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Comment on "Comparison of Techniques for Estimating Annual Lake Evaporation Using Climatological Data" by M. E. Andersen and H. E. Jobson

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Andersen and Jobson [1982] have estimated mean annual evaporation for 30 lakes by using a published version [*Morton*, 1979] of what are now referred to as the complementary relationship lake evaporation, or CRLE, models and by using an evaporation map prepared by the U.S. Weather Service [*Kohler et al.*, 1959]. The two estimates for each lake were compared with evaporation values that have been reported in the literature over the past 31 years. Andersen and Jobson concluded that the evaporation map provides annual evaporation estimates which are more consistent with observations than those derived from the CRLE model. However, there are two reasons why neither the comparisons nor the conclusion have any value. The first reason is that the CRLE model estimates computed by the authors are obviously in error. The second is that the basis of comparison is inadequate in that the majority of the values reported in the literature are alternative estimates and not observations. These inadequacies are discussed in more detail hereinafter.

The CRLE [*Morton*, 1979] model estimates presented by Andersen and Jobson for the last 14 lakes (symbols *I* to *Z*) in Table 2 [*Andersen and Jobson*, 1982, p. 633] are obviously too high. This is because they used the potential evaporation outputs of the CRLE model rather than the lake evaporation outputs. When advised of this they prepared a revised version of Table 2, which is presented in the response to this discussion. Table 1 provides an evaluation of their "revised" results for 13 of the lakes. The "comparable" values are also CRLE model estimates, but the inputs are the monthly mean values of maximum and minimum temperatures, relative humidities at 6-hour intervals, and ratios of observed to maximum possible sunshine duration that were published in the two volumes of Climates of the States [*NOAA*, 1974]. The vapor pressure was estimated to be the average of the saturation vapor pressure at the maximum temperature multiplied by the minimum of the relative humidities and the saturation vapor pressure at the minimum temperature multiplied by the maximum of the relative humidities.

Table 1 shows that the difference between the revised and comparable estimates is less than 25 mm/yr for seven of the lakes and less than 70 mm/year for nine of the lakes. Such differences can be attributed to differences in input data from one set of years to another and thus indicate that the authors have used the CRLE model correctly. However the differences for the other four lakes are too large to be ignored. The difference of the 192 mm/yr between the revised and comparable estimates for Lake Okeechobee can be attributed to the use of data at different locations. Thus the revised value is based on sunshine duration records at Key West, which is approximately 290 km away with an island climate significantly different from that near the lake, and on temperature and humidity records at West Palm Beach, which is approximately 3 km inland from the Atlantic Ocean, whereas the comparable value is based on the sunshine duration records at Lakeland, which is only 160 km away with an inland Florida climate somewhat similar to that near the lake, and on the temperature and humidity records at Fort Myers, which is approximately 20 km inland from the Gulf of Mexico. Although the CRLE model estimates are rather insensitive to the differences in the temperature and humidity records, they would respond significantly to the differences in the ratios of observed to maximum possible sunshine duration, which average 0.73 at Key West and 0.64 at Lakeland, with even greater differences during the months of highest evaporation. The reasons why the revised and comparable values differ by 84 mm/yr for Lake Elsinor and by 80 mm/yr for Amistad Reservoir are not known for sure. However, it is suspected that the revised values for Lake Elsinor and Amistad Reservoir are based on sunshine duration records at Los Angeles and San Antonio, respectively, whereas the comparable values are based on averages at Los Angeles and San Diego and at San Antonio and Abilene, respectively. In such circumstances, when it is known that the nearest records are not representative, it is wiser to use averages. The reason for the 118 mm/yr discrepancy between the revised and comparable values for Walker Lake remains a mystery because the only records that are remotely representative are those observed at Reno, Nevada.

The estimates of lake evaporation that *Andersen and Jobson* [1982] use as standards of comparison are based on pan evaporation, mass transfer, energy budget, or water budget techniques. Many of these standards of comparison are questionable or have been identified incorrectly and can be evaluated adequately only by going back to the original references. The results of such an evaluation are discussed in some detail in the following paragraphs.

The standards of comparison used by the authors for Eagle Lake, Sam Rayburn Reservior, Lake Texarkana, White River Lake, and Lake Thomas are estimates of lake evaporation derived from pan evaporation observations [*Kane*, 1967]. This standard is unacceptable because the evaporation pan values are not observations but merely alternative estimates and rather poor ones at that. *Horton* [1917, p. 198] had the definitive word on the subject when he stated that "the land-exposed evaporation pan appears to be about the poorest device humanly contrivable for the purpose of determining the evaporation losses from broad water surfaces." The main problem is that pan evaporation is similar to potential evaporation in that it responds negatively to changes in the availability of water to the soil-plant surfaces of the surrounding area [*Morton*, 1979]. Such responses are implicit in a tabulation presented by *Hounam* [1973] which shows that the

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TABLE 1. CRLE Model Estimates of Annual Lake Evaporation

Lake	*Morton* [1979] Version: Revised, mm	*Morton* [1979] Version: Comparable, mm	*Morton* [1983] Version, mm
Michie	1279	1276	1206
Hyco	1290	1270	1191
Amistad	1456	1536	1575
Okeechobee	1801	1609	1619
Falcon	1660	1661	1637
Great Salt	1236	1170	1217
Buena Vista	1525	1512	1571
Elsinor	1476	1392	1343
Tulare	1491	1480	1488
Hungry Horse	896	846	834
Walker	1398	1280	1308
Pretty	1043	1020	982
Owens	1468	1451	1658

annual Class A pan coefficient is 0.81 for Lake Okeechobee in Florida, where the average annual precipitation is about 1400 mm, 0.68 for Lake Hefner in Oklahoma, where the average annual precipitation is about 800 mm, and 0.52 for the Salton Sea in California, where the average annual precipitation is about 60 mm. The range of variation is even greater than that shown in the tabulation because *Shih* [1980] has published water budget data for Lake Okeechobee which indicates that a pan coefficient of 0.81 is still too small. With such a wide range of coefficients, the successful use of pan evaporation to estimate lake evaporation is a matter of good luck or good judgement. Because these two attributes are so rare, the results cannot be used to test the validity of other estimates.

It may be noted that the variation of pan coefficients discussed above is exactly as predicted by the complementary relationship between potential and areal evaporation. The CRLE model was developed to take into account the modification of the air as it passes from the land environment to the lake environment, so there is no need to use coefficients that change from lake to lake.

The standard of comparison that is used by the authors for Falcon Lake provides a good example of the dangers involved in uncritical acceptance of published data. It alone increases the standard deviation of the differences between the "estimated evaporation" and the "reported evaporation" in Table 2 [*Andersen and Jobson*, 1982, p. 633] by over 60%. The reference is not identifiable, but it is obvious that the reported evaporation is the long-term average annual evaporation for the Class A pan at the Laredo WB Airport before the records were discontinued in 1965. The values recorded at this station exceed by a large amount those recorded at the Laredo 2 site and the Rio Grande City site which are approximately the same distance away from the lake. Furthermore, there was no attempt to reduce pan evaporation to lake evaporation by application of a pan coefficient.

The standard of comparison for Pretty Lake is the mass transfer estimate of lake evaporation. Such estimates are based on the assumption that the evaporation is proportional to the product of the wind speed and the vapor pressure deficit (the difference between the saturation vapor pressure at the temperature of the water surface and the atmosphere vapor pressure). Normally, the water surface temperature is measured at the lake but the wind speed and atmospheric vapor pressure are measured in the land environment. However, at Pretty Lake the wind speed was observed over the water surface and the atmospheric vapor pressure was observed at the shoreline. The estimates for Pretty Lake differed from normal practice also in that the mass transfer equation was calibrated with the results of a concomitant energy budget study. According to *Ficke* [1972], the mass transfer coefficient derived in this way is 14% to 15% lower than the coefficient predicted for a lake of the same size by *Harbeck*'s [1962] method. This means that the results are 14% to 15% lower as well. The problems associated with both the mass transfer and the energy budget techniques are thoroughly discussed in subsequent paragraphs and are sufficiently serious to render the Pretty Lake evaporation estimates unsuitable as a standard of comparison for passing judgement on the merits of other techniques.

The evaporation values that are used as standards of comparison for Lake Michie and Hyco Lake are classified as water budget estimates. However, the references [*Yonts et al.*, 1973; *Giese*, 1976] indicate that they are actually estimates produced by mass transfer equations that have been calibrated with water budget values estimated during dry periods (when the errors would be quite small despite the general unsuitability of the lakes for water budget studies). The calibration procedure involved the plotting of the water budget values against the products of the wind speed and the vapor pressure deficit. The slope of the resulting relationship was assumed to be the required mass transfer coefficient. There are a number of problems associated with this commonly used procedure, but the most important one is that the atmospheric vapor pressure values that were used in computing the vapor pressure deficits were observed some distance away in the land environment. This means that they were lower than the values over the lake and that the difference would be greater during the dry calibration periods than during periods of normal or above normal precipitation. As the resultant bias would produce estimates of lake evaporation that are too low, the mass transfer estimates of evaporation for Lake Michie and Hyco lake are unsuitable for use as standards of comparison.

Plots of dry period water budget evaporation against the product of the wind speed and the vapor pressure deficit frequently produce negative evaporation intercepts. As exemplified in the Lake Michie and Hyco Lake investigations, this is normally assumed to be the effect of significant unmeasured groundwater inflow. A more likely interpretation is that it is merely an artifact of calibration procedure caused by the difference between the unobserved vapor pressure in the lake environment and the observed vapor pressure in the land environment.

The standard of comparison used by *Andersen and Jobson* [1982] for the four ponds in northwestern Florida is also unacceptable. Although labeled as energy budget estimates, the original reference [*Walsh*, 1971] clearly indicates that the evaporation estimates for the four ponds are based on a mass transfer equation that was calibrated for Lake Hefner in Oklahoma. The energy budget merely demonstrates how inadequate these estimates are because the ratio of the residual (i.e., error) in the energy budget to the evaporation estimate is 119% for pond 1, 107% for pond 2, 59% for pond 3 and 52% for pond 4. Because they are positive and because they and the evaporation estimates appear to be complementary, these residuals provide grounds for belief that the evaporation estimates are much too low.

The authors are also in error in their identification of the methods used to estimate the standard of comparison for Lake Kerr. Thus the so-called water budget estimate is, according to *Hughes* [1974, p. 15], "keyed to the estimate of average yearly lake evaporation of 46 inches given for the Lake Kerr area by Kohler, Nordenson and Baker (1959)." Small wonder that there was such good agreement between reported evaporation and "estimated evaporation, Kohler et al." in Table 2 of Andersen and Jobson. The water balance only balanced through the use of precipitation estimates that were known to be low, unmeasured surface and groundwater inflows that were assumed to be zero, and unmeasured groundwater outflows that were assumed to be significant [*Hughes*, 1974].

High-quality energy budget estimates for Lake Colorado City [*Harbeck et al.*, 1959] and Lake Mead [*Harbeck et al.*, 1958] are used as a standard of comparison by Andersen and Jobson. From a superficial point of view this may seem adequate because the energy budget technique is based on the law of conservation of energy. Furthermore, the Lake Hefner energy budget estimates provided reasonable agreement with the comparable high quality water budget estimates [*Anderson*, 1954] and the Lake Mead energy budget estimates agreed reasonably well with values estimated from a mass transfer equation that was derived from the Lake Hefner water budget data [*Harbeck*, 1958]. However, the energy budget technique is based on a number of questionable assumptions. These are as follows: that the Bowen ratio provides an adequate estimate of the ratio of sensible to latent heat fluxes under all the peculiar conditions of atmospheric stability that can occur over a lake, that the Bowen ratio provides an adequate estimate of the ratio of sensible to latent heat fluxes when the data are averaged over a number of days rather than a number of minutes, and that the extrapolation of the inputs required for the energy budget technique from a few measurement points to an entire lake will not lead to significant error. Moreover, the energy budget concept has never been rigorously tested 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, although it does provide one of the better alternatives.

The energy budget estimates for Lake Mead and Lake Colorado City include energy components, i.e., net waterborne heat inputs or heat rejection from thermal power plants, that are not taken into account in the CRLE model estimates. However, they can be included in the CRLE model estimates whenever they are significant and, as demonstrated for Lake Mead [*Morton*, 1979], this does bring the two estimates closer together.

The energy budget estimates of evaporation from Amistad and Hungry Horse reservoirs are also inadequate as standards of comparison. They are probably not up to the standard of the Lake Colorado City and Lake Mead energy budgets, although this cannot be checked from the references. However, it is known that the so-called annual value that is used as a standard of comparison for Hungry Horse Reservoir is in reality a total for the 7 months of May to October inclusive [*Simons and Rorabaugh*, 1971]. With an average depth of 35 meters the reservoir could store enough heat to make the 12-month annual total approximately 40% higher.

Since the energy budget is merely an alternative method, the only suitable standard for judging the adequacy of other techniques for estimating lake evaporation is the water budget or the law of conservation of mass. Because the evaporation estimate is the residual in the water budget, it includes the effects of errors in the inflow, outflow, precipitation, and water level difference components. Groundwater inflows or outflows have received undue attention because mass transfer calibrations, such as those used for Lake Michie and Hyco Lake, can provide an erroneous indication that they are significant and because, by being unmeasurable, they can be blamed when water budget estimates do not conform to expectations. Although unmeasured groundwater outflows could be of some importance to the water budget of small lakes that are dammed or perched or of small lakes with wide swamp outlets, they are normally small enough to be ignored. Direct unmeasured groundwater inflows may be significant for small lakes that have contributing areas with poorly defined drainage, e.g., Pretty Lake with its swampy basin [*Ficke*, 1972], but usually they are small compared to the measurable groundwater inflows to the tributaries. Therefore the effects of unmeasured groundwater can be minimized in the same way as the effects of unmeasured tributary inflows or errors in the other water budget components, i.e., by selecting lakes with sufficient area to make the volume of evaporation much greater than the probable error. Such lakes are rare, and their suitability for producing estimates of evaporation that can be used as standards of comparison requires careful documentation.

Eight of the water budget estimates of lake evaporation used by *Andersen and Jobson* [1982] as standards of comparison were taken from a paper prepared by *Langbein* [1951] for presentation at a meeting of the International Association of Scientific Hydrology in Brussels. With reference to these and other estimates, *Langbein* [1951, p. 413] observed that "The large proportion of the figures are of unknown accuracy." The water budgets for five of the eight lakes were referenced to other authors, but the water budgets for Great Salt Lake, Red Bluff Lake, and Lake Okeechobee are inadequately documented. The reasons why these three water budgets are judged to be unsuitable as standards of comparison are as follows.

1. Great Salt Lake seems ideal for water budget investigations, and there is little reason to doubt the adequacy of the results. However, the water budget estimates are not comparable with any other technique because they have been reduced by a salinity concentration of between 20% and 25%. Langbein added an adjustment for the effects of salinity which increased the estimate from 1012 mm/yr (the value that was used as a standard of comparison by Andersen and Jobson) to 1265 mm/yr. Either the latter value should be used as a standard of comparison or the estimated values should be reduced by approximately 20%, a reduction that is compatible with the graphical technique proposed by *Harbeck* [1955].

2. Red Bluff Lake seems unsuitable for a water budget study. For example, a consistent error of 5% in the discharge records for the Pecos River, either upstream or downstream of the lake, would produce an error in the evaporation estimates of roughly 24%. Moreover, the estimate has a positive bias because the average reservoir area used in the computation (1420 hectares) does not include the river surface and phreatophytic areas that also contribute to the evaporation losses in

the additional 30 to 40 km of river channel between the upstream and downstream gauges.

3. According to Langbein, the water budget estimate of evaporation for Lake Okeechobee from 1941 to 1947 was 1325 mm/yr. No details on the computation are available, so it is difficult to assess its reality. However, *Shih* [1980] has published the results of a water budget computation for the 26 years from 1952 to 1977. He used the Corps of Engineers estimates (the average of the Class A pan evaporation and the Colorado sunken pan evaporation multiplied by a coefficient of 0.865) (U.S. Army Corps of Engineers, "Monthly water budget report for Lake Okeechobee," (1952–1977) in the water budget and these values, which averaged 1458 mm/yr, caused the water level estimates to exceed the water level observations by an average of 109 mm/yr. Because the water budget estimate is the residual in applying the law of conservation of mass and because the law of conservation of mass has a much better physical basis than the pan evaporation technique, this indicates that the lake evaporation for the 26-year period was 1458 + 109 = 1567 mm/year, a value that is 18% higher than the Langbein estimate for the earlier period.

There appear to be few problems with the water budgets for the five other lakes that were published by *Langbein* [1951] and used as standards of comparison by *Andersen and Jobson* [1982]. The lakes are all in the arid or semiarid areas of California and Nevada and have sufficient area to make the volume of evaporation much larger than the errors in inflow or outflow. However, the original references are all very old and the data used for some of the lakes are not well documented. There is little doubt that the water budget estimates of the evaporation from Lake Elsinor [*Harding*, 1927, 1935] and from Walker Lake [*Harding*, 1935] are realistic enough to be used as standards of comparison. Those for Tulare Lake [*Harding*, 1927, 1935] and Buena Vista Lake [*Young*, 1947] are probably adequate as well, although the use of monthly mean values derived from differing dry periods to establish mean annual evaporation estimates adds an element of doubt. The water budget for Owens Lake [*Lee*, 1927] is probably superior to those for Tulare and Buena Vista lakes but the high salinity (specific gravity of 1.11) makes the evaporation estimate unsatisfactory as a standard of comparison. *Langbein* [1951] made an adjustment for salinity that increased the estimate from 1545 mm/year (the value that was used as a standard of comparison by Andersen and Jobson) to 1715 mm/yr.

The standards of comparison for the remaining seven lakes, i.e., Pyramid, Winnemucca, Silver, Ontario, Dauphin, Hefner, and the Salton Sea, are the water budget estimates that were used previously to test the CRLE model [*Morton*, 1979]. Although these are all well documented, they are not beyond questioning. For example, there have been many water budget estimates of the evaporation from Lake Ontario and some of them, including one published by the author [*Morton*, 1967], exceed that used as a standard of comparison by 10% or more. This could be explained by consistent errors of approximately 1% in the discharge records of the Niagara or St. Lawrence Rivers or of approximately 5% in the estimates of inflow from the areas draining directly into the lake. Such errors are quite probable, despite the great care taken in an internationally coordinated streamflow measurement program, so the questions are justified. However, because the estimate used as a standard of comparison was the product of an international study [*DeCooke and Witherspoon*, 1977], carried out during the well-publicized International Field Year on the Great Lakes, with the benefit of high-quality instrumentation and many previous studies, there would be more questions asked if the results were ignored. It should be noted that similar problems pertain to a lesser extent to the water budgets for Dauphin lake and Lake Hefner but not to the water budgets for Pyramid, Winnemucca, and Silver Lakes and to the Salton Sea, which are located in arid or semiarid areas. The standard deviation from these seven water budget values is 58 mm/yr for the CRLE model estimates and 139 mm/yr for the U.S. Weather Bureau map estimates [*Kohler et al.*, 1959]. If the number of lakes is increased to eleven by adding the results for Buena Vista Lake, Lake Elsinor, Tulare Lake, and Walker Lake the standard deviations are 54 mm/yr (with the comparable CRLE estimates) and 128 mm/yr, respectively.

In using the estimates provided by the pan evaporation, mass transfer, and energy budget techniques as standards of comparison, *Andersen and Jobson* [1982] seem to advocate that scientific advances be tested against the results of the techniques that they were designed to supercede or against the best estimates of other investigators. The reasoning behind this suggestion is quite common in hydrology, but it is so unscientific it is seldom seen in print. When looked at in depth, it is a surefire formula for scientific sterility. It means that techniques that have never been tested rigorously can be perpetuated for decades because any improvement will give different results. This is the case in hydrology, where the only well-authenticated concepts are the laws of conservation of mass, energy, and momentum [*Morton*, 1982*a*, *b*] and where the formulation and testing of new concepts seems to have ground to a halt. For example, lake evaporation studies during the past three decades have been focused on the extrapolation of the Lake Hefner results to areas where there are only land environment data through the use of pan or mass transfer techniques. Furthermore, the unquestioning acceptance of the conventional wisdom has obscured the conceptual indequacies of the extrapolation techniques by conjuring up nebulous groundwater components to rationalize deviations from good quality water budget estimates or by fudging coefficients to eliminate them. With such a complacent attitude there is no incentive to search for improvements or to find good objective data to serve as standards of comparison.

The CRLE models, which are based on the concept that lakes create their own environments, produce results that differ significantly from the conventional pan and mass transfer techniques or from the closely related U.S. Weather Bureau map [*Kohler et al.*, 1959], which are based on the implicit assumption that the lake and land environments are similar. Thus the CRLE model estimates are higher in humid environments and lower in arid environments [*Morton*, 1979]. The important question is which of the estimates is more realistic, and comparing one set of estimates with the others is not going to provide an answer. The only way to obtain on unequivocal answer is to use high-quality water budget estimates as the standard of comparison. In this connection, the complacency associated with the conventional techniques has been most unfortunate, since it has provided little incentive for the initiation and documentation of high-quality water budget studies during the last three decades. Because the CRLE models require no locally calibrated coefficients, they are

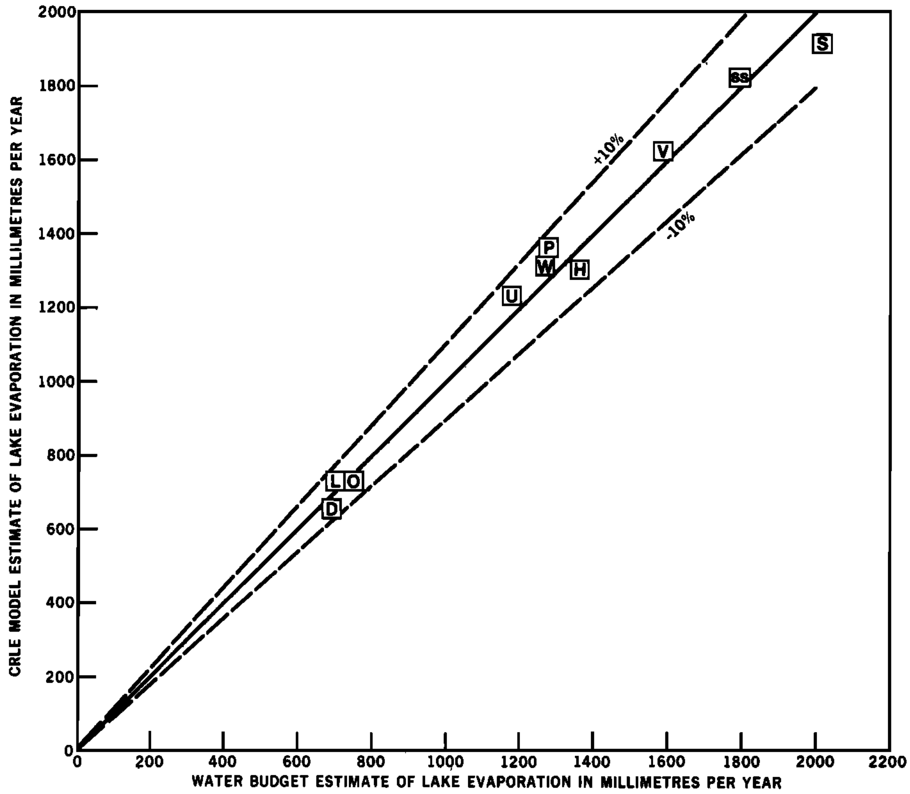

Fig. 1. Comparison of model estimates with water budget estimates of evaporation from Lake Victoria (V), Salton Sea (ss), Silver Lake (S), Lake Hefner (H), Pyramid Lake (P), Winnemucca Lake (W), Lake Ontario (O), Last Mountain Lake (L), and Dauphin Lake (D).

unique in their ability to utilize efficiently the few suitable water budget estimates to provide a rigorous evaluation of the reality of their results.

A new CRLE model has been developed [*Morton*, 1983]. The procedure used to estimate shallow lake evaporation is similar to that in the earlier version [*Morton*, 1979], although there are a number of conceptual improvements. Furthermore, there are two significant practical improvements. The first is the formalization of a technique to correct for upwind edge effects on ponds and other small bodies of water. The second is an approximate routing technique for taking into account the effects of subsurface heat storage changes. The routing technique is similar to those used in hydrology for routing water through natural reservoirs. The storage constant and lag time are related to the average depth, with a small correction for the total dissolved solids. The inputs are the monthly CRLE model estimates of shallow lake evaporation, and the outputs are the monthly estimates of deep lake evaporation.

The test of the earlier version of the CRLE models [*Morton*, 1979] against the annual water budget values for seven lakes has been discussed previously. For the latest version [*Morton*, 1983] the test range has been expanded to Last Mountain Lake in Saskatchewan, Utah Lake in Utah, and Lake Victoria in East Africa. Figure 1 provides a comparison of the annual totals of the model and water budget estimates and Figure 2 provides a comparison of the monthly mean values of the CRLE shallow lake estimates, the CRLE deep lake estimates, and the water budget estimates. The CRLE [*Morton*, 1983] estimates of annual evaporation for 13 lakes are shown in Table 1 where they may be compared with the revised and comparable results of the earlier version [*Morton*, 1979]. They are based on the same input data as those described earlier in connection with the computation of the comparable values.

Table 2 presents monthly mean evaporation values for two of the lakes used in Table 1, i.e., Walker Lake in Nevada and Lake Okeechobee in Florida. The shallow lake estimates are the initial outputs of the CRLE [*Morton*, 1983] model using the climatological inputs described previously in connection with the preparation of Table 1. The deep lake estimates are the result of routing the shallow lake values through a hypothetical heat reservoir that is compatible with the average depth and salinity of the lake. The monthly mean water budget estimates for Walker Lake are those published by *Harding* [1935]. The yearly mean water budget estimate for Lake Okeechobee is the value estimated earlier from the 26-year water budget published by *Shih* [1980].

In conclusion, *Andersen and Jobson* [1982] have failed to demonstrate that the estimates of lake evaporation provided by the CRLE model are in any way inferior to those provided by the U.S. Weather Service map [*Kohler et al.*, 1959] or by any of the alternative techniques. Indeed, a careful reading of the reference material should have indicated that they are superior. Thus the limitations and disadvantages of the CRLE models seem minor in comparison with the advantages that are summarized below.

1. They require 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. They require no local optimization or fudging of coefficients. This means that the results are falsifiable and can be tested rigorously against comparable water budget estimates

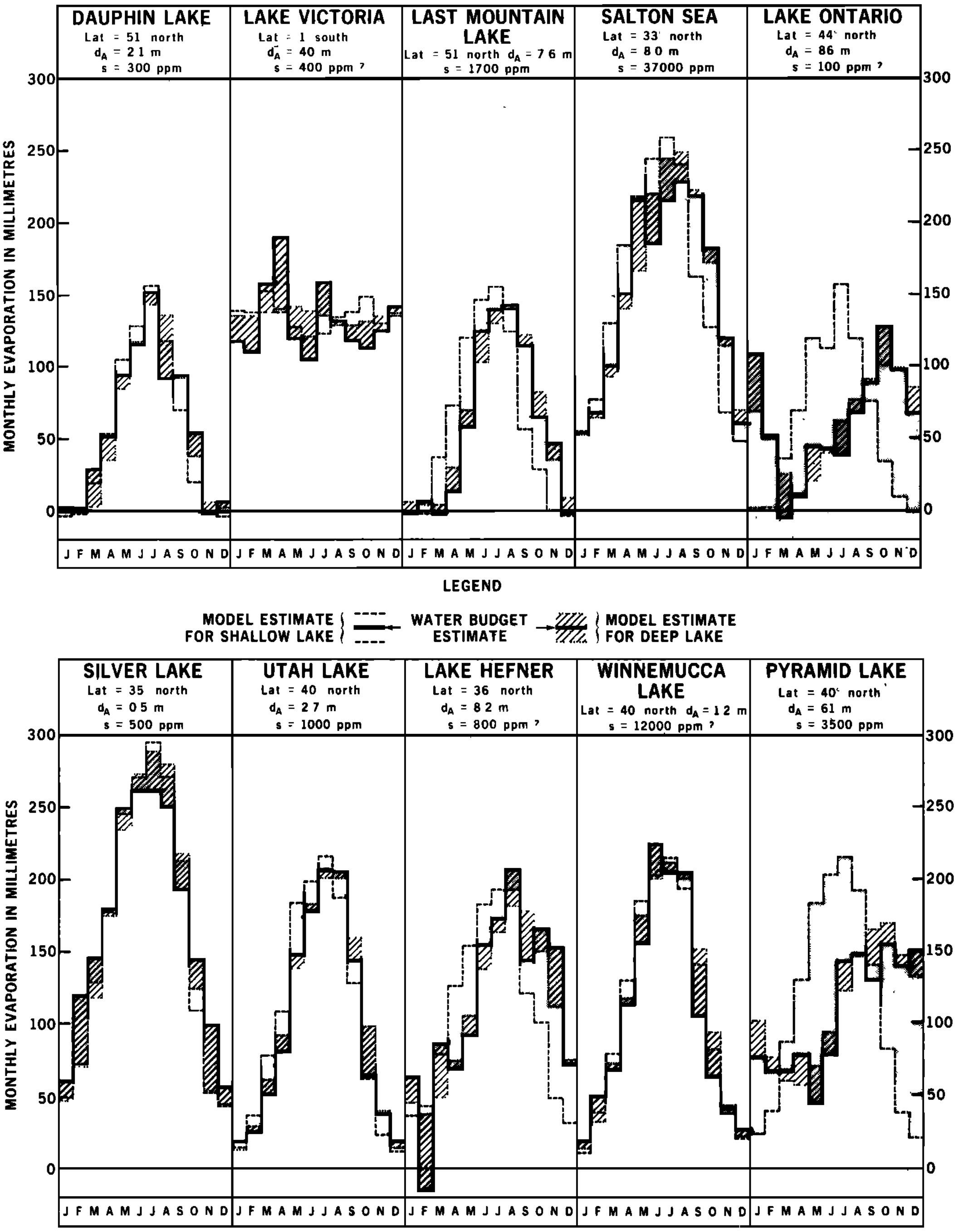

Fig. 2. Comparison of monthly model estimates of shallow lake and deep lake evaporation with comparable monthly water budget estimates.

anywhere in the world. The results summarized herein show good agreement with the corresponding water budget estimates for 10 lakes in North America and one in Africa.

3. They can provide reasonably good monthly estimates for lakes of any area or depth.

4. They have a sound physical basis and are therefore easily adaptable to unusual applications. Thus it is easy to make the adaptations needed 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.

5. 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 planned reservoir on the water balance of a basin.

The foregoing advantages make the CRLE models much superior to the conventional potential evaporation, pan evaporation, or mass transfer techniques that also rely on data observed in the land environment. With regard to the second advantage, it should be noted that 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

TABLE 2. Monthly Mean Estimates of Lake Evaporation

	Walker Lake*			Lake Okeechobee†		
	CRLE Model			CRLE Model		
Month	Shallow Lake, mm	Deep Lake, mm	Water Budget, mm	Shallow Lake, mm	Deep Lake, mm	Water Budget, mm
January	26	73	61	68	68	
February	44	49	46	82	74	
March	81	42	61	123	98	
April	124	55	61	161	136	
May	167	78	76	192	171	
June	192	108	122	189	189	
July	211	138	152	191	190	
August	188	165	168	186	189	
September	138	178	198	153	173	
October	78	171	137	124	143	
November	37	144	122	84	109	
December	22	107	76	66	79	
Annual	1308	1308	1280	1619	1619	1567

*Average depth = 31 meters, salinity = 2500 ppm.
†Average depth = 3 meters, salinity = 200 ppm.

the world without the need for locally calibrated coefficients. Thus, in the event of differences between the estimates provided by the CRLE models and those provided by any other technique (with the exception of high quality water budgets), the first step should be to examine the adequacy of the other technique.

From the considerations presented herein it is apparent that high-quality water budget estimates of lake evaporation are a scarce and valuable resource. One of the major problems is that the selection of standards of comparison from published water budget estimates requires a certain amount of judgement, and if this is done by an individual researcher there will always be suspicions of bias. A possible solution to this and to the problem of scarcity would be the preparation of a world register of lake water budgets by some international agency, for example, the Commission for Hydrology of the World Meteorological Organization. The agency could request each of its members to set up a panel of experts to collate, document, and evaluate all available water budget estimates of lake evaporation with the evaluation oriented toward the question of whether or not the water budget estimates are suitable for use as standards of comparison. Such a register would be of great value to future research on lake evaporation and would be of even greater value if it were kept up to date.

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