Review of

Lake Tahoe Total Maximum Daily Load Report

Menachem Elimelech
Department of Chemical Engineering
Yale University
New Haven, CT 06520-8286
menachem.elimelech@yale.edu

The Lake Tahoe Total Maximum Daily Load (TMDL) Report is a comprehensive document that identifies the contaminants responsible for the deterioration in transparency and clarity of the lake, the sources of these contaminants, and the plan to reduce the input of these contaminants to the lake in order to attain the water quality objectives and restore the lake clarity. It is concluded that the culprit for the deterioration in lake clarity is mainly the presence of suspended inorganic particles and, to a lesser extent, nutrients in the form of nitrogen and phosphorus.

The TMDL report has benefited tremendously from extensive research and monitoring data for Lake Tahoe that started nearly 40 years ago. Research associated with the development of the Lake Tahoe TMDL was designed to build on the extensive information available on the lake and its watershed. The components of the model used to develop the plan to restore the lake clarity are based on completed research projects from the past 10-20 years, most of which have been published in peer-reviewed journals. The published research adds to the credibility of the methodology used and the developed plan. Further, there are additional ongoing research projects that support the next phases of the Lake Tahoe TMDL.

The Lake Tahoe TMDL report is well presented. It clearly states the problem and objectives, provides the necessary background, presents the methodology used to arrive at the plan to attain the TMDL Clarity Challenge, and outlines the implementation steps that need to be taken. The Final Report also refers to the relevant reports and documents when needed. Overall, I find the report to be technically sound and of high quality.

Below are a few comments and suggestions that may help in refining the report at this stage as well as in the next phases of the Lake Tahoe TMDL. Furthermore, replies to the 8 specific issues that the reviewers were requested to address will follow.

Inverse Modeling

The Lake Clarity Model is a mathematical model comprising several sub-models and algorithms. The model can simulate the water quality in the lake (concentrations of particles and nutrients) and link it to water clarity (or Secchi depths), which is essential to achieving the Clarity Challenge. This approach is termed forward modeling. The model has been used to determine the total maximum daily loads of particles and nutrients to the lake and the necessary reductions in the loadings of particles and nutrients from the various sources to attain the Clarity Challenge.

However, there is also a need for an inverse problem modeling as well as a parameter identification algorithm. A robust inverse problem model can be used to optimize performance and minimize costs in the TMDL management system as well as the monitoring program. Currently, the management and monitoring plans/models are conceptual and qualitative in nature, and thus will not yield the most cost-effective outcomes. The inverse problem approach has been used extensively in water quality management covering a wide range of problems. See for example the book by Ne-Zhen Sun (Inverse Problems in Groundwater Modeling, 1994, Kluwer Academic Publishers). Lastly, the inverse problem coupled with a robust parameter identification algorithm can help in finding the unknown physical parameters for the model based on limited experimental data.

Other recent references highlighting the inverse problem modeling with applications to water quality can be found in:

> Zou, R., Lung, W.S., Wu, J. "An adaptive neural network embedded genetic algorithm approach for inverse water quality modeling", *Water Resources Research*, 43 (2007, W08427.

> Shen, J., Jia, J.J., Sisson, G.M., "Inverse estimation of nonpoint sources of fecal coliform for establishing allowable load for Wye River, Maryland", *Water Research*, 40 (2006) 3333-3342.

<u>Role of Particle Aggregation</u>

One of the key steps in the Lake Clarity Model is to link the loadings of particulates and chemicals (nutrients) into Lake Tahoe to the Secchi depth and light attenuation which are measures of lake clarity. Since inorganic suspended particles govern the light attenuation behavior, it is imperative to be able to predict the number concentration and size distribution of particles at various water depths. Thus, even if the other modeling efforts can estimate adequately the inorganic particle loading to Lake Tahoe, the ability to predict the Secchi depth remains the key to the Lake Tahoe TMDL Clarity Challenge.

An important process governing the number and size distribution of particles in lakes (as well as marine environments) is particle aggregation. Examples for the important role of particle aggregation in aquatic systems can be found in the following references (and references therein):

> Weilenmann, U., O'Melia, CR, and Stumm, W. "Particle-Transport in Lakes - Models and Measurements", *Limnology and Oceanography*, 34 (2009) 1-18.

Burd A.B., Jackson G.A., "Particle Aggregation", *Annual Review of Marine Science*, 1 (2009) 65-90.

It is not clear from the Lake Tahoe TMDL report (and related reports) if and how the process of particle aggregation has been incorporated in the Lake Clarity Model. It is likely that the impact of aggregation may not be as significant if the number concentration of particles is relatively low and if the collision (sticking) efficiency is low. The latter is dependent on the water chemistry, namely the total ionic strength, concentration of divalent cations (mostly calcium), and dissolved natural organic matter (NOM). The collision efficiency cannot be predicted from theory but must be determined from experimental measurements Note also that particle aggregation results in fractal aggregates having settling behavior that cannot predicted by the simple Stokes Law.

Beneficial Health Effects to Beaches

The largest source of inorganic particles to Lake Tahoe comes from storm water runoff from urban areas. To achieve the Clarity Challenge, significant reductions in particle loading from urban areas are proposed. This measure will not only improve the lake clarity but will also have beneficial health effects by minimizing potential microbial pathogen loads to recreational beaches along Lake Tahoe. In recent years it has been recognized that microbial contamination of beaches form urban and agricultural runoff is responsible for numerous illnesses. This may be a potential problem for Lake Tahoe and, as such, funding and research programs tackling both lake clarity and microbial contamination of beaches should be promoted. This will lead to more effective use of state and federal funds. Recent papers highlighting the problem of microbial contamination of recreational water include:

Heaney, C.D. et al. "Contact with Beach Sand among Beach Goers and Risk of Illness", *American Journal of Epidemiology*, 170 (2009) 164-172.

Wong, M. et al. "Evaluation of public health risks at recreational beaches in Lake Michigan via detection of enteric viruses and a human-specific bacteriological marker", *Water Research*, 43 (2009) 1137-1149.

Boehm, A.B. et al. "A sea change ahead for recreational water quality criteria", *Journal of Water and Health*, 7 (2009) 9-20.

Potential Detrimental Effects on Lake Water Quality

Suspended particles in lakes play an important role in the transport of heavy and trace metals to the sediments. Heavy and trace metals adsorb to suspended particles which aggregate and settle to the sediment. Thus, lakes with greater concentrations of suspended particles may have lower concentration of dissolved metals in the water. Examples of references describing this phenomenon include:

Sigg, L., Sturm, M., Kistler, D. "Vertical Transport of Heavy-Metals by Settling Particles in Lake Zurich", *Limnology and Oceanography*, 32 (1987) 112-130.

Sigg, L. et al. Cycles of Trace-Elements (Copper and Zinc) in a Eutrophic Lake - Role of Speciation and Sedimentation, In: Aquatic Chemistry - Interfacial and Interspecies Processes. Advances in Chemistry Series, Vol. 244, pages 177-194, 1995.

I wonder if the concentration of heavy and trace metals in Lake Tahoe has ever been correlated to the concentration of suspended particles in the water column. This will give an indication if the proposed reduction in the particle loading will have an effect on the concentration of metals in the lake water.

Finally, it was also requested to determine whether the following eight specific issues are based on sound scientific knowledge, methods, and practices.

1. Determination of fine sediment particles (<16 micrometers) as the primary cause of clarity impairment based on interpretation of scientific studies, available data, and the Lake Clarity Model.

I concur with the analysis and scientific methods leading to this conclusion. This has also been published in the peer-reviewed literature as outlined in the report.

2. Identification of the six sources of pollution affecting lake clarity of which urban upland areas was found to be the primary source of fine sediment particles causing Lake Tahoe's clarity loss.

I concur with the analysis and scientific methods leading to this conclusion. This conclusion was based on extensive data collected over the past 40 years. Some of this data has also been published in the peer-reviewed literature as outlined in the report.

3. Determination that the Lake Tahoe Watershed Model was an appropriate model to estimate upland pollutant source loads.

I am not familiar with this model and thus I cannot provide an assessment of this question. For this question you should rely on a reviewer with expertise in watershed modeling.

4. Determination that estimates of groundwater nutrient loading rates are reasonable and accurate.

I cannot provide an assessment of this question. For this question you should rely on a reviewer with expertise in groundwater hydrology, more specifically someone with knowledge on groundwater – surface water interactions.

5. Pollutant loading rates from atmospheric deposition directly to the lake surface were quantified and in-basin sources were found to be the dominant source of both nitrogen and fine *particulate matter. Direct deposition of dust accounts for approximately 15% of the average annual fine sediment particle load.*

I concur with the conclusion that atmospheric deposition directly to the lake is the dominant source of nitrogen; this was also documented in the peer-reviewed literature. Atmospheric deposition is not the main source of fine suspended particles; the main source of fine particles is the urban upland.

6. Pollutant Reduction Opportunity (PRO) analysis identifies fine sediment particle and nutrient reduction options that can be quantified. The PRO findings offer basin-wide pollutant load reduction estimates and costs for a range of implementation alternatives for reduction loads from urban uplands, forest uplands, stream channel erosion, and atmospheric deposition sources.

It is a reasonable conclusion that the largest, most cost effective opportunities for fine sediment particle load reductions are from the urban upland source. The PRO analysis is interesting and appears to be reasonable; however, the approach used was semi-quantitative in nature. Hence, it may not represent the most optimal solution to the problem in terms of cost and effectiveness. Perhaps the use of more quantitative approaches involving optimization techniques and control theories that are common in the chemical engineering process industry would have resulted in a more optimal solution.

7. Lake Clarity Model was the most appropriate for predicting the lake response to changes in pollutant loads.

I concur that the Lake Clarity Model was appropriate to predict how Lake Tahoe's Secchi depths will respond to changing particle loading. The major components of the model have been published in the peer-reviewed literature as outlined in the report. However, as indicated in my general comments above, it is not clear if and how the aggregation of particles was incorporated in the model.

8. Allocation of allowable fine sediment particle and nutrient loads is based on the relative magnitude of each pollutant source's contribution and the estimated ability to reduce fine sediment particle and nutrient loads

This statement seems reasonable, but see my reservation indicated in item (6) above.