

A Tale of Two Lakes: Environmental Mass Balance Modeling

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OVERVIEW

This module will explore the use of mass balance modeling to assess environmental impacts in lakes. Students will explore simple mass-balance models which result in algebraic solutions. More complex scenarios will utilize EXCEL for model simulation. The module can be a stand-alone component for a general education class in environmental science and/or more complex modeling scenarios can be explored in upper-division undergraduate hydrology and computer science classes. Knowledge of basic algebra and the ability to use EXCEL is required. Upon completion of the module, students will have gained an understanding of the impacts of water diversions on water bodies through the two case studies, Mono Lake and Salton Sea.

INTRODUCTION

Human activities can have large impacts on surface water quality. Water diversions have shrunk the size of lakes and, in regions of high evaporation, increased the water salinity. Numerous examples of the shrinking and salinization of water bodies can be found worldwide. The Aral Sea in Asia has shrunk by over 40% when Russia diverted the rivers for cotton irrigation. The former Owens Lake in California is now a playa causing wind-blown dust pollution after its surface water inflows were diverted into the Los Angeles aqueduct.

We will construct and use simple mass balance models of lakes in order to examine the impacts of water diversions. Case studies from Mono Lake and Salton Sea, California will be described and modeled.

PROBLEM

Models are needed to predict the impacts of water diversions on surface water bodies. Mono Lake had decreasing water levels and increasing salinities after water was diverted from tributaries feeding the lake. A court order has stopped these diversions until the lake has “recovered” to an appropriate level. Mass-balance modeling was used to predict the length of time required for this recovery. Irrigation return flows which currently feed the Salton Sea are anticipated to decrease if a water transfer to San Diego County is approved. Predictions of the changes in water level and salinity for various scenarios is required to assess the environmental impacts.

BACKGROUND

Terminal Lake Hydrology

Both Mono Lake and the Salton Sea are terminal lakes in which the major outflow of water is by evaporation. During evaporation, water is removed from the lake as water vapor but salts remain behind. Salts carried by surface and groundwater inflows are retained in the lake and slowly accumulate over time. Both of these lakes currently have salinities higher than ocean water (Table 1).

Table 1. Water Salinities

Water Type	Salt Concentration (g/l)
Fresh Water	Less than 1.5
Brackish Water	1.5 - 5
Saline Water	5 - 35
Hypersaline Water	> 35 - 40
Ocean Water	32 - 37
Salton Sea, CA	44
Mono Lake, CA	82
Dead Sea	260 - 350
Great Salt Lake, Utah	85 southern portion 250 northern portion

Mono Lake

Mono Lake is one of the oldest lakes in the United States with an age of at least 760,000 years. The lake is situated in the northern end of the Long Valley Caldera (produced by a massive volcanic eruption) east of the Sierra Nevada Mountains in California (Figure 1). The lake waters are hypersaline (82 g/l) and alkaline (ph of 10). The high alkalinity prohibits fish life but algae, brine shrimp and alkali flies flourish (Figure 2). The brine shrimp support large bird nesting and migrating colonies (85% of the California gull breeding population, Figure 3). Underwater, tufa towers are formed by accumulation of calcium carbonate precipitation out from groundwater seepage into the lake. With a drop in lake level, these towers are exposed and provide scenic views (Figure 4).



Figure 1. Location of Mono Lake (indicated by red dot)



Figure 2. Alkali flies and brine shrimp of Mono Lake (from www.monolake.org)

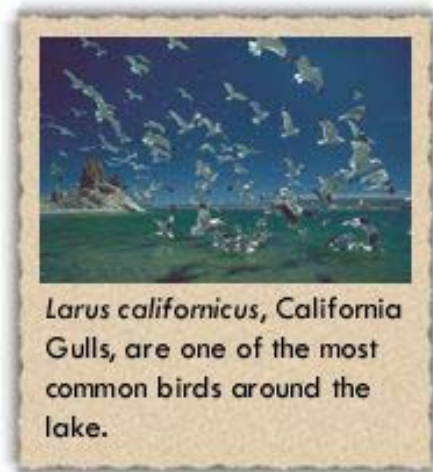


Figure 3. California gulls at Mono Lake (from www.monolake.org)



Figure 4. Tufa towers in Mono Lake

Mono Lake's unique ecosystem was threatened after diversions from streams, which feed the lake, caused a lowering of the water level and an increase in salinity. Figure 5 shows the decreasing water level since water diversions started in 1941. The 20th century low water elevation of 6,372 ft above sea level in 1981 exposed a land bridge to an island used for gull nesting colonies allowing predation (Table 2). The increased salinities are believed to have impacted brine shrimp populations. Tufa towers were exposed and subject to erosion and vandalism (Figure 6).

Mono Lake Level: 1850-Present

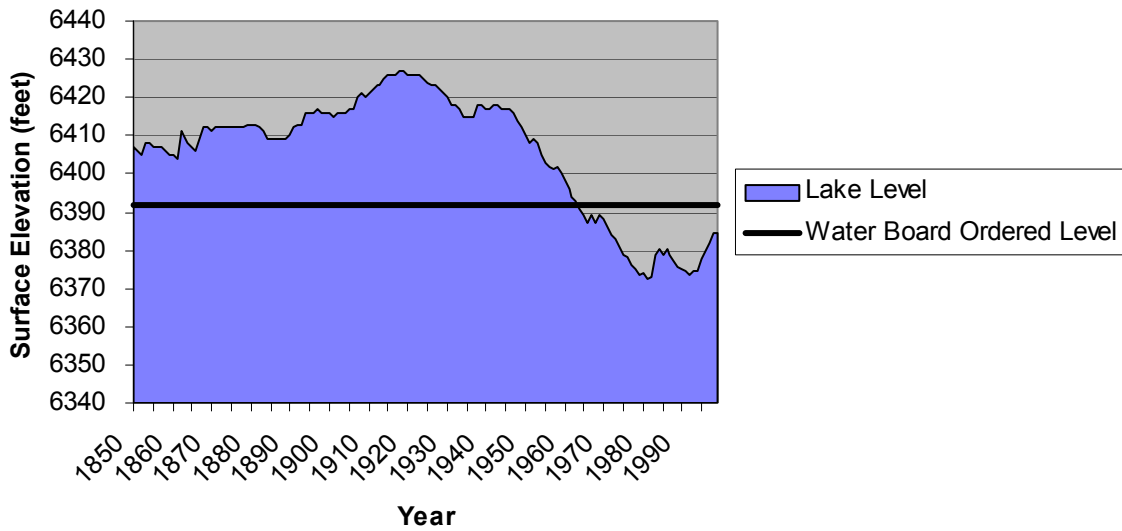


Figure 5. Historical water levels in Mono Lake



Figure 6. Exposure of tufa towers in 1962, 1968 and 1995 (from www.monolake.org).

Responding to lawsuits brought by the Mono Lake Committee, the National Audubon Society and Friends of the Earth in 1983, the California Supreme Court decided that public trust doctrine applies to recreational and ecological values when allocating water rights. These values include scenic views of the lake and its shores, air quality and the use of the lake for nesting and feeding by birds. In 1994, after many years of studies and environmental impact reports, the State Water Resources Control Board modified Los Angeles' Department of Water and Power (DWP) water diversion to ensure protection for Mono Lake and its streams. Water diversions are restricted until a water level of 6,392 ft is reached in the lake (Figure 5, Table 2).

Table 2. Historical and Court-Order Mono Lake Elevations and Impacts

Mono Lake	Elevation	Surface Area (acres)	Salinity (g/l)	Comments
1919	6,428	57,668	42	20 th century highest level
1941	6,417	54,924	51.3	Level before water diversions
1981	6,372	37,688	99.4	20 th century lowest level: 30% reduction of lake volume and land bridge to Negrit Island exposed
1989	6,377	41,531	91.6	Reduced brine shrimp and birds
Court ordered (in 1994)	6,392	48,893	69*	Ultimate Goal
Allowance of water diversions	None if below 6,377	41,531	91.6*	
	Once reaches 6,391: No diversion if below 6,388	47,492	74*	
August 2003	6,382		82*	10 ft below court ordered level (+7 ft since 1994)

Find current conditions at: <http://www.monolake.org/live/level.htm>

* predicted salinities

The Salton Sea

The Salton Sea occupies a topographic basin in Southern California (Figure 7). The Salton Basin has been inundated periodically by waters from the Colorado River over the last several million years. The ancient Lake Cahuilla was a much larger lake due to climatic differences and on occasion overflowed into the Gulf of California. Once Colorado River flows to the basin stopped, the lake evaporated. The current lake in the Salton Basin, the Salton Sea, was formed in 1905 when the Colorado River breached an irrigation channel (Figure 8). The entire flow of the Colorado River flooded the Salton Basin with the Sea rising as much as 7 inches in one day (Salton Sea booklet). The breached bank was repaired in 1907. The Salton Sea is maintained primarily by excess irrigation water flowing from agricultural fields. Indeed, the Salton Basin was designated an agricultural drain in 1928 by the federal government. The designation means its prime purpose is to retain runoff from agricultural activities.



Figure 7. Location of the Salton Sea



Figure 8. Colorado River breaching channel in 1905

The Salton Sea has an interesting land-use history. Besides its prime purpose as an agricultural drain, the Sea has supported recreational activity, fisheries and migratory bird populations. Recreational activity has decreased due to the flooding of resort facilities in the past (Figure 9). A stable shoreline has not been maintained due to the changes in amount of agricultural runoff from year to year (Figure 10). The Sea maintains a fish population consisting primarily of introduced species such as Tilapia (an African freshwater fish). The fish attract and sustain a major bird population (80% of American white pelicans, more than 90% of the North American eared grebe population, over 400 species of birds total).



Figure 9. Former marina at Salton Sea

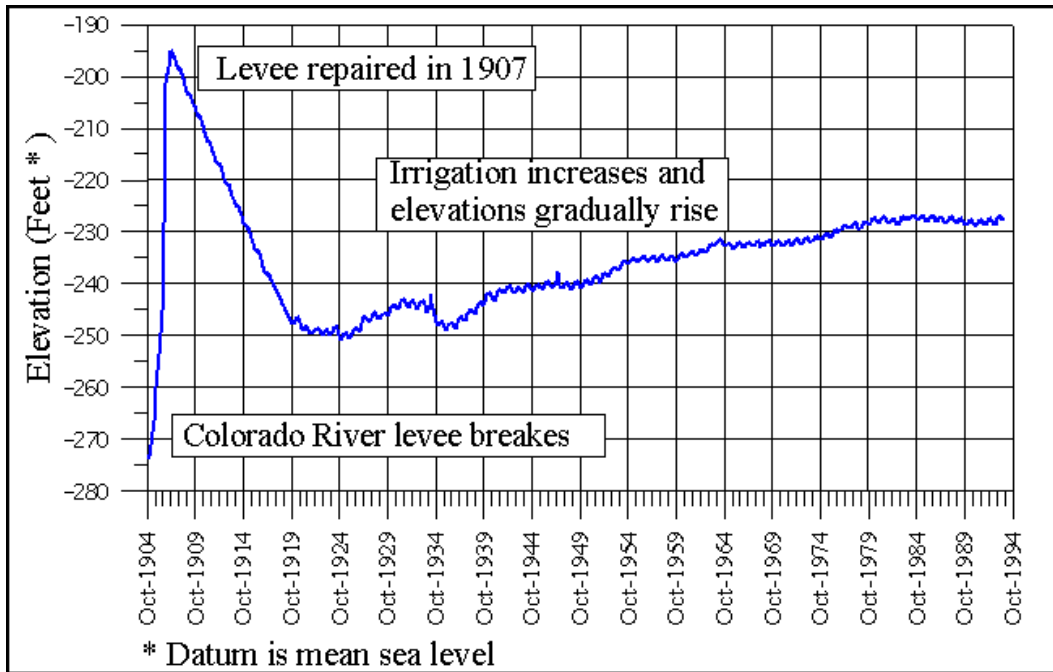


Figure 10. Historical Salton Sea water levels

As you will see from your calculations in this module, the Salton Sea has had a steadily increasing salt concentration. The salinity increase is a natural phenomenon of a terminal lake. However, unless an engineered solution is implemented to slow or stop the salinity increase, the fish will die at salt concentrations above 60 g/l and impact the bird populations. Restoration projects have been discussed for decades but have been hampered by lack of funds (Figure 11).



Figure 11. Possible restoration by the use of evaporators to collect salt

A more recent issue has caused increased concern for the Salton Sea. The irrigation districts of Imperial Valley and the Coachella Valley receive their water from the Colorado River. A water transfer from those irrigation districts to San Diego County and the Metropolitan Water District has been proposed to alleviate water needs in the western urban regions. However, decreasing the amount of irrigation water to agricultural fields will decrease the amount of runoff to the Salton Sea. As you will calculate in this module, the decrease in runoff will have two impacts: dropping water levels and further increasing the rate of salinization. The increase in the salinization will decrease the time available for possible restoration projects. The dropping water levels will expose large areas of the lake bed. Once exposed, the dry lake bed is a source of dust pollution which has been found to be an environmental hazard in the Owens Valley. The Owens “dry” lake was formed after water diversions to Los Angeles in the 1940s. The Owens Valley is now considered one of the dustiest places with dust storms, impaired air quality and impacts to human health. The impacts of both the water transfer and possible restoration projects on water level and salt concentrations have been examined by mass-balance modeling.

Comparison of the Two Lakes

While the two lakes have similar problems due to water diversions/transfers, they are quite different in other ways. Differing climatic and topographic conditions produce two very different lakes. Mono Lake is deeper, smaller in volume and surface area and surrounded scenically by mountains (Figure 12). The Salton Sea is a larger shallower lake surrounded by desert (Figure 13). The much larger water inflows to the Salton Sea compensate for the higher evaporation rate in the desert to create a larger lake (Table 3). The lower salinity of the Salton Sea supports thriving fisheries while highly alkaline Mono Lake is deadly to any fish. Mono Lake could be called a “natural” lake as its inflows are from stream runoff resulting from precipitation in the Sierras. The Salton Sea could be called a “man-made” lake as its inflows are from agricultural irrigation return flow. If irrigation ceased in the Imperial and Coachella Valleys, the Salton Sea would evaporate.



Figure 12. Mono Lake

Figure 13. The Salton Sea

Table 3. Comparison of Mono Lake and Salton Sea

	Mono Lake	Salton Sea
Surface Area (acre)	45,000 (in 2003)	230,000
Current Volume (acre-ft)	2,600,000 (in 2003)	7,625,000
Water Surface Elevation (ft above sea level)	6,382	-228
Annual Stream + Groundwater Inflows (acre-ft)	160,000 (prediversion)	1,360,000
Annual Precipitation (ft)	0.73	0.21
Annual Evaporation (ft)	3.6	6.1
Salinity (g/l)	82	44
Primary Surface Inflow Type	Mountain streams	Agricultural irrigation return flow
Classify	“natural” lake	“man-made” lake
Government Designation	Public trust doctrine applies	Designated an agricultural drain 1928

For extensive information and photographs of both lakes, visit the web sites listed in the Empirical Data section of this module.

Mass Balance Modeling

As the name implies, mass-balance modeling consists of balancing mass inflows of a substance with mass outflows. If the inflows and outflows are not equal, a change in mass will occur. In this type of modeling, a control volume is defined over which the mass balance will be evaluated. All inflows and outflows along the boundary of the control volume must be known over a given period of time. For example, a mass-balance model of a swimming pool over 1 day would require the following data:

Possible Inflows: Mass of water added by a hose to pool over the day
 Mass of water added to the pool by rainfall over the day

Possible Outflows: Mass of water evaporated from the pool that day
 Mass of water removed by splashing over the day

Mass Balance:

Mass of Water Inflow – Mass of Water Outflow = Change in Water Mass in 1 day

Note that for a water volume mass-balance we simply assume the density of the water (mass of water/volume of water) is constant. Water volume is calculated from the water mass and density by:

$$\text{Volume (liters)} = \text{Mass (grams)} / \text{Density (grams/liter)}$$

As all components of mass would be divided by a constant density, we can simply model a water volume balance:

Volume of Water Inflow – Volume of Water Outflow = Change in Water Volume in 1 day

In this model, our control volume is the pool and all possible inflows and outflows are accounted for. An annual mass-balance model would require knowledge of the total or average inflows and outflows in/from the control volume.

A mass-balance of a dissolved solute in water requires additional information. In addition to water inflow and outflow information, the concentration of the solute in the water flows is required. For example, a mass-balance of the chlorine in the swimming pool would require knowledge of the inflows and outflows of chlorine into the pool. In addition, chlorine will degrade due to chemical reactions. Another major assumption for solute mass-balance is a completely mixed control volume (pool in our example). If the water becomes stratified into several layers, several control volumes will be required for modeling.

MODELS

Hydrologic Units

Hydrologist must become experts in the conversion of units. While researchers tend to use the standard scientific system of units (metric) as required for most journal publications, government agencies use English units and other units specific to hydrology. We will be using the units used by government agencies for these exercises.

The unit of volume used commonly in water studies is the acre-ft. One acre-ft is the volume of water that would cover one acre of land with one foot of water.

$$1 \text{ acre-ft} = 326,000 \text{ gallons} = 43,560 \text{ ft}^3 = 1,233,000 \text{ liters}$$

An acre-ft of water would be sufficient to provide for the water supply of two families for a year.

MAJOR CONCEPTS: Back-of-the-Envelope Calculations

We will start our mass balance modeling with very simple models. The simplifying assumptions allow us to reduce the model to a simple algebraic equation. These types of simple “back-of-the-envelope” (referring to writing your calculations on the back of any handy piece of paper) calculations allow for identification of the important modeling variables and concepts.

Simple Annual Steady-State Lake Water Volume Model

To illustrate the concept of mass balance of water volume, we will consider a simplified lake with a flat bottom and constant surface area. This system would be similar to a swimming pool of constant depth. The mass-balance terms for such a system are:

$$\text{Annual Water Inflow} - \text{Annual Water Outflow} = \text{Change in Water Volume}$$

If our lake water volume is at steady state, the change in water volume is zero:

$$\text{Annual Water Inflow} = \text{Annual Water Outflow}$$

The water inflow for this lake is stream flow and precipitation. The water outflow is from evaporation. The total annual streamflow, S, can be obtained from stream gages. Annual precipitation is monitored at a rain gage in a nearby weather station. The total inflow from precipitation is calculated by multiplying the annual precipitation (ft/yr) by the surface area of the lake:

$$\text{Water Inflow from Precipitation} = P \cdot A$$

Where, P = annual precipitation (ft)
 A = lake surface area (acres)

Evaporation rates are more difficult to measure than precipitation. We are going to use the water-balance method of estimating evaporation for this lake system. Evaporation is reported as feet of evaporation for a particular time period (similar to precipitation). The total volume of evaporated water is calculated by multiplying the evaporation rate by the lake's surface area:

$$\text{Water Outflow from Evaporation} = E \cdot A$$

Where, E = annual evaporation (ft)

After substituting appropriate terms in our mass-balance equation:

$$S + P \cdot A = E \cdot A$$

All variables have been measured except the evaporation rate, E. Rearrange the equation to solve for E:

$$E = S/A + P$$

Table 4. Water Inflow Conditions for Mono Lake and Salton Sea

	Mono Lake	Salton Sea
Surface Area (acre)	55,000 (in 1941)	230,000 (currently)
Annual Stream + Groundwater Inflows (acre-ft)	160,000	1,360,000
Annual Precipitation (ft)	0.73	0.21

For Mono Lake:

$$E = \{160,000 \text{ acre-ft} / 55,000 \text{ acres}\} + 0.73 \text{ ft} = 3.6 \text{ ft} = 44 \text{ in}$$

Calculate the Water Budget Terms for the Steady-State Mono Lake:

Annual Stream and Groundwater Inflows: 160,000 acre-ft

Annual Rain Inflow: 40,000 acre-ft

Annual Evaporation Outflow: 200,000 acre-ft

[if you calculated 198,000 acre-ft, remember the issue of significant figures, we only have two significant figures in these numbers]

HOMEWORK PROBLEM 1

You are now prepared to complete the calculations in the first homework problem. You will be conducting the same calculation of annual evaporation and water budget terms for the Salton Sea.

Simple Annual Transient Lake Volume Model

From our steady-state scenario, we see that the only way a lake's volume will remain constant is if the water inflows balance the water outflows. In a transient situation, the total water inflows and outflows are not equal and the water volume of the lake will change.

$$S + (P - A) - (E - A) = dV/dt$$

Where, dV/dt = change in lake volume over time

In our first transient model, we are going to assume that all the variables have been measured including evaporation. We are also going to assume that the water inflows and outflows are constant over time. As our simple model is a lake of constant surface area, our equation becomes:

$$dV/dt = \text{constant}$$

Integration this equation:

$$\int_{V_0}^V dV = \int_{t_0}^t \text{Const} dt$$

$$V - V_0 = \text{constant} (t - t_0)$$

Where, V = volume of lake at time, t

V_0 = volume of lake at time, t_0

Constant = $S + (P - A) - (E - A)$

Let's calculate the change in Mono Lake over time since 1941 with the following parameters:

Table 5. Mono Lake Average Water Flows for 1941

Parameter	Mono Lake
Surface Area (acres)	55,000
Precipitation Inflow (acre-ft) = P A	40,000
Evaporation Outflow (acre-ft) = E A	200,000
Stream + GW Inflow (acre-ft)	160,000
Volume in 1941 (acre-ft)	4,500,000

$$\text{Stream Inflow} + \text{Precipitation Inflow} - \text{Evaporation Outflow} = \text{Change in Volume}$$

$$160,000 \text{ acre-ft} + 40,000 \text{ acre-ft} - 200,000 \text{ acre-ft} = 0$$

We have verified steady-state conditions (numbers are the same as that scenario).

HOMEWORK PROBLEM 2

You are now prepared to complete the calculations in the second homework problem. You will be conducting the same calculation confirming steady-state conditions for the Salton Sea.

Typically, the water level or elevation of the lake is the primary concern. The water level can easily be calculated from the lake volume in our simple swimming-pool model. The bottom of our lake is at a constant elevation. With a constant surface area, the water depth, D, is:

$$D = (V/A)$$

The surface water elevation, E, is calculated by summing the lake bottom elevation, BE, and the water depth:

$$E = BE + D$$

In our transient model, we typically will know our initial water surface elevation and are interested in the amount of drop/rise that occurs. The change in water depth, ΔD , will be:

$$\Delta D = (\Delta V/A)$$

We find our mass balance equation in terms of change in water surface elevation by substituting the above equation:

$$S + (P \ A) - (E \ A) = \Delta V = A \ \Delta D$$

$$\Delta D = S/A + P - E$$

We will now model a scenario in which water diversions by the Los Angeles Department of Water and Power (LADWP) has reduced stream water inflows to 70,000 acre-ft per year.

We will decrease our stream inflows as we want to divert water to the Los Angeles Aqueduct. Calculate the drop in the Mono Lake water surface each year due to the diversions.

Table 6. Initial Conditions for Mono Lake and Salton Sea at Onset of Water Diversions

	Mono Lake	Salton Sea
Water Elevation (ft)	6417 (in 1941)	-228 (present)
Stream Inflow after diversions (acre-ft per year)	70,000 (56% less)	1,160,000 (15% less)
Surface Area (acres)	55,000	230,000
Precipitation (ft)	0.73	0.21
Evaporation (ft)	3.6	6.1

We will calculate the drop in lake water surface each year due to the diversions.

$$\Delta D = S/A + P - E$$

$$\Delta D = 70,000 \text{ acre-ft}/55,000 \text{ acres} + 0.73 \text{ ft} - 3.6 \text{ ft} = -1.6 \text{ ft}$$

In this simple transient model of Mono Lake, the annual drop in water level after diversion would be 1.6 ft. The lake surface elevation was 6,417 ft in 1941 before water diversions. What is the predicted water level in 1981 using this model?

$$\begin{aligned} \text{Water level drop} &= 40 \text{ years} (1.6 \text{ ft/yr}) = 64 \text{ ft} \\ \text{Water Level} &= 6,417 \text{ ft} - 64 \text{ ft} = 6,353 \end{aligned}$$

The measured water level in 1981 was 6,372 ft. As numerous simplifying assumptions were used in this simple model, a match between predicted and measured was not anticipated. More complex versions of this model will be attempted later in this module.

Information on problems encountered due to dropping water levels in Mono Lake are included in Table 2.

HOMEWORK PROBLEM 3

You are now prepared to complete the calculations in the third homework problem. You will be conducting the same calculation of water level drop for the Salton Sea.

Another problem associated with decreasing water inflows into these types of lakes is an increase in salinity. The only water outflow from these lakes is via evaporation. These systems are called terminal lakes. During the evaporation process, water is transferred to the vapor phase but any salts contained in the water remain in the lake. We will examine this process with our mass balance modeling.

Simple Annual Transient Lake Salinity Model

In this model, we will be simulating the salinity of the lake water. Salinity is the concentration of salts in water and can be expressed in many types of units. We will be using units of grams of salt/liter of water (g/l). Although most lake waters have periods of stratification in which water is isolated in differing layers, we will assume that the lake is completely mixed for our modeling. Our simple mass balance scenario requires knowledge of the water budget and the salinity of the various waters in our system. The “mass” we will be balancing in this situation is salt mass.

The total mass, M , of salt in the lake is:

$$M = C V$$

Where, C = salt concentration in water (g/l)

V = lake volume (l)

The total inflows of salt into the lake will be:

$$S C_s + P A C_p$$

Where, C_s = salt concentration in stream water (g/l)

C_p = salt concentration in precipitation (g/l)

S = annual stream inflow (acre-ft)

P = annual rainfall (ft)

A = surface area of lake (acre)

The total outflow of salt from the terminal lake will be:

$$E A C_e$$

Where, C_e = salt concentration in water vapor (g/l) = 0

E = annual evaporation (ft)

A = surface area of lake (acre)

As the evaporation process leaves the salts behind, there is no outflow of salts from the lake. [I must note here that in reality salts will precipitate out into solid form when the water reaches high salinities, greater than 100 g/l. However, we will assume that we have not reached these high levels of salinity in our model.]

We can see that this salinity model can never reach a steady state while there is salt inflow to the lake. The salt inflows will never equal the salt outflows:

$$S C_s + P A C_p = E A C_e$$

$$\text{Where, } C_e = 0$$

Our transient model is:

$$dM/dt = d(CV)/dt = S C_s + P A C_p$$

Let us assume that our lake water volume is at steady state and that the water volume, V , is constant with time:

$$V dC/dt = S C_s + P A C_p$$

$$dC/dt = (S C_s + P A C_p)/V = \text{Const}$$

Assume all the variables on the right side of the equation are constant over the time period to be simulated. Integration results in:

$$\Delta C = C - C_0 = [(S C_s + P A C_p)/V] (t - t_0)$$

$$\text{Where, } t - t_0 = \Delta t = \text{elapsed time since initial conditions}$$

We will assume initial conditions of $C_0 = 0$ g/l and calculate rate of salinity increase for differing lakes.

Table 7. Parameters for Salinity Modeling

	Mono Lake	Salton Sea
Volume (acre-ft)	4,500,000 (in 1941)	7,625,000
Surface Area (acre)	55,000 (in 1941)	230,000
Salinity (g/l)	51.3 (in 1941)	44
Annual Precipitation (ft)	0.73	0.21
C_p (g/l)	0.2	0.2
Annual Stream Inflow (acre-ft)	160,000	1,360,000
C_s (g/l)	0.2	2.2

For Mono Lake:

$$\Delta C = [(160,000 \text{ acre-ft} * 0.2 \text{ g/l} + 0.73 \text{ ft} * 55,000 \text{ acre} * 0.2 \text{ g/l})/4,500,000 \text{ acre-ft}] * (1 \text{ yr})$$
$$\Delta C = 0.0089 \text{ g/l per year}$$

The salinity of Mono Lake in 1941 before LADWP diversions was 51.3 g/l. Assuming all variables in our above model were constant over time, the rate of 0.0089 g/l per year would require 5,800 years to reach a salt concentration of 51.3 g/l:

$$51.3 \text{ g/l} / 0.0089 \text{ g/l per year} = 5,800 \text{ yr}$$

Salinities above 90 g/l are of concern due to the impacts on brine shrimp and bird populations. Using our salt mass balance without water diversions, the salinity would not exceed 90 g/l until another 4,300 years has passed. Similarly the current salinity of 82 g/l should have taken:

$$(82 \text{ g/l} - 51.3 \text{ g/l})/0.0089 \text{ g/l per year} = 3,400 \text{ years}$$

instead of the 62 years which have passed since 1941. The acceleration of the salinization rate was caused by the diversions of surface water inflows into the lake and the subsequent decrease in lake volume.

We can see that these lakes will increase in salinity even without water diversions unless a change in climate occurs. The process can be very slow as seen by Mono Lake.

HOMEWORK PROBLEM 4

You are now prepared to complete the calculations in the fourth homework problem. You will be conducting the same calculation of salinity increase for the Salton Sea.

We cannot use our simple salt mass-balance model to investigate the effects of water diversions. The model assumes a steady-state water balance in the lake with a constant stream inflow. We will investigate the effects on salinity due to water diversions later in this module using a more complex model. However, by simply looking at the form of the salt balance equation, we can see that the rate of salt concentration increase is inversely proportional to the lake's volume. Any decrease in lake water volume caused by water diversions will result in an increase in the salinization rate.

$$dC/dt = (S C_s + P A C_p)/V$$

We can see the impacts of water diversions from these simple models: decreasing water level and an increase in the rate of salinization of lakes. These impacts have caused both

Mono Lake and the Salton Sea to be studied intensively in the effort to find solutions to the environmental problems. In the Mono Lake case, biological studies estimated an approximate optimal water level for the ecosystem to continue to function (6392 ft). The Los Angeles Department of Water and Power was forced to stop or decrease the amount of diversions in order to obtain this water level in a particular period of time. Computer modeling was an important factor in assessing the situation. Similarly, the proposed decrease in irrigation return flow for the Salton Sea is being evaluated to estimate the anticipated water level drops and impacts on salinity. The Salton Sea was already in trouble due to its high rate of salinization and various engineering designs are being assessed to decrease the salinity in a portion of the Sea. More complex modeling is required for these types of studies.

MORE COMPLEX MODELS: Mass Balance Modeling in EXCEL

Variable Surface Area of a Lake

Our swimming pool model is not a realistic depiction of an actual lake. The bottom elevation of a lake varies with the deepest depths generally towards the middle. As the water volume of the lake increases, the surface area will increase. The function relating the surface area to the water volume will be lake-specific and dependent on the lake's bathymetry. With a variable surface area, the water surface elevation cannot be calculated simply from the water volume and surface area. The relationships of the surface area to volume and water elevation to volume for Mono Lake are shown in Figures 14 through 16. The tabulated data are in Appendix A and in the Excel file, lakevolumes.xls. Using EXCEL to fit a trend line to the data allows you to obtain a best-fit line equation which relates the lake volume to surface area and to water level elevation. As seen in Figures 15 and 16, the best-fit model among those available in EXCEL was found to be a third-order polynomial equation.

Refresher on Trend Lines in EXCEL

1. Click on the data point in graph
2. Right click mouse
3. >Add Trendline
4. Under Type tab
 - a. Select a model. For many of the models to be available, you cannot have a zero data point (do not include in plot data).
5. Under Options tab
 - a. Click on Display Equation on Chart
 - b. Click on Display R-squared Value on Chart

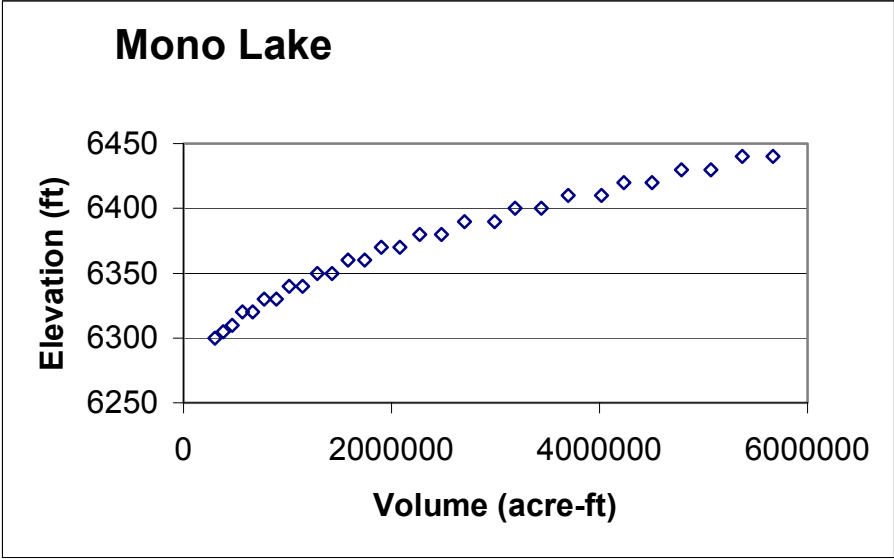


Figure 14. Relationship of Surface Water Elevation to Water Volume in Mono Lake

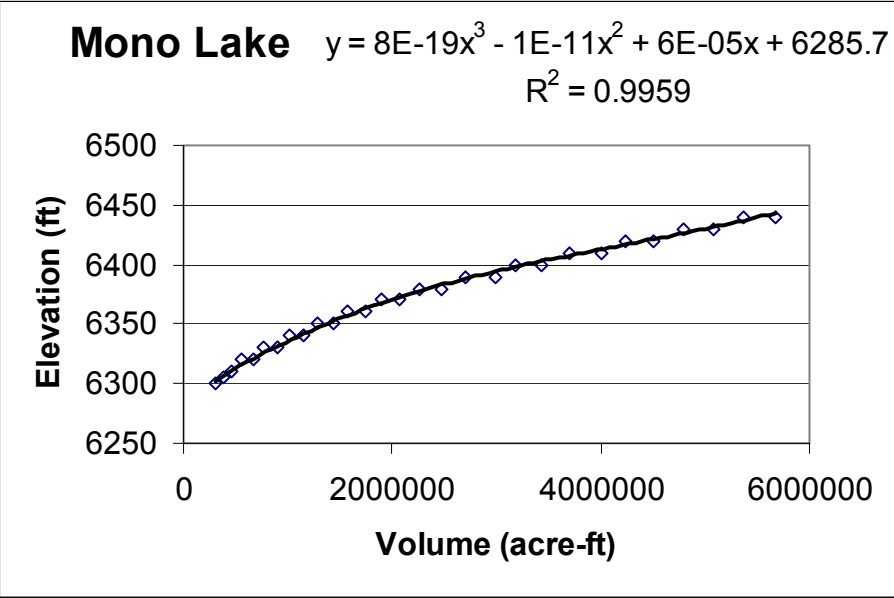


Figure 15. Third-order polynomial function describing elevation as a function of volume

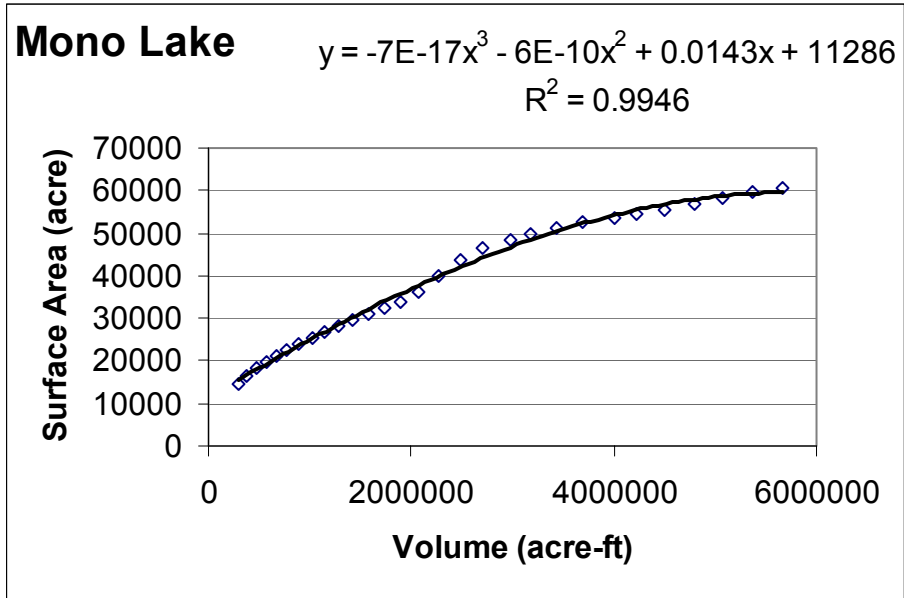


Figure 16. Third-order polynomial equation describing surface area as a function of volume

Comparing predictions of surface area from several models aids in the selection of the appropriate model. Use EXCEL to produce a plot of predicted surface area versus volume [for some reason in EXCEL the resulting line does not always match the trendline EXCEL exhibits]. As can be seen in Figure 17, the best model for Mono Lake’s surface area and elevation as a function of volume is a 3rd order polynomial equation.

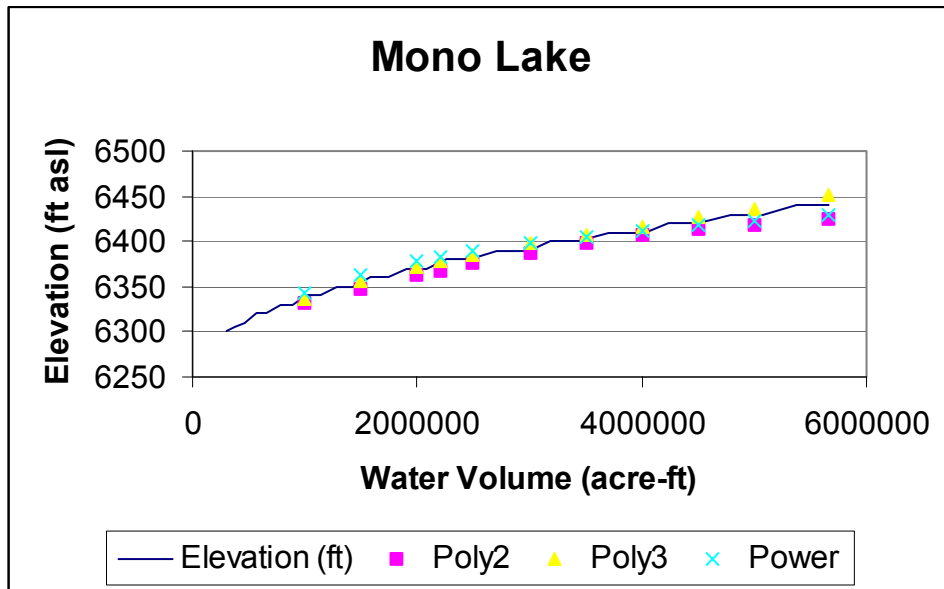


Figure 17. Predicted water surface elevations from various functions

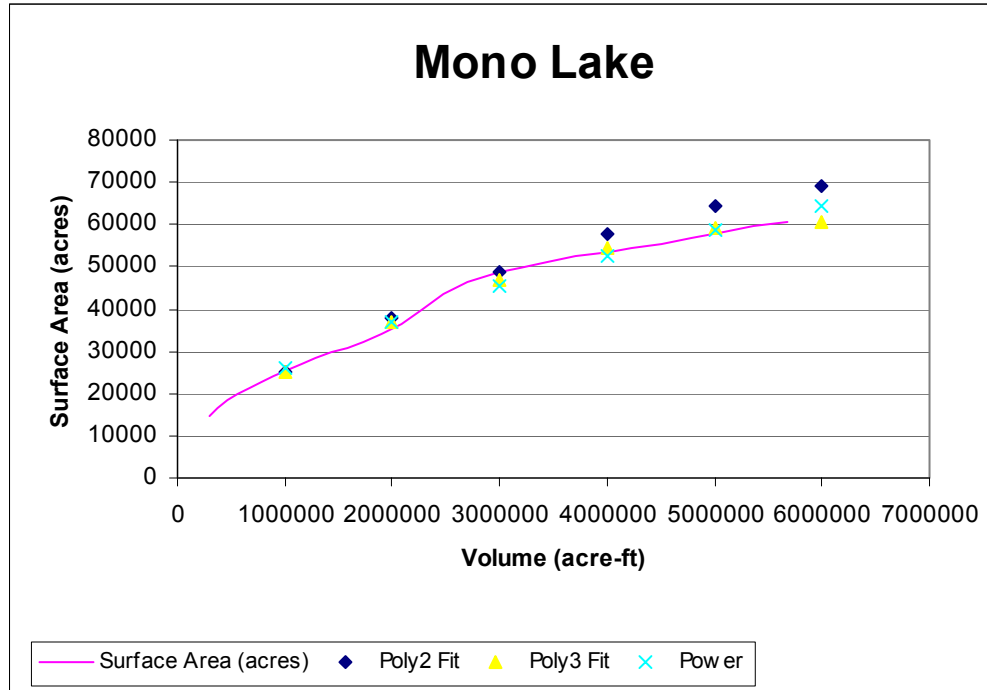


Figure 18. Predicted surface areas from various functions

Using the third-order polynomial equations shown in the figures, the y variable (surface water elevation or surface area of the lake) can be calculated from the x variable (water volume). As can be seen in the figures, the water elevation and surface area increase with increasing water volume. The increase in water elevation and surface area are lake-specific and must be evaluated from bathymetric data as we have done here.

HOMEWORK PROBLEM 5

You are now prepared to complete the calculations in the fifth homework problem. You will be plot the surface area and water level by the water volume from the given bathymetric data. Trend lines and best-fit equations will be obtained to related the surface area and water level to the water volume in the Salton Sea.

Annual Transient Lake Level Model:

Recall our transient water balance model with constant surface area:

$$S + (P - A) - (E - A) = dV/dt$$

Where, S = surface water inflows
 P = precipitation
 E = evaporation
 A = surface area
 V = lake volume

In our simple model, all the variables on the left side of the equation were constant. In the current model, the surface area, A , will vary with volume, V . Notice that the amount of water inflow from precipitation ($P A$) and the amount of water outflow from evaporation ($E A$) will change with changing surface area.

We will set up an EXCEL mass balance model for lake water mass balance which will account for the change in surface area for Mono Lake.

Constant Conditions Since 1941

With no changes in precipitation, evaporation and stream inflow, the Mono Lake conditions of 1941 maintain a steady-state condition with no changes in volume. To maintain significant figures, the Round function of EXCEL must be used. For very large numbers such as $E+04$ use `ROUND(number, -3)` and for $E+05$ use `ROUND(number, -4)`. The EXCEL file, `monomb.xls`, includes a worksheet with the model summarized in the Appendix.

HOMEWORK PROBLEM 6

You are now prepared to complete the EXCEL exercise in the sixth homework problem. You will create a steady-state mass-balance model for the Salton Sea water volume from 2003 into the future.

Water Diversion, No Annual Variation

In simulating the water diversions, we start with the initial conditions found in 1941 and decrease the stream inflow. With a change in the stream inflow, Mono Lake is no longer in steady-state conditions. The water volume and elevation drop with time. The EXCEL file, `monomb.xls`, includes a worksheet (Diversions) with the model summarized in Appendix . A comparison of the EXCEL mass-balance model with our simple model which assumed constant surface area is shown in Figure 19. Accounting for the decrease in surface area and subsequent decrease in evaporation outflow simulates a more gradual drop in surface water elevation for Mono Lake. The actual water elevation in 1989 was 6,377 ft. Our model assuming constant rates of precipitation and streamflow does not account for several wet years that occurred during the early 1980s. The model overpredicts the drop in water elevation but not as much as our “simple” algebraic model.

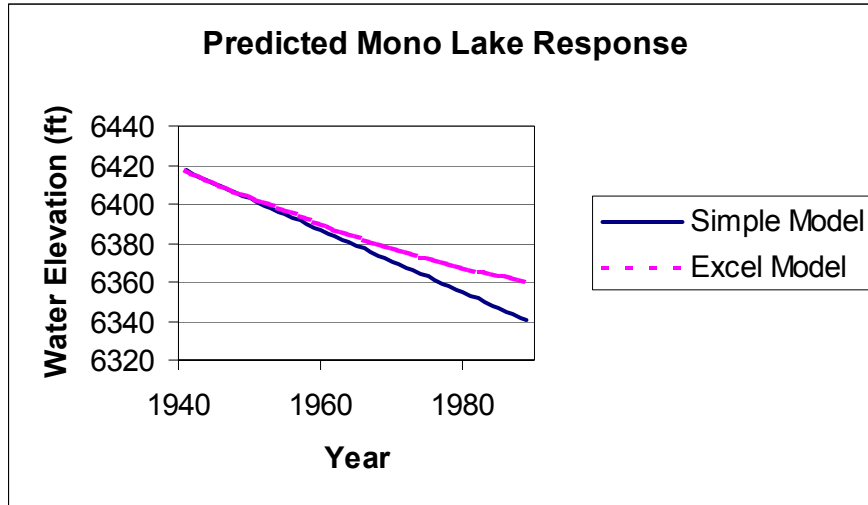


Figure 19. Predictions of Mono Lake water level drop by simple and EXCEL model

HOMEWORK PROBLEM 7

You are now prepared to complete the EXCEL exercise in the seventh homework problem. You will create a mass-balance model for the Salton Sea water volume from 2003 into the future with the proposed water transfer.

Annual Transient Salinity Model:

Recall our transient model:

$$dM/dt = d(CV)/dt = S C_s + P - A C_p$$

In the current version of our model, the lake volume, V , is not constant with time. Similarly, the surface area, A , is a function of the lake volume. We will extend our water mass-balance model to account for salinity changes in Mono Lake.

The model is in monomb.xls in the Salinity worksheet. We simply add a column which shows the initial conditions for salt concentration. The total mass of salt (CV) is calculated from the salt concentration and the lake volume (from our water mass balance). A column is added to show the change in mass from the above equation. For the next time step, the new salt concentration is calculated from the previous salt mass + change in mass divided by the new lake volume.

Using this model to simulate the salinity changes with and without diversions gives us the values in Figure 20. As the changing surface area of the lake does not greatly impact the salt inflow to the lake, the simple model matches the EXCEL model for the no-diversion scenario. However, recall we could not use the simple salt mass-balance model to predict changes due to water diversions as our assumption of steady-state water volume was violated. The predicted salinity value of 129 g/l is higher than the observed value of 91.6 g/l (Table 2). As with the water mass balance model, annual variations in rainfall and streamflow were not accounted for in the model.

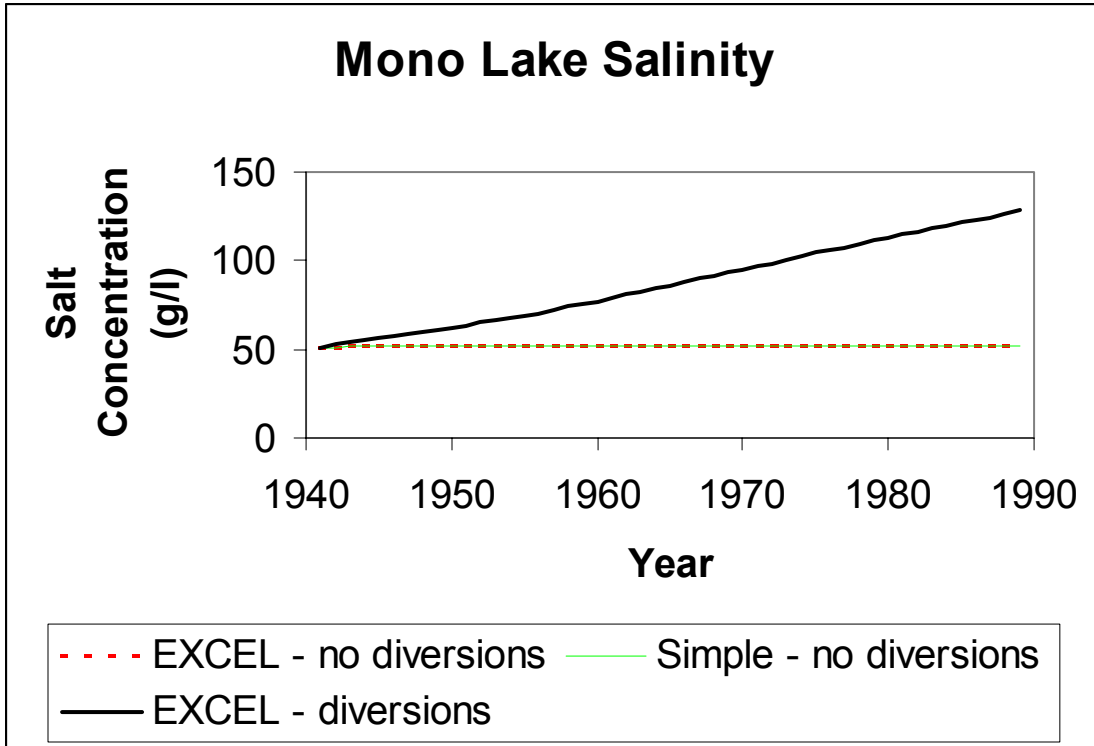


Figure 20. Predicted Mono Lake salinities with steady-state water conditions (no diversions) and transient water conditions (water diversions).

HOMEWORK PROBLEM 8

You are now prepared to complete the EXCEL exercise in the eighth homework problem. You will create a salinity mass-balance model for the Salton Sea water volume from 2003 into the future and examine the effects of water diversions.

EMPIRICAL DATA

General Man's Impacts on Lakes:

http://gep.iatp.org.ua/lake%20_pol.htm

Saline Lakes:

<http://lakes.chebucto.org/saline1.html>

Dead Sea General Information

<http://www.bibleplaces.com/deadsea.htm>

MONO LAKE

General Information from Mono Lake Committee: <http://www.monolake.org/>

Mono Basin Clearinghouse: <http://www.monobasinresearch.org/index.html>

Mono Basin EIR: <http://www.monobasinresearch.org/onlinereports/mbeir.htm>

The Mono Basin Ecosystem: Effect of Changing Lake Level (1987) : pages 22-49 have a good description of the differing mass balance models which have been used for Mono Lake and the potential sources of error:

<http://books.nap.edu/books/0309037778/html/index.html>

Ecological Issues of Changing Lake Levels:

<http://www.naturestudy.org/projects/mono.htm>

CA Historical Society Paper: <http://www.californiahistorian.com/articles/mono-lake1.html>

Feel free to do a web search with "Mono Lake". You will find quite a bit of information and images to use in your project.

SALTON SEA

General History and Major Issues of the Salton Sea:

<http://www.sci.sdsu.edu/salton/EnvirnEconValueSaltonSea.html>

Salton Sea Authority: <http://saltonsea.ca.gov/environ.htm>

UCD Salton Sea Project – some information on circulation patterns:

http://my.engr.ucdavis.edu/~wremg/Salton_Sea/

General information on Salton Sea and web links:
http://www.uleth.ca/vft/SW_USA/salton_sea.html

US Dept. of Interior Salton Sea Restoration Project:
<http://www.usbr.gov/lc/region/saltnsea/ssrest.html>

Imperial Irrigation District:
<http://www.iid.com/aboutiid/env-salton.html>

Imperial Irrigation District Water Conservation and Transfer Project Final EIR
http://www.usbr.gov/lc/region/g4000/IID_FEIS/Vol_1/Contents.pdf
Click on the section you wish to view in the Table of Contents to obtain the pdf file

Measured Salinities in Salton Sea Drains and Results of Mass-Balance Modeling Scenarios
by US Bureau of Reclamation
http://www.waterrights.ca.gov/IID/IIDHearingData/LocalPublish/Appendix_F.pdf

Salton Sea Booklet (large pdf file): 12-page color booklet on the SS situation:
http://cem.uor.edu/salton/ssbooklet_final.pdf

Information on the water transfer controversy:
<http://www.igs.berkeley.edu/library/htImperialWaterTransfer2003.html>

Distribution of the Salton Sea Inflows for possible use in more complex salinity modeling

Salton Sea Inflows	Average Annual Flows (acre-ft) [from 1950-1999]
Alamo River	620,000
New River	440,000
Imperial Irrigation District Flows	93,000
Coachella Valley Water District Flows	115,000
Groundwater Flows from Coachella	1,500
Estimated Unmeasured Inflow	90,500
Total Surface and Groundwater Inflows	1,360,000

CONCEPTUAL QUESTIONS

Briefly describe how to set up a general mass balance model.

What is the difference between a steady-state and a transient model?

In terminal lakes with a steady-state water balance, what is expected to occur to the water level with time?

In terminal lakes with a steady-state water balance, what is expected to occur to the salt concentration with time?

What effect does diversion of water inflows have on lake's water level with time?

What effect does diversion of water inflows have on a lake's salinization rate?

PROBLEMS AND PROJECTS

1. Assuming steady-state conditions and an unknown evaporation rate, calculate the evaporation rate (ft/yr) for the Salton Sea. Calculate the total inflow and total outflow of water for a year. Confirm steady-state conditions. Compare the inflows and outflows of the Salton Sea with the Mono Lake flows.
2. The current conditions at the Salton Sea are:

Table 8. Salton Sea Conditions

Parameter	Salton Sea
Surface Area (acres)	230,000
Annual Precipitation Inflow (acre-ft) = P A	48,000
Annual Evaporation Outflow (acre-ft) = E A	1,400,000
Annual Stream + GW Inflow (acre-ft)	1,360,000

Calculate the total water inflow and the total water outflow. Calculate the annual change in water volume using the mass-balance model. Remember to round your numbers based on significant figures.

3. Using the simple model, calculate the drop in the Salton Sea water surface each year due to the reduced inflows (Table 7) caused by a water transfer. The water surface is currently -228 ft. What would be the water surface elevation in 2018? Calculate the drop in the Salton Sea water surface each year if all stream inflows stopped. How long would it take to dry up? [The deepest point in the Salton Sea is 50 ft]
4. Using our simple transient salinity model, calculate the salinity increase for the Salton Sea. Use the values in Table . Assuming all variables in our model were constant over time, how long would it take the Sea to increase from freshwater (salt concentration of 0 g/l) to the current salinity (44 g/l)? How does the calculated time compare to the time since the Sea was formed in 1905? At this rate of salinization, how long before the Sea reaches 60 g/l and fish die? Do you believe a restoration project can be implemented before this time passes?
5. Using the Salton Sea bathymetric data in the Appendix (also in EXCEL file, ssbath.xls), plot the water surface elevation (y variable) by the water volume (x variable). Using the 2nd order polynomial, 3rd order polynomial, 4th order polynomial and power model, fit a trend line and obtain a best-fit equation relating surface area to water volume. Do the same for water level [however, you will not be able to use the power model due to the negative numbers for elevation]. Using EXCEL and the best-fit model equations, predict surface area and elevation for the differing models and compare to the actual data. Select the

optimal model for predicting surface area and elevation from the Salton Sea's water volume.

6. Using EXCEL, set up a mass-balance model for the Salton Sea. Use parameters given in this module and start with initial conditions from 2003. Simulate with no change in stream inflow and confirm steady-state conditions.
7. Using the Salton Sea EXCEL mass-balance model, simulate the effects of the proposed water transfer (decrease in stream inflow of 200,000 acre-ft). Plot the decrease in surface water elevation and compare to the water level drop predicted by the "simple" algebraic model (in Problem 3). Do the same for stopping all stream inflows.
8. Extend your Salton Sea EXCEL mass-balance model to include salt mass balance. Simulate salt concentration changes with no water diversions. Plot the salt concentration changes from 2003 to 2019 for both the simple and EXCEL model. How do the simple and EXCEL model compare when the water balance is at steady-state? Simulate the salinity changes with a water diversion of 200,000 acre-ft. Plot the change in salinity over time with the water diversion. When will the salinity exceed 60 g/l? What will occur in the Salton Sea at those high salinities?
9. **PROJECT.** In the examples of this Module, we have simulated water and salt balance in Mono Lake assuming constant annual precipitation and streamflow. For this project, explore the effects of varying these parameters (Table 9). Assume that the evaporation rate is constant.
 - a. Simulate the no diversion scenario from 1941 to 1989 using the values of precipitation (ft) and stream and groundwater inflow (acre-ft). Plot the changes in water surface elevation and salinity and discuss.
 - b. Simulate the diversion scenario by subtracting 90,000 acre-ft from the annual stream inflow for each year. Plot the changes in water surface elevation and salinity and discuss. Compare to observed variations in water level and salinity (Source for water level: monoyear.xls). Adjust the amount of water diverted to match the historical water levels.
 - c. Assume a similar distribution of precipitation and streamflow from 2003 to 2050. Using the current volume of Mono Lake (Aug 2003: 2,750,000 acre-ft) and salinity (Aug 2003: 82 g/l), assume no diversions of streamflow are allowed and simulate the annual change in water level and salinity. When will the court-ordered elevation of 6,392 ft be reached?

Table 9. Annual Variations in precipitation and stream inflow for Mono Lake

Year	Precipitation (ft)	Stream Inflow (acre-ft)	Year	Precipitation (ft)	Stream Inflow (acre-ft)
1940	1.06	169,090	1965	1.05	210,243
1941	0.86	256,101	1966	1.23	152,705
1942	0.74	237,207	1967	0.68	278,520
1943	0.80	221,735	1968	1.38	136,457
1944	0.83	159,344	1969	0.85	297,986
1945	1.04	226,496	1970	0.61	161,359
1946	1.04	195,892	1971	0.78	175,985
1947	0.31	136,165	1972	1.05	146,285
1948	0.75	150,045	1973	1.09	198,787
1949	0.55	145,318	1974	0.89	197,495
1950	0.98	170,737	1975	0.66	182,227
1951	1.64	174,371	1976	0.55	102,464
1952	0.50	250,672	1977	1.77	101,036
1953	0.83	152,001	1978	1.18	255,180
1954	0.54	137,125	1979	1.23	184,870
1955	1.34	157,578	1980	0.69	244,246
1956	0.83	241,009	1981	1.05	158,521
1957	1.28	164,336	1982	1.93	296,959
1958	0.83	228,447	1983	0.99	328,582
1959	0.54	125,679	1984	0.58	216,202
1960	0.62	121,858	1985	1.44	169,759
1961	1.08	124,414	1986	0.47	243,424
1962	1.23	197,868	1987	0.67	118,232
1963	0.79	203,922	1988	0.41	120,999
1964	0.93	139,639	1989	0.63	142,081

Data also in EXCEL file, annualvariation.xls [Information from the Mono Lake Environmental Impact Report (EIR)]

10. **PROJECT.** Set up a monthly mass-balance budget for Mono Lake using information in the table below. Calculate and plot the variations in water elevation and salinity within one year due to seasonal variations in precipitation, evaporation and stream and groundwater flow. Set initial conditions with parameters from 1941, 1981 and 2003. Produce plots of the salinity and water level variation. Include historical data from 1981 for water elevation (monomonthly.xls). How much does the water level and salinity vary within each year? What season has the lowest water level? What season has the highest water level? Discuss impacts on birds. Why do you think most of the stream flow is in the spring and early summer? [Hint: Streams are fed by the Sierra Nevada mountains].

Table 11. Estimated monthly variation in hydrologic values for Mono Lake

Month	Precipitation (ft)	Evaporation (ft)	Stream+ Groundwater Inflow (acre-ft)
January	0.13	0	6,400
February	0.05	0	6,400
March	0.02	0	8,000
April	0.06	0.1	8,000
May	0.04	0.3	17,600
June	0.03	0.7	28,800
July	0.07	0.9	35,200
August	0.06	0.8	17,600
September	0.01	0.4	9,600
October	0.04	0.4	8,000
November	0.11	0	8,000
December	0.10	0	8,000

Data calculated by distributing total precipitation, evaporation and stream runoff proportionally over months consistent with information in Vorsters Mono Basin model.

11. PROJECT. How Would You Save the Sea? Investigate the proposed restoration projects for the Salton Sea. Information is available at the web sites provided. Set up a mass balance model with some of these scenarios and investigate. For example: Split the Sea into two regions, with enhanced inflows into one area and removal of salt from another area (evaporators or solar ponds). Assess the rate of salt removal necessary to maintain the Salton Sea salinities at 44 g/l for scenarios with and without water diversions. Discuss possible costs and who should pay.