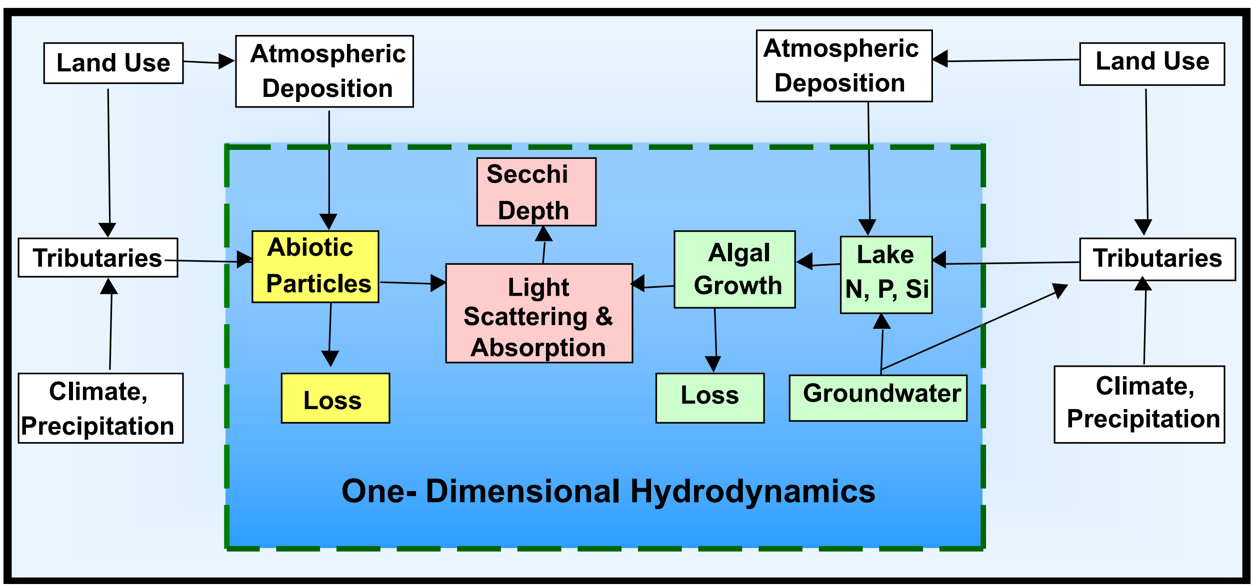
TSAC TAHOE SCIENCE ADVISORY COUNCIL

Report on the Status of the Lake Tahoe Clarity Model

Tahoe Science Advisory Council



December, 2020

1.0 Introduction

At the request of its Bi-State Executive Committee, the Tahoe Science Advisory Council (TSAC) was requested to prepare a Report on the status of Lake Tahoe Clarity model (LCM) including:
1) The identification of the strengths and deficiencies of the existing Lake Clarity components/sub models.
2) A summary of the availability of model inputs (data sources) – e.g. meteorology, water inflows, loads, distributed load sources, remote sensing, and in-lake data, including optical conditions, temperature, chemistry, currents, particles, phytoplankton.
3) The valuation of existing or recommended linkages to external models and reporting mechanisms.
4) Recommendations for next steps.

While the LCM was originally developed to address clarity questions at Lake Tahoe as part of the Tahoe TMDL, the model (or versions of it) has been utilized to address other questions at Lake Tahoe and other lakes in California and Nevada. In preparing this report the sub-committee chose to view the model, and any successors to it, as being a tool that has the potential to address a range of current and emerging issues at Lake Tahoe that extend beyond pelagic clarity, while recognizing that pelagic clarity will remain a management focus.

2.0 The purposes, advances, challenges and limitations of models

Models are quantitative formulations of scientific understanding. They can be applied to yield forecasts or predictions, to simulate various management scenarios, to identify gaps in understanding and in data, and to better analyze individual processes. However, models require careful sensitivity and uncertainty analyses, and data for their development, calibration, validation, and operation. Furthermore, models often do not include all processes relevant to an application, or the model approximations of these processes may be simplistic or even flawed. As a cautionary note, in a highly cited paper, Oreskes et al. (1994) stated 'Models can only be evaluated in relative terms, and their predictive value is always open to question. The primary value of models is heuristic…'.

Several recent publications provide context to help evaluate the LCM and offer perspectives on how to make updates and revisions. Many aquatic ecosystem models now exist, and they vary in their complexity, their mathematical approach and their goals. For example, Mooij et al. (2010) described a variety of lake ecosystem models from steady state and regression models to complex dynamic models, trait-based models and neural networks. They emphasize that calibration and sensitivity and uncertainty analysis should be an on-going aspect of modeling programs. Incorporating several alternative approaches to model specific processes in the same model can provide scientific insight, as illustrated by Tian (2006). Arhonditsis et al. (2014) and Gal et al. (2014) introduce a series of papers that describe recent progress in aquatic ecosystem modeling and highlight the diversity of approaches, process complexity and spatial resolution. Trolle et al. (2012) point out the challenges in developing aquatic ecosystem models that encompass top-down predation and grazing together with bottom-up microbial and nutrient dynamics. Arhonditsis et al. (2008) note that 'all models are simplistic representations of aquatic systems and even the most well studied ecological processes can be mathematically described by a variety of relationships that entail different assumptions and complexity levels.' Moreover, they stress the likelihood of different model structures and parameter sets being similar simulators of the natural system, so-called, model equifinality.

3.0 The strengths and deficiencies of the existing Lake Clarity Model components/sub models

3.1 Background

The LCM is described in Losada (2001), Swift et al. (2006), Sahoo et al. (2010), and the Lake Tahoe Total Maximum Daily Load Technical Report (June 2010).

At the inception of its development in 1997, the LCM was intended to be a state-of-the-art, 1-D, process-based model designed specifically to account for the processes that impacted clarity (i.e., vertical light attenuation) in the pelagic zone of Lake Tahoe, and to evaluate potential management scenarios to address and reverse long-term clarity decline. The model was based on an existing and widely recognized one-dimensional hydrodynamic framework (DYRESM-WQ – see Hamilton and Schladow (1997) and Schladow and Hamilton (1997)) that included algal growth and grazing, simple nutrient cycling, and sediment interaction models. The development of the LCM required the development of new algorithms for light scattering and absorption due to algae, inorganic particles and dissolved organic matter; inorganic particle aggregation; a modified nutrient model to match the available monitoring data; and an oxygen cycling model. It is noteworthy that these developments required research resources and the collection of new data (see for example, Coker 2000; Sunman 2004; Swift 2004; Rabidoux 2005; Terpstra 2005; Jassby 2006).

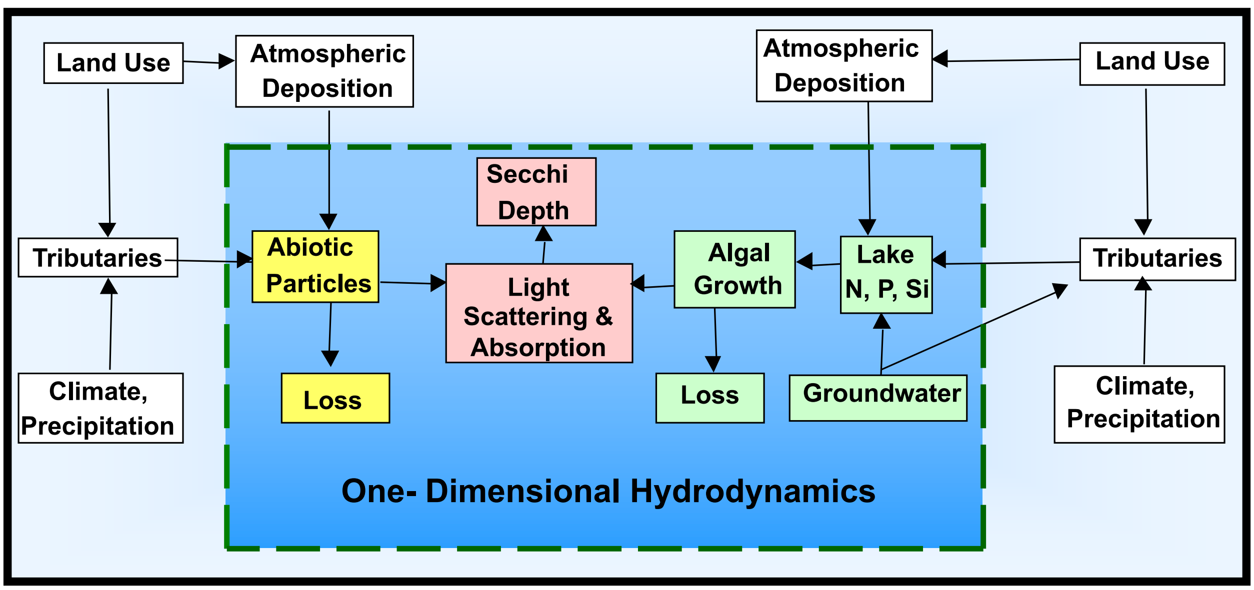


Fig. 1. Schematic of the Lake Tahoe Clarity Model

As indicated in Fig. 1, the LCM comprises a nested set of sub-models – a hydrodynamic model (and coupled with a thermodynamic model), an interacting set of nutrient cycling, algal growth, and algal grazing models; an inorganic particle model that describes particle aggregation and settling; an optical model for predicting light scattering and absorption by particles and dissolved substances; and a Secchi depth model. The overall model is "driven" by a set of external inputs that include meteorological inputs, atmospheric nutrient inputs, groundwater nutrient inputs and stream and non-channelized regions (or intervening zones) inputs of particles and nutrients. These inputs can be provided by direct measurements (along with spatial extrapolation for un-measured inputs) or by modeled inputs. For example, the hydrologic model LSPC (Lake Tahoe Total Maximum Daily Load Technical Report June 2010) was used as part of the TMDL development to provide stream and urban loading inputs to the LCM. The measured stream and urban loading data were used to calibrate the LSPC model.

The LCM architecture has a modular structure, such that the individual sub-models for specific processes are stand-alone modules that can be modified, bypassed, or substituted by different modules. Likewise, the modules can be re-used in a different model framework.

During the period of its development, the LCM was constructed to suit the available monitoring data, the existing understanding of the lake's physics, biology and chemistry and to work within the constraints of computational capacity at that time. In the intervening 20 years, our understanding of lake processes has advanced considerably, and improvements in computational methods and computer hardware have opened up the possibility of utilizing three-dimensional modeling approaches.

3.2 Strengths

3.2.1 Model Structure

The LCM is based on a widely accepted one-dimensional framework that partially accounts for lateral inflows and outflows, albeit it in a 1-D framework. A big advantage of a 1-D framework is rapid runtime speed and the modest memory needs, which allows the possibility of running the model continuously for multiple decades.

3.2.2 Processes

The LCM includes a broad range of lake processes – physical, chemical, biological, water quality, optical – as described above. In addition, it includes algorithms that describe vertical light attenuation. *In brief, its utility is largely limited to processes that can be* characterized as essentially one-dimensional (i.e. vertical). This would include vertical heat flux analysis, evaporation studies (and water level change), mixing depth analysis (although the details of that mixing may be in error for very deep mixing events) and initial estimates of stream insertion (although the algorithm needs to be evaluated and potentially revised on account of more recent studies). The fate of the inflows beyond the initial insertion cannot be modeled.

3.2.3 Calibration and Validation

The LCM has been calibrated and validated for an initial three-year period (2001-2004) (Losada 2001; Swift et al. 2008), and recalibrated and revalidated for a longer period (2001-2009) (Sahoo et al. 2010).

3.2.4 Accessibility

The model is open-source and available at no cost. Its use, together with the use of variants that have been developed for other lakes and reservoirs, has been published.

3.3 Deficiencies

3.3.1 Model Structure

Lakes are inherently three-dimensional (3-D) and a 1-D model cannot represent the full range of changes driven by 3-D processes. While for the TMDL the purpose for the model was the evaluation of pelagic clarity as a function of external loads, a larger array of water quality and ecological issues is now considered important. These emerging issues require an understanding, a spatially explicit representation, and a predictive capacity beyond those possible with a 1-D model.

There have also been large advances in the understanding of lake dynamics, particularly those at Lake Tahoe, over the last 20 years that make evident the limitations of 1-D modeling for a lake as large as Lake Tahoe. For example, the transfer of nutrients from the watershed and the littoral zone to the pelagic is more complex than previously assumed. Physical factors are all spatially variable and cannot be represented in 1-D. Biogeochemical processes are also spatially variable and are more complex than previously assumed. These include transformations such as uptake and recycling by periphyton and metaphyton, trophic interactions, biological connections of animals (mobile or sessile) for example.

3.3.2 Processes

The inability to represent an array of 3-D physical processes that can exert strong impacts on clarity and other water quality and ecological factors is a major deficiency. Important physical processes that cannot be represented include but are not limited to turbulent transport; upwelling; internal wave breaking; lateral water, particulate, and dissolved substance motions; fate of inflows (including groundwater); currents, jets and gyres; heterogeneity; differential heating and cooling; periphyton sloughing; and sediment resuspension.

For example, wind-driven upwelling events, that are now known to occur 12-15 times per year, transfer nutrients, particulates and contaminants vertically, and initiate horizontal jets along the shoreline that facilitate littoral-pelagic exchange. Deep oxygen transfer and renewal are now believed to be controlled by winter-time convection from the shallow shelves at the margins of the lake. These are examples of just two processes that cannot be represented with a 1-D structure, and both of which have important connections to clarity, to other water quality thresholds and to the lake's health.

The treatment of phytoplankton as a single functional group to represent all phytoplankton is overly simplistic. Improvements would entail separation into seven or more functional groups for which sufficient data on their physiology and their abundance now exists. The LCM utilized a single "chlorophyll" group, in part because phytoplankton were not considered to be important in clarity change (see for example Jassby et al. 1999) and it was considered that nutrient dynamics could be adequately captured with this assumption. However, the growing presence of very small diatoms (*Cyclotella*) due to climate change and other factors, and their disproportionate impact on clarity due to their size, makes this improvement a critical issue.

- Phytoplankton biomass, be it as a single aggregated group or separate functional groups, is represented as chlorophyll concentration rather than as carbon concentration. As carbon is a conserved quantity, its use would permit the development of food web models in the future.

- The phytoplankton model also uses the traditional approach of representing biomass as a distributed concentration (effectively treating it as a solute). The representation of phytoplankton biomass should be in terms of biovolume and cell numbers. This is due to the importance of small diatom cells on clarity, and the need to know both the numbers and sizes of particulates to determine the light scattering properties.

- The binary approach to light scattering in terms of organic vs. inorganic particles is probably too simple. *Cyclotella*, for example is organic but has an inorganic silicate frustule, imbuing it with the properties of both types of particles. The way in which the scattering and absorption properties of such cells are modeled needs to be re-evaluated.

- The particle aggregation model (a key component of the clarity determination) uses a fractal approach (Jassby 2006). This approach is computationally intensive, and many simplifying assumptions were made to enable it to operate in the 1-D model framework. These simplifying assumptions need to be re-evaluated to capitalize on improved computational speeds.

- Trophic complexity and interactions are lacking or simplistic. There are two types of trophic interactions and feedbacks to the systems. The first are interactions through the food web (e.g., fish to zooplankton to algae) within the pelagic and littoral habitats and their feedbacks. The second is through the excretion of nutrients of fishes, zooplankton, benthic invertebrates to the habitats in the lake (pelagic, benthic) and the time of year these contributions occur.

4.0 The available data sources

Lake Tahoe, with its long history of data collection and science has an extensive reservoir of data. Much are the data that were collected as part of short-term experiments, student theses, and curiosity driven research over the decades. Such data add fundamental knowledge that can be used to characterize processes (physical, chemical or biological) that form part of a model. Examples would be data on the nutrient excretion rates of specific organisms and sediment oxygen demand. Once known, these rates are generally "fixed" in the model.

The data more generally needed for models fall into two categories: (1) Input data and boundary condition data, and (2) calibration and validation data.

The input data and boundary conditions are what "drive" or externally force the model. The input data include meteorological, streamflow, groundwater, stormwater, atmospheric and river outflow data. They are typically provided as time series data, with the frequency dictated by the processes that are being modeled. Boundary conditions are bathymetric data that define the computational domain. Typically, such data do not change significantly in a lake the size of Tahoe, over the time scale being modeled, and are therefore held constant. A summary of these types of input data available at Tahoe is provided in Table 1.

Table 1. Model input and boundary condition data. The time periods are approximations in some cases.

	Collected By	Time Period	Location(s)	Frequency	Notes
Meteorology					
SW radiation	UC Davis	1998 - present	Tahoe City dock	10 min.	Intermittent calibration; gaps
LW radiation	UC Davis	1998 - present	Tahoe City dock	10 min.	Intermittent calibration; gaps
Air Temperature	UC Davis	2001 - present	7 docks	10 min.	Intermittent calibration; gaps
Relative humidity	UC Davis	2001 - present	7 docks	10 min.	Intermittent calibration; gaps
Precipitation	UC Davis	2001 - present	7 docks	10 min.	Intermittent calibration; gaps
Wind	NASA	2003 - present	4 buoys	10 min	Gaps
Wind	UC Davis	1999 - present	2 buoys; 7 docks	10 min	Intermittent calibration; gaps
Loads					
Streamflow	USGS	1980s-2007	10 streams	continuous	
Streamflow	USGS	2007-present	7 streams	continuous	
Stream Chemistry	UC Davis	1980s-2007	10? streams	~25/year	
Stream Chemistry	UC Davis	2007-present	7 streams	~25/year	
Stream Particles	UC Davis	2000-2003	10 streams	~25/year	
Stream Particles	UC Davis	2008-present	7 streams	~25/year	
Stream temp.	USGS	2014-present	3-4 streams	continuous	
Stream turbidity	USGS	2014-present	3-4 streams	continuous	
Urban nutrients & particles	DRI, UC Davis	2000-2004	Multiple sites	Event	
Urban stormwater	TRCD	2012-present	~5 sites	Event	
Groundwater	-	-	-	-	Assumed as 7% of annual streamflow
Atmospheric Nutrients	UC Davis	1980s-present	1 site (MLTP)	12/year	Earlier sites discontinued
Outflow					
Discharge	USGS	1900-present	1 site (TC)	continuous	Output loads modeled

Bathymetry					
Pelagic	USGS	1999			Completed
Littoral	TRPA	2019			Completed

Calibration and validation data refer to data obtained within the lake that can be used to compare with model outputs. For example, measured Secchi depth, nutrient distributions, and water velocities are needed if those variables are to be modeled. If ecological variables, such as phytoplankton and zooplankton distributions and density are to be modeled, data are also needed. In the process of calibration, model coefficients are adjusted within accepted ranges until a satisfactory fit is achieved between modeled and measured variables. In the process of validation, the previously calibrated model is run with a new set of input data (from a different time period). If a similarly good match is attained, then the model is considered to have been validated and it can be used with confidence to model other time periods.
A caveat to this is that the new periods should feature similar conditions to those appearing in the calibration and validation simulations. For example, in hindsight the period of the TMDL modeling for Lake Tahoe can now be seen to have been a relatively dry time period, hydrologically speaking. The recent wet years of 2017-2019 may not be represented well by the earlier model calibration.

Data from within the lake are also needed to provide "initial conditions" for the model at the commencement of a model run. This provides the model with a starting condition for each variable.

The frequency of data measurements is also important, but highly variable depending on the nature of a specific process and the desired model outputs. External loads (from streams and urban areas), for example, are known to have high temporal variability (the "first flush" phenomenon can range from minutes to hours) yet the frequency of measurement is often far longer (for streams nutrient and particle size measurements occur at 2-week intervals).

Table 2 provides a summary of the available data that may be used for calibration and validation.

Table 2. Model calibration and validation data. The time periods are approximations in some cases. LTP and MLTP indicate the two long-term UC Davis monitoring stations within the lake.

	Custodian	Time Period	Location(s)	Frequency	Notes
Pelagic					
Seabird Profiles (Temperature, conductivity, DO, chl. fluorescence, turbidity, light attenuation, particle size distribution (PSD))	UC Davis	Since 2004	LTP, MLTP	monthly	10 cm resolution
Temp profiles	UC Davis	1968-2004	LTP, MLTP	monthly	13 depths
UV profiles	UC Davis	2006-pres.	LTP, MLTP	monthly	10 cm res.
Chemistry (N, P, DIC, TOC)	UC Davis	1968-pres.	LTP, MLTP	monthly	13 depths
PSD	UC Davis	2000-2004; 2008-pres.	LTP, MLTP	monthly	13 depths

Chlorophyll	UC Davis	1983-pres.	LTP, MLTP	monthly	13 depths
Primary Prod.	UC Davis	1970-pres.	LTP	10d - monthly	Multiple depths
DO time series	UC Davis	2010 pres.	Various sites	30 min	Deep and shallow sites
Phytoplankton ID & enumeration	UC Davis	1968-pres.	LTP, MLTP	monthly	7 depths; temporal gaps
Zooplankton	UC Davis	1967-pres.	LTP, MLTP	monthly	Vertical tow; temporal gaps
Mysis	UC Davis	1979-1986; 1987-1995; 2011-pres.	Various sites	1-3 monthly	Vertical tow; temporal gaps
Secchi depth	UC Davis	1968-pres.	LTP, MLTP	monthly	
Fish	various	1960s – pres.	various	Intermittent	Few “snapshot” surveys with decades between
ADCP (currents)	UC Davis	episodic	various	Hi frequency for 1-3 months	
Turbulence	UC Davis, UCSB, Stanford	episodic	various	Hi frequency for 1-2 months	
Drogues	UC Davis	episodic	Full lake	1-5 days	
Gliders	UC Davis	5 missions 2015-2018	Cross-lake transects	Continuous for ~3 weeks	
Bioacoustic Mysis surveys	UC Davis	2018-2020	Multiple transects	episodic	Project specific
Littoral					
Periphyton surveys	UC Davis	1982-2019	Multiple sites	Monthly for partial year	
Metaphyton surveys	UC Davis	2017-2019	Multiple sites	Monthly for partial year	
Nearshore Network (C,T, Chl. fluorescence, Turbidity, DO, CDOM, wave height)	UC Davis	2014-2020	11 sites	30 s data	Intermittent gaps
Nearshore synoptic surveys of temperature, chlorophyll fluorescence and turbidity	DRI	2001-2015	continuous	quarterly	Intermittent gaps
Fish	Various	1950s – present	Various	Intermittent	Several “snapshot” surveys with decades between

5.0 Evaluation of existing or recommended linkages to external (watershed, climate, ecology) models and reporting mechanisms

5.1 Linkages to external models

As described previously, the linkages to external models can either be models that provide input data (in place of measured data) or models that are called by the LCM to represent a particular process, function, or aspect of the ecosystem.

In the first case, this would represent a relatively small programming adjustment, that would vary according to the nature of the modeled input. A switch from 1-D to 3-D modeling may require some changes when specifying inputs, however. Wind forcing in a 3-D model, for example, may require definition of the spatial variations in wind speed and direction across the water body.

In the second case, where the LCM is calling another model, the process is essentially the same. An external model that is called simply has to conform to the expected input/output exchange, something that is readily programmable.

5.2 Linkages to Reporting Mechanisms

The LCM and many other models calculate far more variables and at far greater frequencies than generally need to be saved to an output file. The variables that are required (e.g., daily Secchi depth, or annual average Secchi depth, or primary productivity at hourly intervals) can readily be programmed and provided as output in different formats.

6.0 Recommendations for next steps in modeling

Lakes are complex, three-dimensional systems with vertical and horizontal variations in physical, chemical and biological processes and conditions occurring across a broad range of temporal scales. For example, streams and local runoff introduce sediments and nutrients that may be transported and dispersed anywhere within the lake by complex physical motions that vary by time of day and time of year. Nearshore regions can have abundant growth of periphyton at specific times of year which can support mobile grazers that can sequester nutrients locally, or transport nutrients offshore and vertically. Likewise, vertically migrating zooplankton can transport nutrients from deep water into the euphotic zone and vice versa. Suspended sediment and phytoplankton that alter the clarity are transported and dispersed by physical processes, and the growth of phytoplankton influences and is influenced by mixing, the availability of nutrients and the light climate. Hence, developing three-dimensional (3-D) models of these interacting processes is challenging, and will require incremental progress. It is also essential if achieving both better understanding and better predictive capability of clarity is desired. 3-D models are used in lakes and reservoirs all around the world. Tahoe, given its iconic status and the scientific and restoration effort that has taken place over the last 20 years, is a notable omission.

As is evident from our evaluation of the existing 1-D LCM, a 3-D LCM must include significant improvements in the algorithms describing important physical and ecological processes. To do this will entail incorporation of advances in lake ecosystem modeling, published empirical and theoretical results, and utilizing existing and new measurements at Lake Tahoe. Given the modular nature of the existing LCM and its use of input data from other models, e.g., watershed loading, we suggest that the multiple-stage process of developing a 3-D LCM allow for the continuation of that model philosophy. In other words, that the 3-D LCM be modular to allow for upgrading of modules as knowledge evolves; have the ability to add new modules to incorporate additional processes in the future as priorities and imperatives change; and the ability to accept input data from either modeled or measured sources.

The initial funding available to support model improvements should allow for substantial progress on algorithm development for hydrodynamic model elements, several key ecological and optical processes, enhancement of particle tracking models, and further evaluation of the fate of watershed inputs (both urban and upland). All these changes will require substantial testing, calibration and validation. We suggest that the following six items should be considered to be the necessary tasks

1) Develop algorithms based on data from Tahoe and other applicable systems to allow for the representation of up to seven phytoplankton functional groups, and, in particular, *Cyclotella* spp.; the functional groups should be represented as particles with defined carbon content and varying chlorophyll content to significantly improve the representation of phytoplankton ecology and include for the first time the impact of small phytoplankton on clarity.

2) Extend the food web model to include phytoplankton and zooplankton (especially Cladocerans, Copepods, Mysis and Rotifers) with higher food web components represented as grazing terms on these groups.
3) Extend the 3-D hydrodynamic model (see Appendix 2) to better represent littoral conditions through invoking an improved nested grid approach.
4) Testing the accuracy of the model to represent deep mixing dynamics and the flux of oxygen at the lake bottom.
5) Evaluate the fate of urban and stream loading of particles and nutrients.
6) The testing, calibration and validation of each of the components and the complete model is an essential part of the effort.

Measurements are complementary to modeling and are needed to parameterize algorithms for specific process, as well as to calibrate and validate models. Conversely, models can be used to design and optimize sampling programs. Hence, we endorse a synergistic combination of measurements and modeling. Measurements essential for modeling the lake include meteorological data and stream and urban stormwater runoff. While more data are always desirable, the existing data can be used to for three-dimensional modeling. Sensitivity analyses with the model can help guide the selection of future sampled variables, sampling sites and frequency of collections. Deployment in the lake of automatic sensing systems to monitor water motions and thermal structure would be advantageous to validate the hydrodynamic model. As the ecological complexity of the modeling advances, sampling across the breadth of food web (including invertebrates and fish) as well as biogeochemical processes may be required.

Progress addressing these measurement/research needs should be evaluated as part of an ongoing, iterative process between the TSAC and Agency representatives. It is the belief of this committee that funding for these needs may come from a range of sources beyond just the Agencies.

One of the major uncertainties that this working group and other TSAC working groups have identified is the status of urban stormwater measurement and modeling. While separate from the lake clarity model, it is a major input to the clarity model. We would recommend that urban stormwater measurement and modeling be reviewed as a separate project.

While process-based, simulation modeling is an important tool, particularly for evaluating the efficacy of past and future management actions, the committee also recommends that other modeling approaches be explored in the future. These would provide the potential to better understand interactions occurring between the lake communities and lake processes. Examples of such modeling would include, but are not limited to, empirical dynamic modeling (EDM) and structural equation modeling (SEM).

7.0 References

Arhonditsis, G.B., G. Perhar, W. Zhang, E. Massos, M. Shi and A. Das. 2008. Addressing equifinality and uncertainty in eutrophication models. Water Resources Research 44: W01420, doi:10.1029/2007WR005862.

Arhonditsis, G.B. et al. 2014. What has been accomplished twenty years after the Oreskes et al. (1994) critique? Current state and future perspectives of environmental modeling in the Great Lakes. Journal of Great Lakes Research 40: 1-7.

Bruce, L.C., D.P. Hamilton, J. Imberger, G. Gal, M. Gophen, T. Zohary and D. Hambright. 2006. A numerical simulation of the role of zooplankton in C, N and P cycling in Lake Kinneret, Israel. Ecological Modeling 193: 412–436.

Ferguson, J.W. 2005. The bioavailability of sediment and dissolved organic phosphorous inputs to Lake Tahoe. M.S. thesis. University of Nevada, Reno.

Coker, J. E., 2000. Optical Water Quality of Lake Tahoe. MS Thesis, University of California, Davis.

Fleenor, W.E. 2001. Effects and control of plunging inflows on reservoir hydrodynamics and downstream releases. Ph.D. dissertation, University of California, Davis.

Gal, G., M. Hipsey, K. Rinke and B. Robson. 2014. Novel approaches to address challenges in modelling aquatic ecosystems. Environmental Modeling & Software 61: 246–248.

Hamilton, D.P. and Schladow, S.G. 1997. Prediction of Water Quality in Lakes and Reservoirs. Part I - Model Description. Journal, Ecol. Modelling 96, 91-110.

Hipsey, M.R., D.P. Hamilton, P.C. Hanson, C.C. Carey, J.Z. Coletti, J.S. Read, B.W. Ibelings, F. J. Valesini and J.D. Brookes. 2015. Predicting the resilience and recovery of aquatic systems: A framework for model evolution within environmental observatories. Water Resources Research 51: 7023–7043.

Hoyer, A.B., S.G. Schladow and F.J. Rueda. 2015. Local dispersion of nonmotile invasive bivalve species by wind-driven lake currents. Limnology and Oceanography 60: 446–462.

Jassby, A.D., Goldman, C.R., Reuter, J.E. and Richards, R.C. 1999. Origins and scale dependence of temporal variability in the transparency of Lake Tahoe, California-Nevada. Limnology and Oceanography 44 (2): 282-294.

Jassby, D. 2006. Modeling, Measurement and Microscopy – Characterizing the Particles of Lake Tahoe. MS Thesis, University of California, Davis.

Losada, J.P. 2001. A deterministic model for lake clarity: Application to management of Lake Tahoe, (California-Nevada), USA. Ph.D. Dissertation, Universitat de Girona, Spain.

Li, Y., G. Gal, V. Makler-Pick, A. M. Waite, L. C. Bruce and M. R. Hipsey. 2014. Examination of the role of the microbial loop in regulating lake nutrient stoichiometry and phytoplankton dynamics. Biogeosciences 11: 2939–2960.

Makler-Pick, V., G. Gal, J. Shapiro and M.R. Hipsey. 2011. Exploring the role of fish in a lake ecosystem (Lake Kinneret, Israel) by coupling an individual-based fish population model to a dynamic ecosystem model. Canadian Journal of Fisheries and Aquatic Science 68:1265–1284.

Mooij, W.M. et al. 2010. Challenges and opportunities for integrating lake ecosystem modelling approaches. Aquatic Ecology 44: 633–667.

Northwest Hydraulic Consultants and others. 2009. Pollutant Load Reduction Model (PLRM), Model Development Document.

Oreskes, N., K. Shrader-Frechette and K. Belitz. 1994. Verification, validation, and confirmation of numerical models in the earth sciences. Science 263: 641–646.

Rabidoux, A. 2005. Spatial and Temporal Distribution of Fine Particles and Elemental Concentrations in Suspended Sediments in Lake Tahoe Streams, California-Nevada. MS Thesis, University of California, Davis.

Reynolds, C.S., J. Alex Elliott and M.A. Frassl. 2014. Predictive utility of trait-separated phytoplankton groups: A robust approach to modeling population dynamics. Journal of Great Lakes Research 40: 143–150.

Rueda, F.J. 2001. A Three-Dimensional Hydrodynamic and Transport Model for Lake Environments. PhD Dissertation, University of California, Davis.

Rueda, F. and G. Schladow. 2003. Dynamics of large polymictic lake. II: Numerical simulations. Journal of Hydraulic Engineering 129: 92e101.

Sahoo, G.B., S.G. Schladow and J.E. Reuter. 2010. Effect of sediment and nutrient loading on Lake Tahoe (CA-NV) optical conditions and restoration opportunities using a newly developed lake clarity model. Water Resources Research, 46: W10505.

Schladow, S.G. and Hamilton, D.P. 1997. Prediction of Water Quality in Lakes and Reservoirs. Part II - Application to Prospect Reservoir. Journal, Ecol. Modelling 96, 111-123.

Sunman, B. 2004. Spatial and Temporal Distribution of Particle Concentration and Composition in Lake Tahoe, California-Nevada. MS Thesis, University of California, Davis.

Swift, T.J. 2004. The aquatic optics of Lake Tahoe, California-Nevada. PhD Dissertation, University of California, Davis.

Swift, T.J., J. Perez-Losada, S.G. Schladow, J.E. Reuter, A.D. Jassby, C.G. Goldman. 2006. Water clarity modeling in Lake Tahoe: Linking suspended matter characteristics to Secchi depth. Aquatic Sciences 68: 1-15.

Tetra Tech. 2007. Watershed hydrologic modeling and sediment and nutrient loading estimation for the Lake Tahoe Total Maximum Daily Load. Report to Lahontan Regional Water Quality Control Board and University of California, Davis.

Tian, R.C. 2006. Toward standard parameterizations in marine biological modeling. Ecological Modelling 193:363–386.

Trolle, D. et al. 2012. A community-based framework for aquatic ecosystem models. Hydrobiologia 683: 25–34.

Appendix 1
Responses to Joint Agencies Perspectives on Lake Clarity Model Review

On November 9, 2020, the Working Group received a set of responses to a meeting held on November 2 between the TSAC Working Group and Agency representatives. The Agencies included Lahontan Water Board, Nevada Division of Environmental Protection, Tahoe Regional Planning Agency, and the US Environmental Protection Agency.

The Working Group is appreciative of the comments, questions and clarifications embodied in these Responses (shown in italics below), and offers the following clarifications and answers.

1. ***Pelagic clarity remains the core concern*** *- Pelagic clarity remains the core concern of agencies and stakeholders (as well as the primary focus of the TMDL) and should be the primary focus of the recommendations of this project.*

   The Working Group appreciates that clarification and is seeking to make recommendations that meet that core concern as well as position the Lake Tahoe community to readily address a broader range of environmental issues in the future.

2. ***Assess management practice impacts on clarity (past and future) -*** *Agencies envision using the model to support evaluation of policy and implementation approaches. Of particular interest is understanding how effective the historic and current focus of reducing pollutant loading to the lake has been.*

   The Working Group shares the vision of using modeling tools to provide support and guidance for implementation approaches. Based on their own experience, combined with the information from the Summer-Winter Clarity Working Group report, this Working Group believes that the range of drivers and conditions that impact clarity are reasonably well understood. However, the available data on the magnitude and distribution of past input loads (as reported in the Summer-Winter Clarity report developed by TSAC earlier this year) combined with the measured effectiveness of implemented projects likely preclude confident assessment of the effectiveness of past actions. To be able to this in the future, the approaches to load monitoring should be reviewed.

   The Working Group believes that an improved modeling capacity will be able to inform the Agencies of the effectiveness of particular types of projects in the future and guide future monitoring strategies, as loading conditions and lake conditions change in response to evolving threats such as climate change, urbanization and wildfires. An improved modeling capacity will also allow for the assessment of new factors that may gain importance in the future, or that were not fully recognized in the past.

3. ***Focus on understanding clarity over the long-term –*** *Agencies are primarily concerned with assessing management of clarity on a multi-year time scale (5-10 years). Predicting clarity*

over shorter timescales is less important than understanding longer term trends in clarity. As the Lake Tahoe TMDL Program approaches its 20-year implementation period, it would be useful to have an understanding of the degree of influence FSP load reductions have had on clarity over that period, relative to other drivers including nutrients, ecological change, climate change and altered lake dynamics.

The Working Group believes that the timescale the Agencies are advocating for are important and can be addressed but should also include consideration of longer timescales to facilitate planning. Factors such as climate change and regional wildfire impact are likely to alter lake behavior in the future. As the Summer-Winter Clarity Working Group showed, statistically significant trends do not exist for past data over periods less than 10 years (based on the historical sampling frequency). An improved model should be able to capture and predict trends in clarity change over the periods indicated, albeit with increasing uncertainty as the timeline is extended. The model will also be capable of providing after the fact understanding of events, thereby becoming part of an adaptive learning and management environment.

4. ***Understanding clarity is not just modeling –*** *During our conversation last week, and in the summer winter clarity trend assessment there were numerous references to additional data that would improve our understanding of clarity. The primary goal is to improve our understanding of the processes and factors that influence the clarity of the lake. If the key to improving our understanding lies outside of modeling (e.g. better load quantification, monitoring program improvements, or understanding ecological dynamics) then we would greatly appreciate those recommendations.*

   The Working Group fully agrees with the Agency representatives that understanding of clarity changes will require more than modeling. The main body of this report provides explicit examples of where current knowledge is lacking in both fully understanding clarity, as well as other important aspects of the entire ecosystem. Modeling can assist in identifying where investments in both monitoring and science should be made.

   We already know, based on the science done over the last twenty years at Tahoe and elsewhere, that the current Clarity Model does not include enough of the important processes that impact clarity and other lake water quality metrics. For that reason, the Working Group is advocating an upgrading of the model. We are also advocating that an early task for the model would be a sensitivity study to help determine which clarity-impacting factors may be more important in specific years, what processes may need to be added to the model, and where the model could be simplified.

5. ***Address relative importance, an opportunity to improve existing understanding -*** *A list of processes the 1-D is incapable of modeling is provided, but it is unclear (a) the relative importance in the control on clarity and (b) whether information and data exist to inform model development. Ranking or grouping these processes in order of significance on*

controlling clarity and identifying the possibility for improving in 1- or 3-D would be useful in providing context for the prioritized workplan to fill research and monitoring gaps.

The current model is known to not include a number of important processes. Therefore, it cannot be used to help us understand the relative importance of controllers of clarity. We know for example that the representation of the physics and the algal dynamics are well below what is needed. Until that is addressed, the model cannot tell us much about the importance of nutrients on clarity. In other words, the obvious shortcomings of the model need to be addressed before the model can be used to assist in addressing all these other questions.

6. ***Cost / Time / Ease of use –*** *In the criteria used for recommending next steps, please consider the trade-offs between cost (to implement and maintain), time to implement and ease of use. Cost information should recognize the need to re-run the model on a set frequency to validate and re-calibrate the model. If the use of an enhanced 1-D or new 3-D model are technically complex, an estimated budget should include funding to support on-going technical support to run the model and/or the development of customized user's manuals and user-friendly interfaces for the models. As we consider changes like moving from 1-D to 3-D or adding additional ecological complexity, consider the additional costs (time/money) of maintaining the additional complexity. On many levels a simpler model that can be run more frequently, by multiple end users is preferable to a more complex one that is never run.*

   We are pleased that the Agencies recognize that running and maintaining any model takes time and effort (and hence budget). An old science adage (attributed to Einstein) is that everything should be as simple as possible, but no simpler. This is especially true for modeling.

   When the Working Group asked about who would be running the model, the answer that was received was that the science community would be, not Agency staff. The request to have a model run by multiple end users is therefore confusing. For the existing 1-D model, an Agency training course was run in about 2007, but we do not believe that any Agency staff ever ran the model after that training. This is not surprising, as "running" models is not simple especially when it is not part of a person's regular duties.

   The dimensionality (1-D or 3-D) is not what makes running a model challenging. It is the scientific familiarity with the system itself (its physics, chemistry, biology etc.), knowing why the model results may not be matching with measurements, appreciating the details of how each process may be simplified in order to model it, the process of calibration and validation, etc. If there is a desire that more people be able to run a model, then this will require investment in staff training in multiple areas, as well as a commitment to having staff regularly undertaking modeling.

7. ***Additional background on 3-D model development*** *– In the meeting there was mention that a 3-D model, or at least the beginnings of a 3-D model exists. More information about*

the existing 3-D model should be included in the white paper as leveraging this effort helps to justify retiring the existing LCM and building from this model.

Appendix 2 describes the history and status of the 3-D model used at Lake Tahoe.

Appendix 2
The Status of the Existing 3-D Tahoe Model

While the evaluation and selection of a 3-D model suitable for Lake Tahoe has not been conducted as part of this report, there has already been extensive use of 3-D modeling over the last 20 years.

The 3-D hydrodynamic model Si3D was originally developed by the USGS for simulating hydrodynamic and salinity conditions in the San Francisco Bay estuary (Smith 1997) and has been subject to continuous improvement and refinement since. It was based on the commercial model developed by Casulli and Cheng (1992). It was subsequently modified to better represent conditions in lakes and reservoirs and applied to Lake Tahoe and Clear Lake, as well as smaller lakes in the US and in Europe (Rueda and Schladow 2003; Rueda et al. 2008; Cowan and Rueda 2005; Hoyer et al. 2014; Hoyer et al. 2015a; Hoyer et al. 2015b; Acosta 2016; Chen et al 2017; King and Cowan 2019). The model has also been used to study underlying physical and biological interactions (see for example, Pasour and Ellner 2010). It is currently being used to study complex upwelling dynamics as described in Roberts et al. (In Press).

The model has an ability to represent important physical including diel and seasonal stratification and mixing, linear and non-linear internal waves, turbulent mixing, and stream inflows; it is computationally efficient, both because of the underlying solver and its parallel architecture; it has the ability to nest fine grids at areas requiring high resolution (e.g. the littoral zone, river deltas); has a publicly accessible source code making it both transparent and amenable to future changes by others; and is available in the public domain (i.e. is free to use).

A set of water quality modules for Si3D exists from the use of the model in the San Joaquin River (Doyle 2011). These are based on part of the Tahoe LCM water quality modules, although not utilizing those parts involving clarity.

References (Appendix 2)

Acosta, M., Anguita, M., Fernández-Baldomero, F.J., Ramón, C., Schladow, S.G. and Rueda, F.J. 2015. Evaluation of a nested-grid implementation for 3D finite-difference Cartesian semi-implicit hydrodynamic models. Journal of Environmental Modelling and Software, 64: 241-262.

Acosta, M.C. 2016. Optimization of 3D Hydrodynamic Models Applied to the Knowledge and Prediction of inland Waters. PhD Dissertation, University of Granada, Spain.

Anguita, M., Acosta, M., Fernández-Baldomero, J. and Rueda, F.J. 2015. Scalable parallel implementation for 3D semi-implicit hydrodynamic models of shallow waters. Environmental Modelling & Software, Vol. 73, 201-217.

Casulli, V. and R. T. Cheng 1992. Semi-implicit finite difference methods for three-dimensional shallow water flow. International Journal for Numerical Methods in Fluids, 15, 629-648.

Chen, S., Lei, C., Carey, C.C., Gantzer, P.A. and Little, J.C. 2017. A coupled three-dimensional hydrodynamic model for predicting hypolimnetic oxygenation and epilimnetic mixing in a shallow eutrophic reservoir. Water Resources Research 53(1), 470-484.

Cowan, E.A. and Rueda, F.J. 2005. Residence time of a freshwater embayment connected to a large lake. Limnology and Oceanography 50(5), 1638-1653.

Doyle, L. 2011. A Three-dimensional Water Quality Model for Estuary Environments. PhD. Dissertation, University of California, Davis

Hoyer, A.B., Wittmann, M.E., Chandra, S., Schladow, S.G. and Rueda, F. J. 2014. A 3-D individual-based aquatic transport model for the assessment of the potential dispersal of planktonic larvae of an invasive bivalve. Journal of Environmental Management, 145: 330-340.

Hoyer, A. B., Schladow, S. G. and Rueda, F. J. 2015a. Local dispersion of a non-motile invasive bivalve species by wind-driven lake currents. Limnology and Oceanography, 60: 446-462.

Hoyer, A.B., Schladow, S.G. and Rueda, F.J. 2015b. A hydrodynamics-based approach to evaluating the risk of waterborne pathogens entering drinking water intakes in a large, stratified lake. Water Research, 83: 227-236.

King, A.T. and Cowan, E.A. 2019. Near-field model for a high-momentum negatively buoyant line source within a three-dimensional hydrostatic lake model. Water Resources Research, 55(2), 1337-1365.

Pasour, V. 2007. Computational and Analytical Perspectives on the Drift Paradox Problem in a Freshwater Embayment. PhD. Dissertation, Cornell University.

Pasour, V.B and Ellner, S.P. 2010. Computational and analytic perspectives on the drift paradox. SIAM J. Applied Dynamical Systems, Vol. 9, No. 2, pp. 333–356.

Roberts, D.C., G.C. Egan, A.L. Forrest, J.L. Largier, F.A. Bombardelli, B.E. Laval, S.G. Monismith and S.G. Schladow (In Press). The setup and relaxation of spring upwelling in a deep, rotationally influenced lake. Limnology and Oceanography.

Rueda, F.J. and Schladow, S.G. 2003. Dynamics of a Large Polymictic Lake. II: Numerical Simulations. Journal of Hydraulic Engineering ASCE, 129(2): 92-101.

Rueda, F.J., S.G. Schladow, J.F. Clark. 2008. Mechanisms of contaminant transport in a multi-basin lake. Journal of Ecological Applications, 18(8), A72-A88.

Smith, P. E. 1997. A Three-Dimensional, Finite-Difference Model for Estuarine Circulation. Ph.D. Dissertation, University of California, Davis.