiation and limnological observations over the 1996-2006 period. The greatest challenge in this analysis was related to the limitations imposed by the existing database. Analyses conducted by Trivett (1984) identified that land-based meteorological observations at the primary meteorological stations were not representative of over-lake conditions. Recommendations for database improvements made in that study were largely not implemented. Consequently, nearly 25 years later, the current analysis required computation and numerous assumptions to provide required meteorological, radiation and limnological inputs from which to assess model performance.

A total of 19 lake evaporation models were selected representative of 6 Groups which ranged from more physically based and data intensive techniques to various levels of empirical formulations. The mass transfer formulation of Trivett (1984) was selected as a “Reference” evaporation in the absence of more direct methods such as from the eddy correlation approach. The Trivett (1984) mass transfer formulation was developed from eddy correlation observations conducted in 1980-1981. The performance of the selected evaporation models was compared to the selected “Reference” evaporation for all years and for all lakes.

Models of the Energy Budget and Combination Group were not recommended for application to Okanagan Lake or the other mainstem lakes because the existing database could not support determination of dominant components such as the heat storage change or the net radiative exchange. Empirical approaches were less demanding in terms of data requirements, however, correspondence with the “Reference” evaporation was generally poor and this was likely related to empirical coefficients not tuned to the Okanagan lakes. Several models compared reasonably well with the “Reference” evaporation (within +/- 20%) using the existing database (e.g. the Penman-Monteith Combination Model, the Stephens-Stewart Radiation-Temperature type model and the Quinn Mass Transfer approach with a variable transfer coefficient). However, the Penman-Monteith model is a data intensive approach and the Stephens-Stewart method only appeared to apply to the Okanagan Lake existing database. The Quinn mass transfer approach may be a viable alternative to the “Reference” evaporation (ETR model). Based on the assessments in comparison to the “Reference” evaporation, it was concluded that only the Trivett (1984) model could be recommended for application to Okanagan Lake and the mainstem lakes at the present time. A strong justification for recommending this model is provided considering that, (a) the derived mass transfer coefficient (M = 0.024) is very similar to that determined in other lakes of various sizes which implies that it is robust and not climate dependant and fully applicable to the Okanagan lakes, (b) it is the only method that is based on near-lake data from Okanagan Lake, and (c) it is derived from eddy covariance observations considered a direct evaporation method. It is noted that the evaporation results for the 120 km long Okanagan Lake is sensitive to the selected meteorological station data for evaporation computations. Future research with lake-representative data is required in order to fully test the suite of models to determine whether use of appropriate data will result in a convergence of evaporation estimates.

Determination of evaporation for the Basin lakes was equally challenging since there was no meteorological, radiation or limnological database available for applying any of the selected 19 lake evaporation models. An existing 500 km x 500 km grid database constructed for the Okanagan basin contained only precipitation and air temperature. It was determined that there was a correspondence between long-term lake evaporation and air temperature. Consequently, a family of curves was derived to describe lake evaporation as a function of air temperature. A 2nd order polynomial formula based on “small” lakes was recommended as a possible method to approximate evaporation from the Basin lakes using the minimal database.

Because of database limitations, the lake evaporation computations and recommendations for applicable lake evaporation formulae in the current analysis can only be considered preliminary. With respect to the requirement to provide a gross error estimate for the ESSA Database, we note that the lake evaporation was modeled with limited or questionable data (i.e. whether the land-based data are lake-representative). We suggest that the approximate range of the standard error of the lake evaporation estimates may be in the order > 25% - 50%.

For investigation of lake processes such as evaporation, the existing database must be enhanced to include meteorology at lake-representative locations, solar (and longwave) observations at least at one site, and lake temperature either from a dedicated temperature mooring or through periodic lake sampling of temperature profiles (see text). Determination of the magnitude and phase of evaporation from Okanagan Lake and the mainstem lakes can only be done with the implementation of an intensive field investigation as outlined in this report. Such a study would allow development of land to lake transfer functions for critical meteorological variables, provide critical measurements relating to the energy terms in many approaches and provide accurate observations for determinatio9n of the lake heat storage. It would allow a detailed analysis of the performance of all of the selected lake evaporation models and recommendation of the optimum model(s) for these lakes.

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