Restoration of the Salton Sea

Volume 1: Evaluation of the Alternatives

Appendix 1H: Empirical Modeling of the Response in the Eutrophication of the Salton Sea to Various Physical Alternatives

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EMPIRICAL MODELING OF THE RESPONSE IN THE EUTROPHICATION OF THE SALTON SEA TO VARIOUS PHYSICAL ALTERNATIVES

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To help understand how the various Salton Sea physical alternatives proposed by the Bureau of Reclamation should affect the eutrophication of the Salton Sea, two empirical models (BATHTUB, and WiLMS) were used to determine how changes in the morphometry and the phosphorus loading to the Sea should affect its average annual phosphorus concentration. Each of these models was previously calibrated using water-quality and nutrient-loading data for 1999 by Robertson and Schladow (2005, in review). Each model was used to simulate the average annual phosphorus concentration in the Sea for the specific alternatives assuming that the response of the water quality in the future marine lakes will be similar to the present Salton Sea.

For each alternative, the potential high and low water levels were obtained from the Bureau of Reclamation and used to estimate the Sea's morphometry. For each alternative, eight phosphorus loading scenarios were produced using the projected flows obtained from the Bureau of Reclamation and two assumed tributary phosphorus concentrations. Four loading scenarios were produced with tributary concentrations similar to that measured in 1999 with flows similar to that measured in 1999, with average projected flows in 2025, with average projected flows in 2025 minus one standard deviation (from the estimated distribution in future flows), and with average projected flows in 2025 plus one standard deviation. Four loading scenarios were produced assuming that phosphorus concentrations in the tributaries would be reduced because of a reduction in tail water: 1999 tributary ortho phosphorus concentrations (particulate phosphorus removed) with 1999 flows, with average projected flows in 2025, with average projected flows in 2025 minus one standard deviation, and with average projected flows in 2025 plus one standard deviation.

To examine how the trophic state of the Salton Sea should change in response to the physical changes and loading changes, three physical configurations were examined: North Marine Lake (Alternative 1), South Marine Lake (Alternative 2) and evolving Sea (Alternative 8). For each alternative, modeling results indicated

that phosphorus concentrations in Salton Sea should have a linear response to a linear change in phosphorus loading (or a linear change in the fraction of the present loading). Changes in phosphorus concentrations were different for each alternative; however, the response consistently varied as a function of the fraction of the original total volume of the Sea. Predicted concentrations were highest for the alternatives which had the smallest fraction of the original volume of the Sea. For almost all alternatives, phosphorus concentrations in the Sea should increase from present conditions, except for the lowest projected flows for the deepest alternatives.

The response in phosphorus concentrations to changes in phosphorus loading and the response in phosphorus concentrations as a function of the fraction of the original total volume of the Sea were combined into a single factor, the loading to volume factor. This factor is computed by dividing the fraction of the original loading by the fraction of the original volume. Future phosphorus concentrations in the Sea were shown to be a direct function of this factor. Therefore, given the phosphorus loading and morphometry of any future alternative, the average annual phosphorus concentration in the Sea can be estimated without additional model simulations.

If each of the alternatives has similar phosphorus loading, the alternative that results in the least eutrophic conditions (lowest phosphorus concentrations) is the alternative which has a morphometry with the highest fraction of the original volume. The response in chlorophyll and Secchi depths for each alternative can then be estimated from the predicted phosphorus concentrations and the response curves previously developed by Robertson and Schladow (2005, in review).

These models simulate steady-state conditions in the Sea; therefore, the simulated changes would be expected to take place several years after load reductions occur.

Introduction

Due to the increased demand for water from the Colorado River and potential changes in climate, the amount of water supplied to the Salton Sea is expected to decrease in the future. The decrease in the amount of water supplied to the Sea will cause a dramatic change reduction in its volume and morphometry. The effects of this reduction on trophic state of the Sea are not well known and may be ameliorated by specific physical configurations (alternatives) that could be designed and implemented. The Bureau of Reclamation has developed several different physical alternatives. The goal of this study is to help understand how the various alternatives should affect the trophic state (primarily phosphorus concentration) of the Salton Sea.

Approach

To help understand how the various alternatives proposed by the Bureau of Reclamation should affect the trophic state of the Salton Sea, two empirical models (WiLMS and BATHTUB) are used to estimate how the changes in the morphometry associated with the design of each alternative and the phosphorus loading to the Sea should affect the average annual phosphorus concentration in the Sea. Each of these models was previously calibrated by Robertson and Schladow (2005, in review) using water-quality and nutrient-loading data for 1999 (Holdren and Montano, 2002) and is summarized here. Each model is used to simulate the average annual near-surface phosphorus concentration for the specific alternatives assuming that the response of the water quality to external phosphorus loading in the future marine lakes will be similar to the present Salton Sea (i.e., the model calibration based on 1999 data is adequate to simulate future conditions). From these results, response curves are developed to estimate the average annual phosphorus concentration in the Sea given the phosphorus loading and morphometry of any future alternative without additional model simulations.

For each alternative, potential high and low water levels were obtained from the Bureau of Reclamation (P. Weghorst, Bureau of Reclamation, written commun., 2005) and used to estimate the Sea's morphometry. For each alternative, eight phosphorus loading scenarios were also produced using the measured flows in 1999 (Robertson, et al., 2005; in review) and the projected flows obtained from the Bureau of Reclamation (P. Weghorst, Bureau of Reclamation, written commun., 2005) and using two assumed tributary phosphorus concentrations (Table 1). Four loading scenarios were produced assuming future tributary concentrations were similar to those measured in 1999 (Holdren and Montano, 2002) with flows similar to 1999, with average projected flows for 2025, with average projected flows for 2025 minus one standard deviation (the standard deviation was calculated from the estimated distribution in future flows), and with average projected flows for 2025 plus one standard deviation. Four loading scenarios were produced assuming that phosphorus concentrations in the tributaries would be reduced because of a reduction in (removal) particulate phosphorus in tail water: 1999 tributary ortho phosphorus concentrations (particulate phosphorus would be completely removed) with 1999 flows, with average projected flows for 2025, with average projected flows for 2025 minus one standard deviation, and with average projected flows for 2025 plus one standard deviation.

Table 1. Eight loading scenarios

Concentration	Flow	Fraction of Present Loading
1999 Concentrations	1999 Flows	1.00
1999 Concentrations	High Projected Flows (Ave Pred. + SD)	0.70
1999 Concentrations	Average Projected Flows	0.63
1999 Concentrations	Low Projected Flows (Ave Pred. - SD)	0.55
1999 Ortho-phosphorus Concentrations	1999 Flows	0.58
1999 Ortho-phosphorus Concentrations	High Projected Flows (Ave Pred. + SD)	0.41
1999 Ortho-phosphorus Concentrations	Average Projected Flows	0.36
1999 Ortho-phosphorus Concentrations	Low Projected Flows (Ave Pred. - SD)	0.32

To examine how the eutrophication of the Salton Sea should change in response to the physical changes and loading changes, three physical configurations were examined: North Marine Lake (Alternative 1), South Marine Lake (Alternative 2) and evolving Sea (Alternative 8). The results for these configurations are used to develop response curves between relative phosphorus loading and projected in-Sea phosphorus concentrations. The response curves are then used to rank future phosphorus concentrations in the Sea for the various alternatives.

Algorithms and Calibration of Models

Of the 13 empirical models contained within WiLMS (Wisconsin Lakes Modeling Suite; Panuska and Kreider, 2002), only three of the models were relatively insensitive to the residence time of water in a lake; most of the models are not capable of simulating water quality in lakes with no outlets. Of these three models, only the Canfield and Bachman (1981) natural-lake model was applicable to the hydrology, loading rates, and phosphorus concentrations of the Salton Sea. This model over-predicted the measured concentration in the Sea by 23 percent. There are no calibration factors in WiLMS; however, the output can be adjusted to account for model biases by reducing all estimated concentrations by 23 percent. Predictions made with this model prior to and following calibration are also shown in Table 2.

Table 2. Calibration factors used for empirical models.

Model	Algorithm Description	Pre-Calibration Concentration	Post-Calibration Concentration	Calibration Factor
	Total Phosphorus - Measured 0.077 mg/L			
BATHTUB	2nd Order, Decay	0.084	0.077	1.18
WiLMS	Canfield and Bachman (1981)	0.095	0.077	-23%

When applying the BATHTUB model (Walker, 1996), specific algorithms must be selected to simulate each water-quality constituent. For phosphorus, the 2nd-order, decay algorithm uses total phosphorus concentrations but represents the effective sedimentation rate as inversely related to the ratio of tributary ortho-phosphorus concentrations to total phosphorus concentrations. Walker (1996) states that the 2nd-order, decay algorithm may be most applicable to lakes with long residence times, such as the Salton Sea. A calibration coefficient of 1.18 was applied to accurately simulate the water quality for 1999 (Table 2). Predictions made with the models prior to and following calibration are also shown in Table 2.

Results

On the basis of results using the Canfield and Bachman model in WiLMS for the North Marine Lake, South Marine Lake, and Evolving Sea, phosphorus concentrations in the Salton Sea should have a relatively linear response to a linear change in phosphorus loading (also presented as a fraction of the total phosphorus loading in 1999 (Fig. 1). On the basis of simulations with WiLMS, a deep evolving Sea should have the lowest annual phosphorus concentrations, ranging from about 60 ug/L (for the reduced concentrations with the lowest flows) to about 120 ug/L (for the present loading), whereas a shallow evolving Sea should have the highest concentrations, ranging from about 100 to 190 ug/L. Almost all alternatives and scenarios resulted in phosphorus concentrations higher than present concentrations (red line in Fig. 1). The linear response varied as a function of the fraction of the original total volume of the Sea. Predicted concentrations were highest for the alternatives that had the smallest fraction of the original volume of the Sea (a fraction of the present volume = 0.19).

Based on results from BATHTUB for the North Marine Lake, South Marine Lake, and Evolving Sea, phosphorus concentrations should have a relatively linear response to a linear change in phosphorus loading; however, scenarios with 1999 concentrations have a different response than scenarios using only dissolved ortho-phosphorus concentrations (Fig. 2). Scenarios with reduced phosphorus concentrations are predicted to have higher phosphorus concentrations if the results are plotted as a function of the fraction of the present loading; however, predicted concentrations are similar to those with similar flows but not reduced concentrations. Based on simulations with BATHTUB, a deep evolving Sea should have the lowest concentrations, ranging from about 90 ug/L (for reduced concentrations with lowest flows) to about 115 ug/L (for present loading), whereas a shallow evolving Sea should have highest concentrations, ranging from about 130 to 170 ug/L. All of the alternatives and scenarios resulted in phosphorus concentrations higher than present concentrations. The linear

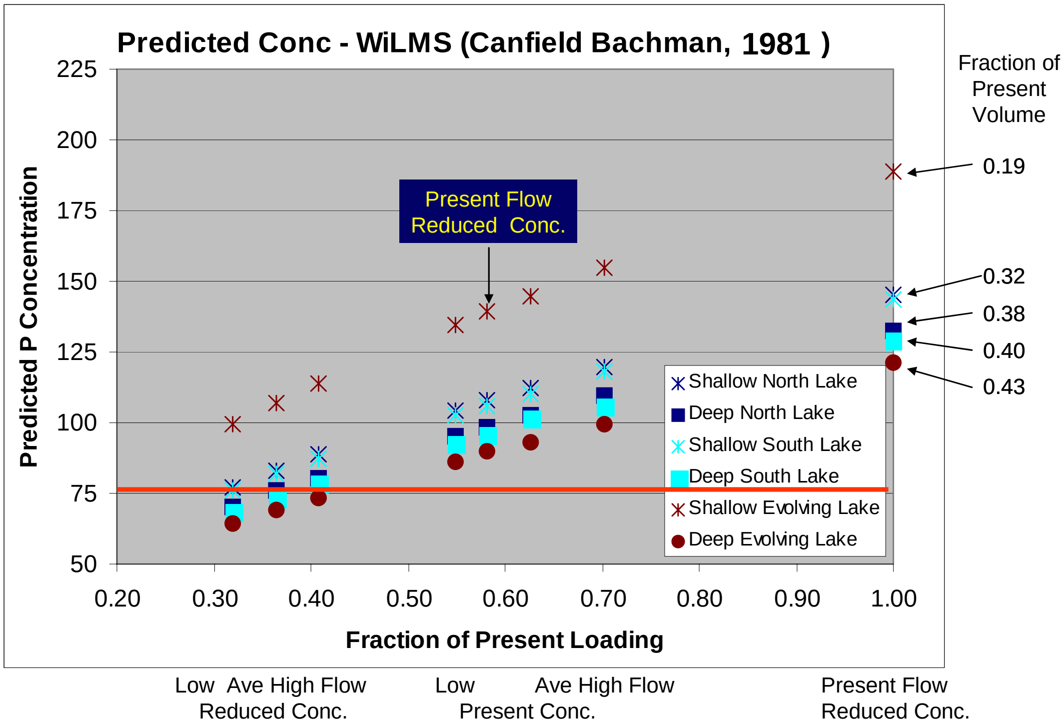

Figure 1.—Predicted annual phosphorus concentrations in the Salton Sea for three different physical alternatives in response to various loading scenarios based on simulations with WiLMS.

response again varied as a function of the fraction of the original total volume of the Sea. Predicted concentrations were highest for the alternatives which had the smallest fraction of the original volume of the Sea.

To extrapolate the response between predicted phosphorus concentrations and the fraction of the phosphorus loading in 1999 and extrapolate the response between predicted phosphorus concentrations and the fraction of the original total volume of the Sea to other alternatives, these two fractions were combined into a single factor, referred to hear as a loading per volume factor. The loading per volume factor is computed by dividing the fraction of the original (1999) loading by the fraction of the original (1999) volume of the Sea. The predicted phosphorus concentrations in the Sea are a direct function of this factor (Fig. 3). If the ratio of particulate phosphorus to dissolved ortho phosphorus is similar to that measured in 1999, results of both models indicate that phosphorus concentrations in the Salton Sea can be predicted based on the lower curve in Figure 3; whereas, if particulate phosphorus is removed because of the reduction in tail waters, the concentrations in the Sea may be slightly higher and follow either the same curve (WiLMS results) or the top curve in Figure 3 (BATHTUB results).

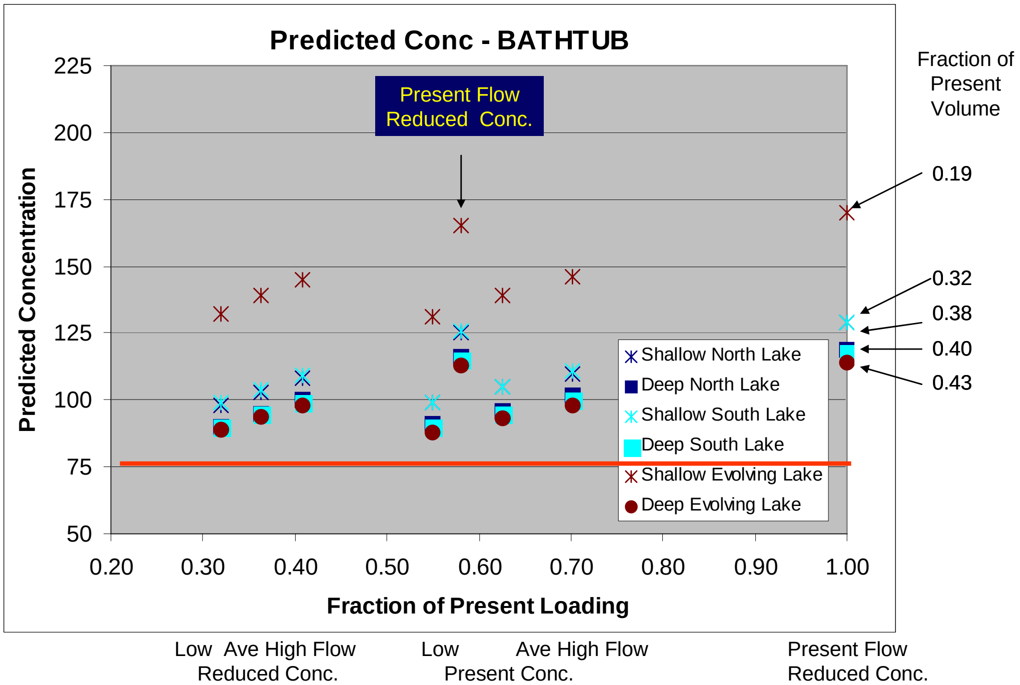

Figure 2.—Predicted annual phosphorus concentrations in the Salton Sea for three different physical alternatives in response to various loading scenarios based on simulations with BATHTUB.

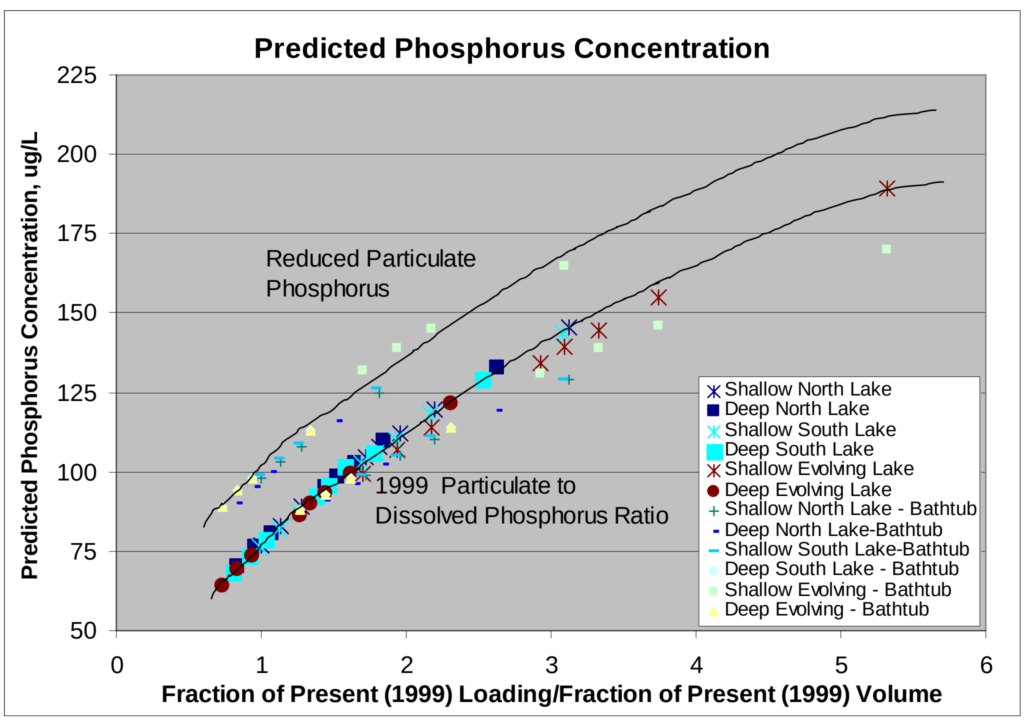

Figure 3.—Predicted annual phosphorus concentration in the Salton Sea as a function of the loading per volume factor (fraction of present, 1999, loading divided by the fraction of the present, 1999, volume).

Therefore, given the phosphorus loading and morphometry of any future alternative, the average annual phosphorus concentration in the Sea can be estimated without additional model simulations. For example, if a future alternative results in a loading per volume factor of 2.0, the future annual phosphorus concentration should be between 110 and 130 ug/L.

Future loading to Sea does not depend on the Sea's morphometry; therefore, the response in annual phosphorus concentrations is primarily based on the alternative's fraction of the 1999 volume (the denominator of the loading to volume factor). For each alternative, potential low and high water levels were obtained from the Bureau of Reclamation (P. Weghorst, Bureau of Reclamation, written commun., 2005) and used to compute the fraction of the 1999 volume. The fraction of the 1999 volume is shown for low and high water levels for each alternative in Figure 4. For specific loading scenarios, alternatives with a larger fraction of the 1999 volume should have the lowest annual phosphorus concentrations. Therefore, the alternative with the highest fraction of the 1999 volume (alternative 3, concentric rings with high water levels) should have the lowest annual phosphorus concentrations, and the alternative with the lowest fraction of the 1999 volume (alternative 5, north marine lake with low water levels) should have the highest annual phosphorus concentrations.

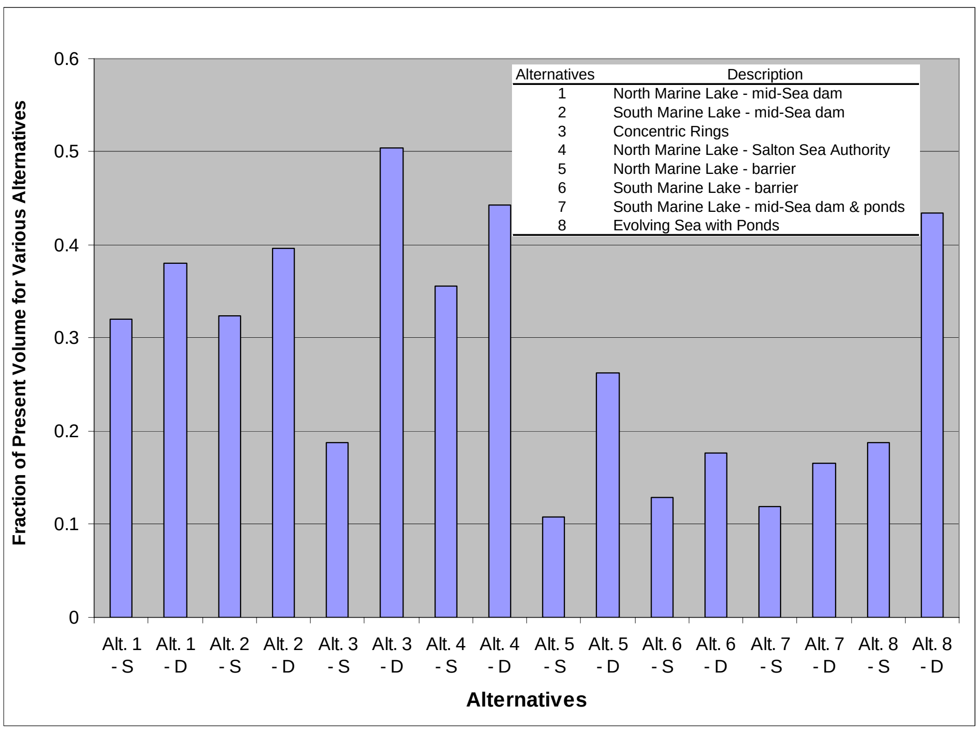

Figure 4.—Fraction of present (1999) volume for various alternatives for the Salton Sea.

The empirical models used in this study simulate the steady-state conditions that should occur as a result of the hydrology and nutrient loading input into the models; however, the simulated changes may be expected to take place several years after load reductions occur because of the phosphorus stored in the sediments of a lake. Exactly how long it would take for these changes to occur is unknown. Therefore, results of the empirical models indicate the potential long-term changes in the water quality of the Salton Sea associated with phosphorus-load reductions, with which there may be much variability because of events like sediment and phosphorus resuspension.

The response in chlorophyll a concentrations and Secchi depths to changes in annual phosphorus concentrations have been previously described by Robertson and Schladow (2005, in review). For any given phosphorus concentration, a range in chlorophyll a concentrations and Secchi depths have been predicted based on the assumptions inherent in the various models. Therefore, given the phosphorus loading and morphometry of any future alternative, the loading per volume factor can be computed. With this value, the annual phosphorus concentration can be directly obtained from Figure 4. This phosphorus concentration can then be used to estimate annual average chlorophyll a concentrations and Secchi depths from the results in Robertson and Schladow (2005, in review). Chlorophyll a concentrations and Secchi depths were shown to have a direct relation to phosphorus concentrations in the Sea; therefore, the alternatives that had the highest predicted phosphorus concentrations are expected to also have the highest chlorophyll a concentrations and shallowest Secchi depths.

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