Status Report on Studies and Research to Address "Guidelines for Evaporation Estimates Required by the Prairie Provinces Water Board"

by

Ron Hopkinson
Hydrometeorologist
Prairie Section
Atmospheric and Hydrologic Sciences Division
Meteorological Service of Canada
Prairie and Northern Region
Environment Canada
#300 - 2365 Albert Street
Regina, Saskatchewan
S4P 4K1

May, 2003

Preface

The sharing of waters in eastward flowing streams among the three prairie provinces is defined in The 1969 Master Agreement on Apportionment (PPWB, 1969). Under the Master Agreement, the Prairie Provinces Water Board (PPWB) is required to monitor apportionment on eastward flowing streams to ensure that the water flowing in these streams is shared equitably and in a manner that meets the terms of the agreement.

The Committee on Hydrology (COH) was established as a standing committee of the Board to provide advice to the Board on water quantity issues related to the agreement. In order to monitor apportionment, the committee has reviewed and approved natural flow computation procedures for a number of major streams. Most of the streams covered under the agreement have some degree of flow modification and/or consumptive use. Thus, the recorded flow at a provincial boundary must be adjusted to account for anthropogenic influences in order to estimate the natural flow, which is needed to monitor apportionment.

Evaporation from reservoirs on these streams is considered to be a consumptive use. For major reservoirs (e.g. Lake Diefenbaker), evaporation has been estimated using the Meyer equation in conjunction with measured water temperatures. For small reservoirs, the estimation of evaporation has been calculated from readily available climatological data using theoretical or empirical methods. The validation of these methods and their applicability to the Canadian Prairies have not been established.

In February 1988, a document was developed by the Committee on Hydrology to help define a research need concerning lake or open water evaporation. This document, “Guidelines for Evaporation Estimates Required by the Prairie Provinces Water Board”, was intended to influence and provide some guidance to researchers at the then, newly-established National Hydrology Research Centre (NHRC) in Saskatoon. A copy of the Guidelines is included as Appendix A.

The COH has been following research developments over the intervening years and in the late 1990s decided that a status report would be helpful to the committee.

There are three estimation methodologies in wide use by prairie hydrologists. The Meyer (1915, 1942) equation was used in a systematic fashion for the Saskatchewan Nelson Basin Board Study (SNBB, 1972). The gross evaporation tables developed for this study have been maintained and updated by the Prairie Farm Rehabilitation Administration (PFRA). For a few major reservoirs of concern to apportionment monitoring, the Meyer equation is applied using measured water temperatures. In the early 1980s, Alberta Environment began using F. I. Morton’s

(1980) evapotranspiration and lake evaporation model - CRAE or complementary relationship areal evapotranspiration. Morton's lake evaporation model was used by Alberta Environment (1982) to estimate lake evaporation for a major modelling study on the South Saskatchewan River basin in Alberta. Subsequently, this model was accepted by the PPWB but until 2002, formal apportionment monitoring of the South Saskatchewan River at the Alberta-Saskatchewan boundary continued to rely on a mixture of Morton and Meyer evaporation estimates from major reservoirs on the plains region in Alberta. Also, evaporation pans have been used to estimate lake evaporation, mainly for international apportionment, on the few streams that are also subject to inter-provincial apportionment under the Master Agreement. Evaporation pan data was used for unofficial apportionment monitoring on Pipestone Creek from the mid 1980s to the late 1990s.

The resulting estimates disagree in terms of annual magnitude as well as the seasonal distribution of evaporation. The opening of NHRC in Saskatoon was seen by the COH and the Board as an opportunity to address these differences and to determine which estimation method was most suitable for the Board's purposes.

A Prairie Evaporation Study (PES) was proposed involving a lined reservoir as a control experiment. This experiment was never conducted due to a lack of funding. A more modest Regional Evaporation Study (RES) was completed based on a field experiment in 1991 but its main focus was areal evapotranspiration. Some other related studies have been initiated and/or completed by NHRC, such as a more modest study of evaporation from lined dugouts at Swift Current. Unfortunately, instrumental problems and a premature cessation to the operation of the dugouts has minimized the usefulness of the results.

Apart from the work at NHRC, there has been some experimentation with automated evaporation pans with some mixed success. The automated evaporation pans need to be checked at least every few days to minimize data loss. There are still some questions as to the best algorithm to use for automated pans. More recently, there has been interest in applying the Penman equation using data collected at sites equipped with a datalogger and a net radiation sensor, as well as temperature, humidity and wind sensors. The Penman equation yields daily evaporation comparable with pan-derived lake evaporation but does not have the operational difficulties associated with the automated pans. Since the Guidelines were drafted in 1988, PFRA has undertaken a thorough review of its methodology and made some significant modifications, including the incorporation of prairie-specific water temperature equations.

This report reviews the results of these research efforts and evaluates the progress made to address the questions posed by the PPWB over a decade ago. It provides some conclusions regarding current state of evaporation estimation for apportionment monitoring. Finally, some recommendations are included for the consideration of the Committee on Hydrology.

The sensitivity of PPWB apportionment monitoring to errors or differences in the estimation of evaporation is the subject of a separate companion report (Hopkinson, 2003).

Table of Contents

Evaporation Requirements of the PPWB

The sharing of surface waters in eastward flowing streams in the prairie provinces was prescribed in The 1969 Master Agreement on Apportionment. Essentially, a province is permitted to use half the water flowing into its jurisdiction and half of the water which arises naturally within that jurisdiction. All eastward flowing streams are subject to apportionment but to date, formal apportionment monitoring has been implemented on only a few major inter-provincial river systems (e.g. the Saskatchewan River) and a few smaller streams that also have an international component (e.g. Battle Creek). Apportionment monitoring was also introduced on Cold Lake, a major lake which straddles the Alberta/Saskatchewan boundary.

To calculate the natural flow at the inter-provincial boundary, the influence of human activities must be determined. Net consumptive water uses for irrigation, manufacturing and for municipal and farm water supply all need to be addressed. In addition, evaporation from reservoirs or lakes with control structures is viewed as a consumptive use. Evaporation has been calculated for the PPWB at a number of reservoirs beginning with Lake Diefenbaker in 1972, Tobin Lake in 1974, St. Mary and Waterton Reservoirs in 1978 and Gleniffer Lake in 1984. For all but the last reservoir, evaporation has been estimated using the Meyer equation and measured or estimated water temperatures. For Gleniffer Lake, Morton's lake evaporation model was used to be consistent with the model of the South Saskatchewan River developed by Alberta Environment.

Alberta Environment uses Morton's lake evaporation model and believes that it is superior to the Meyer equation for estimating lake evaporation. The Prairie Farm Rehabilitation Administration (PFRA) prefers the Meyer equation for its work while Environment Canada continues to use the Meyer equation in its calculations for the Prairie Provinces Water Board. Manitoba also uses Meyer equation evaporation as calculated by PFRA but applies monthly adjustment factors, depending on the size of the lake (Warkentin, 2003). Similarly, Saskatchewan Watershed Authority uses Meyer equation evaporation, as supplied by PFRA, for all of its studies. Saskatchewan has experimented with Morton's model on occasion and used it for the Birch River Natural Flow study but that was an exception to its usual practice (Johnson, 2003). In general, the Meyer equation provides annual estimates that are somewhat larger and have greater variability than those provided by Morton's lake evaporation model. Although several attempts have been made to determine which approach more accurately reflects true lake evaporation, no definitive assessment has been achieved.

With the establishment of the National Hydrology Research Centre in Saskatoon in the latter half of the 1980s, the PPWB Committee on Hydrology proposed that an appropriate line of research for an institution located on the prairies would be evaporation. The Committee prepared some guidelines to specify what results it wished to see from such research projects. This status report attempts to summarize what has been done over the past decade and a half, what remains to be done and how the objectives of the PPWB and its agencies might be met with respect to the estimation of evaporation.

An Overview of Evaporation Estimation Methods in Common Use

Meyer Equation

The Meyer equation dates from 1915 with later refinements in 1942. It requires three parameters:

- wind speed at 7.6 m above ground averaged over a month
- humidity at 7.6 m above ground averaged over a month
- surface water temperature averaged over a month.

The latter parameter is not usually known and must be either measured or estimated. In practice, water temperature is rarely measured and is usually estimated from air temperature using some empirical formula.

This approach was used in the Saskatchewan-Nelson Basin Board Study (1972) which relied on water temperature equations developed for Lake of the Woods. The task of maintaining the SNBB evaporation files after the original study was completed was assumed by PFRA. PFRA (1988) published the results of a thorough review of its evaporation calculations. The PFRA assessment concluded the following:

- a coefficient of 10.1 should be used when dew point data are utilized to estimate the monthly average humidity
- new water temperature equations based on water/air temperature relationships observed for small to medium sized prairie reservoirs were preferable to the Lake of the Woods equations for prairie applications
- better relationships for estimating missing data could be computed from recent high quality data.

PFRA subsequently applied its conclusions to the original set of 14 to 17 stations and expanded the list of stations where evaporation was calculated to over 50 sites across the prairie provinces. An assessment of the 1951 to 1980 normal gross evaporation for the southern prairies was made (PFRA,1989) and subsequently updated to 1961 to 1990 (PFRA, 1994). A related study was undertaken (PFRA, 1995) to assess the impact of using dew point and air temperature determined from 24 values per day as opposed to synoptic values of dew point and climatological extremes of daily air temperature. This study concluded that there was no systematic impact on evaporation estimates. This study was initiated in response to changes in observing programs of Environment Canada and the termination of the data publication, Monthly Record of Meteorological Observations in Canada. Finally, PFRA (2002) has updated the evaporation calculations to the year 2000, computed normal gross evaporation for the period 1971 to 2000 for the prairies, corrected some problems with past data, eliminated some older estimates when there was insufficient local data (e.g. transposition of wind data hundreds of kilometres) and introduced modified water temperature equations for the northern (Boreal) portion of the Prairie provinces.

At Lake Diefenbaker, Environment Canada measured water temperatures and calculated monthly evaporation for the PPWB from 1972 to 1994 using a Meyer coefficient of 9.0 (Hopkinson,1985a). Beginning in 1995, as a result of programs cuts, water temperature was estimated based on multiple linear regression developed for the period of measured water temperatures. A similar approach was used at Tobin Lake (Hopkinson, 1985b) from 1974 to 1994 with subsequent years requiring estimated water temperature. For St. Mary and Waterton reservoirs, a much shorter period of measured water temperature was available because of operational problems (mainly vandalism). Estimated water temperature relationships based on the short period of observations at these two reservoirs are not well established, leading to large uncertainty in the estimated evaporation.

Morton Lake Evaporation Model

F.I. Morton (1975, 1979, 1980, 1983 and 1986) developed his complementary relationship lake evaporation (CRLE) model which is now in usage in Alberta and to some extent elsewhere on the prairies. The model is driven by:

- mean temperature (for set periods of ten days to a month)
- mean humidity (based on dew point or relative humidity data)
- percentage possible total sunshine hours or actual solar radiation for the prescribed period.

In practice, these meteorological parameters have been available for many sites across the prairies. Recently, the availability of sunshine data has been severely reduced because of automation of most meteorological observing programs. Supplementary programs such as evaporation pans and sunshine recorders have been eliminated at most Environment Canada stations because of the lack of a suitable or economical automated replacement system. Further network rationalization being considered by Environment Canada in 2003 could eliminate the sunshine network altogether, to be offset by a mere 50 global solar radiation sites across Canada. Only nine of the proposed RF1 stations would be within the Prairies provinces and only four of those in the prairie ecozone where open water evaporation is high. Such a network would be inadequate for PPWB needs to run Morton's lake evaporation model in any sort of monitoring mode. Alberta plans to operate a network of RF1 sites which could provide the data necessary for the continued use of Morton's lake evaporation model (Figliuzzi, 2002).

Morton's lake evaporation model uses a pseudo-energy budget approach but ignores the influence of wind (advection). The estimates of lake evaporation on an annual basis tend to be significantly less than those based on pan-derived lake evaporation or PFRA's methodology based on the Meyer equation. Also the variability from year to year is much less in the Morton model estimates than in the other methodologies just mentioned. Finally, the distribution of the Morton lake evaporation through the year tends to peak in June (corresponding with maximum solar input) whereas other methods tend to peak in July or even August when air temperature is higher, atmospheric humidity is lower and water temperatures are higher, reflecting the influence of heat storage. Morton (1983) subsequently added a redistribution scheme which accounts for heat storage in a deep lake. This scheme is an add-on procedure which does not change the magnitude of the annual evaporation but rather, redistributes it. Alberta Environment (1987) has updated its procedures to incorporate this scheme.

Provided the input climatological data are available, it is possible to generate lake evaporation estimates over a sufficiently long historical period to be useful for the Board's purposes. Despite generally favourable comparisons with well-known water budget experiments conducted elsewhere (usually the continental USA), there has not been universal acceptance of Morton's lake evaporation model for use in Canada or on the prairies in particular. Validation of the lake evaporation portion of the model is still lacking.

Hopkinson (1984) recommended the use of Morton's lake evaporation model to estimate evaporation at Gleniffer Lake, in part, to be consistent with Alberta Environment's natural flow model for the rest of the South Saskatchewan River.

Pan Derived Lake Evaporation

Evaporation pans have been used to "measure" evaporation for many years. The United States Weather Bureau class A evaporation pan was introduced in Canada in a systematic fashion in the early to mid 1960s. The class A evaporation pan is mounted on a wooden pallet which allows air to flow around the sides and beneath the evaporation pan. To compensate for heat advection through the walls of the pan, a correction procedure, developed by Kohler, Nordenson and Fox (1955), is used to calculate lake evaporation on a daily basis. This scheme is basically 0.70 times the pan evaporation corrected for heat advection through the walls of the pan. The pan coefficient, 0.70, was developed from seasonal empirical relationships between pan evaporation and lake/reservoir evaporation. Actual seasonal coefficients varied from 0.52 to 0.86 (WMO, 1973) so the value of 0.70 is a compromise figure with relatively large error bars. When applied to monthly or daily data, the pan-derived lake evaporation in the early part of the season could be expected to overestimate the actual lake evaporation while the opposite is true in the fall. This is because of the much greater heat storage of even a dugout or small lake compared to the evaporation pan.

In much of southern Canada, evaporation pans are usually in service from May to September. Occasionally this season can be stretched into April and

October depending on the year. The problem with operating the evaporation pan in these shoulder months is dealing with ice formation. Manually-operated evaporation pans in Canada are serviced once per day, usually between 6:00 and 9:00 a.m. LST. Practically speaking, this is the worst possible time during these shoulder months because this is the most likely time to encounter ice formation on the pan. As a consequence, the data from evaporation pans represent less than the total open-water evaporation from lakes and reservoirs because the record is usually missing data for at least the two shoulder months of April and October, and occasionally parts of May and September too.

Hopkinson (1987) demonstrated that the operational season for evaporation pans could be extended to virtually the whole open-water season by servicing the pans in the late afternoon when the day's warmth has melted most, if not all, of the ice that may have been present in the early morning. However, this change in observing protocol was never adopted. It could be utilized for use at evaporation pan stations used solely for apportionment purposes, especially when Environment Canada terminates the pan evaporation network. The caution is that observers must be alert to any severe and prolonged cold spells in order that the pan could be emptied and inverted to prevent ice damage to the pan.

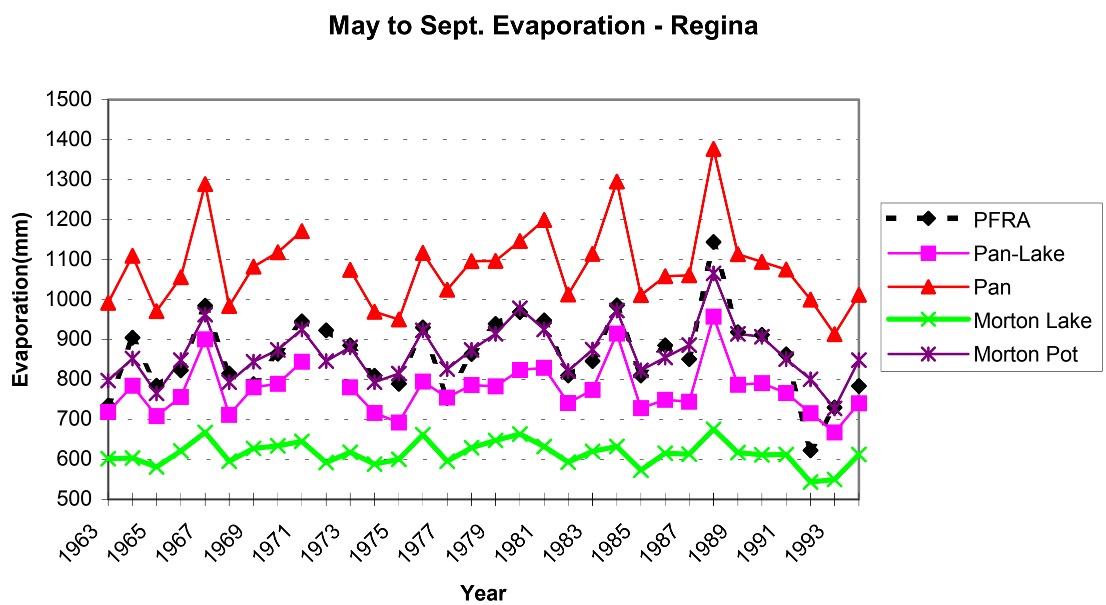

Figure 1: Comparison of seasonal evaporation (May to September) at Regina

On a seasonal basis (May to September), the magnitude of the pan-derived lake evaporation is intermediate between the PFRA estimate and the Morton lake evaporation estimate for the same five month period. The Morton potential evaporation is remarkably well correlated (R^2 = 0.80) with the PFRA evaporation estimate for the May to September period. Both of these estimates over the years

1963 to 1994 are of the same magnitude or about 12% higher than the pan-derived lake evaporation for Regina. It is noted that the measured pan evaporation, which might be thought of as a measure of the potential evaporation, is 40% greater than Morton's potential lake evaporation. Part of the difference could be attributed to heat advection through the walls of the pan while another possible source of difference is the heat exchange with the ground in a shallow lake or pool. Finally Morton's lake evaporation is about 20% less than the pan-derived lake evaporation. Such differences illustrate the problem of using both Morton and Meyer methods for Board purposes. On average for Regina, there is a 40% difference in the PFRA estimate of seasonal lake evaporation and that from Morton's model (see Figure 1). Note that the pan evaporation data were incomplete for 1972 so no value was plotted.

The advantage of the evaporation pan is that it yields a direct measure of evaporative loss. Also, the data are ready for immediate use once the measurement is completed. Its major drawback is that it may not be representative of actual evaporation from a lake or reservoir. Despite this limitation, evaporation pan data are used for international apportionment between Canada and the United States. The above-ground evaporation pan also has the advantage that one can detect leakage from the pan fairly readily. Sunken pans may be technically more correct but it is very difficult to detect if the pan is leaking and take corrective action. Floating pans in the water body of interest are even better but have great operational difficulties including the difficulty of detecting leaks and coping with the wave action.

For the PPWB, most of the reservoirs of interest are moderate to large in area and/or depth and therefore have significant heat storage. This calls into question how representative the pan-derived values are in estimating the lake or reservoir evaporation. As mentioned earlier, the pan-derived lake evaporation does not usually extend to the total open water season. Although evaporation is much less in the shoulder months of April and October, it can represent 10 to 20% of the total open water evaporation in a given year. Finally, the virtual disappearance of the evaporation pan network over the past decade from the prairies due to program reductions in Environment Canada and other government agencies/departments has, for the moment, minimized its possible application for Board purposes. The exception is on Battle, Lodge and Middle Creeks where there is a contract observing program at Altawan.

In the 1990s, there has been considerable interest in automated evaporation pans. McGinn et al (1995) conducted some of the original work in Canada using a new water level sensor mounted on a standard class A evaporation pan. The datalogger is programmed to add water each day to bring the water level back to standard depth. If rainfall causes the water level to exceed the top of the range of the water level sensor, there is an overflow hole in the side of the pan which allows the excess to drain off. Environment Canada's efforts did not utilize the overflow idea but tried to measure rainfall and use this to calculate evaporation from the water level change and the rainfall depth, similar to the old manual program except on an hourly basis. The lack of drain led to considerable data loss during heavy rainfall events whereas the use of rainfall data led to some erroneous results because the evaporation pan is not always a good rain or snow gauge. Neither system tried to remove water from the pan but that was not a problem for McGinn et al, 1995 because of the overflow hole. However, for the Environment Canada observing protocol, this is a problem because the range of the water level sensor is at most 60 mm. Thus after one or more heavy rainfall days with the rainfall exceeded 40 mm, the water level would be above the top of the range that the sensor could measure. On some occasions, as much as a week could pass before evaporation returned the water level within the range that could be sensed by the water level sensor. During such periods, although evaporation was occurring, no water loss (evaporation) could be measured by the water level sensor resulting in a loss of data (Hopkinson, 2000). Cummine (2000) determined that neither system was robust enough to be left completely unattended for the season but that the increased temporal information (hourly) could lead to a better understanding of the evaporation process.

Present Status of Research Versus PPWB Guidelines

This section summarizes progress towards addressing the guidelines sent to the National Hydrology Research Centre in 1988 (see Appendix A).

1. Control Experiment - Prairie Specific

> "Develop a control experiment against which to test which model (Meyer or Morton) provides the best estimate of evaporation in a prairie application. This may require several years of field data."

Lined Reservoir

A proposal to establish a lined reservoir of sufficient size to test the applicability of both the Morton and Meyer models to moderate-sized prairie reservoirs failed from a lack of funding. The cost of such an undertaking was believed to be over one million dollars which was well beyond the financial capabilities of NHRC. Attempts to garner outside funding for such a large project also failed although some support was provided for the Regional Evaporation Study (RES). RES was directed at areal evapotranspiration, not the prime interest of the PPWB. The research results were published by Strong (1997).

> **A lined reservoir could have provided the control study needed to address the Board's principal interest. However the project proposal died and there appears to be little prospect it will ever be undertaken, given the current fiscal climate, a change in focus of NHRC research priorities and the ongoing loss of scientists from Environment Canada. One possible hope would be to encourage a university-led research project that could qualify for funding from agencies like the Canadian Foundation for Climate and Atmospheric Sciences.**

Lined Dugouts

A pair of lined dugouts at the Agricultural Research Station near Swift Current were refurbished in the early 1990s and attempts were made by Dr. G. Strong and others to monitor their water balance. This experiment encountered numerous operational difficulties including problems with water level monitoring and with leakage from one of the reservoirs. Dr. Strong has reviewed the data that were collected in 1994 and has recently published an article describing the results (Strong et al, 2001).

Strong et al (2001) concluded that on a seasonal basis (Jul 1 to Oct 7) the Meyer equation with a constant of 12.0 matched the water balance estimate of evaporation or 567 mm. This Meyer coefficient is in agreement with the advice of

PFRA (2002) which recommends that open water evaporation be increased by up to 20% for dugouts. Also, for this part season, a pan coefficient of 0.85 was required. This value is somewhat high compared to the generally accepted pan coefficient of 0.70. However, it must be remembered that this does not include the months of April to June when even a dugout exhibits considerable heat storage. For those months, the loss of water from a dugout should be significantly less than lake evaporation derived from a class A pan. Morton's lake evaporation was not evaluated but Hopkinson undertook monthly calculations for July, August and September. The Morton (1979) potential evaporation using either sunshine or global solar radiation was very close to the magnitude of the water balance evaporation (586 and 575 mm, respectively) but the Morton lake evaporation was considerably less (409 mm and 395 mm, respectively). The PFRA total value for the same three months is 557 mm, not unlike the Morton potential evaporation.

Figure 2: Comparison of monthly evaporation estimates for Swift Current 1994

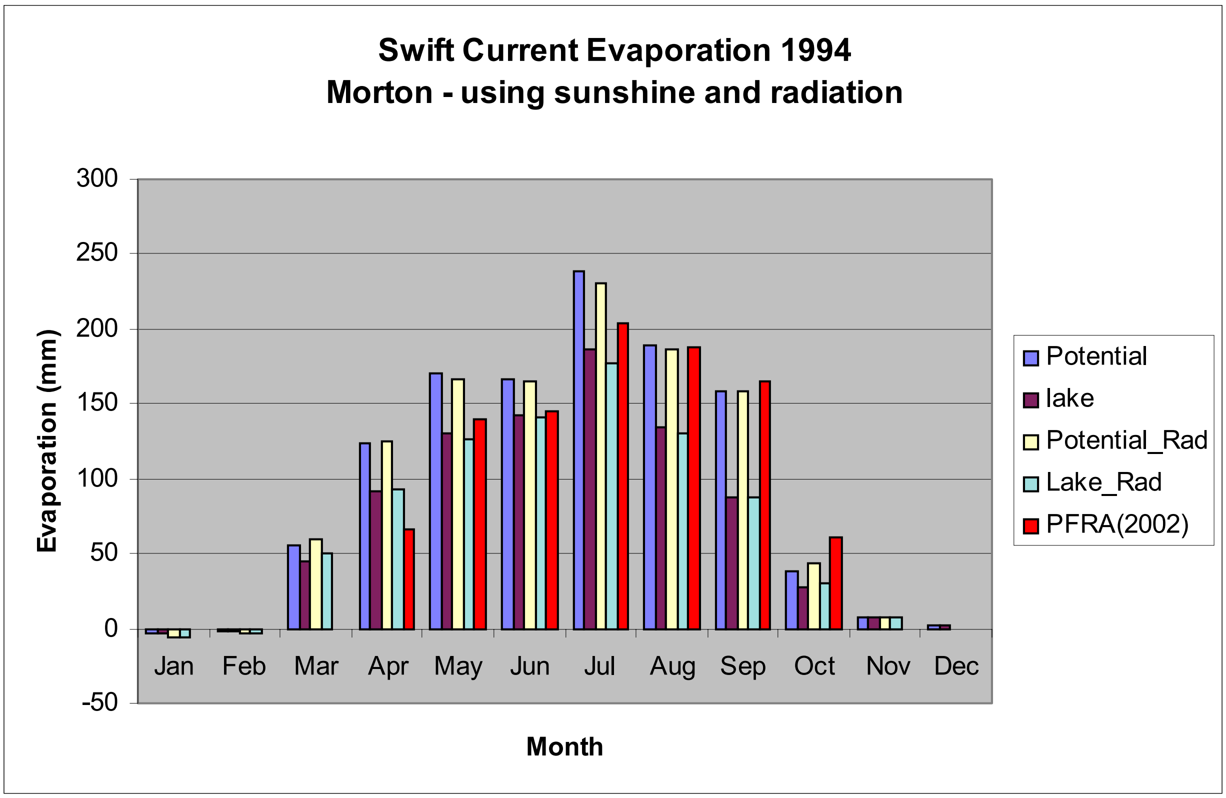

Figure 2 shows the monthly potential and lake evaporation for Morton's model using sunshine versus radiation data. Also plotted are the monthly values from PFRA (2002). There is not much difference between the two Morton model runs using sunshine and radiation. The PFRA values based on the Meyer equation and prairie small reservoir water temperature equations has a similar magnitude in the months July to September to the Morton potential evaporation.

Strong's work provides some reassurance that the Meyer equation and the pan derived lake evaporation yield reasonable estimates of evaporation from small water bodies (dugouts) but it did not address moderate to large lakes/reservoirs of interest to the PPWB.

2. Control Experiment - Historical

"Assess Meyer and Morton models against other control experiments (e.g. Lake Hefner, others)."

No progress has been made in this area. Although this is a potentially useful line of research, little effort has been made to survey what data sets might be available or how they might be obtained and in what format. The main risks are that there could be experimental design problems which could discredit these older control experiments and also, there is the question of applicability of such studies to the Canadian Prairies.

3. Size Range of Water Bodies

"A range of water body sizes should be examined from Lake Diefenbaker to small reservoirs to dugouts."

Large Reservoirs

Dr. B. Kenney was working on eddy correlation measurements of evaporation from instrumented towers and tethersondes on Big Quill Lake. In 1991, a series of tethersonde measurements were made simultaneously on the upwind and downwind shores together with eddy correlation measurements on the downwind shore. There is a rough draft of a manuscript on this but it needs some additional work before it is ready to be published. Dr. Kenney has made no commitment to complete and publish this paper.

Large volumes of field data were collected but with Dr. Kenney's departure due to government downsizing in the mid 1990s, the analysis and a scientific report documenting his results are pending. Part of Dr. Kenney's interest was the role played by evaporation from the droplets produced by breaking waves.

In 1993, Dr. Kenney ran the HEATMEX experiment, jointly with Mark Donelan at NWRI. (Donelan also left NHRC and is now at the University of Miami.) There were six towers in the lake, each with a large number of sensors. This resulted in gigabytes of data and a huge data editing job that took years. Dr. Kenney volunteered three months of his time after he retired to complete the data editing in Miami in the fall of 1998. NHRC provided travel funds to make this possible.

Raoul Granger (2000) wrote a paper that was partly based on the HEATMEX data but the real potential of this data set has yet to be tapped and no other papers have been forthcoming. It is likely one of the most comprehensive sets of measurements ever made on a large lake. There is some interest in this data set from the University of Saskatchewan and York University.

Although Dr. Kenney has retired, these data are potentially of great interest to answering the PPWB's question because evaporation from larger lakes can be significant to apportionment monitoring. Dr. Kenney should be encouraged to complete the analysis and publish the results and to make the data set available to other researchers.

Moderate-Sized Reservoirs

As outlined under guideline 1 above, no progress was made and there is little prospect of NHRC-led research into this area in the future.

No progress has been made on moderate-sized reservoirs. Evaporation from moderate-sized reservoirs is of interest to the PPWB for smaller streams (e.g. Pipestone Creek, Middle Creek Reservoir) where such evaporation can represent a relatively large fraction of the stream's water balance, particularly in a dry year.

Dugouts

Some field data were collected from a pair of lined dugouts at Swift Current in 1993 and 1994. Operational difficulties have limited the analysis and the conclusions which can be drawn (Strong et al, 2001).

Although evaporation from small water bodies like dugouts is usually not a direct concern to the Board for apportionment monitoring, it is of considerable interest to the agencies of the Board.

4. Other Methods

"Examine or develop other methods for computing evaporation with *the* following restrictions:

a) input data should be readily available in machine readable format from at least 1930 (this could be relaxed if a clearly superior method could be applied to at least the last 30 - 40 years or record.

b) monthly input data would be most convenient but daily or even hourly input data may be employed if the aggregate monthly evaporation estimates are clearly superior to those from any model based on monthly data. Evaporation estimates in a monthly format would be best for the current PPWB applications.

c) some agencies of the Board require daily evaporation estimates on an operational basis.

d) new methodologies should be applicable operationally as well as historically."

Without any progress on the basic control experiment, there has been little effort expended to review or examine other possible methods of estimating evaporation. The evaluation and/or development of other methods were expected as a possible result of a control experiment.

Recent changes to the observing network of Environment Canada have virtually eliminated the possible use of evaporation pans as an alternative to either the Morton or Meyer methods. The evaporation pan network has virtually disappeared except for a few contract sites and a few automated evaporation pans. Some of the data from these automated pans has been assessed (Hopkinson, 2000; Cummine, 2000) but except for a few sites operated by Agriculture and AgriFood Canada, the future of automated pan sites is very doubtful, especially with the latest round of network rationalization (cuts) proposed by Environment Canada. Except for Prairie and Northern Region, Environment Canada has terminated the pan network in the rest of Canada already. Automated evaporation pans can be operated with fair success only if they are checked at frequent intervals (every few days). In addition, further work is needed on the observing algorithm and software would need to be written to process the resulting data into a format consistent with manual pan measurements and pan-erived lake evaporation. The prospect of this happening in Environment Canada at this time is negligible.

Also, most observing programs of bright sunshine have been eliminated and these have, for the most part, not been offset by new solar radiation measurements at automatic stations. Thus, the opportunity to use Morton's model currently and in the foreseeable future has been greatly diminished.

Far from introducing new methods of estimating evaporation, there has been a significant reduction in the capability to use either evaporation pans or Morton's lake evaporation model as alternatives to the Meyer equation.

5. Evaporation from Ice and Snow

"If possible, address the magnitude and significance of evaporation from ice/snow covered surfaces (there is a significant difference between Morton and Meyer estimates of winter evaporation)."

Dr. J. Pomeroy (Pomeroy, 1997) in collaboration with various investigators has developed a model of snow accumulation and sublimation for a variety of environments (open prairie, boreal forest and arctic tundra). The utility of this research to the Board's interests has not been assessed.

This topic was identified as a lower priority issue. Although Pomeroy's research has some potential application to apportionment monitoring, issues surrounding the magnitude of open-water evaporation are of greater concern at this time.

6. Improve Estimates of Evaporation in Boreal and Alpine Regions

"The prairies represent the area of most urgent need for improved evaporation estimates but applicability to boreal forest and alpine environments is at least of secondary interest."

Some related work has taken place in the Boreal forest areas of Saskatchewan and Manitoba (BOREAS) and the Prince Albert Model Forest. However these studies were more interested in evapotranspiration from the boreal forest than in open-water evaporation in a boreal region. For the Board's purposes, neither of these research efforts advanced the ability to calculate lake evaporation in these regions. As part of the Mackenzie GEWEX Study, lake evaporation has been measured on Great Slave Lake and some smaller nearby lakes.

To the author's knowledge, no new work has been conducted in alpine regions.

PFRA (2002) has improved its estimates of open water evaporation in the northern Prairie Provinces by modifying its water temperature equations in its latest round of calculations. The magnitude of evaporation in these northern areas is now more consistent with other methods but the water temperature equations are based on very little actual data.

Little significant progress has been made to improve evaporation estimates for forested or alpine regions adjacent to the prairies. Evaporation studies on northern lakes, under GEWEX in the NWT, may find some application in the northern prairie provinces.

Other Related Studies

Strong (1997) published the results of the Regional Evaporation Study (RES). The focus of the study was a 100 km by 100 km box just south of Saskatoon where extra ground-based and upper air observations were used to determine daily evapotranspiration. Essentially, the amount of moisture in the atmospheric sounding is measured and the change is considered to be the result of evapotranspiration from the surface of the 100 km square. Strong admits that his approach worked best on days with little or no horizontal advection of moisture. Strong's moisture budget analysis using synoptic data and local radiosonde data had errors of +/- 4 mm on a daily basis, +/- 2mm over two days and +/- 1mm for periods of six days or more. A comparison of the results with Morton's evapotranspiration model was not attempted because of the limited sampling period for the field experiment and because Morton did not recommend running his model on a daily time-step.

Dr. B. Kenney collected flux measurements of evaporation from towers over and adjacent to Big Quill Lake in 1991 and 1993. Before these data could be analyzed, Dr. Kenney retired early from NHRI and the study was never completed. A large volume of what is believed to be high quality data was collected and edited but is still awaiting analysis. Dr. Kenney has prepared a paper based on work with tethersondes and eddy correlation measurements at Big Quill Lake in 1991 but it has still not been submitted for publication (Kenney, 2002). Granger (2000) has written a paper based on the 1993 data but much remains to be done with this data. He concluded that *land surface data alone is insufficient to parameterize the lake evaporation*. Dr. Kenney now resides in Alberta but has no plans to analyze the 1993 data. Dr. Peter Taylor of York University is interested in the data set to validate a small lake evaporation model which uses a boundary layer approach to evaporation (Taylor, 2002).

BOREAS (Boreal Ecosystem-Atmosphere Study) collected flux data over specific areas of the boreal forest of Saskatchewan and Manitoba. Hydrology-related studies focused mainly on evapotranspiration, not lake evaporation.

MAGS (the Mackenzie GEWEX Study) included an atmospheric moisture budget study similar to RES (Strong et al, 2002). In addition, one part of MAGS included a study of lake evaporation from Great Slave Lake (Blanken et al, 2000) using an eddy correlation approach. Other papers have been submitted for publication that outline the different character of evaporation from small to medium to large lakes like Great Slave Lake. These indicate that large lakes in the southern NWT have significantly greater seasonal evaporation than medium sized lakes and almost twice as much as small lakes. The interaction of radiation, ice cover and advection leads to these different evaporation regimes and may be operating to a lesser extent in the southern prairies. Louie et al (2002) attempted a basin water budget study for the Mackenzie. They found that while the magnitude of evapotranspiration from Morton's model was approximately what was needed to close the long-term water balance, Morton's evapotranspiration did not help to explain the annual fluctuations in the water budget.

Bussieres (1992, 1997) has developed algorithms to determine areal evapotranspiration remotely sensed data from satellite. The emphasis in his work is evapotranspiration, not lake evaporation, but his work could be helpful in evaluating the evapotranspiration portion of Morton's model.

Hopkinson (2002a) reviewed the Penman lake evaporation approach and found that it provides useful estimates of daily evaporation, comparable with pan-derived lake evaporation. Water Survey of Canada is embarking on a field program to implement the Penman approach on the Milk River in southern Alberta as an alternative to pan evaporation measurements. The Penman equation requires net radiation in addition to temperature, humidity and wind speed. Unfortunately, net radiation is not routinely observed except at a handful of Environment Canada radiation stations across the country. The new proposed net radiation network is to be reduced to only six core sites for all of Canada. Thus to use the Penman approach, agencies would need to operate their own observing platform, quality assure and process the data, and apply the Penman spreadsheet to these processed data.

Conclusions

To date, no substantive progress has been made in resolving the issue of whether the Morton or Meyer lake evaporation estimates are better for the size of reservoirs or lakes of interest to the PPWB. A research proposal to construct a moderately large lined reservoir failed because of its considerable cost and a lack of financial backing. Progress on this Prairie Evaporation Study (PES) was stalled in 1990 and there is little or no prospect that it will receive renewed support in today's fiscal climate. The present direction of research in Environment Canada suggests that open water evaporation research on the prairies is a low priority. Finally, the scientists who had an interest in Prairie Evaporation Study have disappeared because of Environment Canada staff reductions and retirements.

A study of data from two lined dugouts near Swift Current has been published. The principal investigator, Dr. Strong, believes that some useful information can be drawn from these data despite significant operational problems with the water level records. For water bodies of the size of dugouts, Strong et al (2002) concluded that the Meyer equation with a constant of 12.0 provided a good estimate of the water budget evaporation, which had a possible error on +/- 4%. Similarly a pan coefficient of 0.85 for the season July 1 to October 7 matched the water budget value. While Strong et al (2002) did not assess Morton's lake evaporation model, Hopkinson determined that Morton's potential lake evaporation for these three months was similar in magnitude to the water budget evaporation from the north dugout. Morton's lake evaporation was about 70% of the water budget and is not applicable to water bodies this small.

PFRA has invested considerable time and resources in improving its procedures for calculating gross evaporation based on the Meyer equation. The number of sites where these estimates are available was expanded from the 17 original SNBB locations to about 50 locations for PFRA's 1961-1990 assessment of evaporation on the prairies and to 55 sites in its 1971 to 2000 report (PFRA, 2002). Besides a thorough review of the climatological data and anemometer histories, the major advance was the introduction of prairie-based water temperature equations which superseded those based on Lake of the Woods as used by the SNBB study. The result is a more consistent set of evaporation estimates for individual sites and for the prairies as a whole. The results are applicable to small to medium-sized water bodies.

Morton's model for estimating evapotranspiration was evaluated by Granger and Gray (1989). They concluded that the model suffers from a number of weaknesses:

- its radiation algorithm
- a lack of a routine for estimating net energy available for evaporation/evapotranspiration during period of soil thawing and

- the assumption that the vapour transfer coefficient is independent of the wind speed.

The model appears to be sensitive to abrupt changes in the dominant weather condition but for periods of fairly stable weather, the averaging period has little influence on the calculated amount so Morton's suggested method for correcting the data is not needed.

A Regional Evaporation Study (RES) was conducted in July 1991 and the results published (Strong, 1997). The study demonstrated that evapotranspiration, as determined from an atmospheric moisture budget approach, varied significantly from day to day, more so than suggested by the Priestly Taylor (1972) method or inferred from satellite calculations. No attempt was made to compare Morton's evapotranspiration model estimates with those from the field experiment.

A study comparing Meyer and Morton evaporation techniques against evaporation pan data (Feng et al, 1989) was inconclusive. Lacking a control experiment, it was not possible to determine which method was better. It was noted that that the Meyer estimates were biased high (+8.7%) with respect to the pan-derived lake evaporation while the Morton model estimates were biased low (-12.7%). Such differences have been noted before (Hopkinson, 1980) and this study did not resolve the issue.

Morton, who died in 1997, was in the midst of reformulating his model but that work remains unfinished. Granger (1997) indicated that he expects Fred Morton's work and notes to be passed on to him to complete revisions that Morton had started. Granger's main interest is in the evapotranspiration portion of the model as opposed to the lake evaporation part. However improvements to one part of the model may be beneficial to both.

The prospect for NHRC-led evaporation studies in the foreseeable future is minimal. Dr. Strong has retired so the main advocate of a control experiment is gone. Also, NHRC's shrinking staff and financial resources are being directed to focus on departmental priorities such as climate change and northern studies (e.g. MAGS). Lake and reservoir evaporation studies for operational or apportionment purposes are not on the books. Thus, the author concludes that there is a negligible chance for the foreseeable future that NHRC will conduct an experiment which will provide an evaluation of the Meyer and Morton models for the size of reservoirs and lakes of importance to the PPWB for monitoring apportionment.

Dr. Kenney's large lake evaporation study was never completed but the data he collected are still available and may yet provide useful data for PPWB's lake evaporation needs.

Automated evaporation pans can provide useful data for application to small reservoirs but only if they are checked every few days. There are still some issues to resolve concerning the observing algorithm and data processing. However, the use of pan data for large lakes or reservoirs for PPWB apportionment requirements is not recommended because of the very different heat storage characteristics of large reservoirs relative to the class A pan. For smaller reservoirs, automated pans may yet provide useful data on a daily or longer basis.

The Penman equation can be applied operationally with today's datalogger technology and sensors. Hopkinson (2001) provided Water Survey of Canada with a spreadsheet that can be used to calculate daily evaporation comparable with pan-derived lake evaporation. This is applicable to small reservoirs such as those on the Battle, Lodge and Middle Creeks, but the Penman equation could be applied to small reservoirs on other streams subject to apportionment.

Recommendations

The relative lack of progress towards resolving the question posed by the PPWB's Committee on Hydrology over a decade ago has been disappointing. The following recommendations are offered for the COH's consideration:

1. The COH contact Dr. Kenney and encourage him to complete his paper for large lake evaporation for the 1991 study.
2. The COH foster/encourage the analysis of the HEATMEX data set of 1993 on Big Quill Lake by interested researchers.
3. The COH should consider other possible options for researching evaporation from moderate-sized reservoirs and lakes (e.g. focussed applied research by NWRI, Provincial Water Agencies and/or Universities).

References

Alberta Environment, 1982. South Saskatchewan River Basin historical natural flows 1912 to 1978 - Appendix 3 Evaporation. Edmonton, Part 1, 39 pp. and Part 2, 44 pp.

Alberta Environment, 1980: Assessment of F.I. Morton's model of lake evaporation. Edmonton, 28 pp.

Alberta Environment, 1987: Evaporation and evapotranspiration in Alberta 1912-1985. Hydrology Branch report, 21 pp. plus tables.

Blanken, Peter D., Wayne R Rouse, Alistair D Culf, Chris Spence, L. Dale Boudreau, Jesse N. Jasper, Bob Kochtubajda, William M. Schertzer, Philip Marsh and Diana Verseghy, 2000: Eddy covariance measurements of evaporation for Great Slave Lake, Northwest Territories, Canada. Water Resources Research Vol. 36, No. 4, p 1069-1077.

Bussieres, N., 1992: GOES evapotranspiration variability mapping for the Canadian Prairies Evaporation Study, July 1991. Proc. 15th Canadian Symposium on Remote Sensing, 1-4 June 1992, Toronto, p 211-212.

_____, R.J. Granger and G.S. Strong, 1997: Estimates of regional evapotranspiration using GOES-7 Satellite Data: Saskatchewan Case Study, July 1991. Canadian Journal of Remote Sensing, Vol. 23, No. 1, p 3-14.

Cummine, James, 2000; Evaluation of automated evaporation pan data in Prairie and Northern Region. AHSD Report 00-01, Winnipeg, 17 pp.

Feng, G.Z., G.S. Strong and W. Nicholaichuk, 1989: Comparison of Meyer and Morton evaporation techniques from open water surfaces. NHRI Contribution No. 89010. Saskatoon, 88 pp.

Figliuzzi, S., 2002: personal communication.

Granger, R.J. and D.M. Gray, 1989: An assessment of Morton's model for estimating areal evapotranspiration. NHRI Contract Report No. 89003. Saskatoon, 61 pp.

_____, 1997: personal communication.

_____, 2000. Potential for the use of Remote Sensing with the Numerical analysis of Advection in the Estimate of Lake Evaporation. Applications of Remote Sensing in Hydrology, Proceedings of the 4th International Workshop, Santa Fe, NM (Nov 4 - 7, 1998) (Pietroniro, Granger and Pultz, eds.) p105-112.

Hopkinson, R.F., 1980: Evaluation of F.I. Morton's lake evaporation model and its application to the Canadian Prairies. Unpublished report to the PPWB Committee on Hydrology. Regina, 20 pp.

_____, 1984: Estimation of evaporation from Dickson Reservoir for natural flow calculations. Environment Canada, Scientific Services Report to the PPWB Committee on Hydrology, Regina, 25pp.

_____, 1985a: Temperature and evaporation on Lake Diefenbaker, 1984. Environment Canada, Scientific Services report No. CSS-R85-02, Regina, 16pp.

_____, 1985b: Evaporation from Tobin Lake, 1984. Environment Canada, Scientific Services Report No. CSS-R85-01, Regina, 14 pp.

_____, 1987: A rational approach to evaporation pan operation in Canada and other cold climates. Paper presented at the 21st Annual Congress of the Canadian meteorological and Oceanographic Society, St. John's, Newfoundland, June 16-19, 1987. Unpublished manuscript.

_____, 2000: A preliminary assessment of automated evaporation pan data collected at Swift Current CDA. Unpublished manuscript, Regina, 19pp.

_____, 2001: Application of the Penman lake evaporation Method. Internal report for Water Survey of Canada, Regina, 16pp.

_____, 2002: Penman evaporation revisited – a practical alternative to pan evaporation. Paper presented to the 36th Annual CMOS Congress, Rimouski, Que, May 22-25, 2002.

_____, 2003: A sensitivity analysis of PPWB apportionment monitoring to evaporation calculations. Draft report (February 2003) to the Committee on Hydrology, Regina, 61pp.

_____, W.D. Hogg, P.Y.T. Louie and X. Zhang, 2000: Evapotranspiration over the Mackenzie basin 1953 to 1995. Paper presented at the 53rd Annual CWRA Conference, Saskatoon, Saskatchewan, June 2000. Unpublished manuscript, 5pp.

Johnson, D., 2003: personal communication.

Kenney, B.C., 2002. Personal communication.

Kohler, M.A., T.J. Nordensen and W.E. Fox, 1955: Evaporation from pans and lakes. U.S. Weather Bureau Research Paper #38, Washington.

Louie, P.Y.T., W.D. Hogg, M.D. MacKay, X. Zhang and R.F. Hopkinson: The water balance climatology of the Mackenzie basin with reference to the 1994/95 water year. Atmosphere-Ocean 40(2), p 159-180.

McGinn, S.M. and H.D.J McLean, 1995: Monitoring free-water evaporation at automated weather stations. Journal of Atmospheric and Oceanic Technology, Vol 12, 1363-1366.

Meyer, A.F., 1915: Computing run-off from rainfall and other physical data. Trans. Am. Soc. Civil Engineers Vol. 79, p. 1067-1086.

_____, 1942: Evaporation from lakes and reservoirs. Minnesota Resources Commission, St. Paul, Minnesota, 67pp.

Morton, F.I., 1975: Estimating evaporation and transpiration from climatological observations. Journal of Applied Meteorology, Vol. 14, p 488-497.

_____, 1979: Climatological estimates of lake evaporation. Water Resources Research, Vol. 15, No.1, p. 64-76.

_____, R. Goard and J. Piwowar, 1980: Programs Revap and Wevap for estimating areal evapotranspiration and lake evaporation from climatological observations. NHRI Paper No. 12, Ottawa, 56 pp.

_____, 1983: Operational Estimates of lake evaporation. Journal of Hydrology, Vol. 66, p. 77-100.

_____, 1986: Practical estimates of lake evaporation. Journal of Climate and Applied Meteorology, Vol. 25, No.3, p. 371-387.

PFRA, 1988: Determination of gross evaporation for small to moderate-sized water bodies in the Canadian Prairies using the Meyer formula. Hydrology Report #113, Regina, 131 pp.

_____, 1989: Gross evaporation for the 30-year period 1951-1980 in the Canadian Prairies. Hydrology Report #121, Regina, 58 pp.

_____, 1994: Gross evaporation for the 30-year period 1961-1990 in the Canadian Prairies. Hydrology Report #133, Regina, 103 pp.

_____, 1995: Determination of coefficients for use in the Meyer formula. Hydrology Report #139, Regina, 24 pp.

_____, 2002: Gross evaporation for the 30-year period 1971-2000 in the Canadian Prairies. Hydrology Report #143, Regina, 114 pp.

Pomeroy, J.W., R.J. Granger, A. Peotroniro, J.E. Elliot, B. Toth and M.Hedstrom, 1997: Hydrological pathways in the Prince Albert Model Forest. NHRI Contribution Series No, CS-97004, Saskatoon, 154 pp.

PPWB, 1969: The Master Agreement on Apportionment. Prairie Provinces Water Board, 1991 amended agreement, 77pp.

Priestley, C.H.B, and R.J. Taylor, 1972: On the assessment of surface heat flux and evaporation using large-scale parameters. Monthly Weather Review Vol. 100, p. 81-92.

SNBB, 1972: Water supply study to the Saskatchewan-Nelson Basin Hydrology, Appendix 4, Volume 1. Saskatchewan-Nelson Basin Board, p. 153-234.

Strong, G.S., 1997: Atmospheric moisture budget estimates of regional evapotranspiration from RES-91. Atmosphere-Ocean, Vol. 35, No. 1, p. 29-63.

_____ and C. Hrynkiw, 2001: Open-water evaporation: the Swift Current water balance study. CMOS Bulletin Vol. 29, No. 2, p40-48.

_____, B. Proctor, M. Wang, E.D. Soulis, C.D. Smith, F. Seglenieks and K. Snelgrove, 2002: Closing the Mackenzie water budget, water years 1994/95 to 1996/97. Atmosphere-Ocean 40(2), p. 113-124.

Taylor; P.A., 2002: personal communication.

Warkentin, A., 2003: personal communication.

WMO, 1973: Comparison between pan and lake evaporation. World Meteorological Organization, Technical Note No. 126, Geneva, 52 pp.

Appendix A

GUIDELINES

FOR

EVAPORATION ESTIMATES

REQUIRED BY THE

PRAIRIE PROVINCES WATER BOARD

developed by

the

Committee on Hydrology

Prairie Provinces Water Board

February 1988

Background

The Prairie Provinces Water Board (PPWB) requires evaporation estimates for the administration of apportionment. Evaporation from impounded water is considered a consumptive use and not part of the natural system (e.g. evaporation from Lake Diefenbaker). Agencies of the PPWB also use evaporation estimates in water supply studies which involve surface storage of water (e.g. reservoirs, dugouts). Related applications involve power production, tailings ponds, sewage lagoons and waterfowl habitat, to name a few.

Monthly estimates of evaporation have proved convenient as a calculation period and in all the applications noted above. For the purposes of the PPWB, an annual estimate distributed in some reasonable fashion is all that is required. In practice, monthly estimates of evaporation are input to natural flow models which form the basis of apportionment monitoring.

The two approaches used by the PPWB are based on the Meyer equation and the Morton lake evaporation model. Both approaches require monthly data (mean temperature, mean humidity, and mean wind speed or total sunshine hours). These meteorological data are available historically at a number of sites across the Prairie Provinces so that calculations of monthly and annual evaporation can be performed back to about 1912. Much of the data prior to 1953 is available in paper copy only so that manual abstraction is needed to assemble the necessary data bases. The PPWB assesses the impact of proposed changes in water use on apportionment by adding the new demand to the current level of use and examining whether the apportionment agreement would have been violated over the period when historical data are available.

There have been some difficulties in using early meteorological data because anemometer heights are not well documented and the method of recording humidity has changed with time. There is also a lack of hydrometric data on all but major river systems in the first half of the century. However, most impact assessments and water supply studies would be viewed as deficient if the 1930s were not included as that presents a critical water supply period on the prairies.

Both the Meyer and Morton methods have been criticized but it is not trivial to demonstrate which is the better model. Attempts to verify the models against a control method (water budget for Weyburn Reservoir or Middle Creek Reservoir) have failed because of questions associated with the control method. A definitive comparison is required to settle which model should be used for PPWB purposes or indeed, whether a new model would be more appropriate.

With these thoughts in mind, the Committee on Hydrology for the PPWB offers the following guidelines for a NHRC-led research project which address not only the needs of the Board but also those of its agencies and other users of evaporation estimates.

Guidelines

1. Develop a control experiment against which to test which model (Meyer or Morton) provides the best estimate of evaporation in a prairie application. This may require several years of field data.

2. Assess Meyer and Morton models against other control experiments (e.g. Lake Hefner, others).

3. A range of water body sizes should be examined from Lake Diefenbaker to small reservoirs to dugouts.

4. Examine or develop other methods for computing evaporation with the following restrictions:

   a) input data should be readily available in machine readable format from at least 1930 (this could be relaxed if a clearly superior method could be applied to at least the last 30 - 40 years or record).

   b) monthly input data would be most convenient but daily or even hourly input data may be employed if the aggregate monthly evaporation estimates are clearly superior to those from any model based on monthly data. Evaporation estimates in a monthly format would be best for the current PPWB applications.

   c) some agencies of the Board require daily evaporation estimates on an operational basis.

   d) new methodologies should be applicable operationally as well as historically.

5.* If possible, address the magnitude and significance of evaporation from ice/snow covered surfaces (there is a significant difference between Morton and Meyer estimates of winter evaporation).

6.* The prairies represent the area of most urgent need for improved evaporation estimates but applicability to boreal forest and alpine environments is at least of secondary interest.

"*" of lesser importance

21 May, 2003