

## **Modeling the water budget and salinity concentration of Walker Lake while increasing ecosystem health by way of desalination or water reallocation**

**Mark Conolly**

**Abstract** The current Walker Lake ecosystem is suffering from rising Total Dissolved Solids levels that are threatening complete fish mortality. The Walker River Basin stretches from the eastern slopes of the Sierra Nevada Mountains in California to the arid desert of western Nevada and is a crucial stopping point for migrating birds, such as the Common Loon and the White Pelican, coming across the great basin. Since the 1880's, agricultural water diversions upstream have reduced freshwater inflow considerably, some years the lake receives no inflow. As a result the Walker Lake's level has dropped dramatically, and TDS levels have jumped from 2,500 mg/L to about 12,400 mg/L in 1996. The effect of the increase in salinity increases mortality of the threatened species, the Lahontan Cutthroat Trout (*Oncorhynchus clarki henshawi*), which damages a cornerstone of the ecosystem's food chain. The LCT population is maintained through artificial propagation at an offsite hatchery, but complete population die off will occur when the lake water reaches 16,000 mg/L TDS which could occur in as little as 3 drought years. This research approach is to set up four different water budget scenarios to predict the lake's salinity after 20 years. I will compare these options on economic, environmental, and policy grounds. The budget scenarios include four possible lake management strategies: 1) No change in strategy with current average inflow, evaporation rate, and a water deficit; 2) desalination; 3) a water rights transfer to add Walker River inflow to the lake; and 4) a hybrid approach including desalination and a water rights transfer. To help alleviate the environmental problems associated with the high salinity on the lake's fishery, I will investigate in this study whether or not desalination can serve as an economically viable solution to the detrimental effects of increasing TDS levels in Walker Lake. However, there is debate as to whether or not this is a sensible option, economically, when compared with the proposed non-technical option of reallocating water rights--the ecological value of the lake and the economic productivity of Walker River Basin agriculture must be considered.

## Introduction

**Walker Lake another Mono Lake** The issue of the salinity of Walker Lake spans 100 years of agricultural water diversion from a hydrographic area of 641,280 acres (158,396 km<sup>2</sup>), and five agricultural areas across both California (22%) and Nevada (78%) (US Geological Survey 1995). Currently, Walker Lake is roughly 2.7 km<sup>3</sup> (2.2 million acre-feet) in volume, 140 km<sup>2</sup> (35,000 acres) in surface area, and 30 m (99 ft) in maximum depth. Freshwater diversion and reservoir construction in the early 1900's has caused the lake to shrink to a quarter of its original volume and half of its surface area. Total dissolved solids (TDS) increased from around 2,500 mg/L in the 1880's to a 1996 level of 12,400 mg/L (Horne and Beutel 1996). The issues brought about by the worsening condition of Walker Lake, are of the same nature as the desiccation of Mono Lake in California, also a terminal lake. According to Botkin *et al.* (1988) the salination of the Mono Lake ecosystem was also due to upstream diversion of fresh water and decreasing lake volume, however, the diversions were used for remote urban use in Los Angeles and not local agriculture. Diversion rose to 90,000 acre-feet/year, when a water budget was created that showed a maximum of 38,000 acre-feet/year (46.9 million m<sup>3</sup>) could be diverted in order to maintain the current viable lake volume. The water was then reallocated accordingly to save Mono Lake.

**Home of the Lahontan Cutthroat Trout** Walker Lake has supported a native population of Lahontan cutthroat trout (*Oncorhynchus clarki henshawi*). Today the fishery is maintained by a State stocking program, and angling and tourism at Walker Lake today account for roughly 50% of the local economy, thus maintenance and improvement of the trout fishery is important. Salinity levels are now approaching lethal levels for Cutthroat Trout at 16,000mg/L (Taylor 1972), which is also true of the Tui Chubb (*Gila bicolor*) the Lahontan Cutthroat Trout's primary food source. Furthermore, during summer lake stratification, the trout are squeezed between the bottom layer of low oxygen water—the hypolimnion, and an upper layer of water too warm for survival—the epilimnion (Horne and Beutel 1996). The Nevada Department of Wildlife had observed that increased salinity levels have appeared to depress the average life span of the trout from around 8 years to only 2 to 3 years. Three low-inflow years (1992 through 1994) resulted in a TDS increase of approximately 2,100 mg/L in Walker Lake. TDS in Walker Lake has reached highs around 15,000 mg/L. Thus, it would take four or five years of consecutive low-inflow years for TDS to increase above toxic levels for the Cutthroat Trout (Nevada Department of Wildlife 1995). It is also understood that salinity reinforced stratification may inhibit mixing between surface water and nutrient rich

bottom water during the summer (Horne *et al.*). In the case of Walker Lake, when freshwater inflow dilutes salinity in surface water, surface water density drops. This leads to an increase in the density difference between surface and bottom water and more stable stratification. Thus, freshwater inflow strengthens stratification and acts to lower the degree of summertime mixing events between the epilimnion and the hypolimnion (see appendix G). This phenomenon has additional effects on nutrient recycling and phytoplankton production which bears magnified food chain damages (Beutel *et al.* 2001).

**The Four Experimental Lake Management Scenarios** In this research the three salinity levels of significance are to be considered: the 12,400 mg/L TDS level in 1996, the optimal level for the fish population of 5,000 mg/L TDS, and the complete fish mortality level of 16,000 mg/L TDS (Beutel and Horne 1996). The modeling in this research is a water budget accounting model that predicts the salinity of Walker Lake based on a 20 year time line. There are four different scenarios examined in order to better consider the peripheral consequences of:

1. No action being taken, business as usual,
2. The reallocation of Walker River Basin water rights by taking water from agriculture etc.,
3. Mechanical desalination of the lake,
4. And a combination of desalination and the reallocation of Walker River Basin water rights.

The first scenario is observing the salinity of the lake in 20 years with current agricultural diversions and, likewise, current water deficit. To contrast this, the second scenario predicts the salinity and lake volume if the lake were to be mitigated by a desalination plant. The third lake management scenario investigates the feasibility of buying the water from upstream agricultural used, which is controlled by the Walker River Irrigation District (WRID). The fourth lake management scenario involves the purchase of water upstream in combination with the technology of a desalination plant. All scenarios are observed with the target goal of 5,000 mg/L TDS within 20 years in mind. This would be optimal for the habitat of Walker Lake.

**Walker Lake water budget** Walker Lake is roughly  $2.7 \text{ km}^3$  (2.2 million acre-feet) in volume and  $140 \text{ km}^2$  (35,000 acres) in surface area. Because freshwater diversion and reservoir construction in the early 1900's has caused the lake to shrink to a quarter of its original volume, TDS increased from around 2,500 mg/L in the 1880's to a 1996 level of 12,400 mg/L. In 1994 the TDS level was at 13,300 mg/L TDS when the water budget estimates were made. At that level an additional 40 million  $\text{m}^3$  (33,000 acre-feet) of water is required for hydrologic equilibrium, and a reduction to 10,000 mg/L requires a one time addition of 700,000 acre-feet combined with an additional 47,000 acre-feet per year to account for increased evaporation (Thomas 1995). Should this defect persist, within 20 years the lake will reach 16,000 mg/L TDS, a level at which the Lahontan Cutthroat Trout and its primary food source the Tui Chubb will reach 100% mortality (Taylor 1972). Already, the fishery is supported wholly by off site hatchery in Mason Valley. There is no sustainable natural reproduction of the trout in the lake, and the hatcheries have to acclimate the fish to the high salinity levels to improve survival success (Nevada Division of Water Planning 1995). The loss of the fishery will represent approximately a 40% loss of the region's economy not only through the lost fishing industry but also through the loss of the bird watching tourism that comes to observe the biannually migrating common loons, white pelicans, grebes, and ducks (Horne *et al.* 1994). These birds depend on Walker Lake as a migratory stepping stone through the Great Basin, which it could not be without fish to consume.

**Water Budget of Walker Lake and the Desalination Option** Based on current surface area and a net annual evaporation of roughly 168.5 million  $\text{m}^3$ /year (137,000 acre-feet/year), the lake receives about 128 million  $\text{m}^3$  (104,000 acre-feet) of water, leaving a deficit of 40 million  $\text{m}^3$  per year (33,000 acre-feet/year) (USGS 1995). In my study I will use the desalinization of brackish water because it has been used as an option to satiate demand for fresh water and has even become a source of potable water for water stressed regions such as the island of Malta. Upon construction, their reverse osmosis plants accommodated the desalination of water that is 13,000 mg/L TDS at a recovery rate of 80%, and with a plant capacity of 4,500  $\text{m}^3$ /day at a 1986 cost of \$.77/ $\text{m}^3$  (Andrews 1986). Similarly, in water deprived Israel, Mekorot--Israel's national water company--designed a brine water reverse osmosis plant that can handle 150,000  $\text{m}^3$ /day with a recovery rate of 92% at a 1996 cost of \$.25/ $\text{m}^3$  (Gluckstern and Priel 1996). This high rate of recovery is crucial for Walker Lake which is already suffering from a lack of freshwater.

**Historical Agricultural Water Use** Farming and ranching is a lucrative industry in Lyon County and especially in its Smith and Mason valley agricultural areas (see appendix H). They have yearly agricultural crop revenues in the range of \$45-50 million per year, in 1992, for example, Lyon County totaled \$65.817 million from farming alone and in one county alone came up with 22 percent of all of Nevada's cash receipts from farming (US Department of Commerce). Finally, farm employment in Lyon County totaled 566 workers, or 7.5% of the county's total employment. Lyon County has nearly 350 farming units. Water rights for agricultural use in this region began in the late-1800s when settlement in these valleys was encouraged by the federal government's various Homestead Acts (beginning in 1862), the Desert Land Entry Act (1877), and the 1894 Carey Act. Unfortunately, there came an increase in demands on sparse and inconsistent surface water flows from Walker River, which forced agricultural interests to begin extensive groundwater pumping operations as a backup to limited surface water supplies. Not only has this increased the cost of farm production, but it has lowered groundwater levels in certain areas. "In addition, any dramatic shift in the uses of water resources in this basin (e.g., increased Indian water rights for the Walker River Paiute Tribe Reservation, increased flows to Walker Lake, greater in-stream flows for fish and wildlife, etc.) are destined to have far-reaching socioeconomic impacts within" (Horton)

For this study to give a fair and comprehensive view at seeking out alternative lake management strategies, adjustments and simplifications must be applied so that the values of water volumes, salt concentrations, and costs are realistic but not exact, which are all discussed in the methods section. In order, to give comprehensible results of these calculations, a perspective that juxtaposes their feasibility with the justification of deviation from exact values is explored in the discussion section, followed by the conclusion.

## **Methods**

**Lake Water Volume Box-models** The water budget model that was created for this research--with the help of Renata Andrade, Ph.D. candidate and Jim Downing, Ph.D. student at UC Berkeley's Energy and Resources Group—is a first-order differential equation that takes into consideration the increase in evaporation with the increase in volume of the lake, and the

increase in salinity with the increased flow of fresh water that still contains dissolved solids and the escape of pure water through evaporation (Harte 1988). The problem involves box-model flows according to a lake scenario (see appendix B). What had to be accounted for was the fact that the concentration of dissolved solids is not in a steady-state in Walker Lake, except for the scenario with the desalination plant, being that it is a terminal lake; the content of dissolved solids will always be increasing. The lake volume only can be calculated to a steady-state model.

**Adjustments to make the model feasible** There were several calculations that were necessary in order to fit inflow and outflow rates into the first-order differential equation. First, I adjusted the water loss to evaporation per square meter of the lake by considering the evaporation rate of 169 million m<sup>3</sup> (137,000 acre-feet per year) from a lake with a surface area of 140 km<sup>2</sup> to be 1,203 L/m<sup>2</sup>/year. The increased surface area was assumed to have the same evaporation rate. This assumption was accepted despite the inevitable increase in altitude and, therefore, possible changes in evaporation rates due to the inexact measurement currently used by the US Geological Survey by the pan evaporation method. This method is inexact because the evaporation pans are placed on dry ground which radiates more heat and drier air and shows higher evaporation rates than the lake surface (Vallet-Coulomb *et al.* 2001). I assumed comparable inexactitude. Based on the historical data of 114 years, Walker Lake's surface area was 280 km<sup>2</sup> at a volume of 11.1 km<sup>3</sup> and in 1996 had a surface area of 140 km<sup>2</sup> with a volume of 2.7 km<sup>3</sup>, I calculated an average linear relationship of  $1.7 \times 10^{-2} \text{ m}^2/\text{m}^3$  surface area to volume increase to simplify the calculation. In reality the surface area increase would look more exponential in relation to volume increase, but this assumption was made for three reasons: the first is that the data to know exactly what the surface area to volume ratio would be at each different volume was not available, second if that were available, the irregularities in the lake basin would make it impossible to plug into a partial first order equation, and third the bathymetry known of the lake shows that the east and west sides of the lake are very steep making it look more like a rectangular box than an inverted cone, and the surface area growth extends north and south (Beutel and Horne 2001).

In order to find the change in salinity and in volume I used the equations:

$$(1) \frac{dV}{dt} = Q_{in} - Q_{out} = Q_{in} - E(t) \text{ and}$$

$$(2) V(t) = [-a/b + ce^{(bt)}] \text{ (see appendix A)}$$

This gave the lake volume after the designated amounts of time which take into consideration the evaporation rates. This is the core mathematical model for all four scenarios, accordingly, the salt mass—which is at a constant yearly input—is simply multiplied by the number of years of input and divided by the volume at that time to get the milligrams per liter of total dissolved solids. In the case of the desalination model the water loss per year of plant operation (8% of total flow through) is subtracted from the volume. Likewise, the amount of salt removed per year of plant operation ( $1.567 \times 10^8 \text{ mg/m}^3$ ) is subtracted from the total salt mass at each time period.

**The Desalination Method** The desalination strategy will tell us the volume of water that needs to run through the desalination plant to get to 5,000 mg/L in 20 years, it will also tell us the reduction in volume from the lake due to brine water disposal. When approaching the method of a proposed desalination plant, research is needed to find an appropriate model from which to infer data. From this, using the example of brine water reverse osmosis in Israel, the cost of such a project is procured and may be superimposed on our lake management model. Of all of the models that I came across, the standard cost prediction spanned a time period of 20 years. This was often predicted to be the life span of each reverse osmosis plant before costly renovations and maintenance is required, and it is set as a standard time period of amortization of the initial capital investment in order to understand the realistic cost estimate of such a project per unit of water produced. This time frame also became important because 20 years is the estimated time for the lake to reach complete fish mortality TDS concentration (16,000 mg/L) if no water improvement plan is implemented (Beutel and Horne 2001). To further adjust the model of desalination to achieve reasonable calculations data was inferred from a brackish water reverse osmosis plant in Eliat, Israel (Gluckstern and Priel 1996). The volume change estimates were derived from a 92% recovery rate of processed water at a rate of 150,000 m<sup>3</sup> per day and a cost of \$.25/m<sup>3</sup>. This cost is exclusive of construction costs of the desalination plant. The desired salinity of Walker lake is 5,000 mg/L TDS to have reasonable habitat health, but the desalination model produces water that is less than or equal to 500 mg/L (the model produces potable water), so only the salt mass removal of the plant per year is considered. The inflow water from Walker

River is set at an average of 200 mg/L, so the mass is determined by the volume of inflow each year.

**Water Right Reallocation Method** Reallocation of water to achieve an optimal TDS level (for the fishery) of 5,000 mg/L using our 20 year time frame, will give us the volume of the lake and the amount of in flow required to sustain such a level. Amount of water needed is important to infer the cost of purchasing the appropriate volume of water including current water price (approximately \$15/acre foot or \$0.012/m<sup>3</sup>) or percent of agricultural productivity lost (proportional to the percent of water taken away from current use, as per water banking study done by the University of Nevada Reno). In exploring the option of reallocation of water away from agriculture, two things must be considered in order to get an estimate of the cost: first the cost of buying the water from the Walker River Irrigation District, and second the unrealized profits from decreased agriculture. The current, 2003, estimate of the cost of water being used for agricultural purposes is about \$15/acre-foot (office of Ken Spooner, WRID unpublished) although it is subject to market fluctuations. The other side to this approach is the loss to agricultural productivity, which is assumed to be directly proportional to the amount of water made unavailable. For instance, if 50% of farm water is taken away then 50% of the revenues are unrealized.

## **Results**

**Salinity Results** Lake management scenario 1: With no action taken and persistence of average Walker Lake water deficit the salinity (TDS) after five years is 14,092 mg/L, after ten years it is 15,176 mg/L, after fifteen years it is 16,353 mg/L, and after twenty years it is 17,633 mg/L. (see table below)

Lake management scenario 2: With a desalination plant that carries a capacity of 102 million m<sup>3</sup> per year the salinity (TDS) after five years is 10,934 mg/L, after ten years it is 10,044 mg/L, after fifteen years it is 8,000 mg/L, and after twenty years it is 5,430 mg/L. (see table below)

Lake management scenario 3a: in this first water reallocation scenario the Walker river inflow was increased to 40 million m<sup>3</sup> surplus of water (an 80 million m<sup>3</sup> increase). The salinity (TDS) after five years is 12,172 mg/L, after ten years it is 11,601 mg/L, after fifteen years it is 11,053 mg/L, and after twenty years it is 10,621 mg/L. (see appendix E) Lake management scenario 3b:



in the second water reallocation scenario the Walker river inflow was increased to 160 million m<sup>3</sup> per year. The salinity (TDS) after five years is 10,795 mg/L, after ten years it is 9,393 mg/L, after fifteen years it is 8,427 mg/L, and after twenty years it is 7,747 mg/L. (see table below)

Lake management scenario 4: This hybridized model combined both the desalination technology with water rights reallocation. Water right reallocation was that of scenario 3a and allowed for an increase of 80 million m<sup>3</sup> (a 40 million m<sup>3</sup> surplus in the first year), and this was combined with a desalination plant with a capacity of 77.4 million m<sup>3</sup> per year. The salinity (TDS) after five years is 10,627 mg/L, after ten years is 9,500 mg/L, after fifteen years is 6,720 mg/L, and after twenty years is 5,061 mg/L. (see table below)

years from present	Scenario 1 lake TDS with current inflow	Scenario 2 lake TDS with desalination	Scenario 3a lake TDS with added 80 million m <sup>3</sup>	Scenario 3b lake TDS with added 160 million m <sup>3</sup>	Scenario 4 lake TDS with desalination and added 80 million m <sup>3</sup>
0	13,000	13,000	13,000	13,000	13,000
5	14,092	10,934	12,172	10,795	10,627
10	15,176	10,044	11,601	9,393	9,500
15	16,353	8,000	11,053	8,427	6,720
20	17,633	5,430	10,621	7,747	5,061

Table III. 1. Four lake management scenarios. Lake TDS in mg/L. See graph 3 in appendix E.

years from present	lake volume (km <sup>3</sup> ) with current inflow	lake volume (km <sup>3</sup> ) with desalination	lake volume (km <sup>3</sup> ) with added 80 million m <sup>3</sup>	lake volume (km <sup>3</sup> ) with added 160 million m <sup>3</sup>	Lake volume (km <sup>3</sup> ) with desalination and added 80 million m <sup>3</sup>
0	2.7	2.7	2.7	2.7	2.7
5	2.5	2.46	2.9	3.27	2.87
10	2.33	2.25	3.06	3.79	3
15	2.17	2.05	3.23	4.26	3.14
20	2.02	1.86	3.38	4.68	3.26

Table III. 2. Four lake management scenarios. Lake volumes in km<sup>3</sup>. See graph 2 in appendix D.

**Cost Results** The costs of the alternatives were approximated according to the different costs of the fresh water being acquired or produced, as well as a rough estimate of the impact of reduced agriculture in the region.

The lake management scenario 1 does not immediately cost any money.

Lake management scenario 2 required 102 million m<sup>3</sup> per year to be desalinated at a cost of \$.25/m<sup>3</sup> which costs \$25.5 million per year and \$510 million for the twenty year run.

Lake management scenario 3a required the purchasing of 80 million m<sup>3</sup> of water from the Walker River Irrigation District at a cost of \$0.012/m<sup>3</sup> (\$15/acre-foot) which costs \$975,000 per year, in addition to the reduction of the annual agricultural revenue. If all water were taken from Lyon County which uses 205 million m<sup>3</sup> and produces \$50 million per year, 80 million m<sup>3</sup> would reduce agricultural production by 20% (80 million m<sup>3</sup>/205 million m<sup>3</sup>) and reduce revenues by \$19.5 million per year. This scenario has an annual cost of \$20.5 million and costs \$409.5 million for the 20 year duration. In lake management scenario 3b with the purchase of 160 million m<sup>3</sup> of water it will carry a per annum cost of \$40.95 million and \$819 million for the 20 year project.

Lake management scenario 4 requires the purchasing of 80 million m<sup>3</sup> of water from the Walker River Irrigation District as well as a desalination plant of 77.4 million m<sup>3</sup> per year. The desalination will come at a cost of \$19.35 million per year and \$387 million for the 20 year project, and the purchase of the water is \$409 million, with a total cost of \$39.83 million per year and \$796 million for 20 years.

Management strategy	Cost Per Year	Cost Full 20 year run
Desalination	\$25.5 million	\$510 million
Reallocation of 80 million m <sup>3</sup>	\$20.5 million	\$409.5 million
Reallocation of 160 million m <sup>3</sup>	\$40.95 million	\$819 million
Desalination and Reallocation of 80 million m <sup>3</sup> 20	\$39.83 million	\$796 million

Table III. 3. Costs of four management strategies.

## Discussion

**Costs of desalination plant** The adjustments made to the inference of data from previous research on desalination plants, was made regardless of the availability of power to run the plant. This has the capacity to change the cost of the desalination method quite considerably. The examples that were referenced had constant costs per unit of water that was desalinated which were inclusive of the cost of the power that is required. This helps us to understand that the only change in the cost to have a larger capacity of desalination would only effect the initial capital investment (which will be discussed) and not the per unit of water increase. In the desalination

study done by Glukenstern *et al.* (1996), the plant was made up of 20 brine water reverse osmosis units, each capable of filtering 7,500 m<sup>3</sup> per day. In order to increase the capacity for more water, additional units were added, which all cost the same to filter the same amount of water for a 20 year period—the lifetime of each unit. These costs did not include the initial capital investment of the installation of the desalination plants. In the projected model for Walker Lake with this exact same technology there would be required 38 units to run throughout the year. The size of the plant does not effect the per square meter cost of desalination which is what I incorporated into this project. I did not take into consideration the initial capital investment that it would cost to install such a plant because there is not enough information to make that assumption. The power costs are also varied by nature of the fact that there are several options to obtain enough energy. Ahmad and Schmid (2002) proposed using photo voltaic cells to power reverse osmosis units in remote arid areas in Egypt similar to the surrounding of Walker Lake, which justified the feasibility of having such a project in an area as remote and arid as Walker Lake.

Because it was difficult to find stable costs of plant installation it was similarly impractical to add an interest rate to the investment in the desalination plant or purchased water rights, due to the fact that the price of water is predictably inconsistent. Ken Spooner of the Walker River Irrigation District referred to the price of \$15/acre-foot as just an estimate and it is sold on the free market and is always subject to market fluctuations. Also, because all of the water cost values, desalinated or purchased, that were calculated for the management scenarios were uniformly lacking interest rates, the costs would like-wise change uniformly if an interest were applied.

What should also be understood about desalination as an option for lake remediation despite the high cost, is the fact that desalination is becoming cheaper and more efficient. The study in Malta by Andrews and Bergman done in 1986 showed a desalination plant that can handle water with 13,000 mg/L TDS at a capacity of 4,500 m<sup>3</sup>/day, with 80 % water recovery and a cost of \$.77/m<sup>3</sup>. However in 1996, just 10 years later, when Glukenstern and Priel did their study in Eliat, Israel, their plant processed water of 13,000 mg/L TDS with 92% water recovery, at a rate of 150,000 m<sup>3</sup>/day, with a cost of \$.25/m<sup>3</sup>. Although the future of water prices can not be predicted, this is a hopeful trend for desalination.

**Considerations regarding salt content** Further simplifications of the desalination model were employed in the desalination management scenario as well as the hybridized management scenario. The assumption came from the salt removal efficiency of the reverse osmosis plants remaining the same as time passes, which is not exact. As the plants continue to function, the lake becomes increasingly less saline so the inflow water is no longer 13,000 mg/L TDS, in fact, by the end it is nearing 5,000 mg/L TDS for both scenarios with desalination as an option. This was justified by the nature of the reverse osmosis semi-permeable membranes to increase efficiency in energy and processing (flow-through) speed as salt concentrations are reduced (Lokiec and Kronenberg 2003). Like-wise, the percent of fresh water recovery is also likely to rise above 92%. The desalination plant's efficiency is subject to salinity concentrations of the feed water as well as the speed at which the water can be pumped and filtered. It might also increase salt removal efficiency to strategically pump water from the hypolimnion of the lake where salinities tend to be higher in periods of stratification (see appendix G). In this way, more salt per unit of lake water processed is removed and it holds closer to the idea that 13,000 mg/L inflow will be a constant amount processed. This simplification was necessary because the data of how these implied facilities function under varied salinities was not available.

Additional factors that may have skewed the predictions of the water level and salinity level of Walker Lake should also be mentioned so that the data may be applied to similar studies when it becomes available. One crucial fact about the lake that little is known about the subsurface (ground water) flow that empties into Walker Lake. The exact salinity of the ground water is not known and is likely to vary according to the water that is used for agriculture and percolated down to the lake. Similarly, agricultural use of Walker River water will increase salinity in both overland flows as well as subsurface flows. This can happen due to increased run-off erosion, and also decrease the freshwater component due to evapotranspiration of the upstream crops (Thomas 1995).

One final salinity consideration that threatens to skew the water budget for the time dependent management scenario models is the change in evaporation rates. Although the methods of this study disregarded any significant impact of the change in altitude in the evaporation rate and, instead, observed surface area as the only main factor in total yearly evaporation, the salinity of the water alone also plays a vital role in the evaporation rate. Whether it be a decrease in salinity from the desalination plant or from a dilution from an increases in less

saline inflow water, if the salinity is lower the evaporation rate will be higher. According to Morrill *et al.* (2001) “salinity affects evaporation solely through a change in surface vapor pressure. As salinity increases, the surface saturation vapor pressure decreases, reducing the lake-to-air specific humidity gradient and reducing evaporation.” This plays a vital role in determining the lake level equilibria at different inflow rates as well as different salinities.

**Governmental Legislation pertinent to the Walker River Basin** With the value of agriculture in mind, the federal government and state governments of California and Nevada are charged with the obligation of protecting the Walker Lake ecosystem, and must find a compromise. There is a high monetary cost to action of any sort in aiding Walker Lake; however, there is a lengthy list of state and federal legislations that would make inaction—as regarding Walker Lake health—illegal.

The trail toward Walker Lake conservation became possible in 1966 with the Endangered Species Preservation Act which was the precursor to the Endangered Species Act of 1973. As a result, federal government has now considered the Lahontan Cutthroat Trout a federally listed threatened species, and the Owens tui chub a federally and state listed endangered species (Trust for Public Land 2002). The National Wild and Scenic Rivers Act of 1968 demanded that rivers which are deemed to have “outstandingly remarkable scenic, recreational, geologic, fish and wildlife, historic, cultural, or other similar values,” are to be free flowing and free of dams, reservoirs, or diversions. Similarly, in 1972, the California Wild and Scenic Rivers Act stated that rivers with extraordinary scenic or recreational value, or fishery or wildlife value should not have any dams, reservoirs, or water diversions. This came the same year as the Clean Water Act, which sought to achieve zero toxic loading for fishable and swim able waters. The “1913 General Water Law” which is the standard for Nevada’s current water laws stated that “Subject to existing rights, all such water may be appropriated for beneficial use as provided in this Act and not otherwise” (Shamberger 1991). The understanding of that law was that agriculture was useful and gets priority over other uses, until 1989 when the Nevada Legislature passed the Assembly Bill (AB) 322 which stated that “the watering of wildlife, and the establishment and maintenance of wetlands, fisheries, and other wildlife habitats” constitutes a beneficial use of water.

**Loss of Species Diversity** The degradation of Walker Lake’s ecosystem is not a new phenomenon, but is a continuing threat that can destroy the lake’s value as a fishery and as a

stopping point for migrating birds. In 1948, after over fifty years of agricultural diversion a TDS level of 6,850 mg/L killed off the last of the Sacramento Carp in Walker Lake. In 1963, a TDS level of 8,440 mg/L killed off all of the Sacramento Perch (Nevada Division of Water Planning 1996). Now the Lahontan Cutthroat Trout and the Tui Chub are threatened with eradication from the lake. The lake has also lost an estimated six species of zooplankton and the remaining two species have dropped in abundance by 50—70% (Beutel and Horne 1997). This also makes keeping a health population of Lahontan Cutthroat Trout alive more difficult by altering the food chain, although the greater affects are unknown.

This reinforces why a target goal of 5,000 mg/L is ideal for this lake. Even though the original salinity was more than 50% less, 5,000 mg/L has the capacity for dramatically increased lake health. The Nevada Department of Wildlife acclimates their trout in water that is 5,000 mg/L so that they become more resilient to the salinity of Walker Lake and avoid immediate death from salinity shock (Dickerson 1999). Taylor stated from his studies on salinity and fish populations in Pyramid lake, “it is desirable to maintain the lowest possible salt concentration to reduce stress on the fish and, thereby, ease management problems” (1972).

## **Conclusion**

California is known for sporadic periods of drought that are hardly predictable. The models used in this study have ignored this fact, and with TDS exceeding 13,000 mg/L (with a threshold of 16,000 mg/L), Walker Lake has very little room for misfortune. The first objective of this project is to reduce the salinity of the water in order to provide a first aid to the ecosystem of Walker Lake. It is important to conserve or even maximize the amount water that remains in the lake because the volume has already decreased so much since human intervention that more water would be a move toward restoration. By observing the graphs in appendix E, concerning the lake salinity, it can be seen that the sharpest decrease in salinity is the addition of 160 million m<sup>3</sup> into the lake. This is also the most expensive option. What compromise this option are two factors that are increased: the evaporation rate and the salt loading rate, which compound each other because the evaporation rate requires the increased inflow and sustains the increased salt loading rate. Economics aside, from an engineering standpoint, it would be easier to maintain the

lake salinity without disrupting the Walker River flows through desalination. The concentration of TDS in Walker Lake did not sky-rocket by way of increased loading, it increased by mass evaporation from a historically large lake. Without desalination, the lake needs to grow considerably in volume (3.2 million acre-feet) in order to achieve the healthy salinity of 5,000 mg/L. However, this begets an increase in evaporation, in turn, creating a demand for an extraordinarily high maintenance flow of water each year. Bearing in mind the terminal nature of Walker Lake, and increased annual inflow—and inextricably linked evaporation rate—will increase the salt loading at a rate of 200 mg per additional liter added to the lake.

The best option for Walker Lake ecologically is the combined added inflow of 80 million m<sup>3</sup> per year combined with the desalination plant with a capacity of 77.4 million m<sup>3</sup> per year. This will get the lake exceedingly close to the 5,000 mg/L goal within 20 years, and it minimally displaces the habitation of the humans in agriculture upstream in the Walker River Basin. Currently, the best option for Walker Lake, economically, still remains to do nothing, however this will change with the intervention of federal and state laws, as court proceedings will increase the cost of finding no alternative. The cheapest option was to divert 80 million m<sup>3</sup> at a cost of \$409.5 million, with a decrease to 10,621 mg/L TDS which is helpful, and will maintain the lake in a healthier state than it is now, but the salinity will eventually increase.

We are charged with a solution for Walker Lake's salinity because human agriculture caused the disappearance of 8.4 million acre-feet with the last 100 years, while setting standards to protect the well-being of the habitat and the species that reside within. Saving Walker Lake is a costly predicament no matter which option for rehabilitation is adopted; however, none of the pertinent environmental laws come with a caveat of cost feasibility. Geoff McQuilkin of the Mono Lake Committee said, "Only one thing makes problems go away: real, workable, effective solutions . . . ideas are cheap, but good ideas are only slightly more expensive."

### **Acknowledgements**

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## Appendix A

Lake Volume model: first order differential equation.

Averages are taken over 114 years of data

$$dV/dt = Q_{in} - Q_{out} = Q_{in} - E(t)$$

$$E(t) = [(1.2 \text{ m}^2/\text{m}^3\text{yr})(A(t))] \quad 1.2 \text{ m}^2/\text{m}^3\text{yr} \text{—evaporation rate at Walker Lake}$$

$$A(t) = A(0) - \Delta A$$

$$A = [280 - (140/114)t] \times 10^6 \text{ m}^2 \quad 280 \text{—original surface area (km}^2\text{)} \quad 140 \text{—current surface area}$$

$$V = [11.2 - (8.4/114)t] \times 10^9 \text{ m}^3 \quad 11.2 \text{—original volume (km}^3\text{)} \quad 8.4 \text{—current volume}$$

$$\Delta A / \Delta V = [(140 \times 10^6) / (-8.4 \times 10^9)] = 1.7 \times 10^{-2} \text{ m}^2/\text{m}^3$$

$$\Delta A = (\Delta V)(1.7 \times 10^{-2} \text{ m}^2/\text{m}^3) \quad A(t) = A(0) - \Delta A = A(0) - (1.7 \times 10^{-2} \text{ m}^2/\text{m}^3)(\Delta V)$$

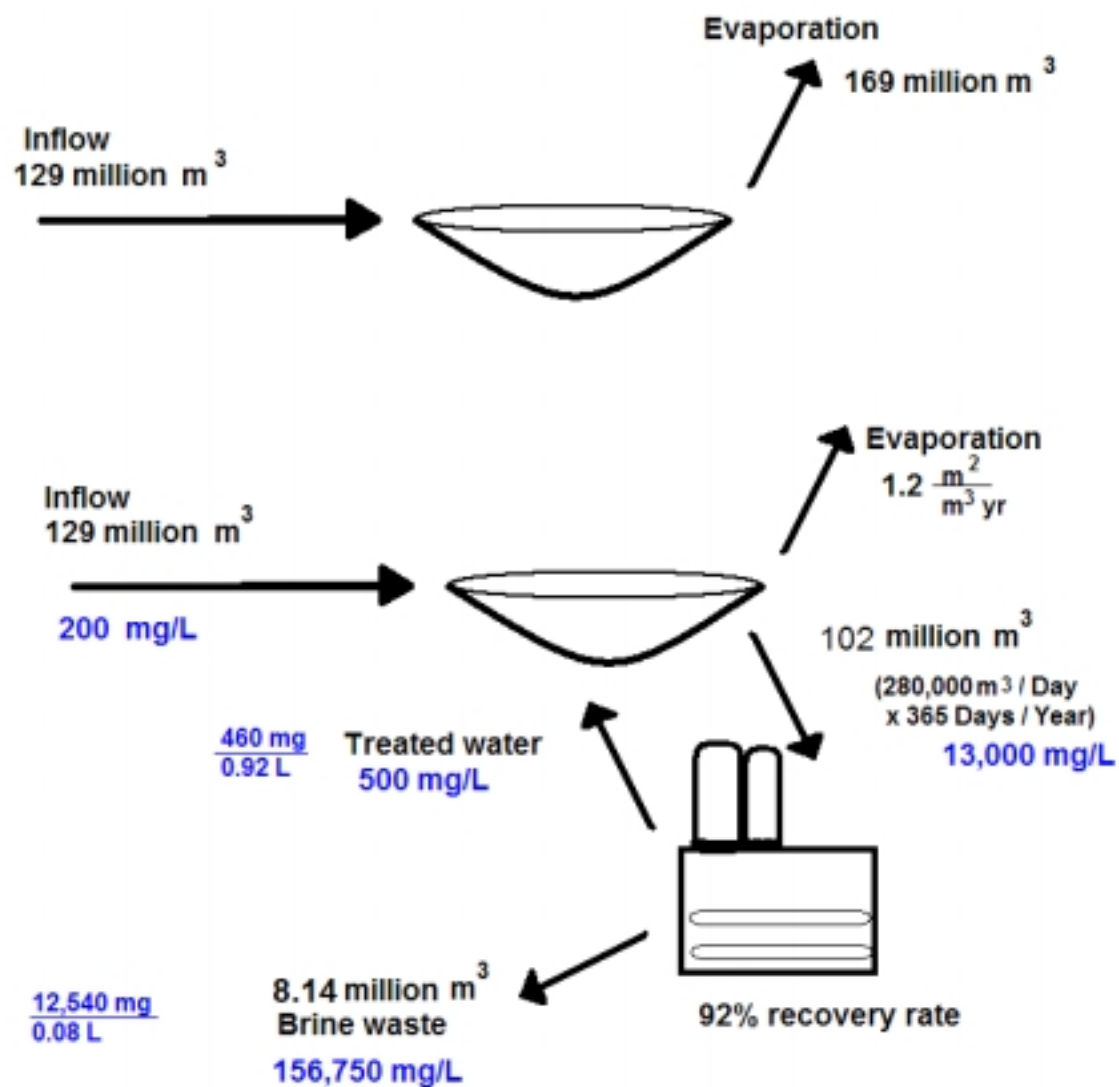
$$\Delta V = V(0) - V(t)$$

$$A(t) = A(0) - (1.7 \times 10^{-2} \text{ m}^2/\text{m}^3)[V(0) - V(t)]$$

$$E(t) = (1.2 \text{ m}^3/\text{m}^2\text{yr}) - (A(t))$$

$dV/dt = Q_{in} - E(t)$  is in the form  $dV/dt = (a + bV)$ , and the general solution can be derived by rewriting the equation as  $dV/(a + bV) = dt$  and integrating both sides. This has the solution of  $V(t) = [-a/b + ce^{(bt)}]$ . The constant,  $c$ , can be determined by solving the equation in the first period when time ( $t$ ) equals 0. We know the volume at time 0 is  $2.7 \times 10^9 \text{ m}^3$ .

## Appendix B



Walker Lake box-models: the first box-model shows the current water deficit using yearly average inflow and evaporation. The second box-model shows Walker Lake with the desalination plant scenario, with an 8% brine water loss at 156,750 mg/L, and the production of 500 mg/L TDS potable water.

## Appendix C

Inflow	Estimated quantity (acre-feet)	Estimated quantity (million m <sup>3</sup> )
Walker River	76,000	94
Local Surface Water	3,000	4
Ground water	11,000	14
Precipitation (4.9 in/yr)	14,000	17
<b>TOTAL</b>	<b>104,000</b>	<b>129</b>
Outflow		
Evaporation (4.1 ft/yr)	-137,000	-169
<b>DIFFERENCE</b>	<b>-33,000</b>	<b>-40</b>

Table 1—Walker Lake water deficit per year

Surface Water Consumed for Average Annual Stream Flows--1939-1993 (million m<sup>3</sup> per year, Rounded)

Valley/Area	Surface Water Inflow	Surface Water Outflow	Surface Water Consumed	Percent of Total Water Consumed
Bridgeport	163	132	31	9.7%
Antelope	241	222	19	6.0%
Smith	233	164	69	21.6%
Mason	294	158	136	42.6%
Lower Reach	158	94	64	20.1%

Table 2--Walker River Basin Water Use by Major Valley or Area

Table 2 Notes: Figures include only surface waters entering and leaving the valleys or areas; excluding ground water pumping and surface waters originating within a valley or area. In this case the consumption includes irrigation evaporation, groundwater seepage, and evapotranspiration by phreatophytes.

Water Budget and Salinity of Walker Lake, Western Nevada," Fact Sheet FS-115-95, Nevada District Office, Water Resources Division, U.S. Geological Survey, U.S. Department of the Interior, Carson City, Nevada, April 1995.

# Principal Agricultural Basin Areas and Water-Righted Acreage

Location	State	Surface Water Righted Acreage <sup>1</sup>	Percentage of total land %
Bridgeport Valley--Upper East Walker Basin above Bridgeport Reservoir	California	29,862	22.8
Antelope Valley and Adjoining Upper West Walker River areas	Mostly in California	20,020	15.5
Smith Valley Area	Nevada	20,439	15.6
Mason Valley Area	Nevada	58,648	44.5
Walker River Indian Reservation	Nevada	2,100	1.6
TOTALS		132,023	

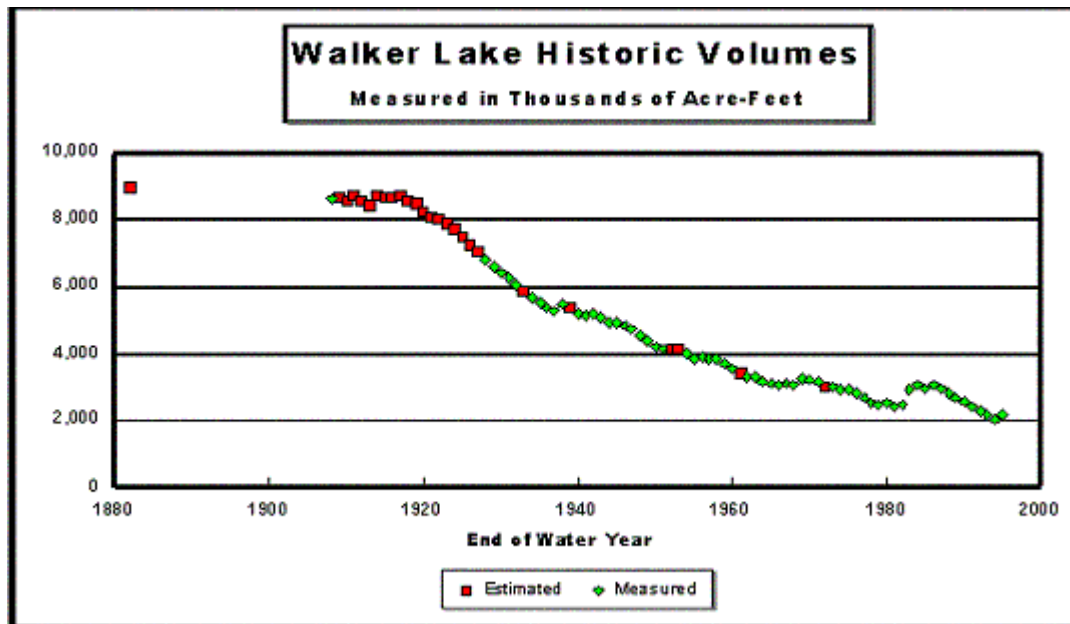
Table 3--Walker River Basin Major Agricultural Areas

## Table 3 Notes:

<sup>1</sup> Figures obtained from Alternative Plans for Water Resource Use--Walker River Basin, Area I, 20, and WALKER RIVER ATLAS, 76.

<sup>2</sup> Figures provided by the Federal Watermaster, Walker River, Yerington, Nevada.

Department of Water Resources, The Resources Agency, State of California, Sacramento, California, June 1992, and personal communication with Roger Bazayiff, Federal Watermaster, 1995.

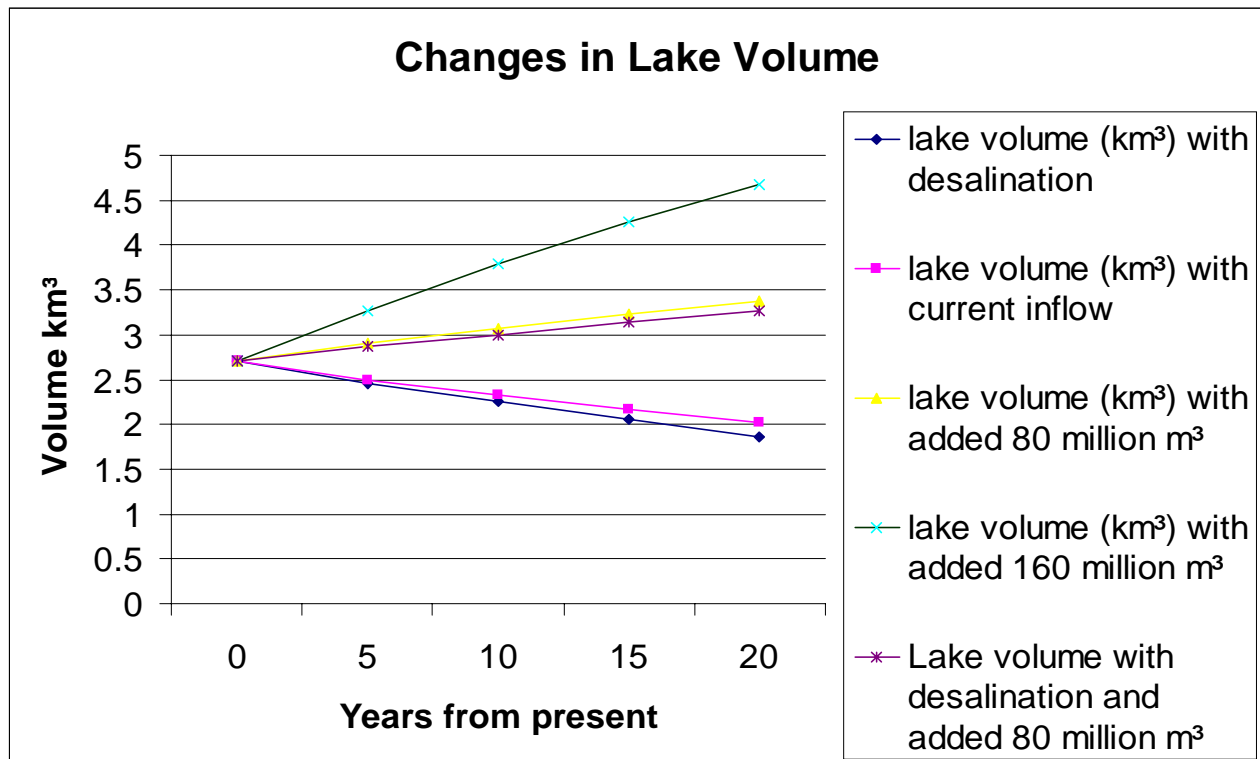


Graph 1--10 million acre-feet is equivalent to  $1.235 \times 10^{10} \text{ m}^3$   
(Nevada Division of Water Planning, Walker River Chronology, 1996)

## Appendix D

years from present	lake volume (km <sup>3</sup> ) with current inflow	lake volume (km <sup>3</sup> ) with desalination	lake volume (km <sup>3</sup> ) with added 80 million m <sup>3</sup>	lake volume (km <sup>3</sup> ) with added 160 million m <sup>3</sup>	Lake volume with desalination and added 80 million m <sup>3</sup>
0	2.7	2.7	2.7	2.7	2.7
5	2.5	2.46	2.9	3.27	2.87
10	2.33	2.25	3.06	3.79	3
15	2.17	2.05	3.23	4.26	3.14
20	2.02	1.86	3.38	4.68	3.26

Table 4--Changes in Lake volume

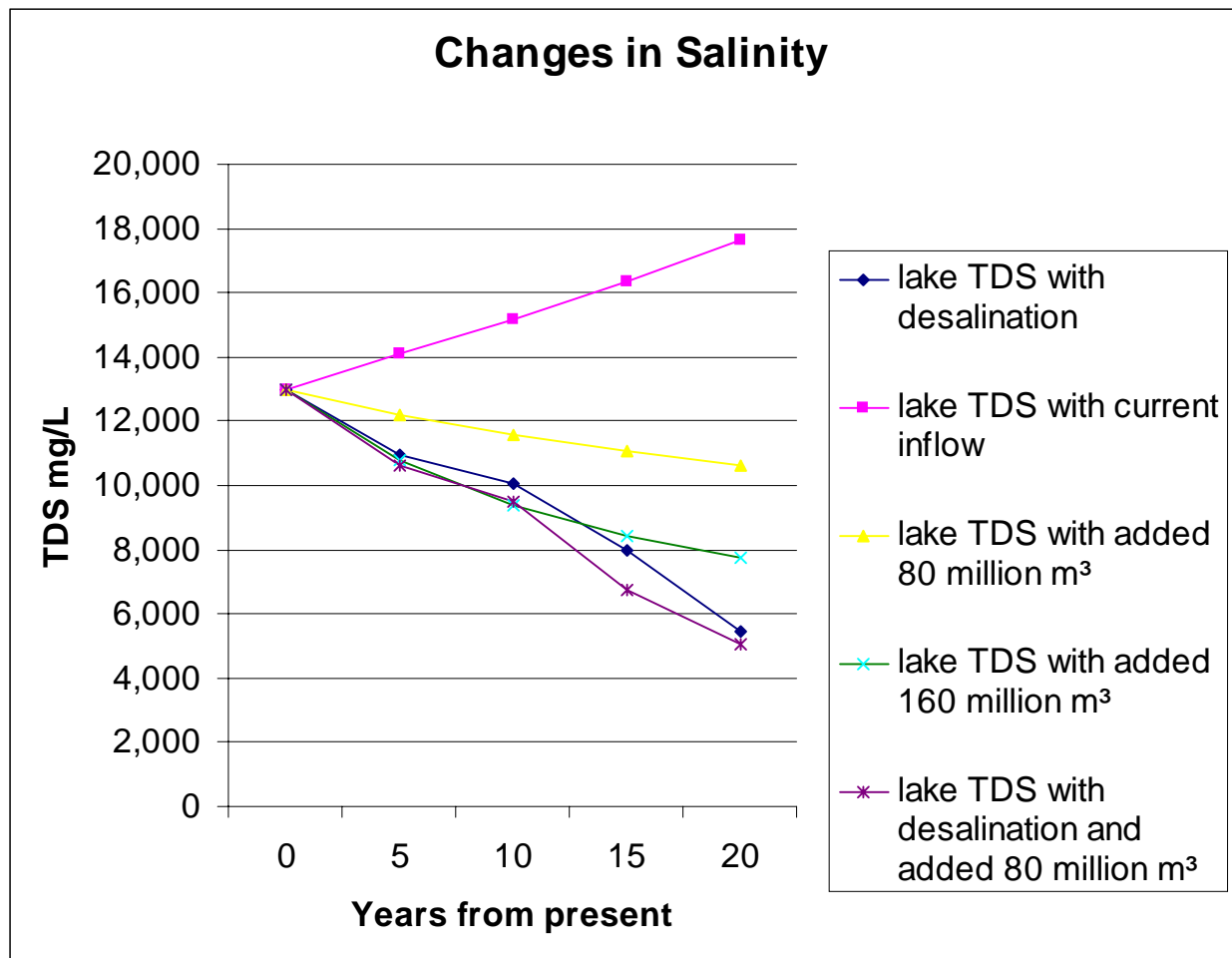


Graph 2—changes in lake volume at 0, 5, 10, 15, and 20, years.

## Appendix E

years from present	lake TDS with current inflow	lake TDS with desalination	lake TDS with added 80 million m <sup>3</sup>	lake TDS with added 160 million m <sup>3</sup>	lake TDS with desalination and added 80 million m <sup>3</sup>
0	13,000	13,000	13,000	13,000	13,000
5	14,092	10,934	12,172	10,795	10,627
10	15,176	10,044	11,601	9,393	9,500
15	16,353	8,000	11,053	8,427	6,720
20	17,633	5,430	10,621	7,747	5,061

Table 5---Changes in Salinity



Graph 3—changes in salinity at 0, 5, 10, 15, and 20 years



## Appendix F

Year	Volume km <sup>3</sup>	Salinity TDS (mg/L)
0	2.7	13,000
5	2.5	14,092
10	2.33	15,176
15	2.17	16,353
20	2.02	17,633

Table 6-- Lake management scenario 1: Walker Lake with current average inflow

Year	Volume km <sup>3</sup>	Salinity TDS (mg/L)
0	2.70	13,000
5	2.69	10,934
10	2.25	10,044
15	2.05	8,000
20	1.86	5,430

Table 7--Lake management scenario 2: Desalination: at  $1.02 \times 10^8$  m<sup>3</sup>/yr flow through

Year	Volume km <sup>3</sup>	Salinity TDS (mg/L)
0	2.7	13,000
5	2.9	12,172
10	3.06	11,601
15	3.23	11,053
20	3.38	10,621

Table 8--Lake management scenario 3a: Water reallocation 80 million m<sup>3</sup> extra per year

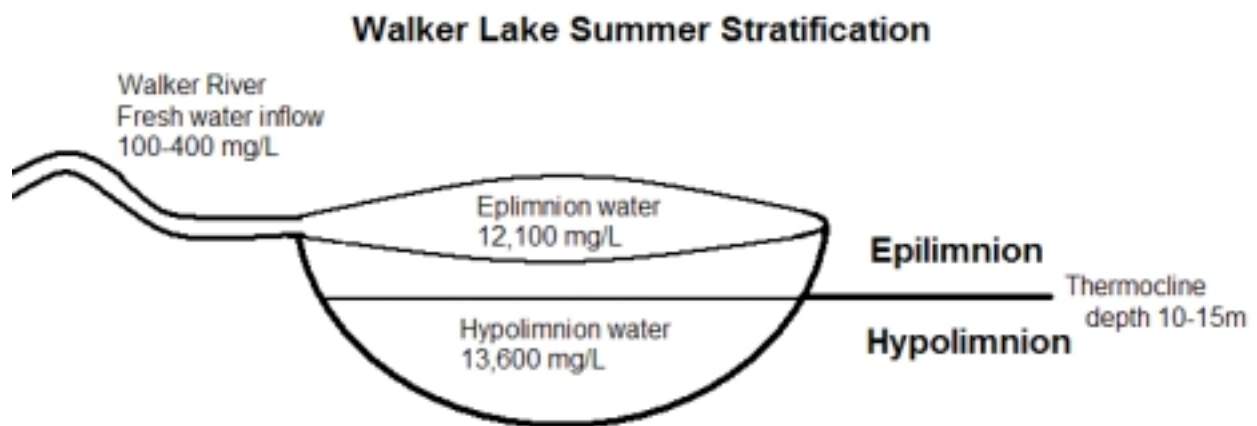
Year	Volume km <sup>3</sup>	Salinity TDS (mg/L)
0	2.7	13,000
5	3.27	10,795
10	3.79	9,393
15	4.26	8,427
20	4.68	7,747

Table 9--Lake management scenario 3b: Water reallocation 160 million m<sup>3</sup> extra per year

Year	Volume km <sup>3</sup>	Salinity TDS (mg/L)
0	2.7	13,000
5	2.87	10,627
10	3.00	9,500
15	3.14	6,720
20	3.26	5,061

Table 10--Lake management scenario 4: Hybrid of 80 million m<sup>3</sup> extra per year and  $7.74 \times 10^7$  m<sup>3</sup>/yr

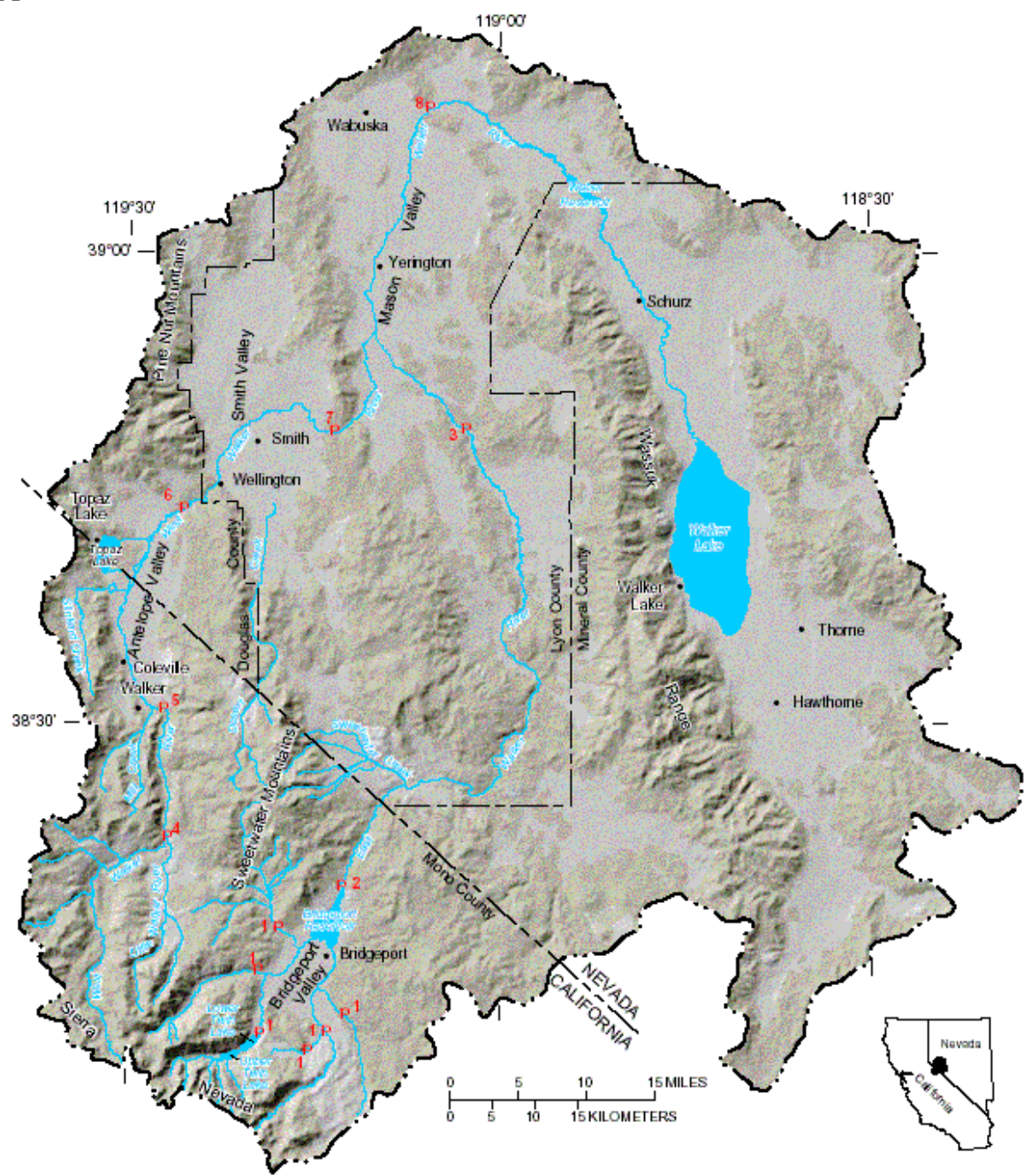
## Appendix G



The Data is from Beutel and Horne (1997) of field tests from September, 1995.

The lake is divided by the metalimnion (or thermocline when regarding temperature) into the epilimnion and the hypolimnion. The hypolimnion is characterized as having high nutrient content, colder temperatures, less incidents of sunlight, and lower levels of dissolved oxygen after some time of stratification and lack of mixing with surface waters. The epilimnion is characterized as having higher temperatures, plenty of sunlight, low levels of nutrients, and high levels of dissolved oxygen. (Horne and Goldman 1994)

Appendix H



## **Appendix I**

### **Story of water use and ownership**

Tables 2 and 3 (see appendix C) shows us that despite there being more than 38% of the Walker River Basin's agriculturally relegated land in California, almost 85% of the total surface water flow consumption occurs in Nevada (see also appendix H). Part of this water consumption can be inferred as inevitable water loss when the distance of flow increases there will be more evaporation, more evapotranspiration by phreatophytes, and more groundwater aquifers to recharge.

As is shown in Table 3 (see appendix C), Nevada clearly has the majority of the water righted acreage; in fact, it has nearly three times what California has. This is not surprising when remembering that only 22% of the Walker River Basin is in California and 78% is in Nevada. California has a bit more than 25% of the water-righted acreage, which is intuitive because the California terrain is less arid and more feasibly irrigable. The percentage of land is merely land area, specifically agricultural land area is predominantly Californian.

Especially considering the tenuous nature of water rights issues in the area, desalination is the most direct solution for salinity and possibly the most economically viable given the decreasing costs of reverse osmosis and compromised agricultural output from reallocation of water rights. The idea of this research is to combine modern fresh water supply techniques, currently used for strictly anthropogenic water diversions, with efforts to restore natural habitats altered by human intervention. These efforts in Walker Lake will not only benefit the Lahontan Cutthroat Trout species, but also the migrating waterfowl that find Walker Lake an essential stopping ground in a desert with few other options (Powers 2002).

### **Current Water Allocation**

Within the Walker River Basin there are nine major water storage facilities before the water enters Walker Lake. Each of the reservoir projects under State Water Law (California and Nevada) claims rights to the water based on "first in time, first in rights." Whereby, the first person to put water to a beneficial use owns the highest priority water right, and each water right owner on a river system has a priority date equivalent to the first date the water was used. Senior

water rights must be completely filled before junior rights receive any water—regardless of the value of the water use. The water must be used at the same location in perpetuity unless the owner of the water rights applies for a transfer. The State may also choose not to grant water rights should usage go below a minimum, meaning that each water right owner is obligated to use up their entire allotment in every period, otherwise they may not receive the same allotment in the next period. (Myers 1997) However, this is not the case for Native American water rights. Native Americans may use less than their allotted amount of water and still have the same allowance for the next period (Report of the Working Group on the Endangered Species Act and Indian Water Rights). This is important to keep in mind from a policy standpoint, as this is egregious inefficiency with desperately needed water.

### **Walker River Basin water rights**

The Black Reservoir on the West Walker River in California has a storage right of 350 acre feet and a priority date of 1907. Green Lakes also in California off of the East Walker River, is made up of the East Lake, West Lake, and Green Lake. They can store 400 acre-feet of water with a senior priority date of 1895. Lobdell Lake is just off the West Walker River in California. It has a storage right of 500 acre-feet and a priority date of 1864. The Poore Lake fed from the West Walker River in California has a storage right of 1200 acre-feet and a priority date of 1901. Upper Twin Lake is on the East Walker River Basin in California and has a water right of 2,050 acre-feet and priority dates of 1905 and 1906. Next, the Lower Twin Lake is also on the East Walker River Basin in California, and has a storage right of 4,050 acre-feet and a priority date of 1888 and 1905. The Bridgeport Reservoir on the East Walker River in California and is owned and operated by the Walker River Irrigation District. It has a storage right of 42,455 acre-feet and a refill right of almost 15,000 acre-feet. Their priority date is 1923 and most of their water goes to Mason Valley and farmers below the reservoir. The Topaz lake reservoir is fed by a diversion canal from the West Walker River and has a storage capacity for 59,439 acre-feet but a storage allowance of 50,000 acre-feet and a refill allowance of an additional 35,000 acre-feet. This water is primarily used for agriculture in the Smith and Mason Valley. Finally, there is the Weber Reservoir which is closest to Walker Lake and is completely inside Nevada. It is directly fed by Walker River, and it is located on the Walker River Paiute Indian Reservation. It was built with a capacity to hold 13,000 acre-feet of water in 1935. Sedimentation may have reduced its capacity to 10,700 acre-feet. The priority date set to the reservation was of 26.5 cubic feet per second

dating back to 1859. A first step toward awarding Walker Lake some water rights came in 1983 when the State of Nevada Department of Wildlife was issued a water right of 575,850 acre-feet per year (711.9 million m<sup>3</sup>/yr) with a priority date of September 17<sup>th</sup>, 1970 (Nevada Division of Water Planning 1996). Although a step in the right direction, because of the late priority date, Walker Lake gets last priority, and this volume of water is scarcely seen.