Lake Modelling : A Review

Umara Zulum[1]*, Vineet Chandan[2], Dr. Malini Prava Sethi[3]

[1]Dept. of Geography, School of Liberal Art, Noida International University, Noida, Uttar Pradesh, India
[2]Assistant Professor, Dept. of Geography School of Liberal Art, Noida International University, Noida, Uttar Pradesh, India
[3]Assistant Professor, Dept. of Geography School of Liberal Art, Noida International University, Noida, Uttar Pradesh, India
Email - zulumumara@gmail.com[1], vineet.chandan@gmail.com [2] malini.pravasehthi@gmail.com[3]

Abstract: *The General Lake Model (GLM) is a one-dimensional open-source code for simulating lake, reservoir, and wetlands hydrodynamics. The Global Lake Ecological Observatory Network (GLEON), a network of researchers utilizing sensors to investigate lake functioning and answer questions about how lakes around the world adapt to climate and land use change, developed GLM to suit their science needs. The breadth and diversity of lake kinds, locations, and sizes, as well as the growing number of observational datasets, necessitated the development of a comprehensive community model of lake dynamics that could answer a variety of scientific and management problems pertinent to the GLEON community. The scientific foundation and numerical implementation of the model algorithms are summarized in this work, along with specifics of sub-models that simulate surface heat exchange and ice cover dynamics, vertical mixing, and inflow–outflow dynamics. We illustrate the model's appropriateness for a variety of lake types with varying shape, hydrology, and climatic circumstances. For integrated simulations of water quality and ecosystem health, GLM allows dynamic coupling with biogeochemical and ecological modelling libraries, and possibilities for interaction with other environmental models are provided. Finally, we examine utilities for analyzing model outputs and assessing uncertainty, as well as model operation in a distributed environment.*

Key Words: *lake, modelling, ecology, ecosystem.*

1. INTRODUCTION:

Lakes and other bodies of water provide a wide range of ecosystem services, including water supply, flood control, hydropower, aesthetic and cultural advantages, as well as fisheries and biodiversity (Mueller et al., 2016). Lakes are frequently regarded as "sentinels of change," providing insight into the long-term viability of activities in their catchments (Williamson et al., 2009). They are also particularly vulnerable to the effects of invasive species and land use development, which frequently result in water quality degradation and ecosystem collapse. Recent estimates have revealed their importance in the Earth system, with energy, water, and biogeochemical exchanges leading to variability in land surface features and feedbacks to regional and global climate (Martynov et al., 2012; Cole et al., 2007). Tranvik et al. (2009), for example, estimate that carbon burial in lakes and reservoirs is significant on a global scale, on the order of 0.6 Pg yr1 or 4 times the rate of oceanic burial.

2. Limnology and eutrophication:

The Oxford English Dictionary defines limnology as "the study of the biological, chemical, and physical characteristics of lakes and other bodies of fresh water." Wetzel (2001), for example, provides a more precise definition that is more closely related to the research community and working tendency of the subject: Limnology is the study of the structural and functional interactions, as well as the productivity, of organisms in inland aquatic ecosystems as they are influenced by the physical, chemical, and biotic surroundings' dynamics. These definitions demonstrate that limnology is an interdisciplinary field in and of itself (Duarte and Piro, 2001). When reading a limnology textbook, the reader will see that the book covers earth sciences, physics, chemistry, and, of course, biology. I'd like to discuss some significant advances in limnological knowledge that have helped us better understand the eutrophication phenomenon. Elevated nutrient status in water systems is referred to as eutrophication. Because of the diminished transparency, unpleasant appearance and odor, prevalence of potentially dangerous organisms, and their repercussions for commercial and recreational usage of the lake, anthropogenic eutrophication of freshwater ecosystems is frequently considered a kind of pollution. Limnological knowledge aided in identifying the primary factors that cause anthropogenic eutrophication. Intra-connections of actors within the lake community have long been considered vital by lake experts (see, for example, Forbes, 1887). This microcosmic picture of the lake ecosystem later constituted the foundation of ecology's early growth. The limnological focus eventually evolved from the lake as an isolated entity to its role as a landscape element, with biologically significant geographical units defined by watershed, or drainage region. It was clear by then that externally obtained materials like nutrients had an impact on the lake's biological parameters, and that water flow was the primary mode of transferring nutrients. This was especially important for eutrophication issues, because much of the phosphorus discovered in lake water came from the catchment in most anthropogenically eutrophic lakes. Because most biologically relevant phosphorus compounds, such as orthophosphate, can bind to fine mineral particles, much of the phosphorus transport occurs when these mineral particles are moved. Rainfall and runoff are linked to erosion and particle movement via complicated and extremely non-linear connections. Adsorbed phosphorus from mineral particles entering the lake may be scavenged by algae or sink with bound phosphorus. When sinking particles are resuspended, the phosphorus connected to them may be permanently buried or reintroduced to the biologically active layers of lake water. Under chemically decreased conditions, phosphorus can also be released from soil particles into water via dissolution. Because phosphorus is one of the most important elements for primary production, or biological production at its most basic level, changes in phosphorus supply are well-known.

A study at the Experimental Lake Area in northern Ontario, Canada, eloquently illustrated the 'phosphorus as the limiting factor' concept (Schindler, 1977). In this experiment, an impermeable curtain was used to divide a lake into two halves, with only one receiving phosphorus fertilizer. Algal bloom and eutrophication were afterwards seen solely in the phosphorus-treated portion of the lake, proving the paradigm. Total phosphorus concentration is often inversely proportional to chlorophyll concentration, which is a widely used proxy for algal content in water. The presence of more algae in the lake has a cascade effect. For starters, algae are not transparent and hence reduce sun irradiation. As a result, the near surface water is selectively heated, while the deeper layers are dimmed. Planktonic algae suspended in the water will benefit from the limited light penetration, causing severe extinctions of bottom plants. The extra algae will eventually be eaten by a member of the upper trophic level, or they will die, sink to the bottom, and decay on their own. The use of oxygen by this breakdown process may eventually result in a lack of oxygen in the lake bottom, making it unsuitable for critical lake species. Algal blooms are frequently regarded as a nuisance to humans, and in the event of cyanobacteria (blue green algae) domination, animals, including humans, may be damaged. Other limnological information aids in eutrophication research by giving physical foundations for lake systems. The thermal energy budget of the lake is an important physical consideration. The majority of thermal energy in lakes comes from the sun's shortwave radiation (visible and near infrared) and is lost to the atmosphere as long-wave radiation (thermal infrared). Thermal energy affects many biological activities directly, but it also has an indirect effect on the whole-lake process by influencing the transport and storage medium, water. Water is a strange liquid in terms of physical chemistry; it has an exceptionally high heat capacity and can store a considerable quantity of heat. This is an important factor to consider while studying many lake dynamics. Perhaps more importantly, liquid water has a unique density property: unlike most other substances, it does not reach maximum density at the melting point. This density property of water is explained at the molecular level by a balance between two opposing processes. First, as the temperature of water rises, the hydrogen bonds that separate water molecules dissolve, causing the molecules to become closer together and more compacted. Second, when the temperature rises, molecules move quicker, occupying more space and lowering the density of water. The characteristic peak density at a temperature (3.98 C) that lies between the melting (0 C) and boiling (100 C) points is the end result of these two mechanisms fighting against one other (under atmospheric pressure). Hydrogen bonds are grouped hexagonally in a sparse and ordered manner in the ordinary solid phase of water (i.e., ice), making ice lighter than water. In lakes, the density of water has a considerable impact on the seasonal temperature distribution. As an example, consider a lake that freezes in the winter. Because ice is lighter than liquid water, it freezes near the surface and insulates the rest of the waterbody from the chilly atmosphere. Because water at 0 degrees Celsius is lighter than water at 3.98 degrees Celsius, the bottom of the lake remains warmer than the top of the water column interfacing ice (0 degrees Celsius). This density difference, together with the ice cover, inhibits layer mixing until the ice melts and the top half of the water warms to 3.98°C. In the summer, solar radiation from the lake surface decreases rapidly, making the upper layers lighter than the bottom layers and separating the top and bottom water layers once more. The balance of wind-driven mixing and the reinforcement of the density gradient by solar heating at the surface determines the thickness of the isothermal top layer. Layers in a stratified water column do not mix readily, but heat exchange occurs owing to turbulent diffusion, gradually warming the lake's bottom as the summer progresses. On a diurnal basis, heat loss on the surface owing to thermal radiation exceeds solar irradiance intake in the autumn. Convective mixing occurs as a result of the density change, which reduces the mixing depth. The entire water column will eventually be combined and become isothermal as the mixing depth increases. This well-mixed state will persist until the water temperature falls below 3.98 degrees Celsius; at this time, lighter and colder water at the surface strengthens its position by losing heat through thermal radiation and becomes even lighter. Physical laws and principles clearly explain these physical events, such as water freezing and thawing, solar energy absorption depth distribution, convection owing to density differences, wind-driven surface-water mixing, and heat diffusion due to temperature gradients. Thermal stratification is the vertical separation of lake water caused by density differences at depths in limnology, and the transient periods between winter cold stratification and summer warm stratification is referred to as spring and autumn turnover. This cycle is visible in a sufficiently deep lake, because stratification isolates deep sediment from the majority of biological activity in the upper section of the lake. This is significant since sediment has long been recognized as a source of nutrients and a major oxygen consumer, with significant implications for the cause and consequences of eutrophication. Of fact, limnology encompasses much more than what I've just covered. In freshwater systems, for example, food webs and biodiversity are a hotly debated topic. Other elements, such as nitrogen, silica, and Sulphur, have cycles that are significant for understanding major chemical pathways and related processes. In the benthic habitat, many complicated combinations of chemical reactions and species interactions occur, and deposited sediment could be examined to analyze past conditions of the lake and its surroundings (paleolimnology). The phosphorus limitation paradigm that I established has subsequently been called into question, with alternative limiting elements such as nitrogen and light being offered (Walz and Adrian, 2008).

3. History of lake models :

Although the goal of constructing a model varied, numerical models have been constructed to reflect some fraction of the processes within a lake. There are two types of motivations for building lake models: heuristic and utilitarian. Some models are created to test the conceptual linkages between known processes that are thought to be significant, and they are then utilized to learn more about the system (conceptual model). Other models are produced and used in the actual world for a variety of objectives, including providing projection and prediction to aid in the formulation of policies.

4. Management plans :

Review publications like Mooij et al. (2010) summarized the evolution of lake models, including their various techniques and levels of detail in lake description. In a nutshell, the earliest lake models are static chemical models (average and non-changing over time) that represent the balance of fluxes into and out of the lake to estimate the steady-state pools of chemical constituents. We witnessed progress in modelling additional biological and physical features of the lake as a result of this kind, and most models are now geared to forecast temporal changes by integrating the time dimension. Dynamic models are what they're called. It was rational to incorporate known processes into models, and models have become more complicated as a result. Increased complexity is a prevalent occurrence in other areas of environmental modelling as well. Unfortunately, increasing complexity has resulted in practical challenges; complicated models take longer to compute, require more information about the lake and inputs, and may become confusing and be able to explain everything, but for the wrong reasons. Lake modelling has a number of hurdles today, ranging from the need for geochemical and biological understanding advances to numerical and technical issues. Finding the right mix of intricacy and simplicity, in my opinion, is the most important. I'm interested in the subject of optimal lake model complexity because it's a challenging question to answer in the standard scientific paradigm. I also believe that determining the correct model complexity is crucial in providing relevant information to model users.

5. History of lake models :

Although the goal of constructing a model varied, numerical models have been constructed to reflect some fraction of the processes within a lake. There are two types of motivations for building lake models: heuristic and utilitarian. Some models are created to test the conceptual linkages between known processes that are thought to be significant, and they are then utilized to learn more about the system (conceptual model). Other models are developed and used in the real world, for example, to provide projection and forecast to aid in the formulation of management plans. Review publications like Mooij et al. (2010) summarized the evolution of lake models and the variety of techniques and degrees of degree of detail in description of lake The first lake models are static chemical models (average and non-changing over time) that explain the balance of fluxes into and out of the lake to establish the steady-state pools of chemical constituents. We witnessed progress in modelling additional biological and physical features of the lake as a result of this kind, and most models are now geared to forecast temporal changes by integrating the time dimension. Dynamic models are what they're called. It was rational to incorporate known processes into models, and models have become more complicated as a result. Increased complexity is a prevalent occurrence in other areas of environmental modelling as well. Unfortunately, increasing complexity has resulted in practical challenges; complicated models take longer to compute, require more information about the lake and inputs, and may become confusing and be able to explain everything, but for the wrong reasons. Lake modelling has a number of hurdles today, ranging from the need for geochemical and biological understanding advances to numerical and technical issues. Clearly, determining which challenge is the most pressing is a subjective matter. Finding the right mix of intricacy and simplicity, in my opinion, is the most important. I'm interested in the subject of optimal lake model complexity because it's a challenging question to answer in the standard scientific paradigm. I also believe that determining the correct model complexity is crucial in providing relevant information to model users.

6. The model :

My Lake is the model that was used in this thesis. The MyLake model is a "one-dimensional process-based model code for simulation of daily vertical distribution of lake water temperature and thus density stratification, evolution of seasonal lake ice and snow cover, sediment water interactions, and phosphorus-phytoplankton dynamics," according to the researchers (Saloranta and Andersen, 2007). MyLake offers a robust physical depiction of a lake and a very rudimentary and aggregated representation of biological processes as compared to other lake models. In comparison to many other physical models, the temporal and physical resolution is minimal: time and depth dimensions only, on a very coarse grid. The model's design premise is to hold processes responsible, which is accomplished by incorporating mostly proven physical principles and simplifying or eliminating less established processes. As a result, the model is unable to mimic processes such as trophic interactions between species, resource competition among species at the same trophic level, or detailed chemical speciation in sediment under changing chemical reduction states. Various factors influence the design and decision to simplify or eliminate procedures. Simple model building decreases the danger of unintentionally faking the fit during the calibration process, which is one of the main reasons for its simplicity. It's long been recognized that the more processes and features provided, the easier it is to appear compatible with observations made independently for model testing purposes (see next section). The straightforward design also allows for the explanation of model simulation deviations if they appear to be regulated by aspects of the system that have been eliminated or simplified. On these missing processes, one would expect the model to perform poorly. 1 The availability of independently acquired observations to question the model simulation is another important reason for the simple construction. Long-term processes, such as nutrient sourcing from the sediment, necessitate long-term observation data for modelling. In our situation, as in many others, there is no observation record spanning decades of changes in sediment-water interaction, making the application difficult and unpredictable. Another benefit is My Lake's inclusion of ice-heat dynamics (Fang and Stefan, 1996; Leppäranta, 1993), which is not included in many lake models. (An exception is the Flake model (Mironov et al., 2010)), despite being an essential seasonal phenomenon in northern lakes. This was judged a vital component because practically all of the lakes considered in this thesis or the corresponding projects freeze during the winter. Also, no model is ideal, and it's hard to fully justify the model's selection, as well as its construction and design. As a result, even after taking everything into account, the choice of model remains subjective. In our case, the model was indeed chosen. 1 'Models are sometimes more intriguing when they fail than when they succeed,' according to one such quote (Aber and Driscoll, 1997). This viewpoint was employed to provide depth to their conversation.

7. Mechanistic representation :

Model calibration is now more than just making subjective manual adjustments to model parameters in order to 'point' and 'shoot' the target observation. I'd want to discuss some common strategies that are pertinent to this thesis. For the sake of simplicity, the majority of the description assumes that we only want to calibrate one parameter. However, these methods are all viable even if we have numerous parameters to calibrate for a single model at the same time, as in the publications mentioned. A Monte Carlo method (see, for example, Mosegaard and Tarantola, 1995) involves taking parameter values at random and producing a variety of results. By enabling ambiguous (i.e., a range of) results, subjectivity concerning parameter value selections is removed. Because we don't know everything about the parameters, the range of results represents uncertainty. Today, a candid depiction of this ambiguity is highly valued. There is a notion known as equifinality that explains the circumstance in which numerous diverse combinations of parameters in a highly non-linear and complicated model create equal or similar results (thus the phrase equip-final-ity) (Beven and Freer, 2001). As a result, the Monte Carlo approach has a strong affinity for the equifinality phenomena and is capable of containing the model's equifinality in principle. Because the range of outputs could be compared against the observation, a modeler could decide which parameter value is best for corresponding to the observation, or choose a subset of parameter values that produce outputs that are within an acceptable level of correspondence, the Monte Carlo method was once a popular calibration method (and is still no less invalid today). However, due of its computational inefficiency, the Monte Carlo approach is no longer recommended for calibration. Even with Latin hypercube sampling, the number of all potential permutations of parameter values grows exponentially as the number of model parameters grows. The Markov chain Monte Carlo (MCMC) approach (see, for example, Andrieu et al., 2003) attempts to overcome the 'traditional' Monte Carlo method's computing inefficiencies. For discovering optimal parameter values, MCMC is an automatic machine learning method. MCMC works in steps, with each step evaluating the performance of a different parameter.

8. Environmental models are:

• Structural uncertainty: Uncertainty arising from the representation of the system (use ensemble of models to minimize this, but still not possible to eliminate).

• Uncertainty due to the way the system is represented (structural uncertainty) (use ensemble of models to minimize this, but still not possible to eliminate).
• Data uncertainty is forced (Vrugt et al., 2008): Uncertainty about the data that is put into the system's correctness (e.g., weather or nutrient loading in the case of My Lake). If the models are utilized in this order, the upstream model's uncertainty will be transferred to the downstream model.
• Uncertainty in projection: Our incapacity to predict future conditions. When we utilize models to forecast future environmental circumstances, the conditions we impose on the model may differ in the real world.
• Epistemological (Epistemic) uncertainty: Uncertainty stemming from the fact that we don't know what we don't know, but we do know that we don't know it.
• Technical error: It's always possible that the researchers or model users made a mistake when writing the model code or administering the model.

9. Conclusion:

The effective methods for simulating lake dynamics are the Finite Difference Method and Finite Element Method. The input data, factors to be examined, and computational methodologies to be used for lake flow and pollution transport are all explained in the study. This research also demonstrates how to address two crucial components in modelling lake dynamics: circulation and pollutant transport. Advanced numerical techniques must be added into the model to achieve precision in the numerical model.

REFERENCES:

1. Aber, J. D., and C. T. Driscoll (1997), Effects of land use, climate variation, and N deposition on N cycling and C storage in northern hardwood forests, Glob. Biogeochem. Cy., 11(4), 639–648. Andrieu, C., N. de Freitas, A. Doucet, and M. I. Jordan (2003), An introduction to MCMC for machine learning, Mach. Learn., 50(1), 5–43.
2. Barton, D. N., S. Kuikka, O. Varis, L. Uusitalo, H. J. Henriksen, M. Borsuk, A. de la Hera, R. Farmani, S. Johnson, and J. D. Linnell (2012), Bayesian networks in environmental and resource management, Integrated Environ. Assess. Manag., 8(3), 418–429.
3. Beven, K., and J. Freer (2001), Equifinality, data assimilation, and uncertainty estimation in mechanistic modelling of complex environmental systems using the GLUE methodology, J. Hydrol., 249(1–4), 11–29. 27
4. Dibike, Y., T. Prowse, T. Saloranta, and R. Ahmed (2011), Response of northern hemisphere lake-ice cover and lake-water thermal structure patterns to a changing climate, Hydrol. Process., 25(19), 2942–2953.
5. Dibike, Y., T. Prowse, B. Bonsal, L. d. Rham, and T. Saloranta (2012), Simulation of north american lake-ice cover characteristics under contemporary and future climate conditions, Int. J. Climatol., 32(5), 695–709.
6. Duarte, C. M., and O. Piro (2001), Interdisciplinary challenges and bottlenecks in the aquatic sciences, Limnol. Oceanogr. Bull., 10(4), 57–61. Fang, X., and H. G. Stefan (1996), Long-term lake water temperature and ice cover simulations/ measurements, Cold Regions Sci. Technol, 24(3), 289–304.
7. Forbes, S. A. (1887), The lake as a microcosm, Bull. Ill. Nat. Hist. Surv., 15, 537–550. Gassman, P. W., M. R. Reyes, C. H. Green, and J. G. Arnold (2007), The Soil And Water Assessment Tool: Historical Development, Applications, And Future Research Directions, Center for Agricultural and Rural Development, Iowa State University.
8. Gelman, A., J. B. Carlin, H. S. Stern, and D. B. Rubin (2003), Bayesian Data Analysis,Second Edition, 2 ed., Chapman and Hall/CRC. Kankaala, P., L. Arvola, T. Tulonen, and A. Ojala (1996), Carbon budget for the pelagic food web of the euphotic zone in a boreal lake (lake pääjärvi), Can. J. Fish. Aquat. Sci., 53(7), 1663–1674.
9. Knutti, R. (2008), Should we believe model predictions of future climate change?, Phil. Trans. R. Soc. A, 366(1885), 4647–4664. Leppäranta, M. (1993), A review of analytical models of sea-ice growth, Atmos. Ocean,31(1), 123–138.
10. Lovett, G. M., D. A. Burns, C. T. Driscoll, J. C. Jenkins, M. J. Mitchell, L. Rustad, J. B. Shanley, G. E. Likens, and R. Haeuber (2007), Who needs environmental monitoring?, Front. Ecol. Environ., 5(5), 253–260. Metropolis, N., and S. Ulam (1949), The monte carlo method, J. Am. Stat. Assoc., 44(247), 335–341.
11. Mironov, D., E. Heist, E. Kourzeneva, B. Ritter, N. Schneider, and A. Terzhevik (2010), Implementation of the lake parameterisation scheme FLake into the numerical weather prediction model COSMO, Boreal Environ. Res., 15(2), 218–230.
12. Mooij, W. M., D. Trolle, E. Jeppesen, G. Arhonditsis, P. V. Belolipetsky, D. B. R. Chitamwebwa, A. G. Degermendzhy, D. L. DeAngelis, L. N. D. S. Domis, A. S. Downing, J. A. Elliott, C. R. Fragoso, U. Gaedke, S. N. Genova, R. D. Gulati, L. Hakanson, D. P. Hamilton, M. R. Hipsey, J. ’t Hoen, S. Huelsmann, F. H. Los,

V. Makler-Pick, T. Petzoldt, I. G. Prokopkin, K. Rinke, S. A. Schep, K. Tominaga, A. A. Van Dam, E. H. Van Nes, S. A. Wells, and J. H. Janse (2010), Challenges and opportunities for integrating lake ecosystem modelling approaches, Aquat. Ecol., 44(3), 633–667. 28

13. Mosegaard, K., and A. Tarantola (1995), Monte carlo sampling of solutions to inverse problems, J. Geophys. Res., 100(B7), 12,431–12,447. Oreskes, N., K. Shrader-Frechette, and K. Belitz (1994), Verification, validation, and confirmation of numerical models in the earth sciences, Science, 263, 641–646. Riley, M. J., and H. G. Stefan (1988), Minlake: A dynamic lake water quality simulation model, Ecol. Model., 43(3–4), 155–182.
14. Saloranta, T. M., and T. Andersen (2007), MyLake - a multi-year lake simulation model code suitable for uncertainty and sensitivity analysis simulations, Ecol. Model., 207, 45–60, 1.
15. Saloranta, T. M., M. Forsius, M. Jarvinen, and L. Arvola (2009), Impacts of projected climate change on the thermodynamics of a shallow and a deep lake in finland: model simulations and bayesian uncertainty analysis, Hydrol. Res., 40, 234–248, 2-3.
16. Schindler, D. W. (1977), Evolution of phosphorus limitation in lakes, Science, 195(4275), 260–262.
17. Solomon, S., D. Qin, M. Manning, M. Marquis, K. Averyt, M. M. B. Tignor, H. L. Miller, and C. Zhenlin (2007), Climate Change 2007: The Physical Science Basis, Intergovernmental Panel on Climate Change.
18. Stock, P., and R. J. Burton (2011), Defining terms for integrated (multi-inter-transdisciplinary) sustainability research, Sustainability, 3(8), 1090–1113. Tarantola, A. (2006), Popper, bayes and the inverse problem, Nat. Phys., 2(8), 492–494. Tominaga, K., J. Aherne, S. A.Watmough, M. Alveteg, B. J. Cosby, C. T. Driscoll, M. Posch, and A. Pourmokhtarian (2010), Predicting acidification recovery at the hubbard brook experimental forest, new hampshire: Evaluation of four models, Environ. Sci. Technol., 44(23), 9003–9009.