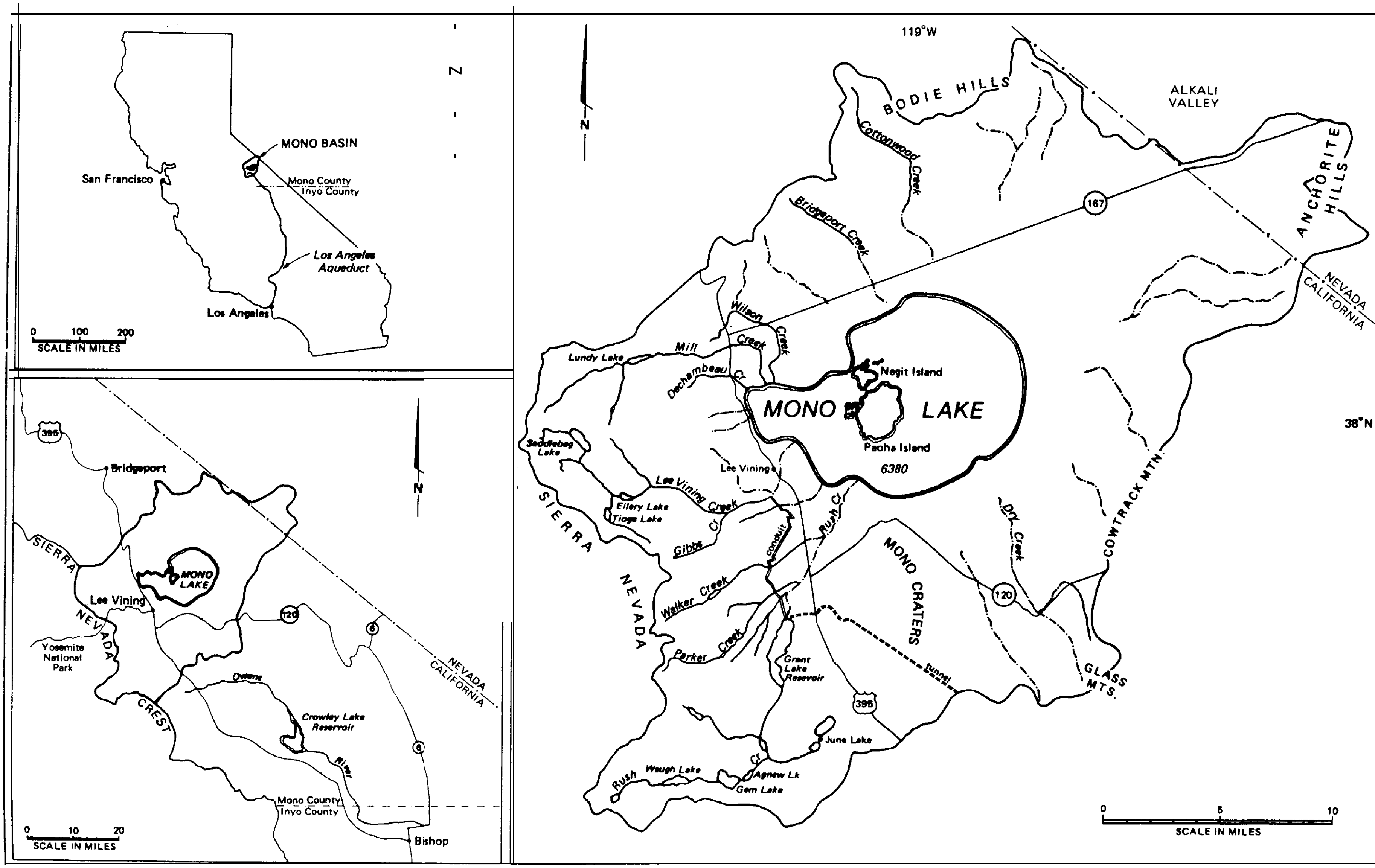
Chapter I: BACKGROUND

ENVIRONMENTAL SETTING

MONO BASIN

Location. The Mono Lake drainage basin (hereafter called the Mono Basin) is located 190 mi east of San Francisco on the western edge of the Great Basin (Figure l-l). Estimates of the area of the basin range from 634 mi^2 (Mason 1967) to 801 mi^2 (CADWR 1960). This lack of agreement may be due in part to the difficulty of interpreting the drainage divide in the remote eastern and southern part of the basin from the available maps and the inclusion of Alkali Valley, a 69 mi^2 enclosed basin in Nevada that may have a subsurface connection to the Mono Basin, as suggested by Van Denburgh and Glancey (1970).[1] After reviewing the literature, visiting some of the areas of greatest ambiguity, and planimetering the basin boundaries, the area of the Mono Basin is estimated to be 695 square mi.

Topography. The Mono Basin is characterized by tremendous topographic contrast. It is surrounded by mountains -- including the Sierra Nevada, Bodie Hills, Mono Craters, Anchorite Hills, and Cowtrack Mt. -- of different heights and varied relief. In most areas stream-dissected mountains grade into a gently sloping alluvial basin floor, except in the southwest portion of the


MONO BASIN
San Francisco
Mono County
Inyo County
Los Angeles Aqueduct
Los Angeles
0 100 200
SCALE IN MILES
N
395
Bridgeport
SIERRA
NEVADA
CREST
Lee Vining
MONO LAKE
Yosemite National Park
120
6
NEVADA
CALIFORNIA
Owens
Crowley Lake Reservoir
River
Mono County
Inyo County
Bishop
0 10 20
SCALE IN MILES
119°W
38°N
BODIE HILLS
ALKALI VALLEY
ANCHORITE HILLS
Cottonwood Creek
Bridgeport Creek
167
Wilson Creek
Mill Creek
Lundy Lake
Dechambeau Cr
Negit Island
MONO LAKE
Paoha Island
6380
Saddlebag Lake
Lee Vining
Lee Vining Creek
Ellery Lake
Tioga Lake
Gibbs Cr
conduit
Rush Cr
Walker Creek
Parker Creek
Grant Lake Reservoir
MONO CRATERS
tunnel
June Lake
Rush
Waugh Lake
Cr
Agnew Lk
Gem Lake
Dry Creek
COWTRACK MTN
GLASS MTS.
0 5 10
SCALE IN MILES

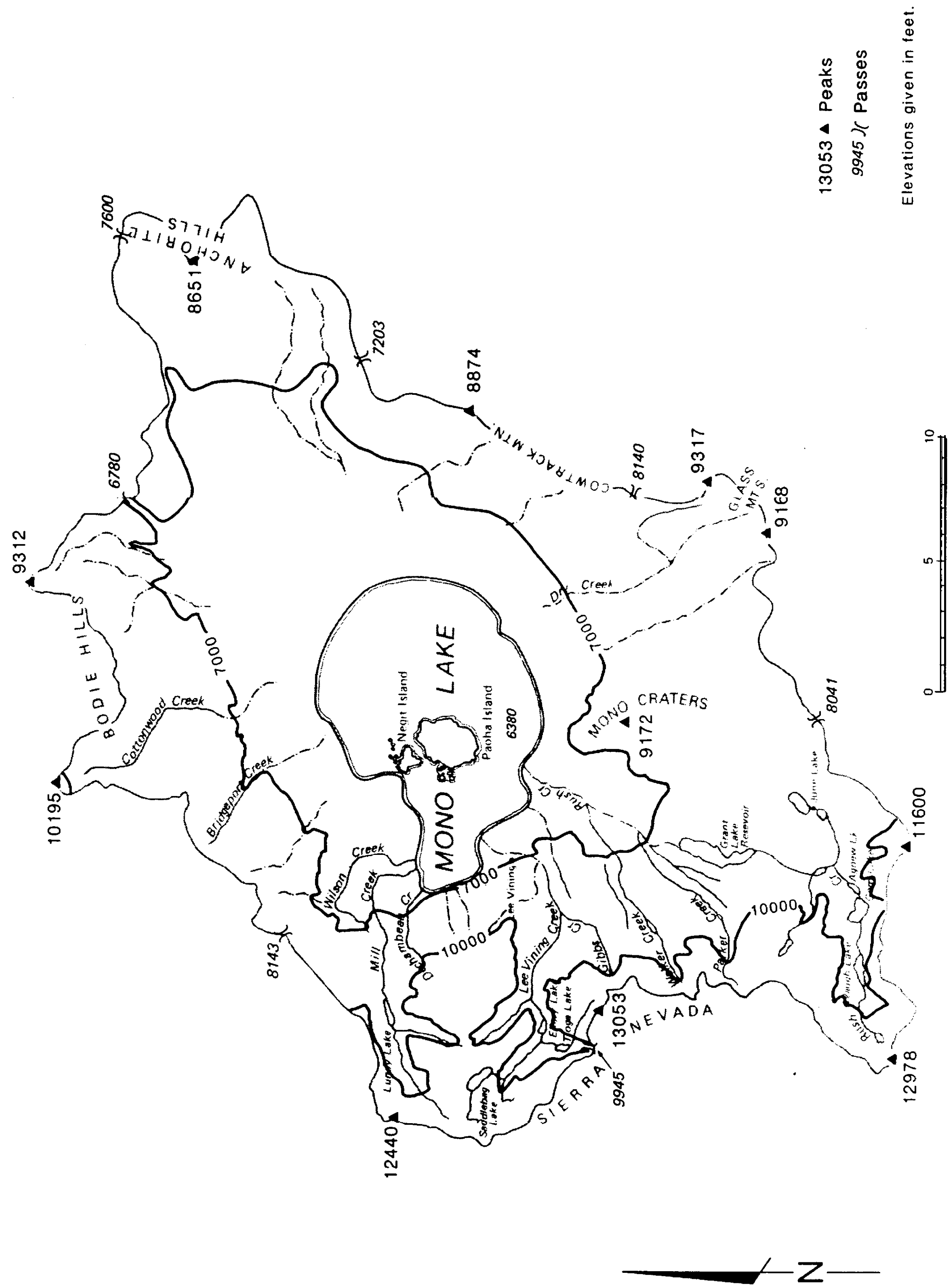
basin where the glacially scoured Sierra Nevada grade Into a piedmont slope of glacial till before intersecting the basin floor. Mono Lake dominates the center of the basin. Within the lake area are two large islands and some 25 small islets. The areas of the principal topographic provinces of the Mono Basin are listed in Table l-l.

Elevations in the Mono Basin range from the lake surface at 6380 ft in January 1984, to Mount Dana on the Sierra Crest, at 13,053 ft. The crest of the Sierra Nevada ranges from 11,000 to 13,000 ft; the summits to the north, east, and south range from 8,000 to 10,000 ft. The basin floor is generally below the 7,000 foot contour except in the south, where the volcanic alluvium grades up to the Mono basin boundary at about 8,000 ft. Figure l-2 shows the elevation of selected summits and principal passes around the basin boundary.

Geology. A simple geological description portrays the Mono Basin as a sediment-filled structural depression -- created by faulting and tectonic downwarping -- that is surrounded by the massive Mesozoic granite and Paleozoic metamorphic rocks of the Sierra Nevada escarpment on the west, the highly fractured Tertiary volcanic rocks of the Bodie Hills, Anchorite Hills and Cowtrack Mountain on the north and east, and the Quaternary volcanic rocks of the Mono Craters and Glass Mountains on the south (Figure l-3).[2] Ridges and layers of glacial debris left by multiple Pleistocene glaciations form a Piedmont slope at the

TABLE l-l. Principal Topographic Provinces of the Mono Basin

Topographic Province	Area (Sq. Miles)
1. Sierra Nevada (including glacial till)	185
2. Other mountains including Mono Craters	186
3. Basin floor	257
4. Mono Lake	67
TOTAL	695


MONO LAKE
Negit Island
Paoha Island
6380
BODIE HILLS
ANCHORITE HILLS
COWTRACK MTN.
GLASS MTS.
MONO CRATERS
SIERRA NEVADA
Cottonwood Creek
Bridgeport Creek
Wilson Creek
Mill Creek
Lee Vining Creek
Rush Cr.
Grant Lake Reservoir
Saddlebag Lake
Lundy Lake
Tioga Lake
7000
10000
10195
9312
6780
7600
8651
7203
8874
8140
9317
9168
8041
9172
11600
12978
13053
9945
12440
8143
13053 ▲ Peaks
9945)(Passes
Elevations given in feet.
SCALE IN MILES
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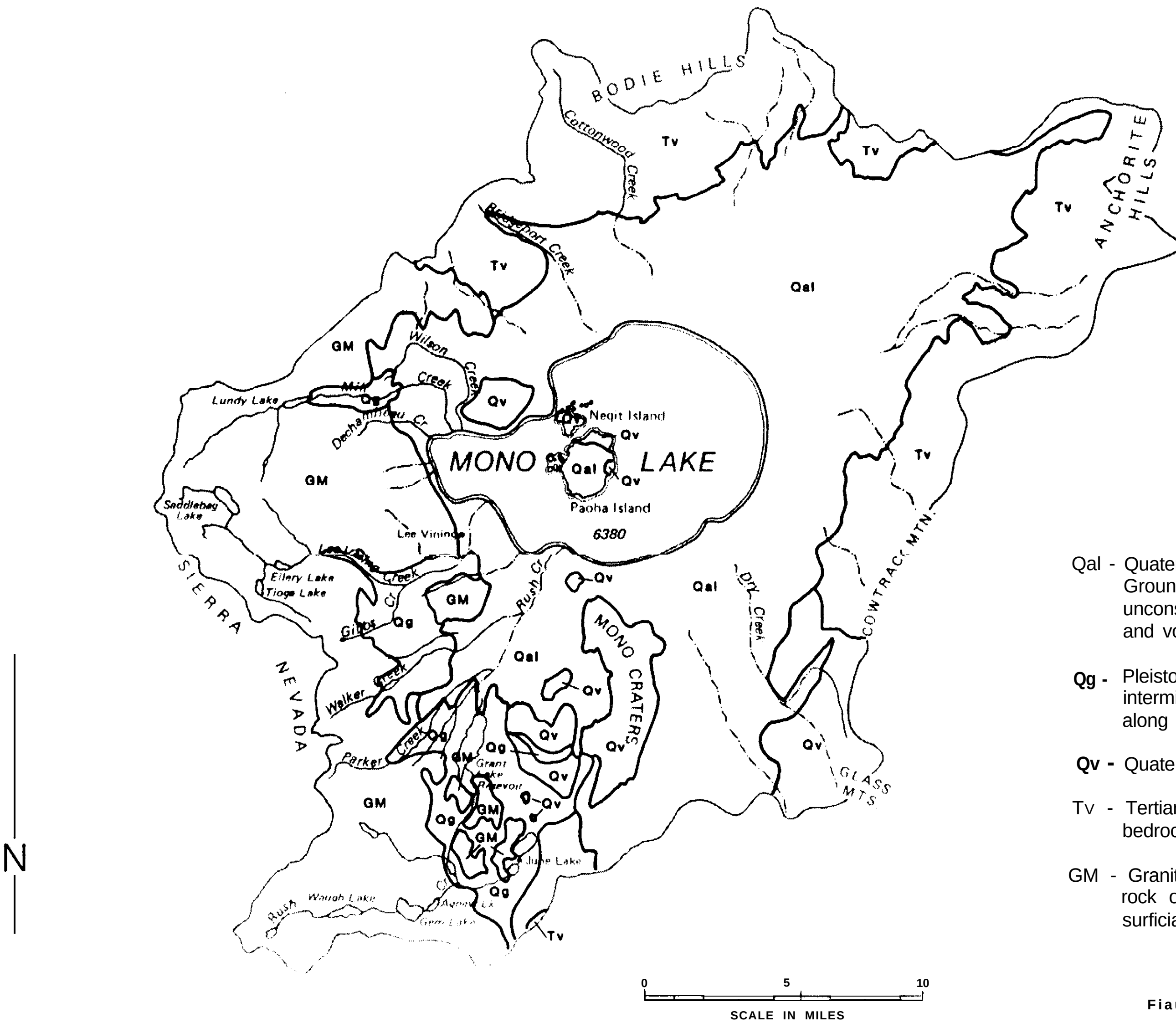
5
10
N



Qal - Quaternary deposits of the Mono Ground-Water Basin - includes unconsolidated lacustrine, riverine, and volcanic sediments.

Qg - Pleistocene glacial deposits - intermixed with fluvial deposits along stream courses.

Qv - Quaternary volcanic bedrock.

Tv - Tertiary sedimentary and volcanic bedrock.

GM - Granitic and metamorphic basement rock of the Sierra Nevada - includes surficial deposits of Quatemary Age.

Fiaure I-3
Geology

base of the Sierra Nevada.

At least 3,000 ft of interfingered layers of gravel, sand, silt, and clay fill the basin depression. The nature and extent of individual layers reflect the glacial and volcanic activity and the climatically-induced fluctuations of Mono Lake during the Pleistocene and Holocene. The permeable volcanic and fluvial deposits are aquifers in the Mono Groundwater Basin (MCWB) while the lacustrine deposits are aquicludes. The Wilson Creek formation, a lacustrine deposit marking the Tioga (late Pleistocene) glacial period, is a major aquiclude in the MCWB separating the aquifers of Pleistocene age and the unconfined and semi-confined aquifers of Holocene age. In this report the MCWB, which is shown in Figure l-4, includes all of the unconsolidated sediments of the basin floor excluding the glacial moraines.[3]

Climate, The Mono Basin is characterized by a high altitude Mediterranean climate with great seasonal and annual precipitation variablility. Over much of the basin the majority of precipitation occurs in the winter as snow; the precipitation varies considerably with elevation and distance from the Sierra Nevada crest, owing to pronounced orographic and rain shadow effects. The area1 distribution of precipitation is more fully discussed on page 54.

The great diurnal and seasonal variation of temperature in the Mono Basin is characteristic of a continental climate.

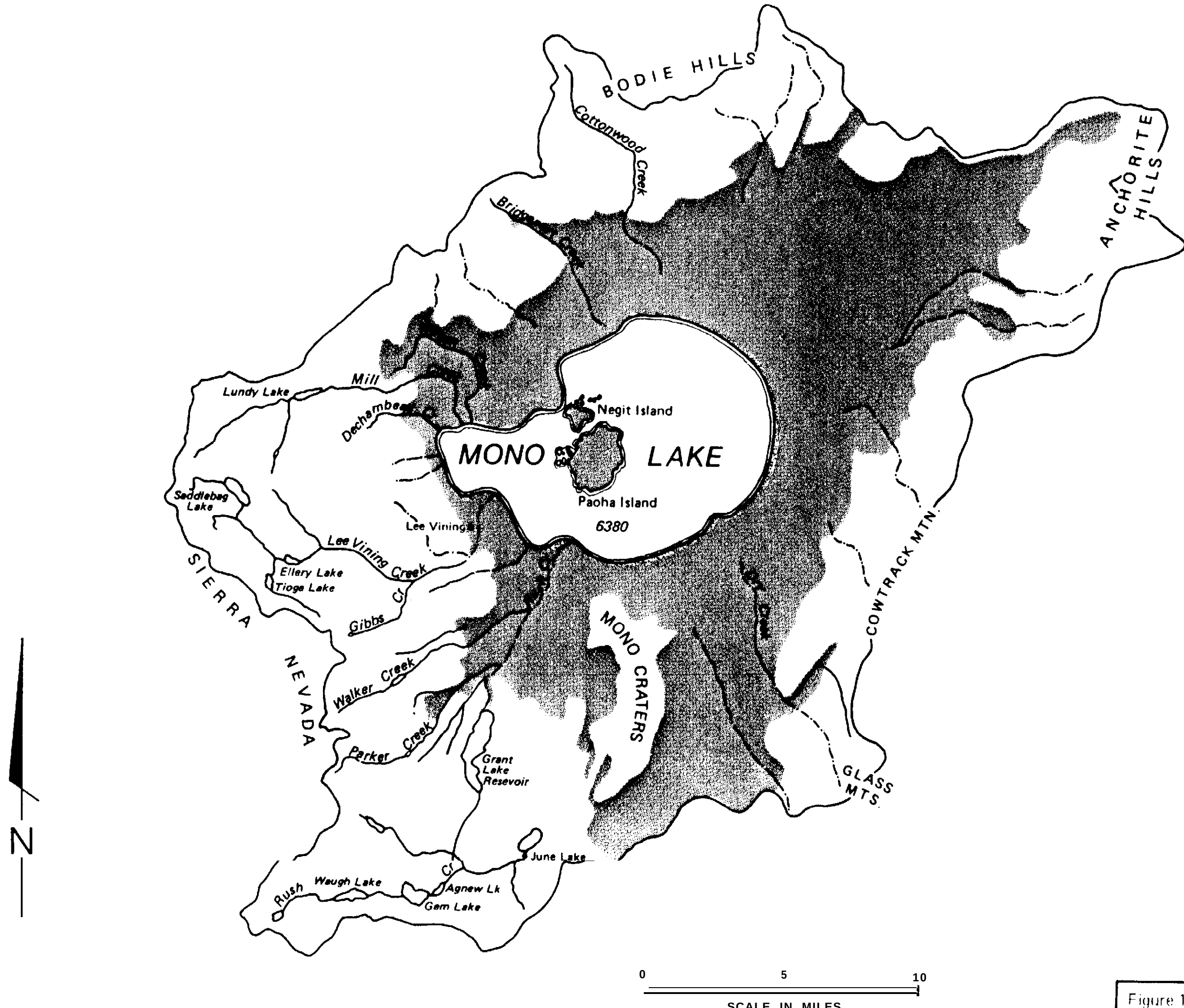


Figure 1-4

Mono Groundwater Basin

Temperatures tend to decrease with increasing elevation, although cold air drainage and wintertime inversions cause localized reversals of this trend. Mean annual temperatures vary from below freezing (around glaciers and permanent snow fields) to about 47 degrees Fahrenheit (F) at the Mono Lake weather station on the northwest shore. [4] Mean daily winter temperatures (December through February) are usually below freezing throughout the basin, while mean daily summer temperatures are between 60 degrees F and 65 degrees F. Significant diurnal temperature fluctuations are the rule, with a 40 degrees F to 50 degrees F daily range in the summer months and a 20 degrees F to 30 degrees F range in the winter months. Summer daily maxima normally range from 75 degrees F to 85 degrees F and winter daily maxima are often above freezing. The monthly temperature characteristics of the Simis climate station for 1981 (a warm year) and 1983 (a cool year) are presented in Figure 1-5.

Mono Lake moderates the local daily and seasonal temperature extremes. The lake's most noticeable influence is an increase in the daily minima. Mason (1967) suggests that the lake may have a significant influence on the climate near it - cooling in the summer and warming in the winter - with possibly greater winter precipitation in areas close to the lake.

The prevailing winds in the Mono Basin are from the southwest. Mean annual windspeed at two basin-floor measurement sites is somewhat greater than five m.p.h. Episodes of strong

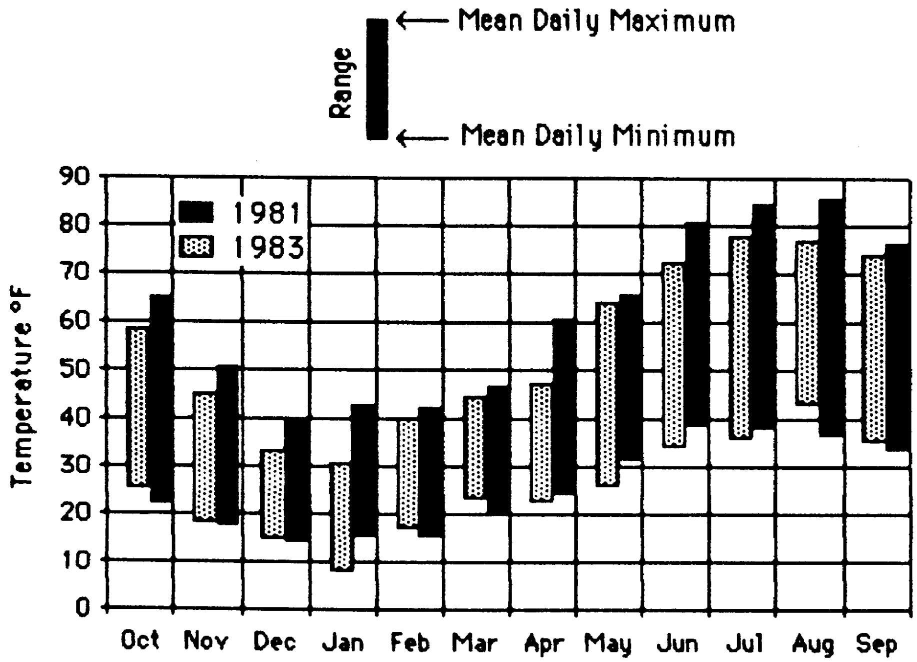


Figure 1-5. Monthly Temperature Characteristics at the Simis Station in 1981 and 1983

winds (sustained speeds in excess of 40 m.p.h.) occur in every month of the year but are more frequent in the late winter and spring months. Light afternoon winds are typical in the summer due to differential heating of the basin floor and mountains.

Other climatic parameters that have been quantitively measured or qualitatively observed include relative humidity and solar radiation. Relative humidity observations confirm that xeric (dry) conditions prevail except during periods of precipitation and fog, although moister conditions exist in the high groundwater areas. Observations at Cain Ranch indicate that an average of about 60% of the days in a year are cloud-free (Black 1958). A compilation of the location and type of climatic measurements made in and near the Mono Basin is given Figure Al-l in Appendix 1.

Hydrology. A broad overview of the Mono Basin hydrology follows. A more detailed, quantitative presentation is given with each of the major water balance components -- precipitation, runoff, evaporation, evapotranspiration, and diversions -- that are discussed in Chapter Two.

All surface water and groundwater is derived from precipitation over the basin, except for one small diversion into the basin from Virginia Creek and a possible subsurface connection to Alkali Valley in Nevada.[5] Since the Mono Basin is hydrographically closed, all surface water and groundwater naturally drains toward Mono Lake.

Most of the surface water in the Mono Basin originates in the Sierra Nevada. It is derived primarily from the spring and summer melt of the previous winter's snowpack; most of the meltwater drains into the five principal streams of the Mono Basin: Rush, Lee Vining, Mill, Parker, and Walker Creeks. Walker and Parker Creeks are tributary to Rush Creek, so only Rush, Lee Vining and Mill Creeks naturally drain into Mono Lake. The remaining streamflow from the Sierra Nevada occurs in small first-order streams, including Horse Meadow, Post Office, Wilson and Dechambeau Creeks, and a few unnamed intermittent creeks. Away from the Sierra, the Mono Basin exhibits only minor amounts of streamflow, reflecting both lower precipitation and more permeable substrates. Three drainages -- Dry Creek, Cottonwood Creek, and Bridgeport Creek -- sustain year-round flow in their upper reaches; most of the flow, however, is absorbed into the ground as soon as it debouches onto the basin floor.

In most years nearly the entire flow of the five principal streams of the Mono Basin is diverted. Rush and Lee Vining Creeks are diverted for export to Los Angeles; Walker and Parker Creeks for in-basin irrigation and trans-basin export; Mill Creek for hydropower production and in-basin irrigation.[6]

Groundwater occurs primarily in the unconsolidated sediments that define the Mono Groundwater Basin, although some also occurs locally in the volcanic bedrock, the unglaciated Sierra bedrock, and the glacial till, The groundwater basin is recharged by: (a) lateral underflow from the surrounding bedrock, through "hidden recharge" (Feth 1964); (b) streamflow that percolates into the sediments, and (c) precipitation that infiltrates directly into the aquifers. In the volcanic and unglaciated bedrock areas, water infiltrates directly into the sub-surface through fractures, cooling joints, and weathered and brecciated surfaces. Groundwater is discharged in hundreds of discrete springs on land and under Mono Lake, chiefly along fault zones. In addition, a significant but unknown amount of groundwater is consumed by vegetation or discharged as diffuse seepage into Mono Lake.[7]

Soil. Soil development in the higher elevations of the Mono Basin is limited by the harsh climate and recent glaciations that left behind steep bedrock and colluvium-covered slopes. Some soil development has occurred on the gentler mountain slopes, in stream valleys, and on the basin floor; lake fluctuations, volcanic activity, and frequent winds limit the stability of basin-floor surface layers and thus inhibit mature horizonation. In general, most of the Mono Basin "soils" are coarse-textured, well-drained, and low in organic matter (Vaughn 1980).[8] The "soils" developed on the lake sediments are finer textured and less well-drained, and sometimes display a hard pan layer several feet below the surface. Saline-alkaline soils with high water tables and salt crusts occur around the margin of Mono Lake. Water in the soil often freezes during the winter thus inhibiting infiltration.

Vegetation. The large scale distribution of vegetation in the basin reflects the temperature and precipitation gradients. According to Ornduff's (1975) classification of California vegetation, the basin contains the Alpine fell-field, Montane meadow, Sub-alpine forest, Pinyon-juniper, and Sagebrush communities. Cheatham and Haller (1975) recognize additional habitat types, including the Jeffrey Pine forest, Riparian Woodland, and Great Basin Marsh. Within these broad distributional groupings, water table depth, edaphic environment (especially the presence of salts), and slope aspect are primary factors in determining vegetation associations.

MONO LAKE.

Mono Lake is by definition a terminal lake because under natural conditions all runoff in the Mono Basin eventually terminates in the lake.[9] According to Lajoie (pers comm 1983) Mono Lake has continuously existed for between 500,000 and one million years, making it perhaps the second oldest continuously existing lake in North America.

Mono Lake is a relatively deep terminal lake (Melak 1983) with a maximum depth near 150 ft and a median depth near 60 ft (based on Scholl et al. 1967). The deeper, western half of the lake, with its steeply sloped subsurface topography, contrasts to the gentler sloping, shallow eastern half. Faulting along the escarpment of the eastern Sierra Nevada has downdropped the western part of the depression the greatest amount, causing the lake to abut the Sierran front, The lake surface elevation of 6380 ft makes Mono Lake the highest terminal lake in North America.

Mono Cake is a highly saline and alkaline lake. Its current salinity of about 80,000 ppm is nearly 2 l/2 times greater than ocean water. The high salinity is a direct result of evaporative concentration of the dissolved ions brought in over a long time by stream water, ground water, and volcanic activity. Sodium is the major cation; chloride and carbonate are the major anions, and sulfate, borate and phosphate concentrations are high (Mason 1967). Mason (1967) presents the most detailed published analysis of Mono Lake's chemistry.

Mono bake is considered a warm monomictic lake because it does not usually freeze, and it normally turns over once a year.[9] The lake's thermal structure undergoes an annual cycle, thermally stratifying In the spring, remaining stratified through the summer, and completely mixing in the late fall so as to become isothermal in the winter. The surface water temperature of Mono Lake during this annual cycle ranges from 75 degrees F to near 32 degrees F (Melak 1983). Because of the lake's high salinity, the lake stratifies sooner than would a fresh water body in its place (Mason 1967). Mono Lake therefore absorbs less heat than a comparative fresh water body due to effective insulation of the epilimnion.

Fluctuations. Since Mono Lake has no outlet, its level and size fluctuate in response to changes in the balance between evaporative outflow and inflow from precipitation, surface water, and ground water. Climatic variation in the late Pleistocene and Holocene caused the area of the lake to fluctuate between 171,000 ac at its overflow elevation of about 7,200 ft and 37,000 ac at its low stand of approximately 6368 ft (Scholl et al. 1967 and Stine pers comm 1984); The surface area has historically fluctuated between 56,700 ac when the level reached 6428 ft in July 1919 and 36,700 ac when the lake dropped to 6372 ft in January 1982.[11]

Historic lake levels can be determined back to 1857, when Colonel A.W. Von Schmidt completed the initial meander survey of Mono Lake. Although the survey did not state the surface elevation of Mono Lake, the 1857 lake level can be established at 6407 + 1 ft, based primarily on the comparison of Von Schmidt's notes and plats with modern topographic maps (Stine 1981). The 6407 +- 1 ft surface level is 21 to 31 ft higher than previously published 1857 surface elevations for Mono Lake. The lake level fluctuations between 1857 and 1883 have been estimated based on cartographic, historical, and climatic evidence. W.D. Johnson, the topographer for Israel Russell's investigation of the Mono Basin (Russel 1889), etched a mark on Negit Island in 1883 at an elevation of 6410 ft, thus providing the first recorded elevation of Mono Lake. Other lake level measurements were made intermittently during the period 1883 to 1912 with reference to benchmarks that have been re-surveyed and subsequently readjusted in height. Since 1912 the lake level has been measured at staff gages on the western margin of the lake. Readings were taken by the United States Forest Service (USFS) from 1912 to 1926; the USFS and Los Angeles Department of Water and Power (LADWP) read the gages from 1926 to 1941; the LADWP has read these gages on a fairly regular basis since 1941. The lake elevations recorded by the USFS and LADWP are referenced to a United States Geological Survey (USGS) datum that was adjusted upwards by 0.37 ft in 1931 because of the 1929 adjustment of level net by the United States Coast and Geodetic Survey (Harding 1962). Although LADWP maintains they adopted the adjustment to the USGS datum (Lund pers comm 1984), a comparison of LADWP and USGS records and a letter from Mike Butcher of the USGS to Joseph Barbieri of the California State Attorney General's Office (July 1984) indicate that LADWP has not made the adjustment. Correct lake elevations are thus 0.37 ft higher than the lake elevations reported by LADWP.[12]

Figure l-6 is a plot of the annual estimated lake levels from 1850 to 1911 and a plot of all of the recorded staff gage measurements made from 1912 through June 1984. This figure is a reproduction of an exhibit prepared by Scott Stine in 1984 for the California State Lands Commission.

Prior to 1941, the level of Mono Lake typically fluctuated one to three feet annually, Without trans-basin diversions the lake reaches an annual high sometime in the late spring or summer in response to the snowmelt runoff and drops to an annual low in the late fall or early winter as inflow/reaches a minimum. In low runoff years, the lake peaks in April or May; in years of high runoff, the lake peaks as late as mid-August. Relatively constant groundwater inflow to Mono Lake tends to dampen the yearly fluctuations. Since 1941, the seasonal fluctuations have been dependent on the magnitude of both the tributary diversions and climatic variation. The annual peak level is usually reached sometime in late winter or early spring, 2 or 3 months earlier than under pre-1941 conditions.

The lake reached its historic high stand of 6428.07 ft in July 1919. The lake dropped nearly 14 ft in the subsequent 15 years due to abnormally dry climatic conditions. Since trans-basin diversions began in 1941 there has been a steady net annual drop in lake level except for the net annual rises that occur in the occasional very wet year.

The magnitude of lake fluctuations is influenced by the level, area, and volume of the lake. The lower the surface elevation, the greater the rise will be for a given high inflow, all other factors being equal; conversely, the higher the lake, the greater the drop for a given low inflow. This point is illustrated by comparing the rises of water year 1983 (5.81 ft) and water year 1938 (3.12 ft); the two years had similar inflow volumes and lake evaporation rates, but the average lake surface area differed by 15,500 ac.

WATER BALANCE THEORY

According to the law of mass conservation, the volume of water in a lake changes over time by an amount equal to the difference between all water flowing in and all water flowing out. The process can be expressed in a continuity equation that is the conceptual basis for a deterministic mathematical model of a lake's water balance (WMO 1975).[13] The general form of the equation for a terminal lake is:

$$I_S + I_G + I_P - O_E - O_{ET} \pm D = \Delta S_L \qquad (1)$$

or

$$I_S + I_G + I_P - O_E - O_{ET} \pm D - \Delta S_L = 0 \text{ where} \qquad (2)$$

I_S, I_G, I_P are surface, groundwater, and precipitation inflows;

O_E, O_{ET} are evaporation and evaportranspiration outflows;

$\pm D$ is a diversion inflow or outflow:

ΔS_L is the lake storage change.

The I's, O's and the AS_L are known as the components of the water balance equation. The components represent the stochastic (i.e. random) hydrologic processes or the deterministic anthropogenic (human-induced) processes that can be quantified for a specified area and interval of time.

Because the components are quantified for a time/space continuum from point data and with imperfect measurement and estimation techniques, errors always occur. The error in each component value is summed into what is called discrepancy, residual, or overall error term of the water balance, so that equation 2 is rewritten as:

$$I_S + I_G + I_P - O_E - O_{ET} \pm D - \Delta S_L = \text{Error (E)} \quad (3)$$

$$I_S + I_G + I_P - O_E - O_{ET} \pm D \pm E = \Delta S_L \quad (4)$$

It must be emphasized the "E" represents the net effect of all component errors and that some may cancel each other. "E" also includes components not taken into account. Thus, a zero or low value of the error term is no assurance that the values of the components are correct. Winter (1981) observes that the component error and the overall error are often neglected in a water balance but they are a general problem in its practical application especially since "water budgets determined by poor methodology without estimates of errors can be very misleading; can give a false sense of security about how well the budget is known; and can lead to considerable waste of lake management and restoration money."

By using the relationship of lake level to volume (as determined by the lake basin morphometry), a lake level change is forecasted by adding the lake storage change calculated by equation 4 to a known lake volume. The following balance equation expresses the forecasting relationship:

$$V_{Initial} + \Delta S_{Calc} = V_{New} \quad \text{where} \qquad (5)$$

$V_{Initial}$ is the lake volume at the beginning of a specified time interval and

$$\Delta S_{Calc} = I_S + I_G + I_P - O_E - O_{ET} \pm D \pm E \text{ and}$$

V_{New} is the lake volume at the end of the time interval.

Equation (5) is the basic equation for a water balance lake level forecast model as each V_{New} becomes the $V_{Initial}$ in each succeeding time interval. Although other models have been used to forecast terminal lake levels [14], a model based on the water balance is the best method because (1) it is conceptually simple and scientifically correct; (2) its accuracy is limited only by the accurate development and prediction of the inflows, outflows and errors; (3) it allows for the assessment of the effect of human-induced and natural changes in the hydrologic system; (4) its results are conditioned by previous lake levels; (5) it allows the forecast to be as short-term (day, month, year) as the data permits (James et al. 1979).

MODEL DEVELOPMENT. Because of the circular nature of reasoning that goes into some water balances, an unreliable water balance developed with imprecise methods can look as good on paper (i.e. have as low an overall error) as one developed with the best computational and methodological techniques. Ideally, then, a water balance forecast model should be developed using a systematic procedure that allows its accuracy and reliability to be evaluated.

Although there is no established procedure for developing a terminal lake level forecast model, the phases of the general modeling process - formulation, calibration, verification, application -- as outlined by McCuen (1976) and applied by Diskin and Simon (1977) and Dooge (1972) to hydrologic models, do provide guidelines for developing a reliable terminal lake level forecast model, Each of the major phases is considered below, and shown in Figure 1-7.

Formulation. Water balance formulation is a multi-step process that results in the identification and quantification of the model's components. The steps should include the specification of the water balance "free-body," time interval, and base period (Hayes et al. 1980 and Peters 1972) so that the components are properly identified, In addition an analysis of the errors incurred in quantification should be included so that the accuracy of the component values can be evaluated (Winter 1981). These steps are outlined below.

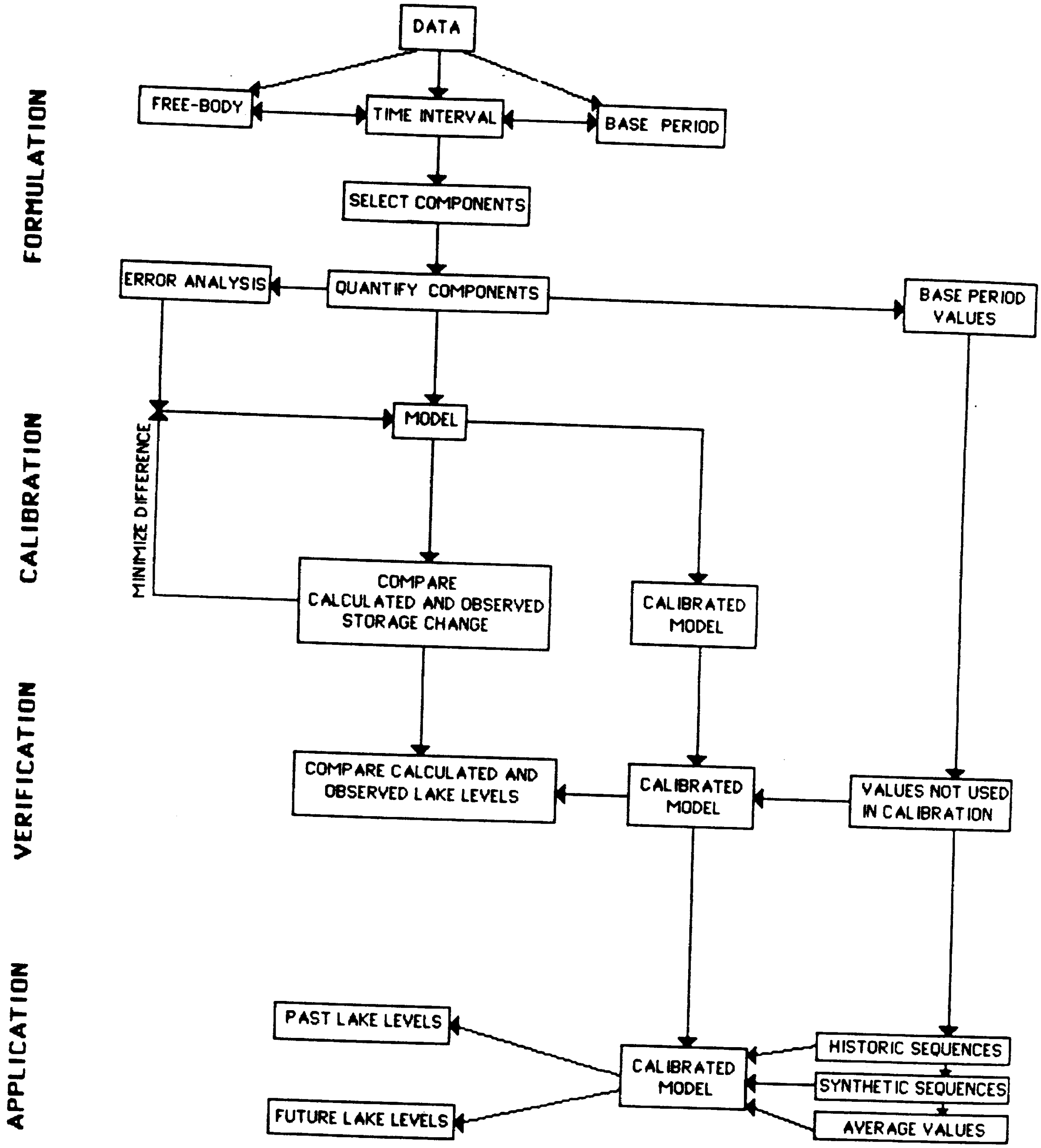


Figure 1-7. Schematic Diagram for Development of Lake Level Forecast Model

The _free-body_ is defined as the area for which the water balance is derived. The importance of a suitable free-body is often overlooked in terminal lake water balances even though the free-body determines the nature, magnitude, and accuracy of the water balance components. Choice of a free-body depends on the purpose of the water balance, the availability of information, and the hydrologic and physical characteristics of the system. An ideal free-body should have a boundary that is fixed over time and whose flows are measurable or easy to estimate across its boundary (Peters 1972). Consequently a fluctuating terminal lake margin in an alluvial basin is a poor free-body boundary. Waddell and Fields (1975) and Steed (1972), for example, acknowledge that Great Salt Lake's fluctuating shoreline decrease the accuracy of surface and groundwater inflow estimates.

The time interval is the unit of time for a single execution of the water balance equation. Water balances may be computed for any time interval - a day, week, month, season, or year - depending on the purpose of the water balance and the availability of data. Forecast models used to specify future operational plans may require a weekly or monthly time interval, while the prediction of long-term trends in the lake surface elevation usually requires only an annual time interval. The shorter time intervals require more detailed accounting of the storage and movement of water and have more precise computational requirements; The choice of the time interval is often determined by the longest time interval required for an accurate estimation of a water balance component. Terminal lake water balances are most commonly developed using an annual time interval because it is difficult to make accurate estimates of evaporation or ground water inflow for shorter time spans.

The base period is the time period - consisting of successive time intervals in the historic record - for which the components are quantified. The base period data establishes the component values and statistical properties that are used in forecasting. The base period that is selected usually depends on the use of the model and the data available for the variable comprising most of the free-body's water supply (Peters pers comm 1984). According to Peters (1972), the base period ideally would (a) be equivalent to the long-term mean water supply period, (b) have wet and dry periods, (c) minimize changes in storage, (d) end near the present, and (e) have long, continuous data sets. Yevjevich (1972) adds that if the base period data are used for forecasting it should be free of significant inconsistencies and non-homogeneities, Because reliable hydrological data have been collected in the Western United States for a limited time, the selected base period often consists of the entire period of record for the variable of interest. In such a circumstance the base period is thus equivalent to what some would define as the long-term mean period (Peters 1972). As the period of record becomes longer and the long-term mean values change, it is important to compare the chosen base period with previously selected base periods, even though it is debatable what the appropriate long-term mean is for an area. In addition, it is instructive to compare other long-term hydroclimatic records (e.g. tree rings *or* terminal lake levels) with the base period record so that it can be analyzed in the context of changing climatic conditions.

An analysis of the physical and hydrological characteristics of the free-body, combined with the specification of the time interval and base period provides the basis for choosing the components that should be quantified. Quantification of these components is the crux of the formulation phase. Component quantification involves computing the value of each variable of the component for each time interval in the base period.[15] The computation may be made by direct measurement of the variable, or by measurements of related variables, or it may be estimated indirectly using other techniques. Computational techniques for the main component variables in a lake water balance are summarized in Winter (1981), Ferguson et al. (1981), and Sokolov and Chapman (1974). All of these authors recommend the independent quantification of all water balance components because component values determined as residuals incorporate the error from other components.

Accurate quantification of the water balance components is extremely difficult, It is important, then, to analyze the overall water balance error and to estimate the individual component error, especially since errors in component quantification may not necessarily be reflected in the overall water balance error (due to the canceling effect of component errors.) Analysis of the component and overall error should be a fundamental part of model development (Winter 1981). In addition, error analysis will identify deficiencies in the network of data collection stations.

The error in each component value is the difference between the estimated value and the "true" value.

$$E_C = V_T - V_E \qquad (6)$$

E_C - component error

V_T - true value

V_E - estimated value

It is assumed for purposes of estimating the magnitude of the errors that a 'true' value is theoretically obtainable by independent "correct" methods of computing component variables,

Component error can be classified into two general types: systematic error or "bias", and non-systematic or "random" error. Aitken (1973) notes that most hydrological models fail to distinguish between the two types of errors. Systematic error is a deviation from a true value caused by either (1) improperly calibrated measuring instruments, (2) assumptions made in the computation of a component value because of the lack of data, (3) other unexplainable inconsistencies, Non-systematic or random errors result from (1) measurement of any variable used in computing component values, and (2) point data extrapolated over time and space. By definition, random error is assumed to be symmetrically distributed about the true value and is therefore represented by a "plus or minus" deviation.

The overall error - also called the residual or discrepancy term (Sokolov and Chapman 1974) - in a lake level forecast model is equal to the difference between the calculated lake storage change resulting from the computed inflows and outflows and the actual lake storage change that results from the actual but unknown inflows and outflows: Thus,

$$\Delta S_c = I_c - O_c = (I_A \pm e_1) - (O_A \pm e_2) \quad (7)$$

$$\Delta S_A = I_A - O_A \quad (8)$$

$$\Delta S_c - \Delta S_A = e_1 + e_2 = E \quad (9)$$

ΔS_c, I_c, O_c - computed values

ΔS_A, I_A, O_A - actual values

e_1, e_2 - individual component error

E - overall error

The overall error thus incorporates the systematic and non-systematic error as well as components not taken into account. A recommended criterion is that the overall error should not exceed the square root of the sum of the square of the error limits of the individual water balance components (Ferguson et al. 1981).

$$E \leq \sqrt{e_1^2 + e_2^2 + \ldots + e_N^2} \qquad (10)$$

where E equals the overall error and $e_1, e_2, \ldots e_N$ equals error limits of individual components. Another measure of the relative magnitude of the overall error term is its ratio ("relative discrepancy") to the total inflow or total outflow (Ferguson *et al*. 1981). A large relative discrepancy suggests that one or more components are imprecisely computed; a small relative discrepancy value cannot be interpreted to mean the component values are computed correctly since component errors can cancel each other out.

The significance of any component or overall error is a matter of judgement. The sensitivity of the calculated storage change to a component error can be analyzed by replacing the computed component value with value(s) estimated to be within the component's error range.

Calibration. In order to make the water balance model operational for the purpose of forecasting it must first be calibrated (Sooroshian 1983). Calibration of a lake level forecast model is the process of logically adjusting the component model values so that the difference between the actual and calculated lake storage change (and thus lake levels) is minimized. Because the difference between the calculated and actual storage change is ascribable to the overall water balance error, calibration can also be viewed as the process of "explaining" the overall error term so that the future error can be logically predicted.[l6] The "explaining" should be physically plausible in order to assure that the model output (i.e. the forecast) is plausible.

Sooroshian (1983) has identified two basic approaches to calibration: the manual approach and the automatic approach. In the manual approach the skill, experience, and intuition of the trained hydrologist are utilized to subjectively adjust the component values and/or "explain" the overall error. An example of manual calibration is the process of making the water balance equation "balance" by ascribing the overall error to components that are hard to quantify such as ground water inflow or ungaged runoff (Sooroshian pers comm 1984), Arbitrarily increasing or decreasing the value of a component variable such as the evaporation rate in order to achieve a better fit between calculated and observed lake levels is also manual calibration. In the automatic approach the adjustment to component values is based on mathematical techniques that commonly involve the optimization of an error function. The automatic approach is not free of subjective judgement because one must still select the appropriate mathematical technique to use and physically explain the results.

The model should be calibrated for a portion of the base period that is long enough to contain data considered fairly well representative of the various phenomena the system experiences and that the model intends to simulate (Sooroshian 1983). Ideally a portion of the base period is excluded from the calibration so that it can be used to verify the model.

Verification. Verification (or validation) tests whether or not the calibrated forecast model is an accurate predictor of lake levels. This is done by calculating lake levels for a time period not used in calibrating the model. These results are then compared with actual (observed) lake levels for the same period. Verification using base period data that were used in the model calibration is not a proper procedure even though it is often mistakenly called verification or validation (see for instance Blevins and Mann 1983).

Model verification identifies deficiencies in the model formulation, calibration procedure, and the data base used to calibrate the model (McCuen 1976). Criteria for determining the acceptability of a particular lake level verification, however, are not established; they depend on the relative magnitude of the lake level change, on the confidence one has in the verification data set, and in the time frame of interest, i.e. short-term fluctuations or long-term trends.

Application. The forecast model is applied to determine (or estimate) past and future lake levels. Hydroclimatic conditions specified by the user as model input determine the values of the model components. Assumptions about the rate of evapotranspiration, evaporation, precipitation, or runoff can be represented as a time series sequence of values that can either be modeled as (a) constant value sequences equal to the base period average, (b) the base period sequences as they actually occurred, (c) synthetic sequences generated by a stochastic model. Management conditions can be any plausible scenario that is consistent with the hydrologic conditions and physical characteristics of the system.

The error of the forecast is a function of the accuracy of the model input. Given the uncertainties in specifying future hydrologic and management conditions, the forecast accuracy decreases as one projects further into the future. If deterministic sequences of past hydroclimatic and management conditions are used as model input, the model output - a single lake level trace -- should only be interpreted to suggest the future lake level trend and the eventual equilibrium lake level (i.e. the level where inflows and outflows are equal and therefore the lake storage and level does not change). If many equally likely synthetic sequences are used as model input, then a frequency analysis is performed on the equally likely lake level output to develop a lake level/frequency relationship. The latter relationship gives the probability of a given lake level at any future time and can be more useful in future planning of operations than a single lake level trace (James et al. 1979), James et al, (1979) detail the application of stochastic models to the Great Salt Lake in particular and terminal lakes in general. They point out a number of problems in deriving a multivariate stochastic model of the hydroclimatic sequences used in terminal lake level forecast model.

PREVIOUS MONO LAKE WATER BALANCE MODELS

A survey of published and unpublished documents indicates that fourteen water balance models have been previously derived for Mono Lake. None of the models are derived with a systematic procedure that explicitly employs all the major phases and steps of water balance modeling outlined in the previous section. The modeling phases and steps do provide a framework for analyzing the structure of the other models. The analysis, which is summarized in Table l-2, reveals the following:

(1) None of the models, except for LADWP (1984 a,b,c,d) explicitly identify the water balance free-body. Except for CADWR (1960), the lake is the implied free-body in all the other models and the stated free-body in the forecast model of LADWP (1984a,d). The lake is a poor free-body because the principal surface inflows are measured five to eight miles away from the lake margin and the margin itself fluctuates widely. As a consequence, most models must compute all or part of the inflow to the lake free-body as a residual, a method to be avoided according to Winter (1981), Ferguson et al. (1981) and Sokolov and Chapman (1974),

(2) The base period usually is determined by the available runoff data. Several of the selected base periods include years prior to 1937 even though reliable measurements of runoff are lacking on most of the

TABLE 1-2. Comparison of Previous Mono Lake Water Balance Models

Model	Formulation					Calibration	Verification	Application
	Free Body	Time Interval	Base Period	Components Computed Independently	Components Computed as a Residual			
Lee (1934)	Lake (implied)	annual	1903-34 for runoff 1911-33 for precipitation	-total surface runoff -Mono Lake precipitation -unmeasureable runoff (underflow) -Virginia Creek inflow -LADWP surface water export -phreatophyte evapotranspiration (ET)	-groundwater inflow and/or groundwater storage change -Mono Lake evaporation (1)	balances equation with residual value that incorporates overall error	none	predict stabilization level with maximum LADWP surface water export and average base period hydroclimatic conditions
Black (1958)	Lake (implied)	annual	1882-1950 (2)	-Mono Lake precipitation -Mono Lake evaporation -LADWP surface water export (3)	-sum of Mill Creek, rest of basin streamflow and springflow	balances equation with residual value that incorporates overall error	none	evaluate brine extraction potential by predicting future salinities assuming maximum LADWP surface water export and average base period hydroclimatic conditions
CADWR (1960)	Groundwater Basin (implied)	annual	1895-1959	-gaged Sierra runoff (4) -ungaged Sierra runoff -rest of basin runoff -Virginia Creek inflow -Mono Lake net evaporation (includes precipitation) -LADWP surface water export -LADWP ground water export -irrigated land ET -urban consumptive use -Mono lake storage change -Grant Lake reservoir net evaporation	-none	decreases Mono Lake evaporation to reduce overall error	none	determine unused water in Mono Basin
Harding (1962)	Lake (implied)	annual	1857-1959	-Mono Lake precipitation -Mono Lake evaporation -LADWP surface water export -Mono Lake storage change	-total surface and subsurface inflow to Mono Lake	balances equation with residual value that incorporates overall error	none	predict stabilization level assuming maximum LADWP surface water export and average base period hydroclimatic conditions; confirm 1857 lake level, and compute average inflow

Model	Formulation					Calibration	Verification	Application
	Free Body	Time Interval	Base Period	Components Computed Independently	Components Computed as a Residual			
Mason (1967)	Lake (implied)	annual	1904-63 for Mill and Lee Vining Creek; 1940-64 for the other creeks	-gaged Sierra runoff (4) -ungaged Sierra runoff -springflow (5) -Mono Lake evaporation (6)	-Mono Lake evaporation (6)	increases evaporation rate to reduce overall error (7)	none	to assess hydrological and limnological relationships
Scholl, et al (1967)	Lake (implied)	annual	1904-62 for Mill Creek; 1940-64 for other creeks	-gaged Sierra runoff -ungaged runoff (8) -Mono Lake precipitation -Mono Lake evaporation	-groundwater inflow (9)	balances equation with residual value that incorporates overall error	none	basis for salt budget
Lee (1969)	Lake (implied)	annual	1954-64	-Sierra runoff (10) -Mono Lake precipitation -Mono Lake evaporation -Mono Lake storage change -LADWP surface water export (10)	-groundwater inflow (9)	balances equation with residual value that incorporates overall error	none	determine magnitude of total groundwater inflow in relation to measured springflow
Corley, et al (1971)	Lake (implied)	annual	1937-70	-gaged Sierra runoff -Mono Lake precipitation -LADWP surface water export -Mono Lake storage change	-sum of Mono Lake evaporation, ungaged runoff, groundwater inflow and stream channel losses	plots sTraight line relationship between Mono Lake elevation and residual value so that residual value in future is derived from forecasted lake elev.	none	predict stabilization level and time assuming different surface water export rates and randomly selected base period values for runoff & precipitation(11)
Moe (1973)	Lake (implied)	annual	1895-1959	-total basin runoff -Mono Lake net evaporation -LADWP surface water export -Mono Lake storage change	-none	none	none	predict stabilization level and time with maximum LADWP surface water export and average base period hydroclimatic conditions
CADWR (1974)	Lake (implied)	annual	1940-72	-Mono Lake evaporation -LADWP surface water export -Mono Lake storage change	-none	none	none	reconstruct Mono Lake levels assuming no LADWP surface water export
Loeffler (1977)	Lake (implied)	annual	1921-75 and 1932-75	-Mono Lake precipitation -gaged Sierra runoff (4,13) -Mono Lake evaporation -LADWP surface water export -Mono Lake storage change	-total surface and subsurface inflow to Mono Lake	derives linear regression between total inflow (residual value) and gaged Sierra runoff	yes; 1941-75 and 1951-75 (14)	predict stabilization level for different LADWP surface water export rates and average base period hydro-climatic conditions

Model	Formulation					Calibration	Verification	Application
	Free Body	Time Interval	Base Period	Components Computed Independently	Components Computed as a Residual			
Cromwell (1979)	Lake (implied)	annual	1951-78	-gaged Sierra runoff -ungaged runoff -Mono Lake precipitation -Mono Lake evaporation (6) -LADWP surface water export -Mono Lake storage change	-Mono Lake evaporation (6)	reduces overall error by assuming ground water inflow equals zero and Mono Lake evaporation equals 39 inches.	none	justify evaporation and groundwater estimates
CADWR (1979)	Lake (implied)	annual	1941-64	-Mono Lake precipitation -Mono Lake evaporation -LADWP surface water export -Mono Lake storage change	-total surface and subsurface inflow to Mono Lake	balances equation with residual value that incorporates overall error	none	predict stabilization level and time for different LADWP surface water export rates and average base period hydro-climatic conditions
LADWP (1984a)(15)	Lake	annual	1941-76	-gaged Sierra runoff (13) -Mono Lake precipitation -Mono Lake evaporation -LADWP surface water export -Mono Lake storage change	-total surface and subsurface inflow to Mono Lake	derives linear regression equation between total inflow (residual value) and gaged Sierra runoff	none	predict stabilization level and time for different LADWP surface water export rates and average base period hydroclimatic conditions
LADWP (1984b) (15)	Valley-fill	annual	1941-76	-Mono Lake precipitation -valley fill precipitation -runoff from hill and mountain areas -Virginia Creek inflow -Mono Lake evaporation -Grant Lake evaporation (16) -urban consumptive use (16) -LADWP surface water export -Grant Lake storage change -Mono Lake storage change -groundwater storage change (17)	-valley-fill vegetation ET	balances equation with residual value that incorporates overall error	none	to assess current and future hydrologic relationships
LADWP (1984c) (15)	Total Watershed	annual	1941-76	-hill and mountain precipitation -valley fill precipitation -Mono Lake precipitation -Virginia Creek inflow -Mono Lake evaporation -urban consumptive use (16) -Grant Lake evaporation (16) -LADWP surface water export -LADWP ground water export -Mono Lake storage change -Grant Lake storage change -groundwater storage change (17)	-valley-fill vegetation ET -hill and mountain ET	balances equation with residual value that incorporates overall error	none	to assess current and future hydrologic relationships

Model	Formulation					Calibration	Verification	Application
	Free Body	Time Interval	Base Period	Components Computed Independently	Components Computed as a Residual			
LADWP (1984d) (15)	Lake	annual	1970-82	-gaged Sierra runoff (13) -Mono Lake precipitation -Mono Lake evaporation -LADWP surface water export -Mono Lake storage	-total surface and subsurface inflow to Mono Lake	derives linear regression equation between total inflow (residual value) and gaged Sierra runoff minus Mill Cr. runoff	none	provisionally updated version of (1984a)

NOTES

(1) Lee (1934) computes the Mono Lake evaporation rate as a residual in a separate balance equation.
(2) Base period selected in which beginning and ending Mono Lake elevation and thus lake volume was the same.
(3) Black (1958) assumes all aqueduct stream runoff would be exported by LADWP.
(4) The gaged Sierra runoff component includes the major streams (Rush, Lee Vining, Mill, Walker, Parker Creeks) that are currently gaged. In the early part of the specified base period most of these streams not continously gaged.
(5) In computing springflows Mason (1967) includes springs (e.g. Villete Springs) which are recharged by Sierra runoff; consequently there is "double counting".
(6) Mason and Cromwell calculate evaporation both as an independent value and as residual value in order to "check" estimates.
(7) Mason (1967) also derives a multiple linear regression equation between the lake level drop (dependent variable) and evaporation, precipitation and LADWP export.
(8) Scholl et al. (1967) does not specify whether it is just ungaged Sierra runoff or non-Sierra runoff.
(9) The groundwater inflow can only be water whose source is not Sierra runoff; otherwise there would be double counting since some of the Sierra runoff contributes to groundwater inflow.
(10) Lee (1969) incorrectly assumes all of the aqueduct runoff is exported; Sierra runoff therefore equals the sum of gaged Mill Creek runoff and ungaged Sierra runoff.
(11) The value of runoff and precipitation in each base period year minus the assumed export amount equals the water availability for the year. Each year's water availability is written on separate cards which are shuffled and randomly selected.
(12) Loeffler derives several models each using different component values. Some of the models are based on the 1921-75 period determined by the runoff record, others were based on the 1932-75 period determined by precipitation record.
(13) The gaged Sierra runoff is not used as a water balance component but instead is used to calibrate total (residual value) inflow.
(14) Loeffler (1977) verifies the 1941-75 period using a model calibrated with 1921-1940 data and verifies the 1951-75 period with 1932-50 data.
(15) LADWP presents four separate models in the same publication. 1984a and 1984d are their forecast models.
(16) Since only a table of numbers is given without any computational explanation, it is suspected - but not known - that at least one of these components is computed as a residual because the inflows and outflows exactly balance.
(17) The groundwater storage change is listed in the water balance table but the value is given as zero; it is an assumed value and not a computed value.

streams. A number of the models (Lee 1934, Mason 1967, Scholl et al. 1967, Loeffler 1977) use different base periods for individual streams and components thereby resulting in non-correlative mean values.

(3) Most of the models, including Lee (1934), Black (1958), CADWR (1960), Mason (1967), Scholl et al. (1967), Moe (1973)) and LADWP (1984 b,c) are mean-value water balances, i.e. one annual water balance is computed using mean base period values; the other models compute the component values for each year in their base period. A mean-value water balance is limited in its application to the analysis of past and future lake level fluctuations. For example, it cannot reconstruct a natural lake elevation or evaluate the effect of climatic variability on lake elevations.

(4) Most of the models quantify only Mono Lake evaporation, Mono Lake precipitation, gaged Sierra runoff, and LADWP export independently. The model presented here independently quantifies 18 different components. Most of these additional components are either not identified by the other models or are quantified as residual values.

(5) None of the previous models include an error analysis, although most acknowledge the imprecision of their component estimates,

(6) None of the models explicitly define their calibration procedure. Most employ a manual calibration approach to make the equation "balance" and thereby eliminate the overall error of the water balance. The implicit nature of the calibration and the commonly used method of assuming the entire residual can be ascribed to a water balance component results from "the lack of agreement or understanding as to what exactly is to be achieved in calibration" (Sooroshian (1983).

(7) None of the models, except for Loeffler (1977), are verified. LADWP (1984a) incorrectly states that their model is "validated" for the 1941-76 period. Loeffler (1977) verifies a model calibrated with 1921 to 1940 data but the model he uses for forecasting is calibrated with data from 1921 through 1975.

Footnotes

(1) The most detailed published topographic maps covering the Mono Basin are the 15 minute (1 to 62,500) quadrangles (with an 80 foot contour interval) compiled by the United States Geological Survey (USGS) in the 1950's and 1960's. The USGS also has compiled 7 l/2 minute (1 to 24,000) ortho-photo quads (with no contour lines) covering the entire basin and a 1 to 125,000 scale map (with a one hundred foot contour interval) covering only the California portion of the Mono Basin. The Los Angeles Dept. of Water and Power (LADWP) compiled detailed (1 to 14,000) topographic maps of portions of the Mono Basin in the 1930's. All of the aforementioned topographic maps were surveyed when Mono lake was 25 to 50 ft higher than the current level. The USGS is currently compiling 7 l/2 minute topographic maps for the whole basin; some of them were issued in preliminary form in 1984. The lakeshore outline on these maps is compiled from 1982 aerial photographs when the lake was approximately 6372 ft above sea level. The current lakeshore outline can be approximately estimated by interpolating between sub-lacustrine contours on the bathymetric map developed by Scholl et al (1967).

(2) The reader is referred to Russell (1889), Lajoie (1968), and Gilbert et al. (1968) for detailed geological accounts.

(3) The glacial moraines are a highly variable mixture of silt to boulder-sized material. There is little information on their groundwater bearing capabilites, although Lee (1969) observed that they can both transmit and impede ground water flow. Lee (1934) described the terminal moraine around the Grant Lake damsite as being composed of "....glacial till, large cobblestones, gravel, sand, silt (glacial meal) all in a tightly packed condition . . . and is relatively impervious to water." LADWP includes the moraines within the ground-water basin. Lipinski (1982) concludes that geologic data are not sufficient to define the aquifers of the basin. He observed that the surface geology and structure of the Mono Basin have been well studied but little information is available regarding the occurrence of pervious and impervious layers in the subsurface.

(4) See Figure Al-l in Appendix 1-A for the sources of climatic data.

(5) Currently the surface water drainage of Alkali Valley is hydrographically separate from the Mono Basin, but a narrow band of alluvium - a remnant of Pleistocene Mono Lake's

(Lake Russell) expanded area - connects the two basins. Van Denburgh and Glancey's (1970) estimated water balance for Alakali Valley indicates that a small water surplus (approximately 1400 ac-ft/yr exists, which they feel would discharge via the subsurface into the Mono Basin. Reconnaissance examination of the area by this author was inconclusive as to whether a subsurface inflow connection exists; it is felt, however, that much of the estimated surplus could be discharged by greater evapotranspiration from Larkin Lake in Alkali Valley than that estimated by Van Denburgh and Glancey. Because of the lack of data in estimating the Alkali Valley water balance, it was decided not to include this as an inflow to the Mono Basin.

(6) Most of Mill Creek's flow is diverted into the Southern California Edison (SCE) hydroelectric plant and then discharged into irrigation channels and Wilson Creek. Wilson Creek eventually flows into Mono Lake.

(7) The lack of information prevents the quantitative evaluation of groundwater flow in the basin. Lee (1969), Loeffler wJ77), and Blevins and Mann (1983) present mainly qualitative and descriptive accounts of the occurrence, recharge, and discharge of groundwater in Mono Basin. Lee (1969), Gradek (1983), and TADWP (in press) map spring locations and measure paramenters such as discharge, total dissolved solids, and temperature.

(8) No Soil Conservation Service (SCS) soil map exists for the Mono Basin. Recent soil mapping by the United States Bureau of Land Management (see for example USBLM 1982) is the best available source of information on the soils of the Mono Basin.

(9) Other phrases have been used to describe terminal lakes, such as enclosed basin lakes, lakes with no outlets, undrained lakes, closed lakes, saline lakes, athalassic lakes, endoreic lakes, bitter lakes, and inland salt lakes.

(10) In the winter of 1982-1983 a large portion of the western half of Mono Lake froze because of sustained below freezing temperatures and over 100,000 ac-ft of stream inflow (compared to an estimated average of about 10,000 ac-ft). In addition, Mono Lake apparently did not turn over in the fall of 1982, 1983, and 1984 because the vertical salinity gradient created by the fresh water "floating" on the surface was stronger than the normal thermal gradient.

(11) There was no Paoha Island when the lake reached its pre-historic low stand of 6368 ft (Stine pers comm 1984). With the island in the lake, the surface area of the lake at elevation 6372 ft (historic low stand) is less than the pre-Paoha lake surface area at elevation 6368 ft.

(12) Prior to the 1977 water year USGS publications show the lake level to be 0.37 ft higher than the UDWP level. Beginning in the 1977 water year, USGS publications do not reflect the difference because the compiler of the publication was not aware of the adjustment to the datum.

(13) WMO (1975) defines a model, as a means of scientific investigation, to be “a generalized image of a physical system which reflects or reproduces the system in a way that, as a result, new information is provided and more detailed knowledge of the system and its quantitative properties is acquired."

(14) Other terminal lake forecast models are based on 1) the correlation of lake levels with solar-climatic cycles (Willet 1977) or other natural cycles (Chappell 1977); 2) indexing precipitation and stream flow to annual spring rises (Peck 1954); 3) stochastic modeling of lake levels (Privalsky 1977). These methods rely on the fact that since terminal lakes have no outlets, surface fluctuations are a reflection of climatic variation, and thus the lake levels can be extrapolated or stochastically modeled from past climatic trends. These methods, however, are limited by our imperfect understanding of climatic change., They also cannot take into account anthropogenic influences (such as tributary diversions) on the lake level/climate relationship.

(15) A "mean-value" water balance is one that computes each components mean base period value for the selected time interval (Sokolov and Chapman 1974),

(16) In many hydrological models calibration is the process of finding a physically realistic set of model parameters that gives the best fit between the actual and calculated model output.