RESPONSE OF WATER CLARITY IN LAKE TAHOE (CA-NV) TO WATERSHED AND ATMOSPHERIC LOAD*

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Abstract. Lake Tahoe (CA-NV, USA), an oligotrophic and subalpine lake, is world renowned for its striking blue color and extraordinary clarity. However, its well-documented history demonstrates the decline in Secchi depth clarity over the last 40 years. The cause of this decline has been variously attributed to increasing algal growth and ultra-fine inorganic particles loads from both terrestrial and atmospheric sources. The Total Maximum Daily Load (TMDL) for Lake Tahoe is a water quality restoration plan required by the U.S. Federal Clean Water Act to ensure that the standard lake clarity of ~30 m, as measured in terms of annual average Secchi depth, is achieved. However, without the tools to quantify load reduction opportunity and lake response, there is a significant risk of implementing ineffective watershed restoration plans. A quasi-two-dimensional lake clarity model aids resource managers by helping to better understand the impacts of load reductions on lake clarity. The model is used to help answer questions such as how much load (nutrient and inorganic particles) reduction is needed to restore Lake Tahoe's clarity to 30m and how quickly will water clarity be restored?

1. Introduction and Cause for Concern

Lake Tahoe is world renowned for its amazing beauty and spectacular water clarity. However, long-term monitoring and research since 1968 shows that its clarity, expressed as Secchi depth, has declined at a rate of approximately 0.22 m per year between 1968 and 2006 (Figure 1). The observed interannual variation is primarily due to meteorological conditions, annual precipitation and runoff (Jassby et al. 2003). The trendline shows that Secchi depth has decreased by 9 m over the last 39 years and suggests that water clarity will continue to decline unless sufficient reductions in pollutant loading can be achieved.

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The declining clarity is attributed to the influx of nutrients (phosphorus and nitrogen) and fine particles (particle sizes ranging 0.5 to 20 μm in diameter) to the lake (Swift et al. 2006). Particles of this size settle extremely slowly and can remain in suspension for an indefinite period of time unless they coagulate/aggregate and settle more rapidly. Fine particles of terrestrial composition (soil) directly scatter light while nutrients (primarily phosphorus and nitrogen) stimulate algal production, which in turn absorbs light. The transport of these pollutants to Lake Tahoe has resulted from a number of activities including, land disturbance to support increasing resident and tourist populations, habitat destruction, air pollution, soil erosion (stream bank, shoreline, and watershed), roads and road maintenance, and loss of natural landscape capable of detaining and infiltrating overland runoff. If the loss of clarity continues at its current rate, there will likely be a change of lake color and trophic status. Therefore, public concern for the clarity of Lake Tahoe is high with local, state and federal agencies and policy-makers developing science-based restoration plans. Central to plans to improve Lake Tahoe's water clarity is the Tahoe TMDL Program.

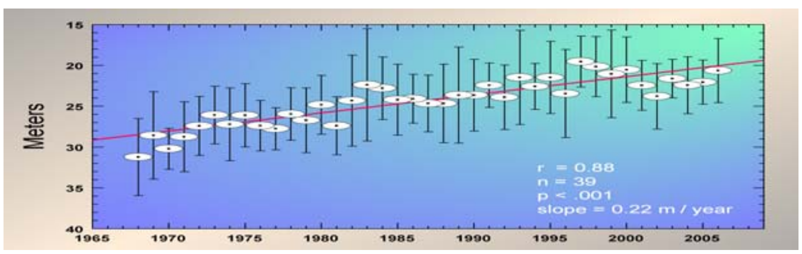

Figure 1. Historical measured Secchi depth and the projected trend. Each annual average value consists of 30-35 individual measurements taken throughout the entire year (Jassby et al. 1999). Vertical bars show the standard deviation surrounding the mean and denotes normal seasonal variation in Secchi depth readings. The n-value is the number of years of measurements.

A Total Maximum Daily Load (TMDL) is, in essence, a water quality restoration plan required by the U.S. Federal Clean Water Act to ensure the achievement of water quality standards in impaired surface water bodies. The Lake Tahoe TMDL is being managed jointly by the States of California and Nevada since the Lake is located in both jurisdictions. The Tahoe TMDL (1) quantifies the source and amount of fine sediment and nutrient loading from a variety of activities and land-uses within the major categories of urban watershed, forest upland, atmospheric deposition, stream channel/shoreline erosion and groundwater, (2) uses a customized Lake Clarity Model (described below) to link pollutant loading to lake response and (3) develops the framework for an implementation plan to achieve an annual average Secchi depth of 29.7 m as required by existing water quality standards.

Without the tools to quantify load reduction requirements and opportunities there is significant risk of implementing ineffective watershed restoration plans. To better understand the impacts of load reductions on lake clarity, a quasi-two-dimensional lake clarity model has been developed by researchers at the UC Davis – Tahoe Environmental Research Center. The model is being used to help resource agencies address the questions: (1) how much load (nutrient and inorganic particles) reduction is needed to restore Lake Tahoe's clarity to its standard for annual average Secchi depth and (2) how quickly will water clarity be restored based on a variety of possible restoration scenarios?

2. Facts about Lake Tahoe

The physical setting of Lake Tahoe is striking, situated near the crest of the Sierra Nevada Mountains at an elevation of approximately 1,897 m above sea level. The lake is bounded by the Sierra Nevada to the west and the Carson Range to the east and elevations within the Tahoe basin range as high as 3,050 m. The California – Nevada state line divides Lake Tahoe's watershed, with approximately 75% of the watershed area and 67% of the lake area lying within California. Lake Tahoe is the eleventh deepest lake in the world, with a maximum and an average depth of 501 m and 305 m, respectively. The maximum width and length of Lake Tahoe are 19.3 km and 35.4 km, respectively. The lake has a surface area of 501 km^2 within a watershed of 813 km^2. The total volume of the lake is 158 km^3 with a mean hydraulic residence time of 650-700 years. The basin consists of a total of 63 inflow tributaries, one outflow tributary and numerous intervening zones that drain into the Lake but not within the channels of the 63 tributaries. The developed land area occupies ~10 percent of the total land area residential, commercial, transportation (roads), utilities and institutional uses.

3. Background of Lake Clarity Model

Many models have been developed for lake management purposes. Often, methods yield satisfactory results for one lake or apply generally for lakes with similar characteristics; however, they are typically not effective for all lakes. The failure of a "one size fits all' approach is largely due to an insufficient understanding of the contributions of nutrients from internal and external sources, and the dynamics of physical, biological and chemical interactions in a particular lake (Riley and Stefan, 1988). Given the unique features of Lake

Tahoe and its oligotrophic nature, it was determined that a customized model that focused on Secchi depth was needed.

To better understand and provide scientific guidance for the improvement of Lake Tahoe's clarity and to help guide TMDL decisions, the UC Davis Dynamic Lake Model (DLM) coupled with the Water Quality Model (DLM-WQ) was developed and used to create the UC Davis Lake Clarity Model (LCM). The DLM-WQ is a complex system of sub-models including the hydrodynamic, ecological, zooplankton, nutrient, particle, and optical sub-models. The optical sub-model was recently described in Swift et al. (2006). The conceptual design of the LCM is shown in Figure 2.

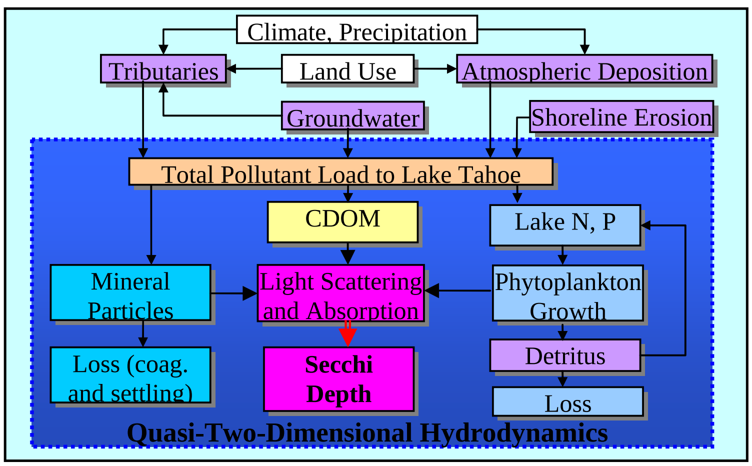

Figure 2. Schematic of lake clarity model. Blue box includes all in-lake processes.

All the LCM sub-models operate inside the blue shaded box in Figure 2. The pollutant sources and amounts of inorganic particle loading from atmospheric deposition, groundwater, tributaries and various land uses (urban and non-urban) are shown at the top of the blue shaded box. Groundwater contributes only nitrogen and phosphorus for algal growth. The optical sub-model estimates Secchi depths based on scattering and absorption characteristics of particles, algae, colored dissolved organic matter (CDOM), and water itself.

4. Results and Discussions

There is a three year measured data set (2000-2002) for lake water temperature, chlorophyll, NO_3^-, NH_4^+, PO_4^{-3}, Secchi depth and particle size distribution and concentration. In lake particles data were binned into the following size classes, 0.5-1, 1-2, 2-4, 4-8, 8-16 and 16-32 µm in diameter. The input values of groundwater discharge and nutrient loading to Lake Tahoe were reported in USACE (2003), atmospheric loads were reported in CARB (2006) and Hackley et al. (2005), and the Loading Simulation Program in C++ (LSPC) generated stream inputs are used in this study (Tetra Tech, Inc. 2005). Particles numbers for stream loading were estimated using regression equations developed by Rabidoux (2005). Values for shoreline erosion were estimated by Adams and Minor (2001). The clarity model was calibrated and validated using the measured lake data of 2000 to 2002. The time series-depth profiles (Figure 3) show that the simulated temperature values were close to measured values. This indicates that the lake clarity model simulates lake dynamics.

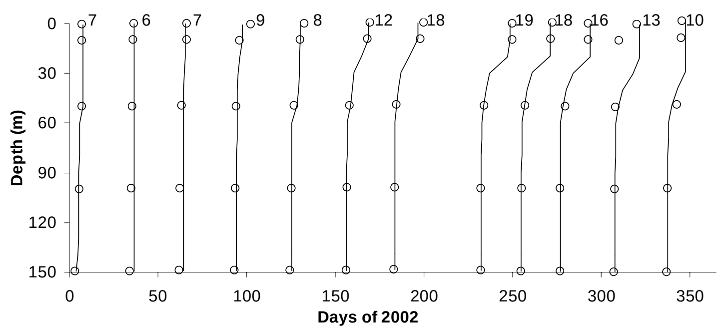

Figure 3. Temporal vertical variations of thermal structure for year 2002. Values within the plot denote the measured surface temperature. Temperature at 150 m deep from surface is around 5 ^{o}C. The hollow circles are the measured data points at 0 m, 10 m, 50 m, 100 m and 150 m deep from the surface and the line represents the simulated temperature.

To run the lake clarity model for different load reduction scenarios into the future, a series of simulation years (20 year period of 2000-2020) was established. To date, this 20-year simulation period has not been informed by actual restoration plans, rather it represents a hypothetical time period chosen to demonstrate the capability of the LCM as a management tool. Since the principal driving force for watershed loading is total precipitation, the baseline (Figure 4) was established by selecting varying precipitation years as future inputs. The choice of future precipitation years was based on previous years; in this regard the selection of future precipitation conditions can be changed.

While a wide variety of load reductions scenarios can be examined, we present model output based on a stepwise reduction in loading over the course of 20 years. For use in the Tahoe TMDL, LCM runs will be modified to examine lake response as a function of annual load reduction based on opportunities for restoration, restoration effectiveness, cost and other factors.

The scenario selected for presentation here includes a 55 percent load reduction from all sources at a uniform rate of 2.75 percent per year for 20 years. The load reduction percentage increases every year. Thus, it is seen that clarity increased and approached the 30 m target in 20 years (Figure 4). Note that presentation of this scenario is not intended to serve as a full alternatives analysis rather to demonstrate the utility of the lake clarity model as a tool to evaluate lake response to nutrient and sediment load reduction.

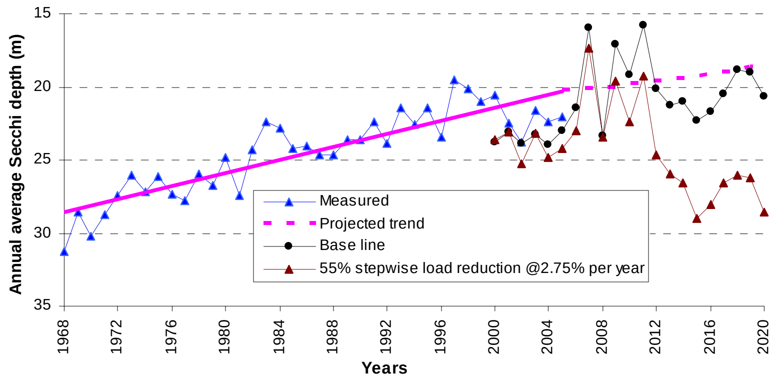

Figure 4. Simulated annual average Secchi depths for 55 percent load reduction from all sources at a rate of 2.75 percent per year for 20 years.

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