Practical Estimates of Lake Evaporation

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ABSTRACT

Practical estimates of lake evaporation must rely on data that can be observed in the land environment. This requires the ability to take into account the changes in the temperature and humidity that occur when the air passes from the land to the lake environment. The complementary relationship between potential and areal evapotranspiration provides such a capability and is used herein, in combination with an approximate technique for taking into account subsurface heat storage changes, as the basis for formulating the complementary relationship lake evaporation (CRLE) model. Because it has a realistic basis, the CRLE model can utilize routine climatological data observed in the land environment to provide estimates of lake evaporation anywhere in the world with no need for locally calibrated coefficients. This potential is demonstrated by comparing model estimates with published water budget estimates for sixteen lakes in North America and one lake in East Africa.

1. Introduction

Practical estimates of lake evaporation must rely on data that can be observed in the land environment. This has been attempted with the well-known pan evaporation, potential evaporation and mass transfer (or bulk aerodynamic) techniques. However, as has been documented elsewhere (Morton, 1983c), these techniques have serious conceptual and empirical failings, the most important of which is that they do not take into account the changes in temperature and humidity that occur when the air passes from land over a lake. Thus a lake creates its own environment which differs more from the land environment when the lake is in an arid region than when it is in a humid region. With an infinite variety of land environments, the coefficients that produce useful results for one lake cannot be transposed with confidence to any other lake.

Changes in temperature and humidity as the air passes from the land to the lake environment are compatible with the concept of a complementary relationship between potential and areal evapotranspiration (Morton, 1975, 1983a). The concept takes into account interactions between the evaporating surfaces and the overpassing air whereby a decrease in the availability of water for areal evapotranspiration causes the overpassing air to become hotter and drier, and this in turn causes the potential evapotranspiration to increase. It provides the basis for what is referred to as a CRAE (complementary relationship areal evapotranspiration) model, which permits areal evapotranspiration to be estimated from its effects on the routinely observed temperatures and humidities used in computing potential evapotranspiration. Because it avoids the complexities of the soil–plant system and the need for locally calibrated coefficients, the model estimates are independent and falsifiable so that errors in the associated assumptions can be detected and corrected by progressive testing against long-term water balance estimates of river-basin evapotranspiration from an ever-widening range of environments. Such a methodology uses the entire world as a laboratory and requires that a correction made to obtain agreement between model and water balance estimates in one environment must be applicable without change in all other environments. The conceptual and empirical foundations of the complementary relationship, its use in providing the basis for operational estimates of areal evapotranspiration, the testing of such estimates against 143 comparable water-budget estimates for river basins in Canada, the United States, Ireland, Australia, New Zealand and several countries in Africa, and the significance of such estimates to the science and practice of hydrology are discussed in detail elsewhere (Morton, 1983a).

The complementary relationship can also take into account the modification of the air as it passes from the land environment to the environment of a shallow lake. Thus a few minor changes (Morton, 1983a, 1983b) convert the CRAE model to a CRWE (complementary relationship wet-surface evaporation) model which can provide estimates of lake-size wet surface evaporation from routine climatological observations in the land environment with no locally calibrated coefficients. Although the lake-size wet surface evaporation corresponds to the evaporation from a lake so shallow that seasonal subsurface heat storage changes are negligible, monthly values can be accumulated to provide reliable estimates of annual evaporation from lakes with depths of up to 30 meters. This capability has been demonstrated by good agreement between the annual totals of monthly CRWE model estimates and the comparable water budget estimates for ten lakes in North America and Africa including two that had average depths exceeding the 30 meter limit by more than 100 percent (Morton, 1983b).

Good monthly estimates of evaporation for lakes of significant depth must take into account seasonal changes in subsurface heat storage by means of vertical temperature profiles. Since this is operationally impracticable, the subsurface heat storage changes have been accounted for in an approximate way (Morton, 1983b) by routing model estimates of lake-size wet surface evaporation through hypothetical heat reservoirs with delay times and storage constants related to the depth and salinity of the lake, using a routing technique similar to those used in routing water through natural reservoirs in hydrology. Although this procedure provided reasonable agreement with water budget estimates for the ten lakes referred to in the preceding paragraph, it proved to be conceptually inadequate when applied to a lake 150 meters deep. This is because it required that the annual lake evaporation be equal to the annual lake-size wet surface evaporation and thus failed to recognize that heat is absorbed into storage during seasons when evaporation consumes a high proportion of the available energy and is released from storage during seasons when evaporation consumes a low proportion of the available energy. The CRLE (complementary relationship lake evaporation) model presented herein has solved this problem by routing the absorbed global radiation (rather than the lake-size wet surface evaporation) through the hypothetical heat reservoir. Although one of the purposes of this paper is to present the formulation of this most recent CRLE model, there are a number of others as well. In the order that they are dealt with these other purposes are

1) To try once more to clarify the workings of the complementary relationship and make them more understandable to hydrologists and meteorologists. This is necessary because textbooks, university courses and the literature dogmatically inculcate a narrow, simplistic and untested view of hydrometeorological processes, a view that the complementary relationship exposes as false.

2) To expand the test range from 10 to 17 lakes. Tabulations of monthly mean water budget estimates of lake evaporation, CRLE estimates of lake evaporation and CRWE estimates of lake-size and pan-size wet surface evaporation for each lake provide a rigorous test of the CRLE model, a demonstration of the workings of the complementary relationship and an up-to-date summary of what are, insofar as is known, the water budgets that comprise our only reliable empirical knowledge of lake evaporation.

3) To evaluate the CRLE model and to indicate how, despite its shortcomings, it is superior to the alternative techniques from the conceptual, empirical and practical points of view.

2. The complementary relationship

A conceptual rationalization and a review of available theoretical knowledge and reliable empirical evidence (Morton, 1983a) have demonstrated that the complementary relationship is one of the better substantiated concepts in hydrology and hydrometeorology. It is expressed in the following equation:

$$E_T + E_{TP} = 2E_{TW}, \tag{1}$$

in which E_T is the areal evapotranspiration, the evapotranspiration from an area so large that the effects of upwind boundary transitions, such as those shown later in Fig. 4, are negligible; E_{TP} is the potential evapotranspiration, as estimated from a solution of the vapor transfer and energy-balance equations, representing the evapotranspiration that would occur from a hypothetical moist surface with radiation absorption and vapor transfer characteristics similar to those of the area and so small that the effects of the evapotranspiration on the overpassing air would be negligible; and E_{TW} is the wet-environment areal evapotranspiration, the evapotranspiration that would occur if the soil–plant surfaces of the area were saturated and there were no limitations on the availability of water.

Figure 1 provides a schematic representation of Eq. (1) under conditions of a relatively high radiant-energy supply (solid line) and a relatively low radiant-energy supply (dashed line). The ordinate represents evapotranspiration and the abscissa represents water supply to the soil–plant surfaces of the area, a quantity that is usually unknown. When there is no water available for areal evapotranspiration (extreme left of Fig. 1) it follows that $E_T = 0$, that the air is very hot and dry and

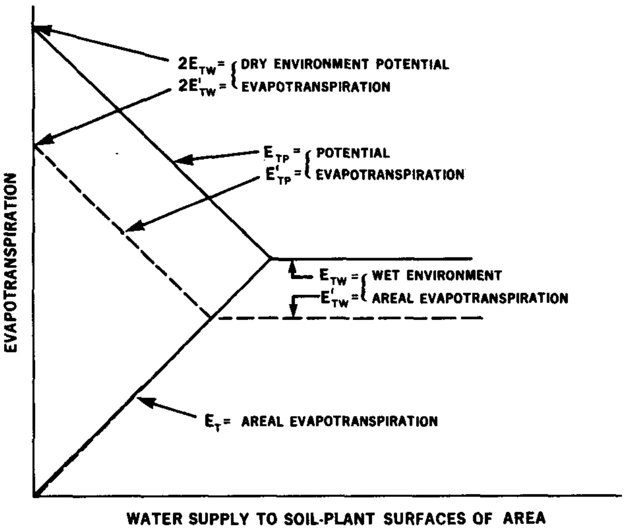

FIG. 1. Schematic representation of complementary relationship between areal and potential evapotranspiration with a relatively high radiant-energy supply (solid line) and a relatively low radiant-energy supply (broken line).

that E_{TP} is at its maximum rate of $2E_{TW}$ (the dry environment potential evapotranspiration). As the water supply to the soil–plant surfaces of the area increases (moving to the right in Fig. 1) the resultant equivalent increase in E_T causes the overpassing air to become cooler and more humid, which in turn produces an equivalent decrease in E_{TP}. Finally, when the supply of water to the soil–plant surfaces of the area has increased sufficiently, the values of E_T and E_{TP} converge to that of E_{TW}.

The conventional definition for potential evapotranspiration is the same as the definition for the wet-environment areal evapotranspiration. However, the potential evapotranspiration that is estimated from a solution of the vapor transfer and energy-balance equations by analytical (Penman, 1948), graphical (Ferguson, 1952) or iterative (Morton, 1983a) techniques reacts to changes in the water supply to the soil–plant surfaces in a way similar to those shown for E_{TP} in Fig. 1, so that what is being estimated can exceed what is being defined by as much as 100%. By taking into account such reactions, the complementary relationship is analogous to the Bernoulli equation for open-channel flow in which the potential energy responds in a complementary way to changes in kinetic energy.

The workings of the complementary relationship are also demonstrated in Fig. 2, which has been prepared from monthly data for the 83.5 km^2 Basin 7 in the Sanguéré area of Cameroon (Casenave, 1978). The demonstration period is the year from 1 April 1974 to 31 March 1975, during which the rainfall was 1114

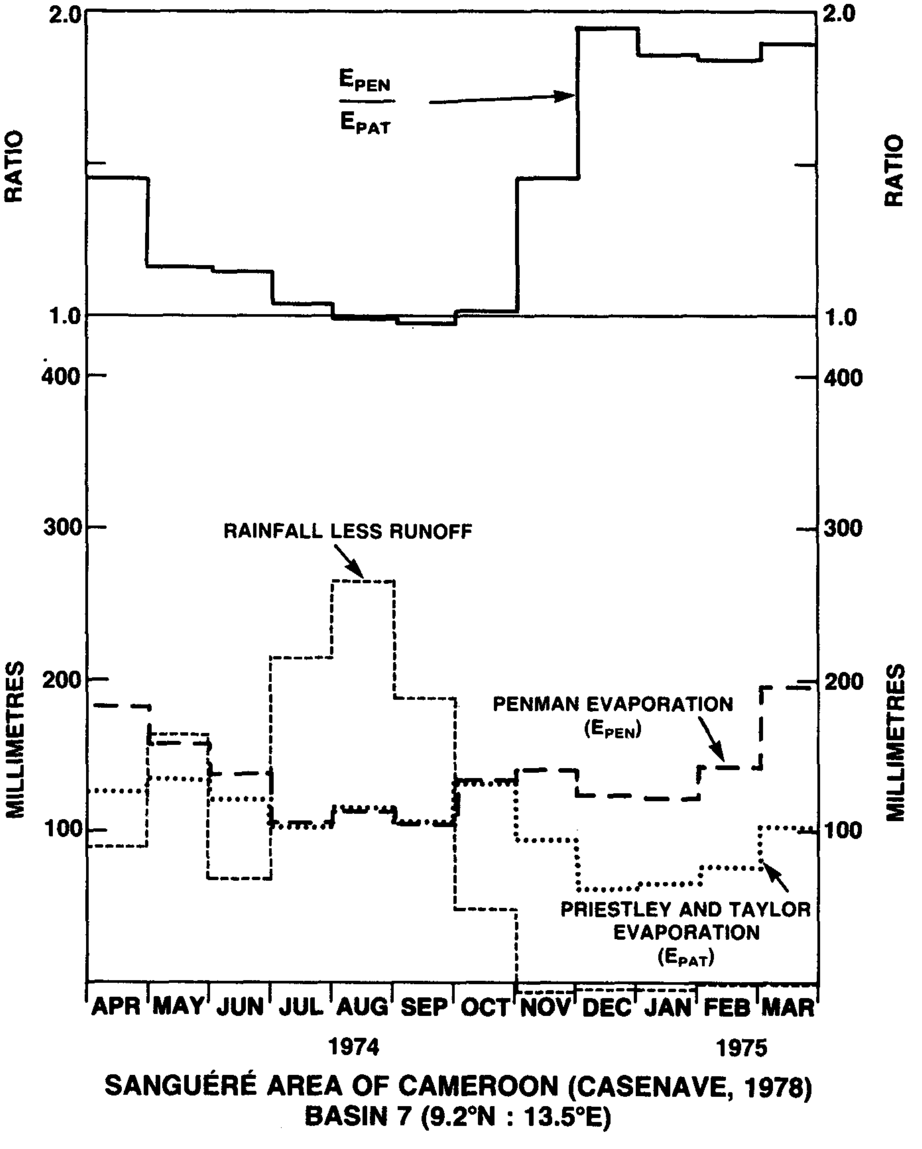

FIG. 2. Workings of the complementary relationship in Basin 7 of Sanguéré area of Cameroon. (Casenave, 1978)

mm, the runoff was 74 mm, the monthly temperatures ranged from 24.9° in January to 32.9°C in March, and the monthly relative humidities ranged from 84% near the end of the wet period in September to 32% near the end of the dry period in March. The short-dash line in Fig. 2 is the difference between monthly rainfall and monthly runoff. It provides a reasonable representation of the water available for evapotranspiration although it ignores the carry-over of soil moisture and groundwater from the seven-month rainy season (April–October) to the five-month rainless season (November–March). The long-dash line is the evaporation estimated from the Penman (1948) equation, $E_{\rm PEN}$, which is a function of the net radiation, temperature, humidity and wind speed. Being an analytical solution of the energy balance and vapor transfer equations, it provides an adequate representation of the potential evapotranspiration. The dotted line is the evaporation estimated from the Priestley and Taylor (1972) equation, $E_{\rm PAT}$, which is a product of a net radiation (the same net radiation that is used to compute $E_{\rm PEN}$) and a slowly varying function of the temperature. In environments like the Sanguéré, where the monthly net radiation never gets anywhere near zero, it provides a good representation of the wet environment areal evapotranspiration. Therefore the ratio of $E_{\rm PEN}$ to $E_{\rm PAT}$ should provide a reasonably good reflection of the ratio of the potential to the wet environment areal evapotranspiration.

The ratios of the Penman evaporation, $E_{\rm PEN}$, to the Priestley and Taylor evaporation, $E_{\rm PAT}$, are plotted as a solid line in Fig. 2. They vary from minima near 1.0 during the wet season to maxima of somewhat less than 2.0 during the dry season. The immediate reasons for this seasonal pattern are the responses of $E_{\rm PEN}$ to changes in the relative humidity, which has average values of about 0.82 during the rainy season and about 0.35 during the rainless season. However, the ultimate cause is the variation in the availability of water for areal evapotranspiration from some value greater than the availability of energy during the rainy season to some value approaching zero during the rainless season. The way that this controls the temperature and humidity of the overpassing air and the ratio of $E_{\rm PEN}$ to $E_{\rm PAT}$ is the essence of the complementary relationship and corresponds almost exactly to its predictions.

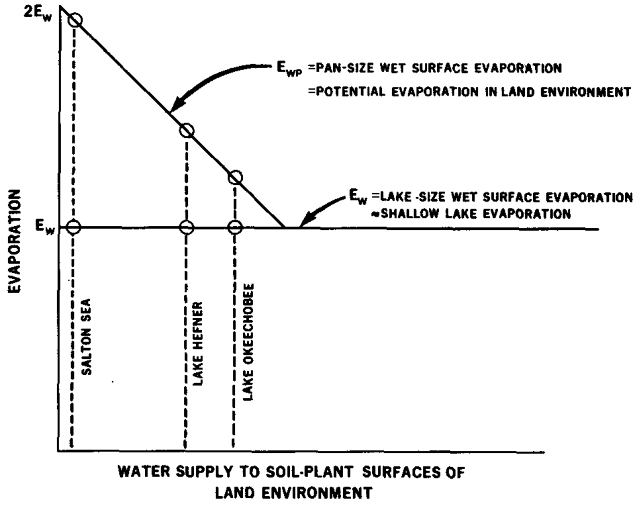

FIG. 3. Schematic representation of relationship between lake-size wet surface evaporation and pan-size wet surface evaporation that shows why there are differences between the coefficients for pans at the Salton Sea, Lake Hefner and Lake Okeechobee.

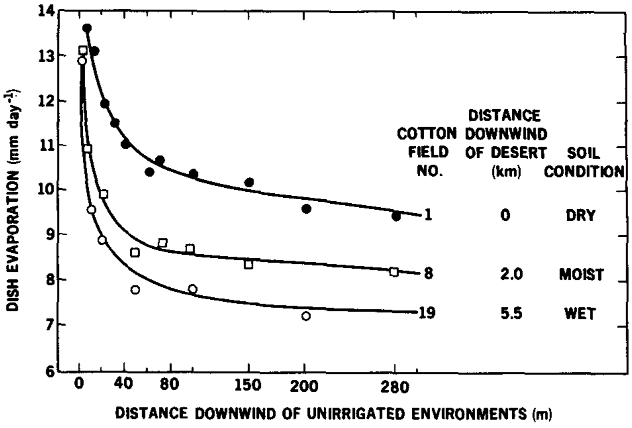

FIG. 4. Comparison of evaporation rates across irrigated cotton fields on 27 December 1963 (Davenport and Hudson, 1967).

The evaporation from a lake-size wet surface, E_W, differs from the wet-environment areal evapotranspiration, E_{TW}, only because the radiation absorption and vapor transfer characteristics of water differ from those of vegetated land surfaces. The potential evaporation (hereinafter referred to as pan-size wet surface evaporation and denoted by the symbol E_{WP}) differs from the potential evapotranspiration, E_{TP}, for the same reasons. Although the lake-size wet surface evaporation would be equal to the evaporation from a pan-size wet surface located in the lake environment it would differ significantly from the pan-size wet surface evaporation in the land environment.

Figure 3 provides a schematic representation of the relationship between pan-size wet surface evaporation and lake-size wet surface evaporation in the land environment under conditions of constant radiant-energy supply. The ordinate represents evaporation and the abscissa represents the water supply to the soil–plant surfaces of the land environment. Since a lake is defined to be so wide that the effects of the kind of upwind transition shown later in Fig. 4, are negligible, the lake-size wet surface evaporation is independent of variations in the water supply to the soil–plant surfaces of the land environment. However, the complementary relationship predicts that the pan-size wet surface evaporation in a completely dry land environment would be twice the lake-size wet surface evaporation and that it would decrease in response to increases in the water supply to the soil–plant surfaces until it reached a minimum equal to the lake-size wet surface evaporation as shown in Fig. 3.

Figure 3 uses data from a tabulation published by Hounam (1973) to explain why the evaporation estimated from pans or climatological observations in the land environment cannot be transposed to other lakes by applying a simple coefficient. The tabulation shows that the annual Class-A pan coefficient is 0.81 for Lake Okeechobee in Florida, where the average annual precipitation is ~1400 mm; 0.70 for Lake Hefner in Oklahoma, where the average annual precipitation is ~800 mm; and 0.52 for the Salton Sea in California, where the average annual precipitation is ~60 mm. These kind of variations undermine the foundations of the well-known pan evaporation, potential evaporation and mass transfer techniques because they indicate that lakes create their own environments, which differ more and more from the land environments as the land environments become more arid. However, they are compatible with the complementary relationship and the kind of interactions shown in Fig. 3 and later in Fig. 4. Thus the plotted points for the Salton Sea, Lake Hefner and Lake Okeechobee have values of E_W/E_{WP} that correspond to pan coefficients of 0.51, 0.70 and 0.81, respectively, and values of water supply to the soil–plant surfaces that are compatible with annual precipitation less runoff totals of approximately 60, 700 and 1000 mm respectively.

Reliable information on the transition that takes place when the air passes from a dry to a wet environment is rare if not nonexistent. However, Davenport and Hudson (1967) have measured the variation in evaporation across a series of irrigated and fallow fields in the Sudan Gezira, using fiberglass dishes with black-painted wells 113 mm in diameter and 36 mm in depth. The dish evaporation provided a somewhat distorted reflection of the potential evapotranspiration. The passage of air from the desert (or from the unirrigated fallow fields) over the irrigated cotton caused the dish evaporation above the cotton to decrease rapidly in the downwind direction and to approach a low constant value within 300 m, the width of the fields. Furthermore, as the air passed from irrigated cotton across unirrigated fallow, the dish evaporation above the fallow increased rapidly in the downwind direction and approached but did not reach the value observed at the upwind edge of the irrigated area. Figure 4 shows the variation of dish evaporation across three irrigated fields on 27 December 1963. The ratio of daily dish evaporation at the downwind edges of the irrigated cotton to that at the upwind edge of the irrigated area was 0.69 for the field with "dry" soil, 0.60 for the field with "moist" soil and 0.53 for the field with "wet" soil. The ratio for the "wet" field approximates 0.50, the ratio of wet environment to dry environment potential evapotranspiration predicted by the complementary relationship.

The decreases in dish evaporation across the cotton fields were associated with decreases in temperature and increases in humidity. The vapor pressures appeared to attain equilibrium values within the 300 m width of the fields, but the temperatures were still decreasing, possibly because the observations were made above the level of the crop and the dishes.

Figure 4 shows how the dish evaporation and potential evaporation increase when the water available for evapotranspiration from the area upwind decreases and how they decrease when the water available for evapotranspiration from the area upwind increases. This is as predicted by the complementary relationship. Moreover, the dish evaporation for the "wet" field provides an indication of what happens over a lake in an arid climate. Thus the low, relatively constant dish evaporation near the downwind edge reflects the potential evaporation over most of the lake, the upwind dish evaporation reflects the potential evaporation in the desert and the ratio between the two is very close to the pan coefficient for the Salton Sea, where the average precipitation is ~60 mm yr^{-1}. Furthermore, the dish evaporation from the "moist" and "dry" fields provides an analogy for what happens over lakes in progressively more humid climates where the contrasts between lake and land environments are less extreme. Because the transition zone is so narrow, the lake evaporation would approximate the low constant downwind value of potential evaporation.

3. Subsurface heat storage changes

Good monthly estimates of lake evaporation must take into account seasonal changes in subsurface heat storage by means of vertical temperature profiles. Because this is operationally impracticable, the subsurface heat storage changes have been taken into account in an approximate way (Morton, 1983b) by routing CRWE estimates of lake-size wet surface evaporation through hypothetical heat reservoirs, with delay times and storage constants related to the depth and salinity of the lake, using a routing technique similar to those used in routing water through natural reservoirs in hydrology. Although this procedure provided reasonable agreement with water budget estimates for ten lakes, including one with an average depth of 61 m and another with an average depth of 86 m, it proved inadequate when applied to a lake with an average depth of 148 m. This is because it required that the long-term average annual lake evaporation be equal to the long-term average annual lake-size wet surface evaporation, a requirement that fails to recognize that heat is absorbed into storage during seasons when evaporation consumes a high proportion of the available energy and is released from storage during seasons when evaporation consumes a low proportion of the available energy. The CRLE model presented herein solves this problem by routing the solar and waterborne heat input (rather than the lake-size wet surface evaporation) through the hypothetical heat reservoir. This solar and waterborne heat input, $G_W{}^0$, is estimated from

$$G_W{}^0 = (1 - a)G + h \qquad (2)$$

in which G is the incident global radiation, a the albedo, $(1 - a)G$ the solar energy input, h the waterborne energy input and the superscript 0 refers to the current month. The quantity h is usually negligible but for small lakes that receive cooling water from thermal power plants and for relatively small, deep reservoirs on large rivers (e.g., Lake Mead) where the difference between the heat content of the inflows and the heat content of the outflows has significant seasonal variations, it should be taken into account. In such cases the monthly values would be estimated separately and added to the input assembly.

The next step is to estimate the delayed solar and waterborne energy inputs ($G_W{}^t$) from

$$G_W{}^t = G_W^{[t]} + (t - [t])(G_W^{[t+1]} - G_W^{[t]}) \qquad (3)$$

in which $[t]$ and $t - [t]$ are the integral and fractional components of the delay time, t, in months [see Eqs. (6) and (7)], $G_W^{[t]}$ is the value of $G_W{}^0$ computed $[t]$ months ago, and $G_W^{[t+1]}$ is the value of $G_W{}^0$ computed $[t + 1]$ months ago. This procedure, which requires the storage of $G_W{}^0$ for the past $[t + 1]$ months, has been developed to estimate the value of solar and waterborne energy inputs with a delay time that has both integral and fractional components from the values for two of the preceding integral months.

The final step is to compute the available solar and waterborne energy, G_L, from the following well-known linear routing procedure:

$$G_{LE} = G_{LB} + \frac{G_W{}^t - G_{LB}}{0.5 + k} \qquad (4)$$

$$G_L = 0.5(G_{LE} + G_{LB}) \qquad (5)$$

in which G_{LB} and G_{LE} are the available solar and waterborne energy at the beginning and end respectively of the current month and k is the storage constant [see Eqs. (6) and (8)]. This procedure requires that G_{LE} for the current month be stored and converted to G_{LB} for the next month. Although errors arising from the arbitrary initial selection of G_{LB} and of the previous $[t + 1]$ values of $G_W{}^0$ wear off quite quickly, the CRLE model requires that the computations for first year be repeated three times and that only the results of the third trial be accepted as correct. Although this procedure eliminates the error resulting from arbitrarily selected initial conditions, it does not eliminate the error resulting from the implicit requirement that the total available solar and waterborne energy during the first year be equal to the total solar and waterborne energy inputs during the first year. However, experience indicates that the latter type of error is probably quite small (Morton et al., 1985).

The soft water delay time in months (t_0), the lake delay time in months (t) and the storage constant in months (k), are estimated from

$$t_0 = 0.96 + 0.013d \quad \text{with} \quad 0.039d \leqslant t_0 \leqslant 0.13d \qquad (6)$$

$$t = t_0/(1 + s/27000)^2 \quad \text{with} \quad t \leqslant 6.0 \qquad (7)$$

$$k = t_0/[1 + (d/93)^7], \qquad (8)$$

in which d is the average depth of the lake in m, and s is the salinity (or total dissolved solids) in ppm.

The foregoing relationships were derived from monthly or monthly mean values of water budget evaporation for nine lakes over a period of a year and from the comparable estimates derived from this version of the CRLE model, using many different combinations of k and t. The methodology required 1) a percentage adjustment to the monthly model estimates to make the annual total equal the annual water budget total, 2) the sequential accumulation of the deviations between these adjusted monthly values and the corresponding monthly water budget values, and 3) the selection of those values of k and/or t that minimize the annual range between the maximum and minimum accumulated monthly deviations. Equation (8) was derived first from the best combinations of k and t_0. It was then incorporated into the model and used to find the best values of t_0 for use in the derivation of Eq. (6) and its constraints. Eight of the lakes have soft water, with salinities of 3700 ppm or less, so that Eq. (7) depends almost entirely on data from the Salton Sea, which had a salinity of 37 000 ppm. The constraint on Eq. (7) is applied because there is no evidence to justify extrapolation of the delay time past the logical maximum value of 6 months.

Equation (6) and its constraints and Eq. (8) are shown graphically on Fig. 5 together with the best combinations of k and t_0 for each of the nine lakes. An exponential asymptotic transition between $0.13d$ and $0.039d$ could have been used as an option to Eq. (6) and its constraints but was thought to add a pseudoscientific elegance to what is essentially a crude relationship.

It should be noted that the conceptual basis for the routing technique is grossly oversimplified. Thus it assumes that all heat inputs are automatically absorbed into a single storage reservoir and that all reservoir releases are linearly related to the heat content whereas both heat absorption and heat releases are influenced more by vertical density differences. This is complicated by the way that the density of water reaches a maximum at 4°C. In spite of these weaknesses the routing technique is well worthwhile because it has the potential to provide reasonably realistic seasonal patterns of evaporation for many lakes and to account for the effects of great depth in reducing the annual lake evaporation.

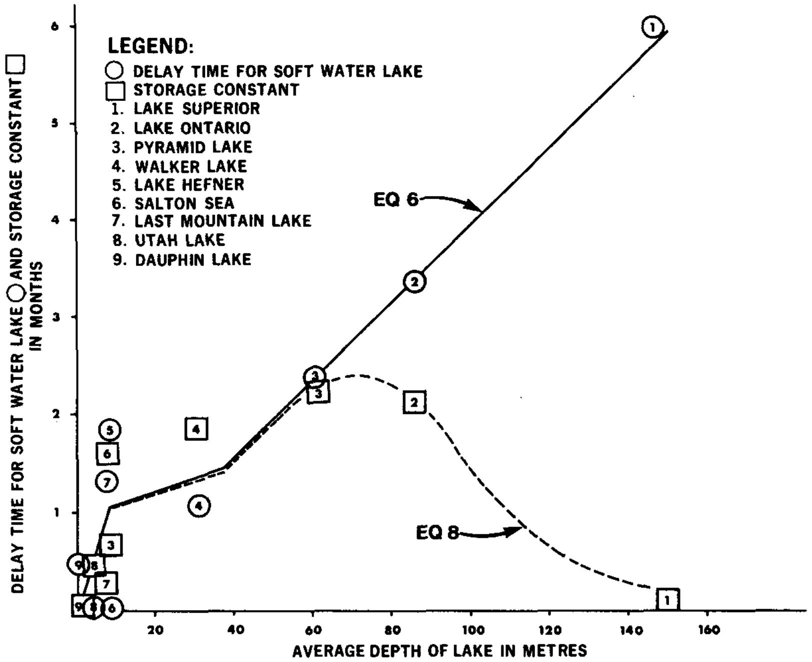

FIG. 5. Relationships between lake depth, delay time and storage constant.

4. Complementary relationship models

In the CRAE model the potential evapotranspiration (E_{TP}) is estimated from a quickly converging solution to the energy balance and vapor transfer equations and the wet environment areal evapotranspiration (E_{TW}) is estimated from the equation for potential evaporation proposed by Priestley and Taylor (1972) as adjusted to account for the effects of large-scale advection during winter. The two coefficients needed for the adjustment and the vapor transfer coefficient needed in the computation of E_{TP} have been calibrated using data for dry months in arid regions where the sum of E_{TP} and the precipitation approximates $2E_{TW}$ (Morton, 1983a). The CRWE model (and hence the CRLE model) have been calibrated using the same data. It is emphasized that this was a once-only calibration and that the models can now be applied without the need for locally calibrated coefficients.

The CRAE, CRWE and CRLE models have been combined into one main program. The FORTRAN version of this program, which is known as Program WREVAP, has been thoroughly documented and published (Morton et al., 1985) while a version prepared for use on the Hewlett-Packard HP-41CV and HP-41CX hand-held calculators can be made available on request. The CRAE and CRWE options are practically identical to those documented previously (Morton et al., 1980; Morton, 1983a; Morton, 1983b). The only differences are

1) The provision of greater flexibility in the selection of time periods that can vary in length from one day to one month has led to the use of values for the declination and radius vector of the sun that are averages of the daily values for each day of the period rather than the value for the middle day of the period. This practice has a minimal effect on the results in that it may increase the estimates by 1 mm/month during the Northern Hemisphere spring and decrease the estimates by 1 mm/month during the Northern Hemisphere fall (Morton et al., 1985).

2) The minimum constraint on the net longwave radiation has been changed from 5% to 3% of the surface longwave radiation. This has little effect because it applies only under very hot, humid and cloudy conditions such as those prevailing in a lowland equatorial rain forest during the rainiest part of the year.

3) The effects of salinity on the CRWE estimates of wet surface evaporation have been taken into account by dividing the soft water estimates by $(1 + s/10^6)$. This provides somewhat better agreement with the results obtained by Adams (1934) for Great Salt Lake brine than Langbein's (1961) suggestion that the soft water estimates be multiplied by $(1 - s/10^6)$.

The CRLE model differs from the CRWE model primarily because G_L, the available solar and water-borne energy estimated from Eq. (5), replaces $(1 - a)G$, the absorbed global radiation that is a component of Eq. (2), in all further computations. Thus the net available energy, the difference between G_L and the net longwave radiation, takes the place of the net radiation, the difference between $(1 - a)G$ and the net longwave radiation, in the evaporation computations. Unfortunately, this seemingly simple change is exceedingly difficult to implement because it requires the use of data that were produced in the computations for previous time periods. This complexity is evident in the flow chart for Program WREVAP (Morton et al., 1985) where the part used by the CRLE model adds approximately 70% to the length used only by the CRAE and CRWE models.

The CRLE option differs from the CRWE option in two other ways. They both hinge on the possibility that the release of stored heat during the late fall and winter months will create an open water environment when the land environment is frozen up. This is considered possible when the available solar and waterborne energy exceeds the solar and waterborne energy input, when the potential evaporation equilibrium temperature exceeds the air temperature and when the net available energy corresponding to a lake surface at air temperature exceeds zero. The simultaneous fulfillment of these three criteria requires that

1) Any potential evaporation estimate that is less than the lake evaporation estimate be set equal to the lake evaporation estimate. With any one of the three foregoing criteria not in effect, the CRLE model would react in the same way as the CRAE and CRWE models and reduce the lake evaporation estimate to the potential value.

2) The evaporation be computed using the latent heat of vaporization even when the air temperature is below freezing. With below freezing temperatures and any one of the three foregoing criteria not in effect, the CRLE option, like the CRAE and CRWE options, would utilize the latent heat of sublimation.

The location characteristics required for the CRLE option of Program WREVAP are the latitude in decimal degrees, the altitude in meters above sea level (with the average atmospheric pressure in mb as an option), the average salinity (total dissolved solids) of the lake in ppm and the average depth of the lake in meters. For the CRWE option the average depth is not needed and for the CRAE option both the average depth and the average salinity are replaced by the long-term average annual precipitation in mm.

The climatological data inputs are the same for the CRAE, CRWE and CRLE options of Program WREVAP. The required humidity input may be the dew point temperature in °C (or °F), the vapor pressure in mb or the relative humidity as a ratio; the required temperature input may be in °C (or °F); and the required insolation input may be the sunshine duration as a ratio of the maximum possible sunshine duration, the sunshine duration in h d^{-1}, the incident global radiation in ly d^{-1} or the incident global radiation in MJ m^{-2}/d. No other climatological or hydrological inputs are required.

The CRLE model outputs are rather insensitive to changes in latitude of less than 1°, to changes in altitude of less than 200 m, to changes in average depth of less than 5 percent and to changes in salinity of less than 5000 ppm. For soft water lakes, which have concentrations of total dissolved solids significantly less than 5000 ppm, the salinity inputs can be guessed. With regard to the climatological requirements, the CRLE model estimates are most sensitive to errors in the required sunshine duration or radiation inputs. They are relatively insensitive to errors in the humidity and the temperature inputs. Furthermore it does not matter much where in the vicinity of the lake the temperature and humidity inputs are observed because the complementary relationship automatically takes into account the effects of differing surroundings. Thus the difference between estimates derived from observations in the land environment and estimates derived from observations over the lake would be due primarily to the relatively minor effect of the difference in humidity on the estimates of net radiation. In this, the CRLE model differs from CRAE model because the latter requires accurate temperature and humidity data from a representative location.

The optional outputs for Program WREVAP are 1) the CRLE model estimates of lake evaporation, potential evaporation and the net available energy corresponding to lake surfaces at air temperature; 2) the CRWE model estimates of lake-size wet surface evaporation, pan-size wet surface evaporation and the net radiation corresponding to wet surfaces at air temperature; or 3) the CRAE model estimates of areal evapotranspiration, potential evapotranspiration and the net radiation corresponding to soil–plant surfaces at air temperature. All of these estimates are in mm or mm of evaporation equivalent. The potential impacts of some of these outputs on lake studies are not immediately apparent and these are discussed below.

1) The lake-size wet surface evaporation, when accumulated over a number of years, can provide a reasonable estimate of the annual evaporation from any lake with an average depth of 30 m or less (see discussion in a subsequent section). Because it is independent of depth, it is ideal for generalized scientific, geographic or comparative purposes, such as the preparation of maps.

2) When derived from climatological observations in the land environment, the pan-size wet surface evaporation can provide an estimate of the evaporation at the upwind edge of the lake. Therefore it can be useful in estimating the evaporation from ponds, i.e., the evaporation from bodies of water that are intermediate in area between a pan and lake, as described in the next section.

3) The areal evapotranspiration, when subtracted from the lake evaporation, can provide an estimate of the net reservoir evaporation, the amount by which the reservoir evaporation exceeds (or will exceed) the evapotranspiration that would have occurred from the

flooded area in its natural state. The net reservoir evaporation is an important quantity because it represents the impact of a reservoir on the water balance of a drainage basin.

4) The potential evaporation has no real world meaning because the estimates are sensitive to both the energy regime of the lake environment and the temperature and humidity regime of the land environment and the two regimes can be significantly out of phase. Thus the energy maximum for Lake Superior occurs during the winter when low radiant energy causes the temperatures and vapor pressures in the land environment to be near their minimum values for the year. It should be noted that the lake evaporation estimates do not share this lack of meaning because they take into account the effects of the lake on the overpassing air.

Program WREVAP has a number of time period options that can vary in length from one day to one month. The nature of the complementary relationship is such that estimates for time periods shorter than 5 d would always be suspect and the dimensions of the routing constants (t and k) ensure that lake evaporation estimates for time periods other than a month will be unrealistic. These time period constraints are more than adequate for practically all hydrological applications. However there are occasions, as in real-time hydrological forecasting, when daily updating would be convenient and for this reason a technique has been developed whereby hydrologically meaningful daily values can be estimated in such a way that the errors resulting from the use of short time periods do not accumulate (Morton et al., 1985).

5. Pond evaporation

Pond evaporation is the evaporation from a body of water so small that the effects of the upwind boundary transition cannot be ignored. The nature of the transition is shown in Fig. 4 where the dish evaporation at the upwind edge of the cotton fields is analogous to E_{WP} and the dish evaporation at the downwind edge of the cotton fields is approaching a low constant value that is analogous to E_L. The approximate effects of the transition on E_{LY}, the evaporation from a pond with a wind fetch of Y, have been formulated elsewhere (Morton, 1983b). The resultant equation is

$$E_{LY} = E_L + (E_{WP} - E_L)(C/Y)\ln(1 + Y/C) \quad (9)$$

in which the constant C is 13 m, the geometric mean of the constants required to define the shapes of the three curves in Fig. 4.

In order to compute pond evaporation it is necessary to know the average wind fetch (Y), the pan size wet-surface evaporation (E_{WP}), as computed from the CRWE model (or the CRLE model with $d = 0$), and the lake evaporation (E_L), as computed from the CRLE model with d = the average depth of the lake. This means that it is necessary to use both the CRWE and CRLE models before Eq. (9) can be applied.

6. Test of CRLE and CRWE models

In testing lake evaporation models the only standards of comparison that have any basis in reality are estimates based on the energy budget technique or estimates based on the water budget technique.

Energy budget estimates of the lake evaporation are based on the law of conservation of energy. The available energy (e.g., the sum of the net radiation, changes in subsurface heat storage, net waterborne heat inputs, etc.) is apportioned between sensible and latent heat by using the Bowen ratio. However the Bowen ratio is based on the assumption that the eddy transfer coefficients for heat and water vapor are equal, an assumption that has always been open to doubt, particularly under inversion conditions when the downward flux of sensible heat has to overcome the effects of buoyancy. Lang et al. (1983) have analyzed the results of eddy-correlation and Bowen-ratio instrumentation in a rice field and found that the ratio of the eddy transfer coefficient for heat to the eddy transfer coefficient for water vapor under inversion conditions was somewhere between 0.6 and 0.8. With such a difference the Bowen-ratio energy budget estimates of lake evaporation would be much too high during the summer months when daytime inversions tend to prevail. Moreover, the energy budget concept has never been tested rigorously by applying an identical technique to a number of lakes in different environments and comparing the results with the water budget estimates. The nearest approach to such a test was performed in Australia (Hoy and Stevens, 1979), but this was not satisfactory because the lakes were unsuitable for water budget studies and it was assumed that the energy budget estimates were superior. The word "identical" should be stressed because it is easy to obtain preconceived results through judicious selection from the many different published methods for estimating components of the energy budget. For these reasons the energy budget technique is not suitable as a standard of comparison for judging other techniques.

Water budget estimates of lake evaporation are based on the law of conservation of mass. Thus the evaporation is equal to the sum of the difference between the inflow and outflow volumes (divided by the lake area), the precipitation and the decrease of lake level. Although the estimates or measurements of precipitation and the outflow are normally quite straightforward, there are problems with the other components. Those associated with the changes in level contribute to error in the seasonal distributions but have no significant effect on the annual totals. A much more serious problem is that some of the tributary inflows and all of the groundwater inflows are usually unmeasured or unmeasurable. The only way to circumvent this predicament is to select lakes with sufficient area to make the volume of evaporation much greater than the possible error in the estimated inflows. Such lakes are rare and found most freqently in arid and semiarid environments. Although scarce and prone to error, the water budget estimates for such lakes provide the only real information that is available for the study of lake evaporation and the only standards of comparison that are available for judging the reality of other estimating techniques.

The selection of water budget estimates of lake evaporation for use as standards of comparison requires a certain amount of judgment and if this is done by an individual researcher there will always be suspicions of bias. It has been suggested (Morton, 1983c) that a possible solution to this problem and to the problem of scarcity would be the preparation of a world register of lake water budgets by some international agency. In the meantime, a survey of the English-language literature has led to the conclusion that there are only 17 lake water budgets suitable for use as standards of comparison and that some of these are questionable. The application of the selection criteria can be exemplified by reference to the Great Lakes of North America. Thus the Lake Superior water budget estimates (Derecki, 1980) are excellent because they are adequately documented and because the volume of evaporation is much greater than errors in the estimated inflows. On the other hand, the Lake Ontario water budget estimates (DeCooke and Witherspoon, 1981) are acceptable only because the quality of the work done during the International Field Year on the Great Lakes (IFYGL) outweighs the prospect that a 1% bias in either the St. Lawrence River outflows or the Niagara River inflows could produce an error of 10% in the evaporation estimates. Although Lake Erie has inflows that are somewhat smaller and an area that is somewhat larger, its water budget is beyond the limits of acceptability. This is because the records of inflow from its major tributary, the Detroit River, are of much poorer quality than those for the inflow to Lake Ontario from the Niagara River, because water level fluctuations due to wind setups and seiches are 3 to 4 times larger on Lake Erie than on Lake Ontario and because the water budget was not included in the IFYGL.

TABLE 1. Evaporation from Dauphin Lake in Manitoba, Canada for 24 months, 1967–68.

Latitude = 51.25° Altitude = 260 m
Average depth = 2.0 m Salinity = 300 ppm
—Dew points, air temperatures and sunshine duration at Dauphin
—Water budget evaporation from Morton (1979)

	Wet surface evaporation (CRWE estimate)		Lake evaporation	
Month	Pan-size E_{WP} (mm)	Lake-size E_W (mm)	CRLE estimate E_L (mm)	Water budget estimate E_B (mm)
Jan	−4	−4	−4	−2
Feb	−2	−2	−2	0
Mar	20	18	6	28
Apr	60	53	36	52
May	138	106	87	94
Jun	174	128	124	117
Jul	190	156	146	152
Aug	150	117	135	92
Sep	114	70	90	94
Oct	22	20	42	54
Nov	1	1	8	−1
Dec	−4	−4	−3	6
Annual	859	659	665	690

TABLE 2. Evaporation from Last Mountain Lake in Saskatchewan, Canada for 24 months, 1973 and 77.

Latitude = 51.1° Altitude = 490 m
Average depth = 7.6 m Salinity = 1700 ppm
—Dew points, air temperature and sunshine duration at Regina, Moosejaw, Saskatoon and Wynyard
—Water budget evaporation from Morton (1983b)

	Wet surface evaporation (CRWE estimate)		Lake evaporation	
Month	Pan-size E_{WP} (mm)	Lake-size E_W (mm)	CRLE estimate E_L (mm)	Water budget estimate E_B (mm)
Jan	−3	−3	7	−2
Feb	−2	−2	−4	6
Mar	46	36	0	−2
Apr	107	72	14	14
May	161	117	53	58
Jun	189	144	90	124
Jul	204	152	128	140
Aug	174	120	138	142
Sep	87	54	121	113
Oct	45	28	82	64
Nov	−3	−3	42	46
Dec	−3	−3	24	−1
Annual	1005	715	695	702

Tables 1–17 summarize the monthly or average monthly values of the pan-size wet surface evaporation (E_{WP}), as estimated by the CRWE model, the lake-size wet surface evaporation (E_W), as estimated by the CRWE model, the lake evaporation (E_L), as estimated from the CRLE model, and the lake evaporation (E_B), as estimated from the water budget, for each of the 17 lakes. For ten of the lakes (Tables 1–10) the comparisons are in real time, i.e., the input data for the CRWE and CRLE models are for the same months as the water budget estimates. However, for seven of the lakes (Tables 11–17), the input data are long-term monthly means which were derived from data in the two volumes of *Climates of the States* (NOAA, 1974), using a procedure described elsewhere (Morton, 1983c). The water budget estimates for the six lakes of Tables 12–

TABLE 3. Evaporation from Lake Ontario North America Great Lakes System for 12 months ending 31 March 1973.

Latitude = 43.25° Altitude = 75 m
Average depth = 86 m Salinity = 100 ppm
—Dew points, air temperatures and sunshine duration at Kingston, Toronto and Rochester
—Water budget evaporation from DeCooke and Witherspoon (1981)

	Wet surface evaporation (CRWE estimate)		Lake evaporation	
Month	Pan-size E_{WP} (mm)	Lake-size E_W (mm)	CRLE estimate E_L (mm)	Water budget estimate E_B (mm)
Jan	5	5	66	95
Feb	1	1	39	53
Mar	51	35	39	14
Apr	92	78	22	9
May	154	126	22	49
Jun	138	122	29	33
Jul	176	156	52	32
Aug	147	129	77	60
Sep	98	81	89	96
Oct	44	32	87	128
Nov	9	9	92	101
Dec	−2	−2	95	74
Annual	913	772	709	744

TABLE 5. Evaporation from Lake Winnemucca in Nevada, for 32 months in 3 years ending 30 April 1938.

Latitude = 40° Altitude = 1160 m
Average depth = 1.2 m? Salinity = 13000 ppm?
—Dew points, air temperatures and sunshine durations at Reno
—Water budget evaporation from Harding (1962)

	Wet surface evaporation (CRWE estimate)		Lake evaporation	
Month	Pan-size E_{WP} (mm)	Lake-size E_W (mm)	CRLE estimate E_L (mm)	Water budget estimate E_B (mm)
Jan	14	10	11	18
Feb	57	38	32	49
Mar	117	78	68	68
Apr	183	128	113	113
May	259	183	172	155
Jun	294	200	199	223
Jul	338	212	214	204
Aug	325	191	196	203
Sep	252	139	149	105
Oct	151	81	95	63
Nov	61	36	45	42
Dec	25	20	25	26
Annual	2076	1316	1319	1269

17 were among the eight lake water budget estimates summarized by Langbein (1951) for a meeting of the International Association for Scientific Hydrology in Brussels during 1951. With regard to the two omissions from Langbein's (1951) summary, the water budget evaporation for Red Bluff Lake on the Pecos River in Texas had a significant positive bias because the average

TABLE 4. Evaporation from Utah Lake in Utah, for 36 months ending 30 June 1973.

Latitude = 40.2° Altitude = 1372 m
Average depth = 2.7 m Salinity = 1000 ppm
—Dew points and air temperatures at Salt Lake City
—Sunshine duration at Salt Lake City and Grand Junction
—Water budget evaporation from Fuhriman et al., (1981)

	Wet surface evaporation (CRWE estimate)		Lake evaporation	
Month	Pan-size E_{WP} (mm)	Lake-size E_W (mm)	CRLE estimate E_L (mm)	Water budget estimate E_B (mm)
Jan	21	16	15	14
Feb	62	40	25	19
Mar	123	82	58	39
Apr	157	112	92	87
May	250	173	143	148
Jun	301	196	185	178
Jul	346	209	210	218
Aug	315	182	200	205
Sep	212	126	140	142
Oct	104	61	98	64
Nov	38	26	49	29
Dec	16	15	20	14
Annual	1945	1238	1235	1157

TABLE 6. Evaporation from Pyramid Lake in Nevada, for 24 months, 1935–36.

Latitude = 40° Altitude = 1160 m
Average depth = 61 m Salinity = 3500 ppm
—Dew points, air temperatures and sunshine durations at Reno
—Water budget evaporation from Harding (1962)

	Wet surface evaporation (CRWE estimate)		Lake evaporation	
Month	Pan-size E_{WP} (mm)	Lake-size E_W (mm)	CRLE estimate E_L (mm)	Water budget estimate E_B (mm)
Jan	32	24	103	76
Feb	60	38	72	66
Mar	128	88	57	67
Apr	186	130	49	78
May	256	182	58	44
Jun	300	201	82	79
Jul	340	213	122	143
Aug	326	190	152	148
Sep	254	140	155	130
Oct	152	82	152	155
Nov	64	38	128	139
Dec	25	20	119	150
Annual	2123	1346	1249	1275

TABLE 7. Evaporation from Lake Hefner in Oklahoma, for 16 months ending 31 August 1951.

Latitude = 35.6° Altitude = 365 m
Average depth = 8.2 m Salinity = 800 ppm?
—Dew points, air temperatures and sunshine durations at Oklahoma City
—Water budget evaporation from U.S. Geological Survey (1954)

	Wet surface evaporation (CRWE estimate)		Lake evaporation	
Month	Pan-size E_{WP} (mm)	Lake-size E_W (mm)	CRLE estimate E_L (mm)	Water budget estimate E_B (mm)
Jan	57	34	49	63
Feb	67	44	37	−16
Mar	135	80	45	86
Apr	180	127	63	69
May	190	155	120	92
Jun	212	182	156	155
Jul	228	192	185	174
Aug	252	194	188	206
Sep	156	120	158	143
Oct	166	101	136	165
Nov	85	48	84	152
Dec	50	30	65	72
Annual	1778	1307	1286	1361

TABLE 9. Evaporation from Salton Sea in California, for 24 months, 1961–62.

Latitude = 33.25° Altitude = −71 m
Average depth = 8.0 m Salinity = 37000 ppm
—Dew points and air temperatures at Sandy Beach
—Sunshine duration at Yuma
—Water budget evaporation from Hughes (1967)

	Wet surface evaporation (CRWE estimate)		Lake evaporation	
Month	Pan-size E_{WP} (mm)	Lake-size E_W (mm)	CRLE estimate E_L (mm)	Water budget estimate E_B (mm)
Jan	100	53	56	54
Feb	140	74	56	67
Mar	220	126	82	99
Apr	308	178	126	149
May	340	209	166	216
Jun	382	236	215	185
Jul	382	248	256	215
Aug	381	231	252	228
Sep	308	176	206	218
Oct	238	122	161	182
Nov	125	66	112	118
Dec	82	46	77	60
Annual	3006	1765	1765	1791

reservoir area used in the computation (14.2 km^2) did not include the river surface and phreatophytic areas that also contributed to the evaporation losses in the additional 30–40 km of river channel between the upstream and downstream gauges. Similarly, the water budget evaporation for Owens Lake was in the western

TABLE 8. Evaporation from Silver Lake in California, for 12 months ending 30 April 1939.

Latitude = 35.4° Altitude = 280 m
Average depth = 1.0 m? Salinity = 500 ppm?
—Relative humidities and air temperatures at Silver Lake
—Global radiation inputs are monthly Las Vegas means for 5 years ending December 31, 1964
—Water budget evaporation from Blaney (1957)

	Wet surface evaporation (CRWE estimate)		Lake evaporation	
Month	Pan-size E_{WP} (mm)	Lake-size E_W (mm)	CRLE estimate E_L (mm)	Water budget estimate E_B (mm)
Jan	80	48	46	60
Feb	104	62	57	119
Mar	181	129	116	145
Apr	255	178	169	179
May	332	246	237	249
Jun	350	271	268	262
Jul	373	295	301	262
Aug	344	271	280	251
Sep	274	213	221	193
Oct	174	109	122	144
Nov	94	52	58	98
Dec	70	43	45	56
Annual	2631	1917	1920	2018

TABLE 10. Evaporation from Lake Victoria in East Africa for 60 months, 1970–74.

Latitude = −1.0° Altitude = 1134 m
Average depth = 40 m Salinity = 400 ppm
—Dew points and air temperatures at Mwanza and Entebbe
—Sunshine duration are overlake averages
—Water budget evaporation from Kite (1981)

	Wet surface evaporation (CRWE estimate)		Lake evaporation	
Month	Pan-size E_{WP} (mm)	Lake-size E_W (mm)	CRLE estimate E_L (mm)	Water budget estimate E_B (mm)
Jan	162	140	139	119
Feb	157	138	124	112
Mar	179	153	140	139
Apr	154	138	140	154
May	146	128	146	151
Jun	151	121	134	166
Jul	157	123	132	175
Aug	172	135	128	137
Sep	170	139	126	109
Oct	182	148	135	114
Nov	152	130	138	107
Dec	158	135	142	110
Annual	1940	1628	1624	1593

TABLE 11. Evaporation from Lake Superior North American Great Lakes System, 1942–75 inclusive.

Latitude = 47.55° Altitude = 183 m
Average depth = 148 m Salinity = 200 ppm?
—Humidity, temperature and sunshine duration inputs are from long-term monthly values for Sault Ste. Marie, Michigan and Thunder Bay, Ontario
—Water budget evaporation from Derecki (1980)

	Wet surface evaporation (CRWE estimate)		Lake evaporation	
Month	Pan-size E_{WP} (mm)	Lake-size E_W (mm)	CRLE estimate E_L (mm)	Water budget estimate E_B (mm)
Jan	−3	−3	85	96
Feb	−2	−2	55	75
Mar	26	25	42	41
Apr	80	67	21	−1
May	128	104	6	−3
Jun	148	131	−6	−13
Jul	172	151	−6	−4
Aug	137	116	9	17
Sep	75	60	42	50
Oct	35	27	79	62
Nov	8	8	105	91
Dec	−3	−3	96	106
Annual	801	681	528	517

desert area of California where no representative climatological observations were available. Furthermore, both lakes lacked monthly water budget estimates.

TABLE 12. Evaporation from Great Salt Lake in Utah, for water years 1919, 1928, 1931 and 1934.

Latitude = 40.8° Altitude = 1280 m
Average depth = 6 m? Salinity = 210,000 ppm
—Humidity, temperature and sunshine duration inputs are from long-term monthly mean values for Salt Lake City
—Water budget evaporation from Langbein (1951)

	Wet surface evaporation (CRWE estimate)		Lake evaporation	
Month	Pan-size E_{WP} (mm)	Lake-size E_W (mm)	CRLE estimate E_L (mm)	Water budget estimate E_B (mm)
Jan	8	8	11	6
Feb	37	27	17	6
Mar	83	60	39	15
Apr	133	97	71	61
May	192	139	114	131
Jun	229	157	144	158
Jul	278	174	173	162
Aug	250	148	161	186
Sep	184	107	122	168
Oct	103	59	87	73
Nov	32	22	44	30
Dec	9	9	22	15
Annual	1538	1007	1005	1011

TABLE 13. Evaporation from Walker Lake in Nevada, for years 1928–32 inclusive.

Latitude = 38.8° Altitude = 1230 m
Average depth = 31 m Salinity = 2500 ppm
—Humidity, temperature and sunshine duration inputs are from long-term monthly values for Reno
—Water budget evaporation from Harding (1935)

	Wet surface evaportion (CRWE estimate)		Lake evaporation	
Month	Pan-size E_{WP} (mm)	Lake-size E_W (mm)	CRLE estimate E_L (mm)	Water budget estimate E_B (mm)
Jan	36	27	63	61
Feb	62	44	37	46
Mar	119	82	39	61
Apr	172	125	51	61
May	224	167	83	76
Jun	263	191	118	122
Jul	316	210	165	152
Aug	293	187	183	168
Sep	223	138	173	198
Oct	137	78	159	137
Nov	60	37	119	122
Dec	25	22	87	76
Annual	1930	1308	1277	1280

The sources of data for the model and water budget estimates are presented in sufficient detail in Tables 1–17 with the following two exceptions:

TABLE 14. Evaporation from Tulare Lake in California, during years 1906–16 inclusive.

Latitude = 36.8° Altitude = 61 m
Average depth = 2.0 m? Salinity = 15000 ppm?
—Humidity, temperature and sunshine duration inputs are from long-term monthly mean values for Fresno
—Water budget evaporation from Harding (1927)

	Wet surface evaporation (CRWE estimate)		Lake evaporation	
Month	Pan-size E_{WP} (mm)	Lake-size E_W (mm)	CRLE estimate E_L (mm)	Water budget estimate E_B (mm)
Jan	34	26	23	37
Feb	73	48	36	40
Mar	141	99	78	76
Apr	195	142	124	91
May	278	188	174	152
Jun	312	214	206	213
Jul	363	231	234	244
Aug	323	203	214	183
Sep	252	151	167	183
Oct	175	96	115	91
Nov	68	43	61	61
Dec	23	21	32	31
Annual	2237	1462	1464	1402

TABLE 15. Evaporation from Buena Vista Lake in California, during years 1937–45 inclusive.

Latitude = 35.2° Altitude = 88 m
Average depth = 1.5 m? Salinity = 15000 ppm?
—Humidity and temperature inputs are from long-term monthly mean values for Bakersfield and sunshine duration inputs are from long-term monthly mean values for Fresno
—Water budget evaporation from Langbein (1951)

	Wet surface evaporation (CRWE estimate)		Lake evaporation	
Month	Pan-size E_{WP} (mm)	Lake-size E_W (mm)	CRLE estimate E_L (mm)	Water budget estimate E_B (mm)
Jan	45	30	27	30
Feb	92	53	43	46
Mar	164	106	90	73
Apr	218	147	135	110
May	304	193	183	152
Jun	344	219	213	158
Jul	403	238	240	216
Aug	367	211	218	259
Sep	279	159	172	198
Oct	199	104	118	116
Nov	84	49	63	64
Dec	36	26	33	43
Annual	2535	1535	1535	1465

TABLE 16. Evaporation from Elsinore Lake in California, for the years 1916–34 inclusive.

Latitude = 33.7° Altitude = 384 m
Average depth = 3.8 m? Salinity = 4200 ppm
—Humidity and temperature inputs are from long-term monthly mean values for Long Beach and sunshine duration inputs are from long-term monthly mean values for Los Angeles and San Diego
—Water budget evaporation from Harding (1935)

	Wet surface evaporation (CRWE estimate)		Lake evaporation	
Month	Pan-size E_{WP} (mm)	Lake-size E_W (mm)	CRLE estimate E_L (mm)	Water budget estimate E_B (mm)
Jan	83	48	46	37
Feb	101	64	48	33
Mar	144	105	76	67
Apr	163	127	106	116
May	185	150	138	143
Jun	186	155	153	165
Jul	227	187	170	201
Aug	216	172	179	198
Sep	178	134	161	168
Oct	144	95	127	134
Nov	101	61	85	79
Dec	72	43	59	49
Annual	1800	1341	1348	1390

TABLE 17. Evaporation from Lake Okeechobee in Florida, during the years 1941–49 and 1952–77 inclusive.

Latitude = 27.0° Altitude = 4 m
Average depth = 3 m Salinity = 200 ppm?
—Humidity and temperature inputs are from long-term monthly mean values for Fort Myers and sunshine duration inputs are from long-term monthly mean values for Lakeland
—Water budget evaporation from Langbein (1951), Shih (1980) and Morton (1983c).

	Wet surface evaporation (CRWE estimate)		Lake evaporation	
Month	Pan-size E_{WP} (mm)	Lake-size E_W (mm)	CRLE estimate E_L (mm)	Water budget estimate E_B (mm)
Jan	102	68	67	76
Feb	114	82	69	86
Mar	164	123	102	126
Apr	205	161	135	170
May	243	193	179	180
Jun	220	189	199	161
Jul	226	191	201	182
Aug	220	186	192	175
Sep	181	153	170	137
Oct	162	123	135	119
Nov	126	84	97	81
Dec	107	66	78	74
Annual	2070	1619	1624	1567

1) The water budget estimates for Utah Lake (Table 4) during the months April–October are averages for the three years. However, the values for the months November–March are five-month totals averaged over two years with the monthly distribution estimated from snow pan and saline pan observations. The winter water budget estimates for the third year were rejected because of high unmeasured inflows.

2) The water budget data for Lake Okeechobee (Table 17) represents a synthesis of various sources. The annual total is from a water budget computation by Shih (1980) for 27 years from 1952 to 1977. He found that an average annual evaporation input of 1458 mm caused the computed end-of-year water level to exceed the actual end-of-year water level by an average of 109 mm. Although the corrected average annual water budget estimate of 1458 + 109 = 1567 mm is more realistic than the value of 1325 mm obtained by Langbein (1951) for the years 1941–47, the latter estimate provides the only guide to the seasonal distribution. Therefore the monthly estimates presented by Langbein (1951) are multiplied by 1567/1325 to make the annual total equal 1567 mm.

Tables 1–17 have been prepared to illustrate the effects of size and depth on evaporation and to assess the reality of the CRWE and the CRLE models. Thus the differences between E_{WP} and E_W demonstrate how the complementary relationship takes into account the effects of an environment created by a lake-size wet surface in reducing the evaporation that would occur from a pan-size wet surface in the land environment; the differences between E_W and E_L demonstrate how the CRLE model takes into account the effects of depth and subsurface heat storage changes on evaporation; and the differences between E_L and E_B demonstrate how closely the CRLE model estimates conform to the water budget estimates, the only suitable standard of comparison.

Figure 6 has been prepared to summarize the comparisons of annual lake evaporation shown in Tables 1-17. It shows the annual CRLE model estimates plotted against the comparable water budget estimates for the 17 lakes, together with the line of equality and the lines representing errors of plus and minus 10 percent. The agreement is very good with a maximum absolute deviation for the annual values of 98 mm, a maximum percentage deviation of less than 7 percent and no significant bias.

The comparisons between the monthly CRLE model estimates, E_L, and the monthly water budget estimates, E_B, in Tables 1-17 are not nearly as good. However part of the problem is with the water budget estimates and the difficulties involved in measuring end-of-month water levels. Thus discontinuities in the records for Lake Victoria in East Africa (Table 10) required that the end-of-month water levels be derived from some sort of computation technique rather than from actual daily levels. Even the most carefully conducted water budgets are not immune as is evident in Table 7 where the monthly water budget estimates for Lake Hefner (U.S. Geological Survey, 1954) during January, February and March of 1951 are obviously unrealistic whereas the sum for the three months seems quite believable. This could be explained by an end-of-January water level that was 10-20 mm (half an inch) too low and an end-of-February water level that was 20-30 mm (one inch) too high. With the possibility of this kind of error the results should be assessed on a seasonal basis with the methodology described in section 3 in connection with the formulation of Eqs. (6)-(8).

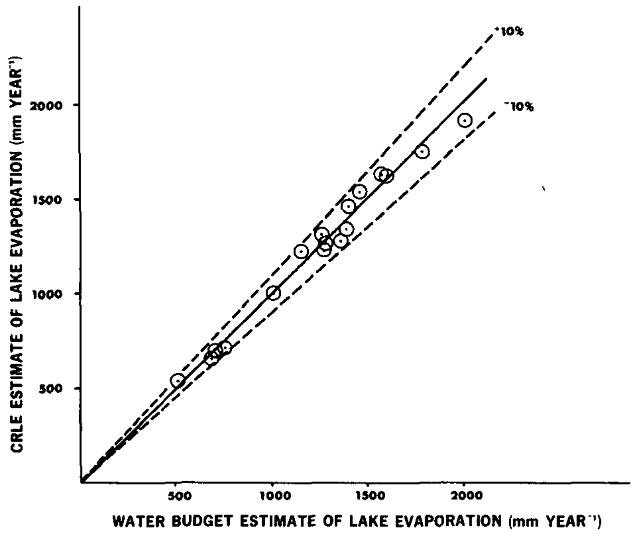

FIG. 6. Comparison of CRLE model estimates with water budget estimates of annual evaporation.

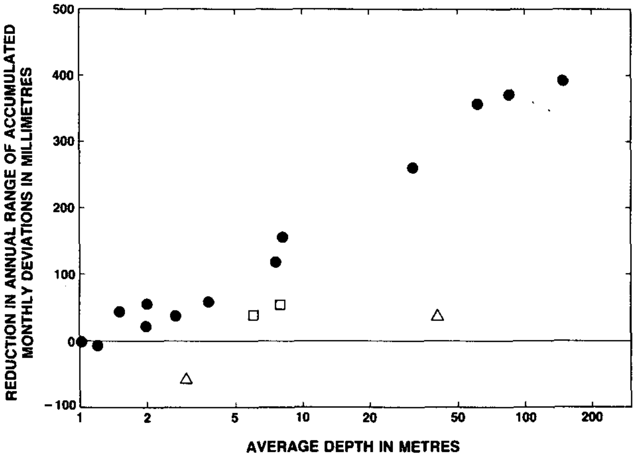

FIG. 7. The effects of the routing technique in reducing the annual range of accumulated monthly deviations.

As described in section 3, the computation of the annual range of accumulated monthly deviations requires a percentage adjustment to the monthly model estimates to make the annual total equal to the annual water budget total; the sequential accumulation of the deviations between these adjusted values and the corresponding monthly water budget values; and the subtraction of the annual minimum accumulated deviation from the annual maximum accumulated deviation. The effects of the routing technique can then be assessed from the reduction in the annual range resulting from the use of the CRLE model rather than the CRWE model. The reductions for each lake have been computed from the data in Tables 1-17 inclusive and plotted against the corresponding average depths on semilogarithmic paper in Fig. 7. The good relationship defined by the solid circular points inspires confidence in the applicability of the routing technique to 13 of the lakes, all of which have latitudes greater than 30° and salinities of less than 5000 ppm. It also indicates that the CRLE model has little advantage over the CRWE model at depths less than 1.5 m. The two outliers denoted by open triangles are for Lake Okeechobee in Florida and Lake Victoria in East Africa. Although it is possible that these unconformities are the result of the inadequacy of the routing technique at low latitudes, it is much more probable that they are due to the previously noted inadequacies in the monthly water budget estimates. The other two outliers, those denoted by the open squares, are for the Salton Sea and Great Salt Lake and it is quite probable that they reflect the inability of the routing technique in general and Eq. (7) in particular to take into account the dampening effect of high salinity on the storage and release of heat. Although improvements must await the availability of new and better water budget data, it should be noted that the current routing procedure produces better seasonal distributions for saline lakes than the CRWE model.

The comparisons in Tables 1–17 indicate that annual values of lake-size wet surface evaporation can provide reasonable estimates of annual lake evaporation for lakes with average depths of less than 30 m. The significance of this finding is that the maps of mean annual lake evaporation and net reservoir evaporation (the difference between lake evaporation and areal evapotranspiration) for Canada and the southeastern United States that have been published elsewhere (Morton, 1983b) can provide realistic results for lakes with average depths of less than 30 m even though they are in reality based on the CRWE estimates of lake-size wet surface evaporation.

7. Concluding discussion

There is agreement in Tables 1–17 between the annual CRWE estimates of lake-size wet surface evaporation and the annual water budget estimates for the 14 lakes with average depths less than 60 m. This provides good evidence that the complementary relationship can account for the effects on the lake evaporation of the difference between the lake and the land environments. However the conceptual and empirical bases for the routing technique in the CRLE model are not nearly so good. Thus there is a good probability that it does not adequately reflect the dampening effects of high salinity on the storage and release of heat and there is a remote possibility that it is inadequate at low latitudes. However, in spite of these potential weaknesses the routing technique provides reasonably realistic seasonal patterns of evaporation for 13 soft-water, midlatitude lakes and accounts for the effects of great depth in reducing the annual lake evaporation (e.g., Table 11 for Lake Superior). Moreover, complicated improvements are not warranted until such time as they can be evaluated with more and better water budget data.

One of the objections to the CRWE and CRLE models is that they do not take into account the effects of wind speed on lake evaporation. In a discussion presented elsewhere (Morton, 1983b) it was concluded that the use of the land environment wind speed does not significantly reduce error in the estimates of lake evaporation and may quite possibly increase it.

The CRLE and CRWE models do not take into account the kind of upwind shoreline transition shown in Fig. 4. Therefore they are applicable only to lakes or lake-size wet surfaces. However, the results can be applied to ponds or other small bodies of water when modified using Eq. (9).

When evaluated out of context the CRLE model seems to be no big deal. There is no denying that its ability to take into account the transition between land and lake environments is simply spinoff from another more general concept; that the subsurface heat storage routing process depends on the crude fitted relationships shown in Fig. 5; and that it has been tested against water budgets for only 17 lakes, some of which are on the borderline of acceptability. However, in spite of these drawbacks, the CRLE model remains demonstrably much superior to its conventional alternatives in the reality of its conceptual basis, the rigor of its test procedure, the versatility of its applications and the general availability and economical nature of its required input data. The weaknesses of the alternative pan evaporation, potential evaporation, mass transfer and energy budget technique have been documented elsewhere (Morton, 1983c).

Some obvious advantages of the CRLE model that are unmatched in their accumulated effects by any alternative are

1) It requires as input only land environment observations of temperature, humidity and sunshine duration and the results are relatively insensitive to errors in temperature and humidity.

2) It can provide reasonable looking monthly estimates for lakes of any size or any depth.

3) It has a sound physical basis and is, therefore, easily adaptable to unusual applications. Thus it is easy to estimate the effects of heat rejection from thermal power plants and to estimate the effects of net waterborne heat inputs to deep reservoirs on large rivers in hot, arid climates [see Eq. (2)].

4) The same input data and an almost identical model can be used to provide an estimate of the evapotranspiration that has taken place in the area where a reservoir is planned or the evapotranspiration that would have taken place if a reservoir did not exist. The difference between the estimated lake evaporation and the estimated evapotranspiration, the net reservoir evaporation, is an important quantity because it represents the effect of an existing or a planned reservoir on the water balance of a basin.

Probably the most important advantage of the CRLE model is that it has no need for locally calibrated coefficients. This means that the results are independent and falsifiable so that errors in the associated assumptions can be detected and corrected by progressive testing against comparable water budget estimates from an ever-widening range of environments. Thus the discovery in the literature of reliable, well-documented water budget estimates for Lake Superior (Derecki, 1980) demonstrated the existence of flaws in the previous version of the routing procedure (Morton, 1983b) and led to the development of the current version. This is the antithesis of "tuning" because the changes that were made to produce good agreement between model and water budget estimates for Lake Superior were applied without modification to the model estimates for the other 16 lakes. Because of its falsifiability, the CRLE model is unique in its ability to utilize efficiently the small number of water budget estimates to provide a rigorous evaluation of the reality of its results. No other technique (including the energy budget technique) has been tested so rigorously and therefore no other technique can be used with such confidence to provide estimates of lake evaporation anywhere in the world with no need for locally calibrated coefficients. Thus in the event of differences between the CRLE estimates and those of any other technique (except those of high quality water budgets) the first step should be to examine the adequacy of the other technique.

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