Appendix A. Mono Lake Monthly Water Balance Model

The hydrology of Mono Lake has been analyzed by constructing a monthly water budget that includes inflow terms, a storage change term, and an outflow term. The monthly inflows are the gaged and ungaged monthly streamflows, groundwater inflows, and direct precipitation on the lake surface. Ungaged streamflow and groundwater inflows are called "unmeasured inflows". The monthly change in storage is calculated from the measured change in elevation and Mono Lake surface area. The outflow term is the unmeasured evaporation that is estimated from an assumed monthly evaporation rate and the lake surface area. The water budget method attempts to estimate each of these terms to provide a consistent description of Mono Lake hydrology.

Methods for Estimating Terms

The basic data needed to calculate an accurate monthly water budget for Mono Lake are:

- bathymetry (lake surface area and volume at each elevation),
- monthly water surface elevations,
- monthly lakewide average precipitation,
- monthly surface water and groundwater inflows, and
- monthly lakewide average evaporation.

Bathymetry data for this appendix were obtained from the combination of aerial photogrammetry by Pacific Western Aerial Surveys and a detailed bathymetric survey of Mono Lake conducted by Pelagos Corporation for LADWP in summer 1986, when Mono Lake elevation was approximately 6,380 feet. Raw data were obtained from 60,000 depth soundings throughout Mono Lake. The depth soundings were converted into 5-foot depth contours, and the area within each contour interval was estimated. Interpolation methods were used to obtain measurements of 1-foot area increments.

Monthly Mono Lake surface elevations were obtained from LADWP records of periodic (but not always end-of-month) elevation measurements, linearly interpolated to end-of-month estimates. LADWP records were adjusted by adding 0.37 foot (4.5 inches), so that the elevations are consistent with the U.S. Geological Survey (USGS) 1929 sea level datum.

Monthly lakewide average precipitation data are estimated from LADWP monthly Cain Ranch precipitation records. Because Mono Lake is in the "rain shadow" of the Sierra Nevada crest, it is reasonable to suppose that the lakewide average precipitation is less than the Cain Ranch (elevation 6,850 feet) average of 11 inches. A precipitation station at Simis Ranch on the eastern side of Mono Lake has an estimated (short-term record) average precipitation of 7.5 inches. Each of the previous water budgets for Mono Lake use Cain Ranch as an index of lakewide precipitation. Vorster (1985) and LADWP (1990) annual water balance models each assume an average lakewide precipitation of 8 inches (73% of Cain Ranch average). The variations in lakewide precipitation are assumed to follow the Cain Ranch pattern.

Monthly surface water and groundwater inflows can only be partially measured with streamflow gages on the major tributaries (Mill, Lee Vining, Walker, Parker, and Rush Creeks). Because of irrigation diversions downstream of the gages on each tributary, the available flow records are only approximate estimates of the total surface water and groundwater inflow to Mono Lake. Additional inflow may exist that is proportional to the measured runoff, or the additional inflow may be a constant term that does not depend on variations in surface runoff. Each of the previous water budgets for Mono Lake has used the measured runoff as an index for estimating the total inflow term.

Monthly lakewide evaporation can be estimated from local evaporation pan measurements, observed changes in lake elevation, assumed relationships with meteorological data (wind and humidity), or heat budget modeling of Mono Lake surface temperatures (Romero 1992). Because the lakewide evaporation cannot be measured directly, any of these methods can provide only assumed evaporation rates. Favorable comparison between these methods of estimation increases the confidence in the assumed monthly evaporation pattern for Mono Lake.

Available Hydrologic Data

The available hydrologic data for 1941-1989 are given in the basic data file MONOWB.WK1, available from SWRCB consultants. The year and month are followed by the end-of-month elevation (USGS datum). The surface area and monthly volume changes are calculated by interpolation of the 1-foot interval bathymetry data that is given in data file BATHY.WK1. The monthly Cain Ranch precipitation is provided in the next column. The precipitation volume estimate is calculated from the average lake area and the precipitation depth.

The available streamflow measurements are given in the next several columns. Previous water budget models used various sums and adjustments to arrive at an index of surface runoff into Mono Lake. Because the total runoff from the four diverted tributary creeks are used as the index of runoff-year types (wet, normal, or dry) for Mono Basin, flow measurements for these creeks are used for the monthly Mono Lake water budget runoff index. For the historical period of 1941-1989, LADWP measured the spill at Lee Vining Creek intake and the releases and spills from Grant Lake reservoir to Rush Creek. The sum of these values was taken as the surface inflow to Mono Lake from the four diverted creeks. Releases from Walker and Parker Creeks were generally used for irrigation and were not included in the surface inflow estimates, although in wet years some nonirrigation releases were made.

For a portion of the historical period, LADWP operated streamflow gages on Lee Vining Creek (1941-1969) and Rush Creek (1952-1967) near their mouths at Mono Lake. These records provide an indication of the portion of the creek flows that infiltrated or were evapotranspirated on irrigated pasture or in the riparian corridors. They cannot provide a better estimate of the inflow to Mono Lake because the infiltrated water would enter as groundwater flow.

The next column is the difference between the observed monthly change in Mono Lake volume and the estimated terms for measured inflow and precipitation. The missing terms, evaporation and unmeasured inflow, are more difficult to identify.

The average monthly evaporation pattern was estimated from the observed loss of water from Mono Lake. The observed monthly changes in Mono Lake volume are usually less than the estimated inflows (measured surface flows plus precipitation) and these differences are greatest in the warm summer months. These average differences were used to approximate the monthly evaporation rates.

Surface inflow from portions of Mono Basin without streamflow gages and groundwater inflow cannot be measured. Some reasonable estimate for these unmeasured inflows must be used; a constant long-term average and/or some fraction of measured precipitation or gaged runoff can be used.

Because both evaporation and unmeasured inflows must be estimated from the change in Mono Lake volume that is not explained by measured inflows and direct precipitation, the magnitude of one term must be assumed to calculate the magnitude of the other. An independent estimate of annual evaporation based on temperature modeling by the University of California, Santa Barbara (UCSB) (1992) was used to set the magnitude of annual Mono Lake evaporation at 48 inches. This allowed the magnitude of the unmeasured inflow to be estimated to complete the monthly Mono Lake water budget model.

Previous Mono Lake Water Balance Models

SWRCB staff evaluated two annual (runoff year) water budget models and determined that the historical accuracy of both models, when compared with recorded Mono Lake volume changes from 1937 to 1989, was essentially equivalent (Rich pers. comm.). Vorster (1985) had developed a model that included many separate hydrologic terms, although several could not be measured directly. LADWP

(1990) had developed a model with fewer terms that lumped many measured and unmeasured inflows into a single "runoff factor" regression equation. The following review of each model will explain the basic techniques of constructing a water balance model.

Vorster Model

Vorster (1985) summarized all previous water budgets for Mono Lake and analyzed all available hydrologic data to estimate terms for an annual water balance for Mono Lake. LADWP runoff and lake elevation data for 1937-1983 formed the basis for estimates of the annual water budget terms. Vorster attempted to separate each identifiable hydrologic term to provide an accurate and reliable water budget and sensitivity analysis. However, because data were not available for direct estimation of each term, several terms were based on assumptions and indirect evidence. The accuracy of each individual term is unknown, although the overall match with the historical Mono Lake elevation record is good.

Vorster's model is based on the following water budget terms:

- Precipitation at Mono Lake is assumed to average 8 inches and to fluctuate with Cain Ranch measurements.

- Evaporation is assumed to average 45 inches, to fluctuate with Long Valley evaporation pan data, and to be reduced slightly (3-5%) by Mono Lake salinity.

- Sierra Nevada runoff as measured at streamflow gages (150 thousand acre-feet per year [TAF/yr]) is increased by 11% to account for unmeasured Sierra runoff, with an additional 20 TAF assumed from non-Sierran areas, 9 TAF from precipitation on land around the lake, and 1.5 TAF from Virginia Creek diversions. The total average inflows are 197.5 TAF and can be estimated as 111% of measured runoff plus a constant of about 30.5 TAF.

- Several water losses are assumed; bare ground ET around the lake perimeter averaged 5.5 TAF, Grant Lake reservoir evaporation averaged 1.5 TAF, phreatophytes around the lake account for 3 TAF, riparian ET averaged 1.5 TAF, irrigated pasture ET averaged 8 TAF, and the export of groundwater in the Mono Craters Tunnel accounts for about 7 TAF. These relatively constant losses total 26.5 TAF.

- The recorded LADWP exports from West Portal are subtracted from the available water.

- A final regression of unexplained lake volume changes with evaporation and runoff is used to correct the average 2.5 TAF/yr error in the modeled estimates of Mono Lake volume change during 1937-1983. The resulting estimates of Mono Lake elevation had an average error of 0.25 foot (3 inches).

The Vorster water balance includes many separate hydrologic terms that can be evaluated throughout the basin but does not provide validation of the individual estimates because hydrologic data are not collected for each identified term. The ability of the model to account accurately for the net water balance for Mono Lake suggests that the relative magnitude of the assumed inflows and losses is correct.

LADWP Model

LADWP developed a water balance with precipitation, evaporation, and a single net inflow term that used the available streamflow and diversion data to estimate the total releases toward Mono Lake. For an assumed evaporation rate, LADWP used a regression analysis to adjust the estimated inflows to match the historical fluctuations in Mono Lake volume for 1937-1989.

The LADWP-90RY model is based on the following water balance terms:

- Precipitation at Mono Lake is assumed to average 8 inches and to fluctuate with Cain Ranch measurements.

- Evaporation is assumed to average 41 inches, to fluctuate with Long Valley evaporation pan data, and to be reduced slightly (3-5%) by Mono Lake salinity.

- Sierra Nevada runoff as measured at streamflow gages (148 TAF/yr average) is decreased by irrigation diversions (7.5-12 TAF/yr), storage in Grant Lake reservoir, and West Portal exports. This is the measured portion of the estimated net inflow toward Mono Lake.

- A linear regression of unexplained historical lake volume changes with estimated releases to the lake is used to estimate the total inflow. The regression equation was estimated to be:

  Unmeasured inflow = 18.5 - .0585 x measured releases to Mono Lake

The LADWP formulation recognizes that the only available data are the measured streamflows, diversions, and lake level fluctuations. However, the regression equation for the unmeasured inflow could also be formulated in terms of the measured runoff, rather than the releases toward Mono Lake. Nevertheless, the historical match is comparable to the Vorster model, with an average error of 0.25 foot (3 inches).

Mono Lake Bathymetry

The bathymetric data for Mono Lake are summarized by the surface area and volume at 1-foot intervals from the lake bottom at elevations of 6,230-6,440 feet. The bathymetric data originated from a bottom depth-sounding survey conducted by Pelagos for LADWP in 1986 (Pelagos 1986) when the lake surface elevation was approximately 6,380 feet. The transects for the sounding equipment required at least 5 feet of depth. Aerial photogrammetry was used to estimate 5-foot elevation contours from 6,372 to 6,430 feet.

These basic data have been modified slightly in the elevation range of 6,365-6,430 feet and were extended to 6,440 by SWRCB consultants who mapped several contours based on visible benchmarks on aerial photographs (see Appendix G). The bathymetry data for elevations 6,300-6,440 feet are given in Table A-1. Estimates of salinity and specific gravity (density) are given for reference. The surface area of Mono Lake for elevations between 6,340 feet and 6,440 feet are shown in Figure A-1. The areas mapped by the SWRCB consultants are shown for comparison with the Pelagos bathymetry. The volume of Mono Lake for elevations between 6,340 and 6,440 feet is shown in Figure A-2.

The 1-foot incremental areas are the basic building block for the bathymetric data; the lake surface area is the sum of the incremental areas to that elevation, and the incremental volumes are calculated from the average area at the top and bottom of the increment. Review of the original Pelagos incremental area data showed that large incremental areas occurred near the 5-foot contour elevations, with much smaller increments midway between the 5-foot contours. This result is attributable to the SURFACE II graphics interpolation program used by Pelagos. SWRCB staff and consultants determined that this effect could be eliminated by 11-foot interval linear smoothing of the incremental area values (Rich pers. comm.).

Figure A-3 shows the original Pelagos and "smoothed" 1-foot incremental area values for Mono Lake between elevations of 6,350-6,420 feet. The largest incremental areas (more than 600 acres per foot of elevation) occur in the range of 6,365-6,375 feet because the shoreline slope is generally smallest at these elevations. The smallest incremental areas (about 200 acres per foot of elevation) occur between elevations 6,400 and 6,415 feet where the shoreline is steepest. The smoothing has relatively small effects on the lake surface and volume increments used in the water budget.

The bottom of Mono Lake is at about 6,230 feet elevation. At an elevation of 6,370 feet, the lake surface area is approximately 35,820 acres (56 square miles), and the lake volume is approximately 2.1 million af (MAF). At an elevation of 6,420 feet, the lake surface area is approximately 55,500 acres (87 square miles), and the lake volume is about 4.5 MAF. For the August 1989 point of reference for this EIR, Mono Lake surface elevation was 6,376.3 feet above sea level, with a surface area of about 41,000 acres and a volume of approximately 2.33 MAF.

In the water balance model, monthly volume changes of the lake were estimated from the surface areas interpolated from the 1-foot bathymetric data.

Evaporation and Precipitation

The monthly evaporation rates (inches/month) were assumed to be constants for each year. The monthly volume change from evaporation was estimated for the 1940-1989 historical period as the assumed evaporation rate multiplied by the surface area of the lake at the beginning of the month. The monthly precipitation contribution to the lake volume was estimated using the observed monthly Cain Ranch precipitation multiplied by the lake area. As previously noted, the average 1940-1989 Cain Ranch annual precipitation was approximately 11 inches. This is slightly higher than the estimated lakewide average precipitation of 8 inches based on maps of precipitation contours (Vorster 1985, LADWP 1990). This uncertainty in net evaporation (evaporation minus precipitation) is accounted for in the residual inflow estimate discussed in the next section.

The available hydrologic data were used to provide the initial estimate of monthly evaporation for Mono Lake. The monthly measured change in Mono Lake volume was compared with the estimated inflows from precipitation and measured surface inflows. This residual volume change was then divided by the surface area to give a residual elevation change in inches. These monthly estimates were averaged for each calendar month. The results provide an estimate of the minimum possible monthly average evaporation because any unmeasured inflows must be balanced by additional evaporation to match the historical surface elevation changes. Figure A-4 shows all the monthly estimates of "missing water", sorted by calendar months. These monthly residual estimates are scattered because of data errors and unmeasured inflows.

The monthly averages of these residual estimates of minimum evaporation rates are listed in Table A-2. The seasonal pattern is quite reasonable. The annual average sum of "missing water" is about 38 inches. This can be interpreted as the minimum possible evaporation because unmeasured inflows must be balanced by increased evaporation. This initial evaporation pattern can be confirmed with other estimates of evaporation for Mono Lake.

Two evaporation pan records for Mono Basin are available. A floating pan was maintained by LADWP in Grant Lake reservoir from 1942 to 1969, and a land pan replaced the floating pan in 1968 (elevation 7,200 feet). Measurements are only obtained in nonfreezing months, and Cain Ranch precipitation estimates are used to correct the actual pan data. Nevertheless, the average May-October Grant Lake reservoir evaporation measurements given in Table A-2 suggest a similar, but greater, seasonal pattern when compared to the residual monthly estimates.

The second evaporation pan record was collected at the Simis Ranch meteorological station from 1980 to 1983 (Vorster 1985). The monthly average values were higher than Grant Lake reservoir data but followed a similar seasonal pattern.

Temperature and salinity modeling of Mono Lake by UCSB staff independently estimated the evaporation for 1990 that provided the best match with biweekly surface temperature measurements. The annual value was approximately 48 inches (Romero 1992). This value was therefore selected for use in the Mono Lake monthly water budget model. Figure A-5 shows the sensitivity of modeled Mono Lake surface temperatures to the evaporation coefficient. The resulting annual evaporation rates are shown. The best estimate was determined to be 0.8 times the base estimate. UCSB staff plan to collect daily surface temperatures and complete local meteorological data in hopes of determining an even more accurate estimate of Mono Lake evaporation. However, some uncertainty will always remain in evaporation and all other terms of the water budget.

Unmeasured Inflows

The monthly water balance model uses the monthly residual water estimates to determine the monthly fractions of an assumed total annual evaporation (Table A-2). A linear regression equation was then estimated between unmeasured inflows and monthly runoff to complete the monthly water budget. Both the constant and the fraction of runoff increase with the assumed evaporation. For the assumed evaporation of 48 inches, the constant term is 2,915 af/month (34,992 af/year), and the fraction of runoff is 22.8%. This 22.8% fraction of runoff regression term includes Mill and DeChambeau Creeks because the runoff term was selected to correspond to the diverted tributary creeks. Because the Mill and DeChambeau Creeks average 18% of the diverted creeks' runoff, unmeasured inflow is about 5% of diverted creeks' runoff, plus the constant term of about 35 TAF/yr.

This regression of unmeasured inflows is consistent with the assumed evaporation rate because the runoff from Mill and DeChambeau Creeks is about 18% of the diverted creeks' total runoff. If the runoff variable term is assumed to equal runoff from Mill and DeChambeau Creeks, then at least 44 inches of evaporation are required for an 18% runoff term in the unmeasured inflow regression. Alternatively, if the total unmeasured inflow term is assumed to equal runoff from Mill and DeChambeau Creeks, then at least 37 inches of evaporation are needed. The assumed 48 inches of evaporation are consistent with this unmeasured inflow regression estimate.

Model Calibration with Observed Lake-Level Fluctuations

The monthly water balance can be summarized as:

- assumed constant annual evaporation of 48 inches, distributed in constant monthly fractions;
- measured Cain Ranch monthly precipitation;
- monthly releases from Lee Vining, Walker, Parker, and Rush Creeks to Mono Lake; and

- # additional monthly inflow of 2,916 af plus 22.8% of monthly runoff from the four diverted creeks; the total additional inflow averages 63,116 af per year.

These monthly estimated evaporation and additional inflow terms, together with the measured historical releases to Mono Lake from the diverted tributaries, provide an accurate simulation of the observed variations in lake volume and surface elevation. Figure A-6 shows the simulated and observed Mono Lake elevations for the 1941-1989 period. The average error for the 49-year period is 0.5 foot. However, the average absolute error since 1965 when the lake level declined below 6,390 feet is only 0.27 foot.

The calibration using the assumed 48 inches of evaporation and results for a 36 inch evaporation estimate are shown. Lower evaporation rates are balanced by smaller unmeasured inflows regressions, so that the resulting match with the historical Mono Lake elevation pattern is nearly identical. The simulated elevations remain consistently below the measured elevations from about 1950 to 1983, suggesting an error in the measured inflow terms.

The monthly water budget terms can be summarized with annual values for the historical period 1941-1989, as shown in Figure A-7. The terms are shown as cumulative annual values. The first term is the unmeasured inflows that fluctuate with runoff. The next term is precipitation on Mono Lake. The third inflow is the measured releases to Mono Lake from the four diverted creeks. These inflow terms have varied from about 50 TAF to more than 350 TAF. When the assumed 48 inches of evaporation are subtracted from these inflows, the final estimated change in Mono Lake volume is given. For calibration purposes, the actual observed changes in Mono Lake volume also are shown.

This monthly water budget for Mono Lake is considered adequate for purposes of this EIR and was used in the aqueduct simulation model (Auxiliary Reports 5 and 18) and, in modified form, in the extended drought analysis (Appendix H).

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