Appendix F1

EVAPORATION SUMMARY REPORT

F1.0 EVAPORATION FROM OKANAGAN LAKES

F1.1 INTRODUCTION AND OBJECTIVES

Evaporation from lakes in the Okanagan Basin, particularly from the large lakes lying in a north-south orientation in the main valley bottom (Figure F1.1) is a potentially significant component of the water balance of each lake. However, little previous research as been done to quantify the amount of water lost to the atmosphere through evaporation from these lakes. As part of the Canada-British Columbia Okanagan Basin Agreement (C-BCOBA, 1974), a comprehensive program was initiated during April – October 1971 to provide data on each lake's trophic status and study the physical factors which affect lake chemistry and biota. In that study, mean monthly evaporation values were derived for Okanagan Lake based on corrected pan evaporation from the Summerland climate station (C-BCOBA, 1974). The Summerland data was modified for elevation and latitude for application over the Okanagan Basin. However, ten years later, using eddy correlation observations from Penticton, Trivett (1984) concluded that Okanagan Lake evaporation had been significantly overestimated in the 1974 study. Since the 1984 Trivett study, little work has been done to resolve the difference between the 1974 and the 1984 studies.

Therefore the Working Group requested that Environment Canada undertake a study of lake evaporation, with a particular focus on resolving the differences between these two studies. Environment Canada made maximum use of the existing database to make calculations of lake evaporation for each main lake using 19 potentially relevant models. They were asked to recommend a model (or suite of models) that was most suitable for estimating lake evaporation. The Working Group also requested that Environment Canada recommend a method for estimating evaporation from the upland reservoirs in the Basin.

Specific objectives were as follows:

- Evaluate the existing database for use with evaporation calculations;
- Consider a range of lake evaporation models for possible application to the Okanagan Basin;

- Compute evaporation for the 6 mainstem lakes using existing meteorological, radiation and limnological data over the period 1996-2006;
- Evaluate the performance of selected lake evaporation models through daily, annual and long-term means;
- Outline the limitations of evaporation calculations based on the existing database with respect to data availability and reliability;
- Recommend an optimum model or combination of models to calculate mainstem lake evaporation;
- Recommend a model for computing lake evaporation from the upland lakes and reservoirs;
- Identify the data requirements for the models and suggest enhancements to the existing database;
- Suggest a plan for future intensive investigation of lake evaporation; and
- Evaluate the uncertainty in the computed evaporation estimates and assign Data Error estimates.

This Section of the report provides a brief summary of the work undertaken by Environment Canada in pursuit of these objectives. The full report from Environment Canada is reproduced in Appendix F2.

F1.2 CHARACTERISTICS OF THE VALLEY BOTTOM LAKES

Figure F1.1 shows the locations of the major valley bottom lakes and the locations of the meteorological stations that provide data for calculating lake evaporation. Table F1.1 lists the main physical characteristics of the main valley bottom lakes. Okanagan Lake is the largest of these lakes; it is approximately 120 km long and ranges from 1.5 to 5 km wide.

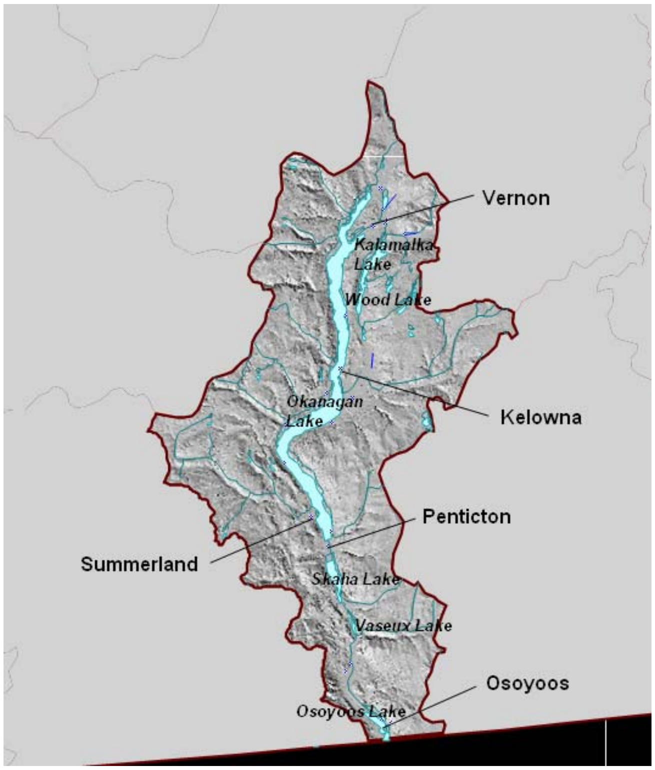


Figure F1.1 Okanagan Basin and location of the 6 main lakes and primary meteorological stations providing data for calculating lake evaporation

Table F1.1 Physical characteristics of the six mainstem lakes

	Kalamalka	**Wood**	**Okanagan**	**Skaha**	**Vaseux**	**Osoyoos**
Surface Area ($x10^6$ m^2)	25.9	9.3	348.0	20.1	2.75	15.0
Volume ($x10^6$ m^3)	1,520	200	26,200	558	17.7	254
Mean depth (m)	59	22	76	26	6.5	15
Maximum depth (m)	142	34	242	57	27.0	63
Water Residence time (yr)	65	30	60	1.2	0.03	0.7

F1.3 LAKE EVAPORATION MODELS

Environment Canada identified 19 potentially relevant models that could be used to estimate evaporation from the major valley bottom lakes in the Okanagan Basin.

These models can be grouped into six categories, as follows:

- Bowen-Ratio Energy Budget models;
- Combination models;
- Solar Radiation – Temperature models;
- Temperature – daylength models;
- Temperature models; and
- Mass Transfer models.

Environment Canada investigated 19 individual models within these six groups – details on these 19 models are provided in Appendix F2. Table 2 of Appendix F2 lists, for each of these 19 models, the central principle of evaporation and the data requirements of the model.

F1.4 CLIMATOLOGICAL AND LIMNOLOGICAL DATABASES

Application of these 19 models required data from a variety of sources. Meteorological data from five stations were used in this study: Penticton Airport, Kelowna Airport, and Summerland, Osoyoos and Vernon Climate Stations (Figure F1.1). As shown in Table F1.2, air temperature was available at each of the stations for the period examined (1996 – 2006). However, data for other variables useful for computing evaporation was less available.

This study applied evaporation models that utilize the available meteorological records. The accuracy of model-estimated evaporation depends on three key factors:

- how representative the meteorological and limnological data are to over-lake conditions;
- the assumptions used to apply the data; and
- the quality and completeness of the meteorological records.

For example, for Okanagan Lake, there is no single climate station that represents conditions along the entire 120 km length. Ideally, data would be available from several lake-representative stations, however often only one particular site provides the required suite of measurements. This one site may not be representative of conditions everywhere along the lake. The other mainstem lakes are small relative to Okanagan Lake, so typically measurements are used from the climate station closest to that particular lake. For Okanagan Lake, Penticton meteorological station was chosen.

As the data records for meteorological stations are not complete for all the required input variables (Table F1.2), a procedure was adopted of designating a Primary station and a Secondary station. If a value was still missing, then a long-term mean value from a selected meteorological station was applied. The stations assigned for Primary, Secondary and Mean meteorological data are listed in Table F1.3.

Table F1.2 Completeness of daily meteorological records at the five climate stations

	Penticton A CS	**Kelowna A CS**	**Summerland CS**	**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%

Table F1.3 Listing of stations for primary, secondary and mean meteorological data used to calculate evaporation from each mainstem lake

Lake	Primary	Secondary	Mean (1996-2006)
Kalamalka	Vernon	Kelowna	Vernon
Wood	Vernon	Kelowna	Vernon
Okanagan-Lake	Penticton	Summerland	Penticton
Okanagan-North	Vernon	Kelowna	Vernon
Okanagan-Central	Kelowna	Penticton	Kelowna
Okanagan-South	Summerland	Penticton	Summerland
Skaha	Penticton	Osoyoos	Penticton
Vaseux	Osoyoos	Penticton	Osoyoos
Osoyoos	Osoyoos	Penticton	Osoyoos

Notwithstanding these limitations in the meteorological data from the land-based stations, this study's most severe limitations were:

- the lack of air temperature, humidity and wind data relevant to conditions in the lower atmosphere directly above each lake; and
- the lack of radiative flux values, water temperature, lake heat content, and advected heat.

Accordingly, the following assumptions were invoked to calculate lake evaporation:

- some required variables, not available at all stations, could be supplied from other stations with measured values;
- data missing from a primary station's records could be replaced with data from a nearby secondary site;
- missing data from both primary and secondary meteorological stations could be replaced by long-term mean values (1996-2006);
- water surface temperature could be approximated using the Hyatt Logistical model extended to all lakes;
- heat content derived from limited 1971 data could be spline-interpolated and extended to all years (1996-2006) and the derived change in heat storage would be valid;

- Bowen Ratios computed from non-over-lake data and water temperature assumptions are valid; and
- as no data were available to test computed solar and longwave radiation fluxes, it is assumed that the computed radiation values are applicable to all the mainstem lakes.

These estimation procedures are outlined in Appendix F2. Based on the length of the list of assumptions needed to calculate evaporation, confidence in the results is significantly limited.

F1.5 ANNUAL EVAPORATION RESULTS

Table F1.4 provides a summary of the mean annual evaporation (mm/yr) from the 6 mainstem lakes over the period 1996-2006, based on the 19 evaporation models. The results indicate a wide range in the estimates for each lake. For Okanagan Lake, the estimates range from 271 mm to 1227 mm.

Table F1.4 also provides data on the annul volume of water evaporated from each lake. Each mainstem lake has different physical properties such as surface area, depth and volume (Table F1.1) which affect lake heat storage and the effective surface area available for evaporation. This data is graphically represented in Figure F1.2 for the 5 smaller lakes and in Figure F1.3 for Lake Okanagan. A significantly greater annual volume of water is evaporated from Okanagan Lake than from any of the other mainstem lakes.

Table F1.4 Summary of the mean annual evaporation rates (mm/year) and total evaporation (x 10^6 m^3/year) from the 6 mainstem lakes for the period 1996-2006 based on the 19 evaporation models

Group and Model	**Model Abbr.**	**Kalamalka**		**Wood**		**Okanagan**		**Skaha**		**Vaseux**		**Osoyoos**	
		Evap[1]	**Vol[1]**	**Evap**	**Vol**	**Evap**	**Vol**	**Evap**	**Vol**	**Evap**	**Vol**	**Evap**	**Vol**
Energy Budget													
Bowen Ratio	**EEB**	657.4	**17.03**	616.8	**5.74**	759.5	**264.30**	746.7	**15.01**	923.0	**2.54**	861.8	**12.93**
Combination													
Priestly-Taylor	**EPT**	632.2	**16.37**	612.7	**5.70**	668.4	**232.61**	729.5	**14.66**	818.9	**2.25**	782.7	**11.74**
deBruin-Keijman	**EDK**	647.4	**16.77**	627.5	**5.84**	689.5	**239.96**	751.6	**15.11**	834.4	**2.30**	801.9	**12.03**
Penman-Monteith	**EPM**	338.4	**8.76**	352.1	**3.28**	531.6	**185.01**	472.1	**9.49**	399.9	**1.10**	399.9	**6.00**
Penman	**EPN**	692.6	**17.94**	677.1	**6.30**	884.6	**307.83**	934.2	**18.78**	942.9	**2.59**	914.1	**13.71**
Penman Kimberly	**EPK**	688.6	**17.83**	657.8	**6.12**	728.0	**253.33**	765.9	**15.40**	793.1	**2.18**	764.3	**11.46**
Brutsaert-Striker	**EBS**	899.4	**23.29**	877.2	**8.16**	745.5	**259.43**	1023.6	**20.57**	1177.7	**3.24**	1150.6	**17.26**
deBruin	**EDB**	691.6	**17.91**	691.6	**6.43**	1226.7	**426.91**	1230.9	**24.74**	1046.1	**2.88**	1046.1	**15.69**
Solar Radiation – Temperature													
Jensen-Haise	**EJH**	782.4	**20.26**	782.6	**7.28**	880.2	**306.30**	883.7	**17.76**	971.8	**2.67**	971.8	**14.58**
Makkink	**EMK**	661.5	**17.13**	661.5	**6.15**	710.5	**247.24**	713.0	**14.33**	754.9	**2.08**	754.9	**11.32**
Stephens-Stewart	**ESS**	506.1	**13.11**	506.2	**4.71**	565.3	**196.73**	567.7	**11.41**	620.6	**1.71**	620.6	**9.31**
Turc	**ETU**	185.0	**4.79**	186.3	**1.73**	271.0	**94.31**	271.2	**5.45**	280.9	**0.77**	280.9	**4.21**
Temperature – Day length										*			
Hamon	**EHM**	612.4	**15.86**	612.4	**5.70**	660.1	**229.73**	657.6	**13.22**	706.3	**1.94**	706.3	**10.59**
Blaney-Criddle	**EBC**	791.4	**20.50**	791.5	**7.36**	883.0	**307.29**	881.5	**17.72**	956.6	**2.63**	956.6	**14.35**
Temperature													
Papadakis	**EPA**	826.4	**21.40**	826.1	**7.68**	910.2	**316.74**	910.4	**18.30**	1030.6	**2.83**	1030.6	**15.46**
Hargreaves-Samani	**HER**	866.0	**22.43**	865.9	**8.05**	941.1	**327.50**	945.8	**19.01**	1009.7	**2.78**	1009.7	**15.15**
Mass Transfer													
Ryan-Harleman	**ERH**	623.1	**16.14**	682.0	**6.34**	896.6	**312.01**	794.2	**15.96**	747.2	**2.05**	747.2	**11.21**
Trivett	**ETR**	261.8	**6.78**	282.7	**2.63**	488.0	**169.81**	439.0	**8.82**	368.9	**1.01**	368.9	**5.53**
Quinn	**EQN**	199.6	**5.17**	215.4	**2.00**	431.0	**149.98**	386.8	**7.78**	296.4	**0.81**	296.4	**4.45**

Evap[1]: Evaporation in terms of depth of water evaporated (mm/year). Vol[1]: Evaporation in terms of volume of water evaporated (x 10^6 m^3/year).

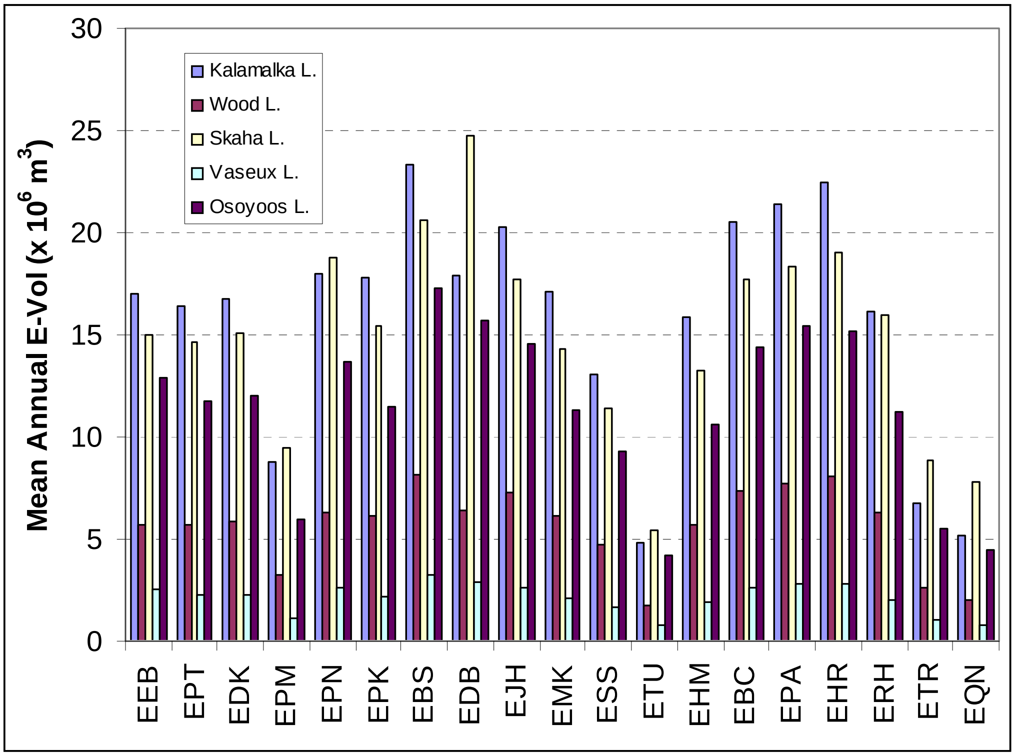


Figure F1.2 Comparison between 11-year mean annual volumes of water evaporated from Lakes Kalamalka, Wood, Skaha, Vaseux, and Osoyoos for each of 19 evaporation models

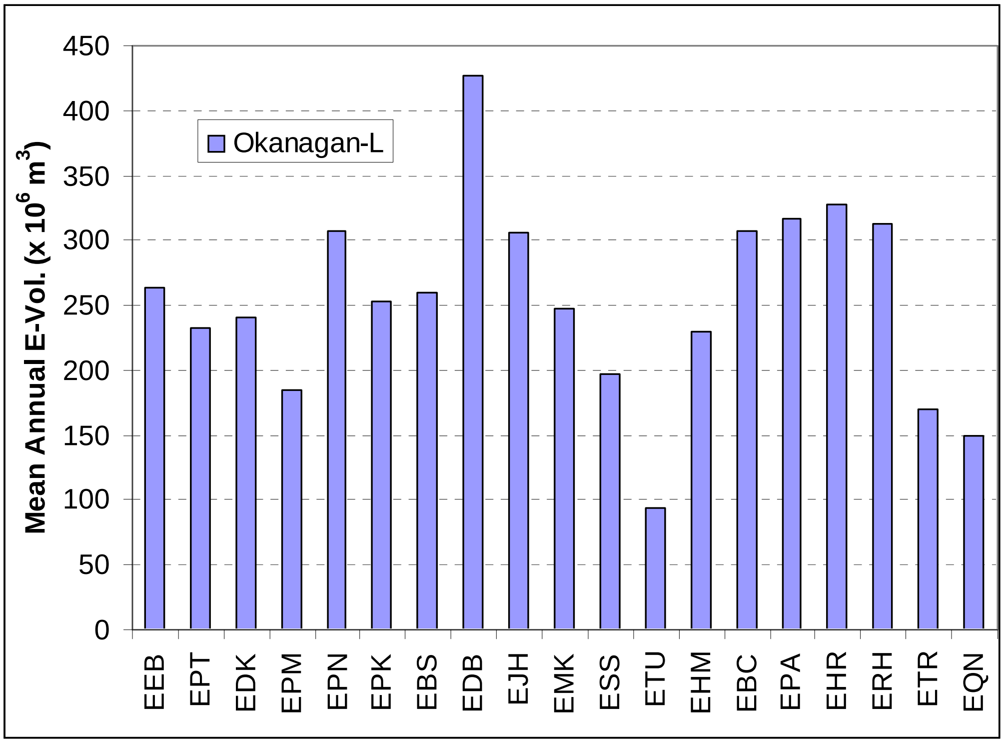


Figure F1.3 Comparison between 11-year mean annual volumes of water evaporated from Okanagan Lake for each of 19 evaporation models

F1.6 RECOMMENDED EVAPORATION MODEL FOR THE MAINSTEM LAKES

The recommended evaporation model for a particular lake is usually related to an accuracy assessment of the model result compared to direct measurements. However, this study was forced to rely on the existing database which does not include detailed lake observations and where the land-based meteorological data is not representative of lake conditions. Accordingly it is very difficult to compare model results against any standard. Nevertheless, Environment Canada stated a preference for the Trivett equation (ETR), one of the Mass Transfer group of models. This preference was because of the following advantages of the Trivett (1984) approach:

- ***Validity of the Mass Transfer Coefficient (Trivett, 1984)***: The Mass Transfer formula incorporates a mass transfer coefficient derived from eddy covariance observations conducted close to Okanagan Lake from May 1980 to April 1981. The eddy covariance observations are considered a direct measure of evaporation.

- ***Similarity of the Mass Transfer Coefficient Values in Other Lakes***: The mass transfer coefficient (M=0.024) (Trivett, 1984) is very similar to values derived for other lakes of varying sizes. The similarity of these mass transfer coefficients suggests that the Okanagan Lake coefficient is applicable to all the mainstem lakes.

- ***Impacts of the Lack of Over-lake Observations***: The lack of direct over-lake data measurements has resulted in large divergences in lake evaporation estimates from the various evaporation models. Over-lake measurements could include lake temperature, vapour pressures, heat fluxes and heat content. While the Mass Transfer approach does require representative over-lake observations of wind speed, water surface temperature and air temperature, it has an important advantage in that it does not require heat fluxes or heat content observations. Heat flux or heat content measurements do not exist for any representative stations for the 1996-2006 period.

- ***No Requirement for Heat Storage***: The evaporation calculations for some models were "forced" with estimated data where the data were derived using various assumptions. With reference to heat content, the cumulative evaporation results strongly suggest that application of heat content from just one year (1971), over all years (1996-2006) likely contributes to error in the Energy Budget and Combination approaches since the heat storage change is a dominant term, especially for Okanagan Lake. The Mass Transfer method does not require lake heat storage change.

- ***No Requirement for Radiation Flux Components***: There were no direct observations of the net radiation over water, and no continuous measurements of solar or longwave radiation, which are used in some evaporation models. The advantage of the Mass Transfer method is that it does not require net radiation, solar or longwave radiation data.

Nonetheless, as noted above, even the Trivett method suffers from significant data shortcomings. Therefore, for the purposes of calculating lake evaporation in the Okanagan Basin Hydrology Model, the Working Group selected the Penman-Monteith method. This choice was made because:

- The Penman-Monteith model is the same model used by the Okanagan Water Demand Model to estimate evapotranspiration from irrigated areas within the Basin – thus promoting consistency between the water demand model and the water supply model used in The Phase 2 project;

- The Penman-Monteith method provides estimates that are generally within 20% of Environment Canada's preferred method (the Trivett method); and
- There are well-documented methods to estimate the parameters required by the model where the required data is missing.

Annual estimates of lake evaporation using the Penman-Monteith were calculated in the customized MikeSHE-based Okanagan Basin Hydrology Model, and are reported in Section 15.0.

F1.7 RECOMMENDED EVAPORATION APPROACH FOR OTHER BASIN LAKES

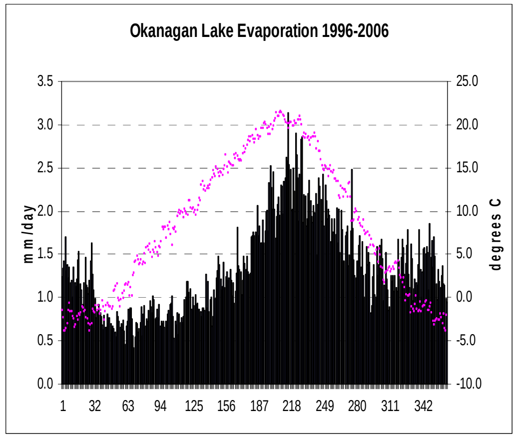
Environment Canada developed a procedure for generalizing lake evaporation estimates to other lakes in the Basin. Because of the wide availability of air temperature [both from existing meteorological stations and from the 500 x 500 m climate grid (Duke et al., 2008)], simple relationships were sought using air temperature as predictor variable.

Examples of the annual cycle for long-term air temperature and calculated evaporation are shown in Figure F1.4 for Okanagan, Kalamalka, and Osoyoos Lakes. Evaporation results shown in Figure F1.4 were determined using the Trivett (i.e. the ETR) method. Figure F1.5 shows a generalization of the regressions 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. In general, the shape of the original regression curves is similar for all lakes, showing lowest evaporation during the air temperature range 0^0C to 10^oC, and higher evaporation at higher air temperatures.

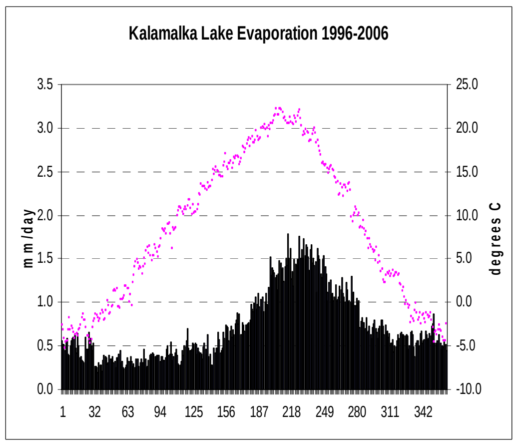
This procedure yields a family of curves ranging from large lakes (Okanagan Lake) to the smaller lakes. Future work could establish a GIS inventory of the Basin lake size distribution over the basin 500m x 500m climate grid (Duke et al., 2008). Based on mean air temperature over the grid, the evaporation from each lake or groups of lakes could be calculated using this approach. Its advantages are:

- the regression equation only requires air temperature data which can be derived from the 500 m x 500 m Okanagan Basin climate grid (Duke et al., 2008);
- 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, indicating that there is an acceptable relationship between estimated evaporation and associated air temperatures;
- the regression formulation can be applied over the standard 1996 – 2006 period using the current climate database (1996-2006);
- the regression formulation can be extended to year 2100 based on any one of several available climate scenarios;

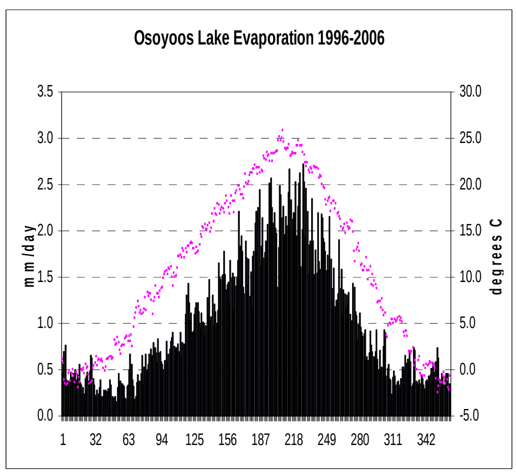
In order to compute lake evaporation for smaller lakes within the basin, a simple approach such as this should be followed.



(a)



(b)



(c)

Figure F1.4 Examples showing a comparison between long-term evaporation from the Trivett (ETR) model (block bar graph) and air temperature (curve with points) from different meteorological stations (a) Okanagan evaporation and Kelowna air temperature, (b) Kalamalka Lake evaporation and Vernon air temperature, (c) Osoyoos Lake evaporation and Osoyoos air temperature

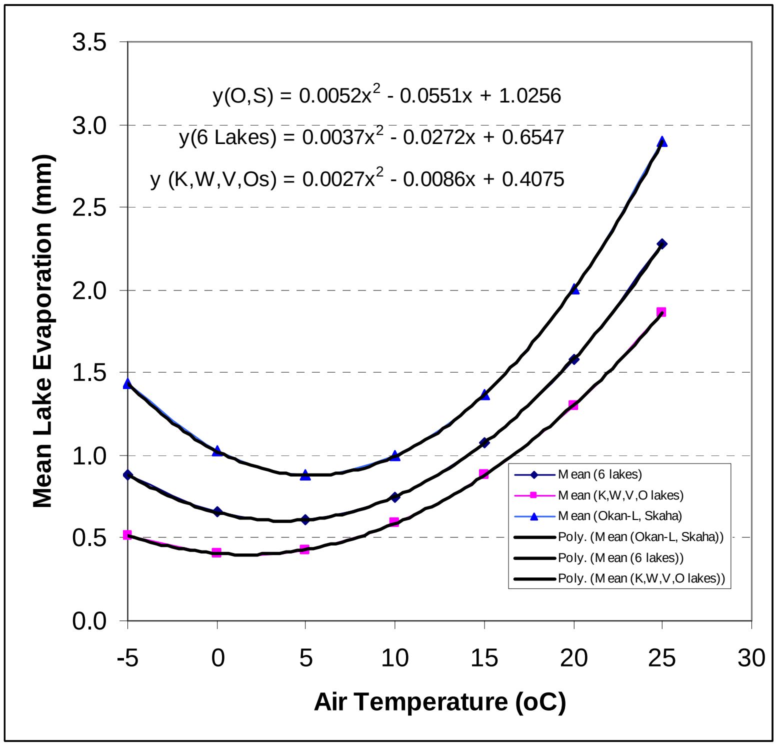


Figure F1.5 Generalized regression curves between computed lake evaporation (ETR model) and station air temperature based on 11-year means. Upper Curve (triangles) represents the average of Okanagan and Skaha Lakes. Lower Curve (squares) represents the average of Kalamalka, Wood, Vaseux and Osoyoos Lakes. Middle Curve (diamonds) represents the average of all 6 lakes.

F1.8 SUMMARY AND CONCLUSIONS

Environment Canada conducted an evaluation of 19 potentially relevant models for computing lake evaporation in the Okanagan Basin. Estimates of lake evaporation for Okanagan Lake range from 271 mm/year to 1227 mm/year. The Trivett (1984) method (the ETR method) is based on data considered more reliable than the data underlying the other models. For this reason, Environment Canada stated a preference for this method. Because of data shortcomings associated with this model and all the models, however, the Working Group believes that this advantage is minor, and that none of them can be considered significantly superior to any others. The Working Group chose the Penman-Monteith method for use in water supply modelling. The results of this method are generally within 20% of those for the ETR method, and it is the same model used for estimating evapotranspiration in the Okanagan Water Demand Model.

A method for computing lake evaporation for upland reservoirs based on air temperature has been proposed, and illustrated with evaporation data calculated using the ETR method. One of the key advantages of this method is that daily air temperature data are available throughout the Basin from the 500 m by 500 m climate grid. It is recommended that a simple air temperature-based method such as this be adopted for the purpose of estimating lake evaporation data for upland reservoirs.

Further meteorological and limnological data collection and evaporation model development should be implemented to determine the magnitude and timing of evaporation from Okanagan Lake, the mainstem lakes and the upland Basin lakes. This would allow development of land to lake transfer functions for critical meteorological variables, provide critical energy measurements, and provide accurate lake heat storage measurements. The improved database would allow more detailed lake evaporation modelling and indicate the optimal model(s) for these lakes. With improved knowledge of evaporation volumes and timing, the accuracy of the water budget for the lakes and for the Basin as a whole would be improved.

F1.9 REFERENCES

Canada-British Columbia Okanagan Basin Agreement (C-BCOBA) 1974. Technical Supplement II to the Final Report: Water Quantity Computer Modelling. Office of the Study Director. Penticton, B.C.

Duke, G., Nielsen, D., Taylor, B., Cannon, A., Van der Gulik, T, Newlands, N., Frank, G. and Smith, S. 2008. Climate Surfaces for the Okanagan Basin Water Supply Demand Project. Abstract presented in One Watershed – One Water Conference Abstracts, October 2008, p. 9.

Trivett, N. 1984. Lake Okanagan Evaporation Study. Canadian Climate Centre Report No. 84-2. Atmospheric Environment Service, Downsview, Ontario.