Oct 2013

GLM

General Lake Model

Model Overview and User Information

v1.3.2

M.R. Hipsey, L.C. Bruce & D.P. Hamilton

The University of Western Australia
Achieve International Excellence

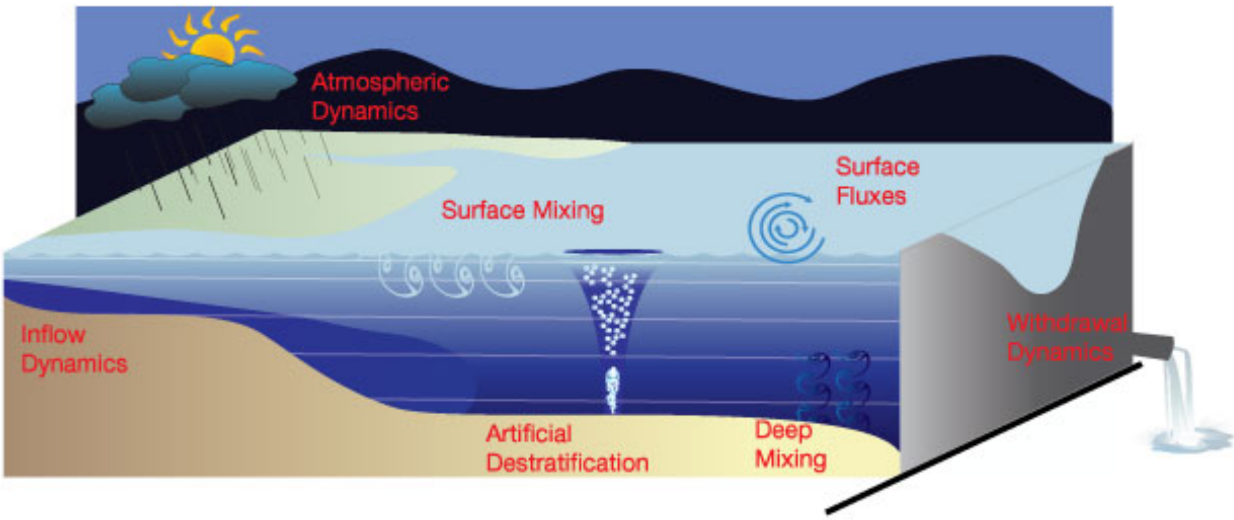
Aquatic Eco Dynamics

Summary

This document summarises the basis and operational details for the 1D lake water balance and vertical stratification model: GLM (The General Lake Model). GLM has been designed to be an open-source community model suited to environmental modelling studies where simulation of lakes or reservoirs is required. The model couples with the Framework for Aquatic Biogeochemical Models (FABM) for integrated simulations of lake and reservoir water quality and ecosystem health.

This first section summarises the theory around the model design including information about the simulation of surface exchanges and ice-cover dynamics, vertical mixing and inflow/outflow dynamics. A summary of typical parameter values for lakes and reservoirs collated from a range of sources is included.

The final section provides an overview of setting up and running the model including an outline of file formats and approaches for plotting the results. This document also identifies a workflow for model assessment and calibration.



Contents

The General Lake Model (GLM)

Overview

The *General Lake Model* (GLM) is a one-dimensional hydrodynamic model driver for lakes and reservoirs. It is suited for application to lentic inland water systems ranging from shallow ponds to deep lakes and large or small drinking water or irrigation reservoirs. These may be fresh or saline in nature. GLM conducts a lake water and energy balance and also computes vertical profiles of temperature, salinity and density. The model is simple in nature but able to account for the effect of inflows/outflows, mixing and surface heating and cooling, including the effect of ice cover on heating and mixing of the lake.

Since the model is one-dimensional it assumes no horizontal variability and users must therefore ensure the lake conditions match this "one-dimensional assumption". Under this assumption the model is ideally suited to long-term investigations ranging from seasons to decades, and for coupling with biogeochemical models to explore the role that stratification and vertical mixing play on the dynamics of lake ecology. In particular, the model couples with the Framework for Aquatic Biogeochemical Models (FABM) for integrated simulations of lake and reservoir water quality and ecosystem health, and precompiled binaries are provided of GLM coupled with FABM.

The model has been developed as an initiative of the Global Lake Ecological Observatory Network (GLEON) and in collaboration with the Aquatic Ecosystem Modelling Network (AEMON) that started in 2010. The model was first introduced in Leipzig at the 2nd Lake Ecosystem Modelling Symposium in 2012, and has since developed rapidly with application to numerous lakes within the GLEON network and beyond. It is envisioned the initiative will be an open-source community model suited to environmental modelling studies where simulation of lakes or reservoirs is required (eg. see Trolle *et al.,* 2012).

Model Description

GLM incorporates a flexible Lagrangian layer structure similar to the approach of several 1-D lake model designs (Imberger and Patterson, 1981; Hamilton and Schladow, 1997; McCord *et al*., 2000; Casamitjana *et al*., 2003; Gal *et al.,* 2003; Chung *et al*., 2009). The Lagrangian design allows for layers to change thickness by contracting and expanding in response to inflows, outflows, mixing and surface mass fluxes. Each layer is subject to an energy and salt balance on a sub-daily time-step, and when sufficient energy becomes available to overcome vertical density gradients, two layers will merge thus accounting for the process of mixing. Layer thickness is set within the model in order to sufficiently resolve the vertical density gradient. Unlike traditional fixed grid models, where mixing algorithms are typically based on vertical velocities and numerical solution of the advection-dispersion equation, numerical diffusion of the thermocline in GLM is limited, making the approach superior for simulating stratified water bodies over the long-term.

Although GLM is a new model code, many of the heating and mixing algorithms have been based on equations presented by Hamilton and Schladow (1997) and also described in the above references. GLM has been written with a modernised code structure and features a number of customisations to make the model easy and efficient to use.

Layer structure

The model is composed of a series of horizontal layers numbered from the lake bottom to the surface. The number of layers is adjusted to maintain the assumption that each layer must have homogenous properties across the layer. Initially, the layers are assumed to be of equal thickness, and the initial number of layers, *NLEV(0),* depends on the user-defined minimum and maximum layer thickness limits set, and the lake depth (both defined in `glm.nml`, see model setup section). As the model progresses through time, density changes due to surface heating , vertical mixing, and inflows and outflows lead to dynamic changes in layer properties and layers will combine or split. The number of layers, and therefore grid-resolution will change over time, so that *NLEV = NLEV(t).* Layer thicknesses will change each time step as layers expand or contract in order to maintain the maximum thickness required to resolve the vertical density gradient.

Energy budget

In the surface layer, a balance of shortwave radiation flux, net longwave radiation flux, sensible heat and latent heat of evaporative heat fluxes determine the net rate of cooling and heating. This is computed sub-daily (usually hourly).

The model accounts for the surface fluxes of sensible heat and latent heat using commonly adopted bulk aerodynamic formulae. For sensible heat:

$$\phi_H = -\rho_a c_p C_H U_x (T_a - T_s) \qquad (1)$$

where c_p is the specific heat, C_H is the bulk aerodynamic coefficient for sensible hear transfer (~1.3x10^{-3}), T_a the air temperature (^{o}C) and T_s the temperature of the surface layer (^{o}C).

For latent heat:

$$\phi_E = -\rho_a C_E U_x \, (e_a[T_a] - e_s[T_s]) \qquad (2)$$

where C_E is the bulk aerodynamic coefficient for latent heat transfer, e_a the air vapour pressure and e_s the saturation vapour pressure at the surface layer temperature (hPa). The vapour pressure can be calculated by the following formulae:

$$e_s[T_s] = exp\left[2.303\left(7.5\frac{T_s}{T_s+273.15}\right) + 0.7858\right] \qquad \text{Option 1} \qquad (3)$$

$$e_s[T_s] = 10^{\left(9.28603523\frac{2322.37885\,T_S}{T_S+273.15}\right)} \qquad \text{Option 2}$$

and:

$$e_a[T_a] = \frac{RH}{100} e_s[T_a]$$

Shortwave radiation is able to penetrate according to the Beer-Lambert Law, and longwave radiation can either be specified as net flux, or incoming flux. The incoming flux may be specified directly or calculated by the model based on the cloud cover fraction and air temperature.

Short wave radiation is calculated as:

$$\phi_{SW}(z) = (1 - \alpha_{SW})\hat{\phi}_{SW}\; exp[-K_w z] \qquad (4)$$

$$\alpha_{SW} = \begin{cases} 0.08 + 0.02\; sin\left[\frac{2\pi}{365}d - \frac{\pi}{2}\right] & : northern\ hemisphere \\ 0.08 & : equator \\ 0.08 - 0.02\; sin\left[\frac{2\pi}{365}d - \frac{\pi}{2}\right] & : southern\ hemisphere \end{cases} \qquad (5)$$

where $\phi_{SW}(z)$ is the short-wave radiation at depth, z (m), α_{SW} is used to account for the effect of albedo on the penetration of ϕ_{SW} and d is the day of the year. K_w is the light extinction coefficient, either set as constant or obtained from a coupled water quality model.

Long wave radiation is calculated as:

$$\phi_{LW_{in}} = \sigma[T_a + 273.15]^4 \times (1 + c_1 C) \times \left(1 - c_2\; exp\left[-c_3 {T_a}^2\right]\right) \qquad (6)$$

$$\phi_{LW_{out}} = \varepsilon_w \sigma [T_s + 273.15]^4$$

$$\phi_{LW_{net}} = \phi_{LW_{in}} - \phi_{LW_{out}}$$

where σ is the Stefan-Boltzman constant, C the cloud cover fraction (0-1), ε_w the emissivity of the water surface and constants, c_1 = 0.275; c_2 = 0.261; c_3 = 0.000777x10^{-4}.

Surface mass fluxes

The model accounts for surface mass fluxes of evaporation, rainfall, R, and snowfall, S, (m day^{-1}):

$$\frac{dh_s}{dt} = \lambda\phi_E + R + S \tag{7}$$

where h_s is the height of the surface layer (m), dt is the time step (s), and λ is the latent heat of evaporation. Note that this equation does not include changes to h_s as a result of mixing dynamics or ice formation/melt as described in the following sections.

Snow & ice model

The algorithms for GLM ice and snow dynamics are based on previous ice modelling studies (Patterson and Hamblin, 1988; Gu and Stefan, 1993; Rogers *et al.,* 1995; Vavrus *et al.,* 1996). To solve the heat transfer equation, the ice model uses a quasi-steady assumption that the time scale for heat conduction through the ice is short relative to the time scale of meteorological forcing (Patterson and Hamblin, 1988; Rogers *et al.,* 1995).

The steady-state conduction equations, which allocate shortwave radiation into two components, a visible (A1=70%) and an infra-red (A2=30%) spectral band, are used with a three-component ice model that includes blue ice, snow ice and snow (see Eq. 1 and Fig. 5 of Rogers *et al.*, 1995). Snow ice is generated in response to flooding, when the mass of snow that can be supported by the ice cover is exceeded (see Eq. 13 of Rogers *et al.,* 1995). By assigning appropriate boundary conditions to the interfaces and solving the quasi-steady state of heat transfer numerically, it is possible to determine the upward conductive heat flux between the ice or snow cover and the atmosphere, ϕ_0. The estimation of ϕ_0 involves the application of an empirical equation to estimate snow conductivity (K_s) from its density, where the density of snow is determined as outlined in Figure 1.

At the ice (or snow) surface, a heat flux balance is employed to provide the condition for surface melting,

$$\begin{aligned} \phi_0(T_0) + \phi_{net}(T_0) &= 0 && T_0 < T_m \\ &= -\rho L \frac{dh_i}{dt} && T_0 = T_m \end{aligned}$$

where L is the latent heat of fusion (see physical constants, Table 2), h_i is the height of the upper snow or ice layer, t is time, ρ_i is the density of the snow or ice, determined from the surface medium properties, T_0 is the temperature at the solid surface, T_m is the melt-water temperature (0°C) and $\phi_{net}(T_0)$ is the net incoming heat flux, at the solid surface:

$$\phi_{net}(T_0) = \phi_{LWin} - \phi_{LWout}(T_0) + \phi_H(T_0) + \phi_E(T_0) + \phi_R(T_0)$$

where ϕ_{LWin} and ϕ_{LWout} are incoming and outgoing longwave radiation, ϕ_H and ϕ_E are sensible and evaporative heat fluxes between the solid boundary and the atmosphere, and ϕ_R is the heat flux due to rainfall. These heat fluxes are calculated as above with modification for determination of vapor pressure over ice or snow (Gill 1982) and the addition of the rainfall heat flux (Rogers *et al.,* 1995). T_0 is determined using a bilinear iteration until surface heat fluxes are balanced (i.e. $\phi_0(T_0) = -\phi_{net}(T_0)$) and T_0 is stable (± 0.001°C). In the presence of ice (or snow) cover, surface temperature $T_0 > T_m$ indicates that energy is available for melting. The amount of energy for melting is calculated by setting $T_0 = T_m$ to determine the reduced thickness of snow or ice (as shown in Eq. 8).

Accretion or ablation of ice is determined through the heat flux at the ice-water interface, q_f. Solving for heat conduction through ice yields:

$$q_f = q_0 - A_1 I_0 \{1 - \exp(-\lambda_{s1} h_s - \lambda_{e1} h_e - \lambda_{i1} h_i)\} - A_2 I_0 \{1 - \exp(-\lambda_{s2} h_s - \lambda_{e2} h_e - \lambda_{i2} h_i)\} - Q_{si} h_s,$$

where I_0 is the shortwave radiation penetrating the surface (also termed $\hat{\phi}_{SW}$), λ and h are the light attenuation coefficient and thickness of the ice and snow components designated with subscripts *s, i* and *e* for snow, blue ice and snow ice respectively, and Q_{si} is a volumetric heat flux for formation of snow ice, which is given in Eq. 14 of Rogers *et al.* (1995). Within GLM the ice and snow light attenuation coefficients are fixed to the same values as those given by Rogers *et al.* (1995). Reflection of shortwave radiation from the ice or snow surface is a function of surface temperature and ice and snow thickness (see Table 2, Vavrus *et al.,* 1996). Values of albedo are derived from these functions vary from 0.08 to 0.6 for ice and from 0.08 to 0.7 for snow.

The imbalance between q_f and the heat flux from the water to the ice, q_w, gives the rate of change of ice thickness at the interface with water:

$$\frac{\mathrm{d}h_i}{\mathrm{d}t} = \frac{q_f - q_w}{\rho_i L},$$

where r_i is the density of blue ice and q_w is given by a finite difference approximation of the conductive heat flux from water to ice:

$$q_w = -D_w \frac{\Delta T}{\Delta z},$$

where D_w is molecular conductivity and ΔT is the temperature difference between the surface water and the bottom of the ice, which occurs across an assigned depth Δz. A value for Δz of 0.5 m is usual, based on the reasoning given in Rogers *et al.* (1995) and the typical vertical resolution of a model simulation (0.125 – 1.5 m). Note that a wide variation in techniques and values is used to determine the basal heat flux immediately beneath the ice pack (e.g., Harvey, 1990).

Figure 1 shows the overall decision tree to update ice cover, snow cover and water depth. The ice cover module described above is activated automatically when water temperature first drops below 0 ^{o}C. The ice thickness is set to its minimum value of 0.05 m, (as suggested by Patterson and Hamblin 1988, and Vavrus *et al.* 1996). The need for a minimum ice thickness relates primarily to horizontal variability of ice cover during the formation and closure periods. The ice cover equations are discontinued and open water conditions are restored in the model when the thermodynamic balance first produces ice thickness < 0.05 m. The effects of snowfall, rainfall, and compaction of snow are described through appropriate choice of one of several options, depending on the air temperature and whether ice or snow is the upper boundary (Figure 1).

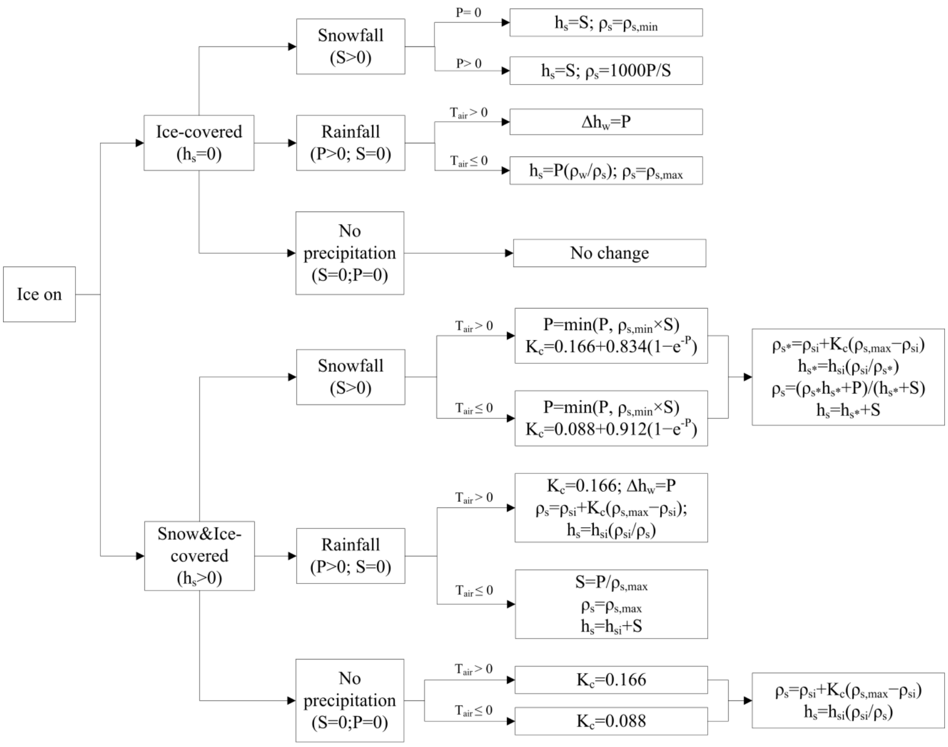


Figure 1: Decision tree to update ice cover, snow cover and water depth according to snow compaction, rainfall (P) and snowfall (S) on each day, and depth of snow cover (h_{si}) and snow density (r_{si}) for the previous day.

Density of fresh snowfall is determined as the ratio of measured snowfall height to water-equivalent height, with any values exceeding the assigned maximum snow density (r_{max} = 300 kg m^{-3}) truncated to the upper limit. The snow compaction model is based on the exponential decay formula, with selection of snow compaction parameters based on air temperature (Rogers *et al.,* 1995) as well as on rainfall or snowfall. The approach of snow compaction used by Rogers *et al.* (1995) is to set the residual snow density to its maximum value when there is fresh snowfall. This method is found to produce increases in snow density that are too rapid when there is only light snowfall, and so a gradual approach to increasing snow compaction is adopted.

Vertical mixing

GLM works on the premise that the balance between the available energy, E_{TKE}, and the required energy to undergo mixing, E_{PE}, controls the surface mixed layer (SML) deepening rate dh_{mix}/dt. The model calculates the available kinetic energy due to contributions from wind stirring, shear production between layers, convective overturn, and Kelvin-Helmholtz billowing, which combined are summarised according to (Imberger and Patterson, 1981; Imberger, 1985):

$$E_{TKE} = \underbrace{0.5 C_K (w_*^2)\,\Delta\mathrm{t}}_{convective\ overturn} + \underbrace{0.5 C_W (\psi^3\, u_*^3)\,\Delta\mathrm{t}}_{wind\ stirring} + \underbrace{0.5\ C_S \left[u_b^2 + \frac{u_b^2}{6}\frac{d\xi}{dh} + \frac{u_b \xi}{3}\frac{du_b}{dh}\right]}_{\substack{shear\ production \\ K-H\ production}} h_{s-1}$$

where u_* and w_* refer to the velocity scales in the horizontal and vertical respectively. The energy required to lift up water at the bottom of the mixed layer, denoted here as layer *i-1,* with thickness h_{i-1}, and accelerate it to the SML velocity is required for mixing to occur. This also accounts for energy consumption associated with K-H production and expressed as, E_{PE}:

$$E_{PE} = \left[\underbrace{0.5 C_T (w_*^3 + \psi^3\, u_*^3)^{2/3}}_{acceleration} + \underbrace{\frac{\Delta\rho g h_{mix}}{\rho_o}}_{lifting} + \underbrace{\frac{g\xi^2}{24\rho_o}\frac{d(\Delta\rho)}{dh} + \frac{g\xi\Delta\rho}{12\rho_o}\frac{d\xi}{dh}}_{K-H\ consumption}\right] h_{s-1}$$

for these, the length scale of the K-H billows is summarised as:

$$\xi = KH \frac{\rho_o {u_b}^2}{g\Delta\rho}$$

and the velocity of the lower layer is approximated from:

$$u_b = \frac{{u_*}^2 t}{h_{mix}} + u_o$$

The model first calculates these energy arguments and then loops through layers from the top to the bottom until there is insufficient energy available to left up the next i^{th} layer.

Mixing below the SML is modelled using a characteristic diffusivity, $K = K_\varepsilon + K_m$, based on

$$K_\varepsilon = \frac{\alpha_{TKE}\varepsilon_{TKE}}{N^2 + 0.6\, {k_{TKE}}^2 {u_*}^2}$$

and K_m is the fixed molecular diffusivity of scalars. α_{TKE}= 0.5 and k_{TKE} is defined as the wavenumber. For ε_{TKE}:

$$\varepsilon_{TKE} = \begin{cases} \epsilon & z_i < (H_t - h_{mix}) \\ \epsilon\ exp\left[-\dfrac{H - h_{mix} - z}{h_{sig}}\right] & z_i < (H_t - h_{mix}) \end{cases}$$

where h_{sig} is the first moment distance of the N^2 distribution below h_{s-1} where N^2 is the buoyancy frequency:

$$N^2 = \frac{g\Delta\rho}{\rho\Delta z}$$

Inflows and outflows

Any number of inflows to the domain can be specified and these are applied at the end of the sub-daily loop, i.e. once a day. Depending on the density of the river water, the inflow will form a positive or negatively buoyant intrusion. As the inflow crosses layers it will entrain water until it reaches a level of neutral buoyancy. At its point of neutral buoyancy it is then assumed to insert as a new layer of thickness depending on the inflow volume at that time (including the effects of entrainment); it may then amalgamate with adjacent layers depending on numerical criteria within the model.

The model operates by estimating the increase in inflow thickness due to entrainment by:

$$h_i = 1.2 E dx + h_{i-1}$$

where h_i is the inflow thickness, E is the entrainment rate and dx is the distance travelled by the inflowing water, calculated from the flow rate and inflow thickness. For the initial calculation:

$$h_0 = \left(2 {Q_i}^2 \frac{Ri}{g'} \, tan^2 \beta \right)^{0.2}$$

where Q is the flow rate provided as a boundary condition, Ri is the Richardson number, g' is reduced gravity and β is the slope of the inflow at the point where it meets the water body. The flow is estimated to increase according to:

$$Q_i = Q_{i-1} \left[\left(\frac{h_i}{h_{i-1}} \right)^{5/3} - 1 \right]$$

and E is calculated from either:

$$E = \frac{3}{4} \left[\frac{5 \, tan\Phi}{F^2} - \frac{5 C_D}{\sin \beta} \right] \frac{F^2}{(3F^2 + 2)}$$

or:

$$E = 1.6 \frac{{C_D}^{1.5}}{Ri}$$

where C_D is the user specified drag coefficient for the inflow and Ri of the inflow is estimated from:

$$Ri = \frac{C_D \left(1 + 0.21 C_D \, sin \left[\frac{\beta \pi}{180} \right] \right)}{sin \left[\frac{\beta \pi}{180} \right] sin \left[\frac{\Phi \pi}{180} \right] / cos \left[\frac{\Phi \pi}{180} \right]}$$

Outflows can be specified at any depth over the water column and they are accounted for by removing water from the layer at the depth defined at the outlet point and computation of the Grashof number:

$$Gr = \frac{N^2 A_i^2}{{u_{out}}^2}$$

Model Setup Data Requirements

The model requires the user to supply a hypsographic curve, $A = A(h)$, to describe the storage, elevation, area & volume relationship, meteorological time-series data for surface forcing, and daily time-series of volumetric inflow and outflow rates. Further details of the model setup and file formats are outlined in the GLM Setup section.

A summary of relevant parameters within the model and their default values are summarised below in Table 1 for general lake parameters, and for the snow-ice model specifically in Table 2.

Table 1. Summary of GLM physical parameters with recommended values and references.

Symbol	glm.nml ID	Description	Units	Default	Reference	Comments
Model Structure						
h_{min}	min_layer_thick	Minimum layer thickness	m	0.5	-	Standardised for multi-lake comparison
h_{max}	max_layer_thick	Maximum layer thickness	m	2	-	Should be estimated relative to lake depth.
Lake Properties						
K_w	Kw	Extinction coefficient for shortwave radiation	m^{-1}	0.2	Lake specific	Should be measured, e.g. mean of simulation period
Surface Thermodynamics						
C_H	ch	Bulk aerodynamic coefficient for sensible heat transfer	-	0.0014	Fischer et al. 1979	From Hicks' (1972) collation of ocean and lake data; many studies since use similar values.
C_E	ce	Bulk aerodynamic coefficient for latent heat transfer	-	0.0013	Fischer et al. 1979	
C_M	coef_wind_drag	Bulk aerodynamic coefficient for transfer of momentum	-	0.0013	Fischer et al. 1979	
λ	-	Latent heat of evaporation	$j\ kg^{-1}$	2.453×10^6	Standard	Not adjustable in GLM.nml
ε	-	Emissivity of the water surface	-	0.97 0.95	Standard	Water only, no ice Ice or snow
σ	-	Stefan-Boltzmann constant	$W\ m^{-2}\ K^{-4}$	5.67E-08	Standard	Not adjustable in GLM.nml
Mixing Parameters						
C_K	coef_mix_conv	Mixing efficiency - convective overturn	-	0.2	Yeates & Imberger 2004	Selected by Yeates et al (2004) from a range given in Spigel et al. (1986)
C_W	coef_wind_stir	Mixing efficiency - wind stirring		0.23	Spigel et al. 1986	From Wu 1973
C_S	coef_mix_shear	Mixing efficiency - shear production	-	0.3	Sherman et al. 1978	Best fit of experiments reviewed
C_T	coef_mix_turb	Mixing efficiency - unsteady turbulence (acceleration)	-	0.51	Casamitjana et al. 2003	
K_H	coef_mix_KH	Mixing efficiency - Kelvin-Helmholtz turbulent billows		0.3	Sherman et al. 1978	"a good rule of thumb..."
α_{TKE}	coef_mix_hyp	Mixing efficiency of hypolimnetic turbulence	-	0.5	-	
Inflows & Outflows						
C_D	strmbd_drag	streambed_drag	-	0.016		
u_{out}	-	Maximum withdrawal velocity	$m\ s^{-1}$	-	Casamitjana et al. 2003	

Table 2. Summary of ice model parameter descriptions, units and typical values.

Symbol	Description	Units	Default value
I_{e1}	Waveband 1, snow ice light extinction	m^{-1}	48.0
I_{e2}	Waveband 2, snow ice light extinction	m^{-1}	20.0
I_{i1}	Waveband 1, blue ice light extinction	m^{-1}	1.5
I_{i2}	Waveband 2, blue ice light extinction	m^{-1}	20.0
I_{s1}	Waveband 1, snow light extinction	m^{-1}	6
I_{s2}	Waveband 2, snow light extinction	m^{-1}	20
D_z	Distance of heat transfer, ice water	m	0.039
r_e	Density, snow ice	kg m^{-3}	890
r_i	Density, blue ice	kg m^{-3}	917
r_s	Density, snow	kg m^{-3}	variable
c_{pi}	Heat capacity, ice	kJ kg^{-1} $^oC^{-1}$	2.1
c_{pw}	Heat capacity, ice	kJ kg^{-1} $^oC^{-1}$	4.2
K_c	Compaction coefficient	-	variable
K_e	Thermal conductivity, snow ice	W m^{-1} $^oC^{-1}$	2.0
K_e	Thermal conductivity, blue ice	W m^{-1} $^oC^{-1}$	2.3
K_e	Thermal conductivity, snow	W m^{-1} $^oC^{-1}$	variable
K_e	Thermal conductivity, sediment	W m^{-1} $^oC^{-1}$	1.2
K_e	Thermal conductivity, water	W m^{-1} $^oC^{-1}$	0.57
L	Latent heat of fusion	kJ kg^{-1}	0334

GLM-FABM-AED Setup

Overview

Here a description of the structure of a GLM setup is described. GLM requires a configuration files and several time-series input files and integrates with FABM for water quality simulations (Figure 3).

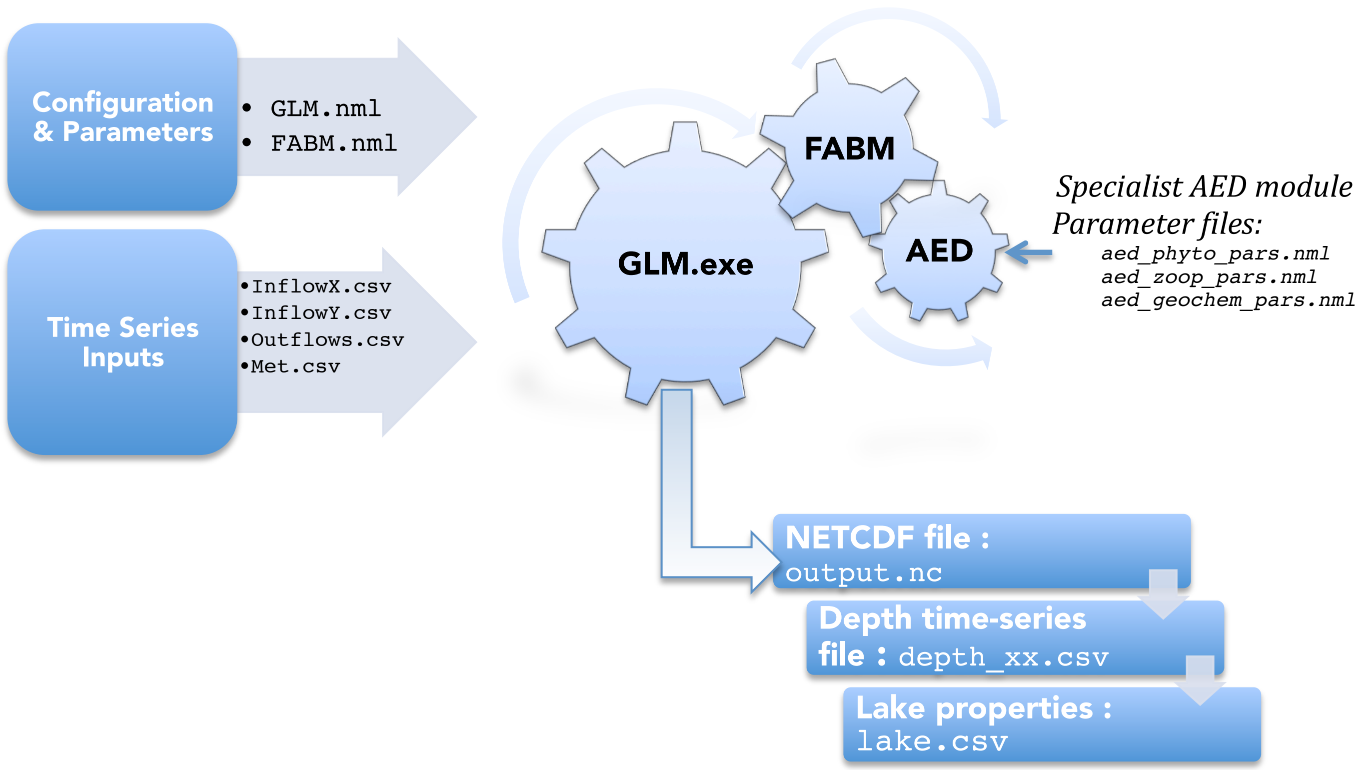


Figure 3: Flow diagram showing the files required for operation of the model.

Input files

Physical model configuration: glm.nml

The file `glm.nml` is the main configuration file for the physical model, and some details related to the FABM coupling. The nml file includes detailed description of the different namelist options for each block; if these values are not present default values will be assumed. It is a namelist (text) file with blocks for:

- `&glm_setup`: General simulation info
- `&fabm_setup`: Details about the FABM coupling
- `&time`: Time controls
- `&morphometry`: Lake morphometric information
- `&output`: Output file details
- `&init_profiles`: Initial profiles
- `&meteorology`: Information about surface forcing and meteorology data
- `&inflows`: Information about inflows
- `&outflows`: Information about outflows

Meteorology: `met.csv`

The meteorological conditions are provided as a daily or sub-daily time-series of data with a fixed number of columns, as outlined in Table 3. It contains seven compulsory columns, and several optional columns after these depending on the user-defined configuration switches for `snow_sw` and `rain_sw` in the `glm.nml` file. Note that if daily data is supplied then the surface heating and cooling will still be conducted at the model time-step, but using daily averaged data, with the exception of solar-radiation which will be fit to an idealised 24 hour night-day cycle.

Table 3: Outline of the meteorological boundary condition file required by the model.

Met.csv column	Units	Description
(1) TIME	YYYY-MM-DD *HH:MM:SS*	Date (Time)
(2) SHORTWAVE RADIATION	W/m^2	Daily average shortwave radiation. Note that the daily value is internally distributed to a sub-daily time step by assuming and idealized diurnal cycle.
(3) LONGWAVE RADIATION	W/m^2 if `lw_type` = LW_IN or LW_NET or 0 – 1 if `lw_type` = LW_CC	Longwave radiation input is either direct incident intensity, net longwave flux, or estimated from cloud cover fraction.
(4) AIR TEMPERATURE	°C	Daily average air temperature 10m above the water surface
(5) RELATIVE HUMIDITY	%	Daily average relative humidity (0-100%) 10m above the water surface.
(6) WIND SPEED	m/s	Daily average wind speed 10m above the water surface
(7) RAINFALL	m/day	Daily rainfall depth
(8) SNOWFALL (optional)	m/day	Daily snowfall depth (optional – include if `snow_sw` is T)
(9-14) RAINFALL WQ DEPOSITION CONCENTRATIONS (optional)	mg/L	… (optional – include if `rain_sw` is T)

Inflows: `inflows.csv`

Any number of inflows can be simulated by the model with the configuration and filenames set in the `glm.nml` file. For each inflow there is an associated inflow file of the format outlined in Table 4. At this stage the file only excepts daily data as the inflow calculation is done once a day. It contains four compulsory columns for time, flow, temperature and salinity, and optional columns for FABM constituents.

Table 4: Outline of the inflow boundary condition file required by the model.

Inflow.csv column	Units	Description
(1) TIME	YYYY-MM-DD	Date
(2) INFLOW	ML/day	Daily flow rate. Convert from m^3/s by multiplying by 86.4.
(3) STREAMFLOW TEMPERATURE	°C	Average daily streamflow temperature
(4) STREAMFLOW SALINITY	mg/L	Average daily streamflow salinity
(5 … n_{WQ}+4) STREAMFLOW FABM PARAMETER CONCENTRATIONS	mmol/m^3	Average daily streamflow FABM constituent concentrations.

Outflows: `outflows.csv`

Any number of outflow fluxes can be configured and these are set as consecutive columns in the file `outflows.csv` (Table 5). Only daily flow rates are required and FABM variables are not required.

Table 5: Outline of the outflow boundary condition file required by the model.

Outflow.csv column	Units	Description
(1) TIME	YYYY-MM-DD	Date
(2 … n_{OUT}+1) OUTFLOW	ML/day	Daily outflow rates of each outflow

Running the model

The model may be run by navigating to the directory where the `glm.nml` and `fabm.nml` files are and executing the model executable glm.exe. This can be located in different directory and added to the system path if desired.

Windows users may wish to add the command into a `glm.bat`:

```
..\bin\glm.exe >glm.log
```

which will create a file that can simply be double-clicked from windows explorer. The model will output to the netcdf and/or csv files that can then be plotted.

Note that the Windows pre-compiled model executable is distributed in a 32-bit and 64-bit release, so please choose what is appropriate for your system.

Outputs and post-processing

The model includes several types of outputs, including the NETCDF file, an optional csv time-series file at a certain point, and an optional live contour plot as the model runs to enable the modeller to monitor simulation progress.

Live output plotting: `plots.nml`

If the model is run with the optional command line argument "`--xdisp`" then the model will display live plots of output parameters. The number of plots, parameters to plot and the colour bar limits are set in the file `plots.nml`.

```
&plots
  nplots       = 4
  plot_width   = 400
  plot_height  = 200
  title        = 'Temperature','Salinity','DO (mg/L)','Chl-a'
  vars         = 'temp','salt','aed_oxygen_oxy','aed_phytoplankton_green'
  min_z        =  0.0,     0.0,              0.0,                          0.0
  max_z        = 27.0,    0.91,            800.0,                         20.0
/
```

Note that as of v1.3.2 the GLM plotting library will plotGLM variables including temp (T), salt (S), rad (ϕ_{SW}), extc (K_w) and all FABM variables including diagnostic variables stored in the NETCDF file.

Plotting in EXCEL

For simple time-series plots, the user can configure outputs from the model directly to a csv file for a certain depth (defined relative to the bottom), and this information is defined in the `glm.nml &output` section. The columns to plot must also be listed here and are user-definable. They can include any FABM variables.

Plotting with PyNCview

Not yet supported.

Plotting in R

Plotting the GLM output.nc in "**R**" is possible, though no plotting scripts are provided at this stage.

Plotting in MATLAB

For more advanced or customised plots, then the user may load the `output.nc` NETCDF file into MATLAB. Recent versions of MATLAB (MATLAB 2011a or after) natively support NETCDF and can load the file directly. An example MATLAB script for plotting is shown below - this can be customised as required.

```
foldername = '../MyGLMSim/';
outname    = '../ MyGLMSim /figures /';
mkdir([outname]);

data       = nldncGLM([foldername,'/output.nc'])

varNames   = names_netcdf([foldername,'output.nc']);
varsToPlot = varNames([20:64]);

for ii = 1:length(varsToPlot)
    newFig  = plotGLM(varsToPlot{ii},data);

    figName = [outname,'/', varsToPlot {ii},'.png'];
    print(gcf,'-dpng', figName,'-opengl');
    close all
end
```

Model Validation & Parameter Optimisation

There are numerous ways that model users may wish to assess model performance and to optimise their calibration with observed data. As part of a GLEON (gleon.org) lake modelling working group, a specific workflow for model assessment and calibration has been trialled and is outlined next. The approach a) uses the GLEON "LakeAnalyzer" analysis scripts to assess model comparisons across a range of metrics, and b) combines these assessment scripts with a Markov Chain Monte Carlo (MCMC) procedure.

Running the LakeAnalyzer validation

As part of a multi-lake comparison GLM has been compared against numerous different metrics of model performance. These include simple measures like surface or bottom temperature, however it is also possible to compare the model's performance in capturing higher-order metrics relevant to physical limnology. To calculate these on the model and field data, the LakeAnalyzer routines provided by Read *et al*. (2011). These have been adapted for GLM use and can be called via the run using the `calcGLMModelFit.m` and `plotGLMModelFit.m` scripts. An example output from Lake Kinneret is shown in Figure 4.

Field Files: `model_fld_temp.wtr` & `model.bth`

Together the `model_fld_temp.wtr` and the `model.bth` file give observed water temperature data and lake shape details that are compared against the model output. Both files are in a comma separated format and the same as what is required for running LakeAnalyzer.

The `model_fld_temp.wtr` file is a simple file consisting of time-stamped thermistor chain data. The first row given the date and thermistor chain ID's (Figure 5a). Note the date format must be saved as **YYYY-MM-DD**, prior to saving as a csv file.

The `model.bth` file is a simple two column file consisting of each thermistors depth, and the area of the bathymetry at that depth (Figure 5b). Save the files as csv.

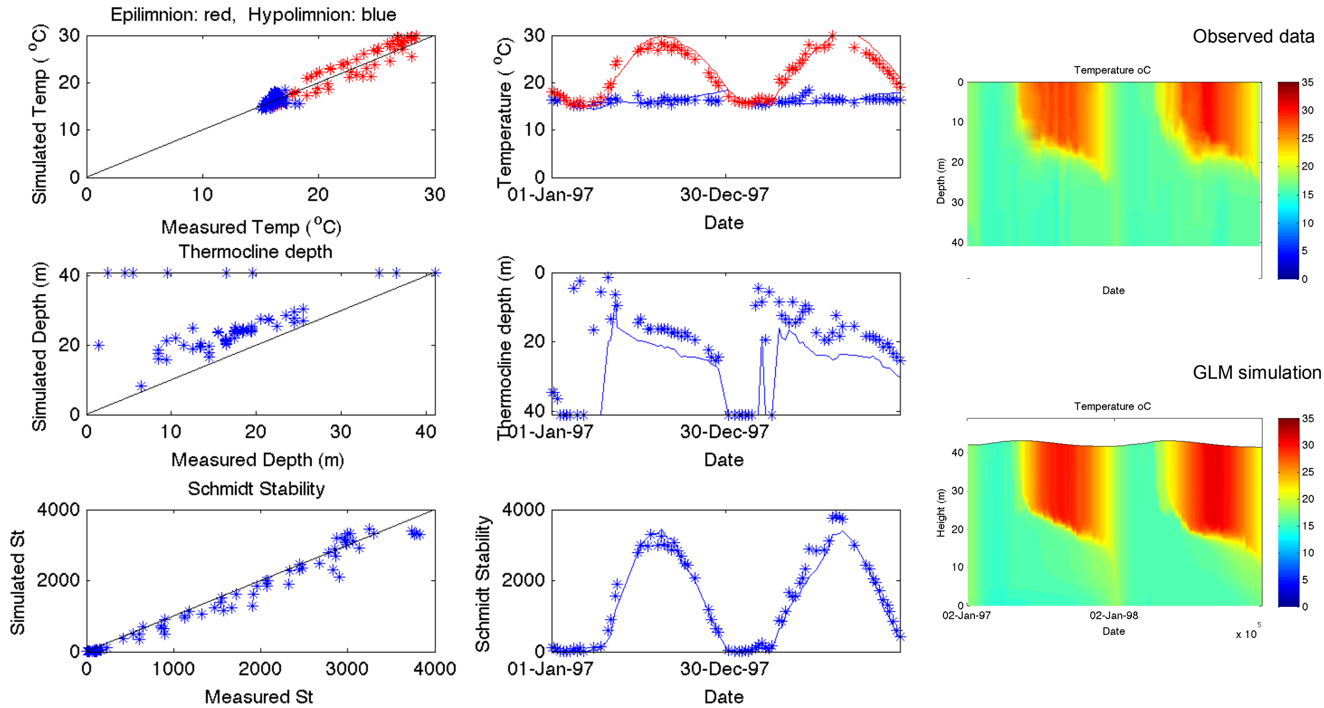


Figure 4: Example output from the GLM Lake Analyzer model assessment scripts.

Thermistor Chain ID's

Date Time (ISO Format)

	A	B	C	D	E	F	G
1	DataTime	temp0	temp0.5	temp1.0	temp1.5	temp2.0	temp2.5
2	1997/01/01 00:00	18.014375	18.0141875	18.014	18.00883333	18.00366667	18.00164583
3	1997/01/05 00:00	18.014375	18.0141875	18.014	18.00883333	18.00366667	18.00164583
4	1997/01/14 00:00	17.8175	17.80947222	17.80144444	17.79955556	17.79766667	17.79033333
5	1997/01/19 00:00	17.36322785	17.36197756	17.36072727	17.34280114	17.324875	17.3104375
6	1997/01/26 00:00	16.94884375	16.95194568	16.95504762	16.95589881	16.95675	16.95598611
7	1997/02/02 00:00	16.19581481	16.19803241	16.20025	16.20218056	16.20411111	16.20318056
8	1997/02/09 00:00	15.3412	15.34665556	15.35211111	15.35186806	15.351625	15.35142361
9	1997/02/16 00:00	15.95333333	15.92305556	15.89277778	15.867	15.84122222	15.83379861
10	1997/02/24 00:00	15.16827273	15.16909091	15.16990909	15.16889205	15.167875	15.16438194
11	1997/03/02 00:00	16.247	16.25240909	16.25781818	16.18484659	16.111875	15.85782639
12	1997/03/09 00:00	15.22820588	15.20935294	15.1905	15.1785	15.1665	15.1604375
13	1997/03/30 00:00	15.99888889	15.99727778	15.99566667	15.99138889	15.98711111	15.98499306
14	1997/04/13 00:00	16.949	16.9379375	16.926875	16.90325	16.879625	16.848
15	1997/04/29 00:00	19	19	19	18.5	18	18
16	1997/05/04 00:00	19.8	19.8	19.8	19.8	19.8	19.8
17	1997/05/13 00:00	23.90209859	23.9003618	23.898625	23.89447917	23.89033333	23.87566667
18	1997/05/18 00:00	24.57325	24.5649375	24.556625	24.54453472	24.53244444	24.52807222
19	1997/06/29 00:00	27.4	27.4	27.4	27.35	27.3	27.05
20	1997/07/06 00:00	27.5	27.5	27.5	27.5	27.5	27.5
21	1997/07/20 00:00	27.2	27.2	27.2	27.2	27.2	27.2

Each Thermistor in the wtr must be represented by a depth

Bathymetry Depths	Bathymetry Areas
0	170000
1	167000
4	162000
5	161000
6	160000
7	158000
8	157000
9	155000
10	153000
11	151000
12	150000
13	148000
14	146000
15	143000
16	139000
17	136000
18	132000
19	128000
20	123000
21	118000
22	113000
23	107000
24	102000
25	96400
26	90975

Figure 5: Outline of the required field data files to run the model validation for a) model_fld_tmp.wtr and b) model.bth.

Running the MCMC optimisation

As part of the modelling process, users may desire to calibrate their model to get the best fit with available field data. GLM may be run with a Markov Chain Monte Carlo (MCMC) routine that can be used to provide improved parameter estimates. On the GLM website we provide a version of GLM that works with the MCMC code provided by Haario *et al.* (2006), though users may wish to develop their own optimisation approach.

The MCMC routines are available as MATLAB scripts that will call `glm.exe` during the optimisation process. This is run using the `runMCMC.m` script. We have also prepared a pre-compiled form of the procedure that can run on windows machines via the command prompt, independent of MATLAB being installed, by running `runMCMC.exe`.

Note that for the pre-compiled version that has been supplied, users must have the MATLAB runtime environment (MCR) installed (http://www.mathworks.com.au/products/compiler/mcr/).

To run the model as part of the MCMC routine, users must prepare several extra files and directories. These include files for providing the observed field data (as above) and also files associated with the MCMC routine:

- Field/model.bth
- Field/model_fld_temp.wtr
- InputFiles/glm_init.nml
- InputFiles/mcmc_config.nml

The model will run and output a log of model RMSE and other information about the performance of different parameter combinations. These will be written to files in the `Results/` folder.

MCMC files: `glm_init.nml` & `mcmc_config.nml`

The `InputFiles/glm_init.nml` file is simply a duplicate of the starting simulation GLM nml file. The structure of this file is described in the above sections.

The `InputFiles/mcmc_config.nml` file is a namelist file which specifies certain parameters which governs how the optimisation routine functions. Currently, there are four sections:

- `&config`
- `&dataset`
- `&ssh`
- `&params`

The `&config` section contains the following variables:

- *Fld_temp_file* – Path to model_fld_temp.wtr file
- *Varname* – GLM variable name of data within the wtr file (e.g. 'temp')
- *Remote* – Switch for whether routine is run locally (0) or an a server via ssh (1)
- *Nsim_ini* – Number of simulations to run to get base values (should be between 10 and 1000)
- *Nsim_full* – Number of optimisation simulations to run (should be between 100 and 10000).

The `&dataset` section contains the following variables:

- *Data_Subsets*
- *Model_Fit* – Type of error calculation (e.g., RMSE, Nash-Sutcliffe, R^2, etc)

The `&ssh` section contains the following variables:

- *Host_Name*
- *Usr_Name*
- *Password*
- *Remote_Dir*
- *Run_GLM*
- *Output_File*
- *Varname*

The `&params` section contains the following variables and these are those that are to be included in the parameter optimisation. The values assigned to these variables is the starting parameter vector:

- *coef_mix_conv* – Coefficient related to mixing within glm.nml (see Table 1)
- *coef_wind_shear* – Coefficient related to mixing within glm.nml (see Table 1)
- *coef_mix_turb* – Coefficient related to mixing within glm.nml (see Table 1)
- *coef_mix_kh* – Coefficient related to mixing within glm.nml (see Table 1)
- *coef_mix_hyp* – Coefficient related to mixing within glm.nml (see Table 1)
- *ce* – Bulk transfer coefficient for latent heat, C_E.
- *ch* – Bulk transfer coefficient for sensible heat, C_H.
- *coef_wind_drag* – Bulk transfer coefficient for momentum, C_D.

Examples & Support

Downloads & Further Support

To download the model, visit:
http://aed.see.uwa.edu.au/research/models/GLM/

Support and FAQ's are available at the Aquatic Ecosystem Modelling Network (AEMON) website:
http://sites.google.com/site/aquaticmodelling/

For specific development requests, please contact Dr Louise Bruce, or A/Prof Matthew Hipsey from the School of Earth and Environment, at the University of Western Australia.

louise.bruce@uwa.edu.au
matt.hipsey@uwa.edu.au

Example Applications

Numerous applications are presented online as part of the GLM Multi-Lake Comparison Project (MLCP):

http://aed.see.uwa.edu.au/research/models/GLM/Pages/projects.html

Two example setups - "*warmlake*" and "*coldlake*" - are also available for download including a tutorial on their use. These simulations demonstrate working setups configured using various simulation options, including ice-cover for *coldlake*.

References

Casamitjana, X., Serra, T., Colomer, J., Baserba, C. and Pérez-Losada, J., 2003. Effects of the water withdrawal in the stratification patterns of a reservoir, *Hydrobiol.*, 504(1-3): 21-28

Chung, E.G., Bombardellia, F.A. and Schladow, S.G., 2009. Modeling linkages between sediment resuspension and water quality in a shallow, eutrophic, wind-exposed lake. *Ecol. Model.*, 220(9-10): 1251-1265

Fischer, H.B. List, E.J., Koh, R.C., Imberger, J. and Brooks, N.H., 1979. Mixing in inland and coastal waters. Academic, New York.

Gal, G., J. Imberger, Zohary, T, Antenucci, J., Ania, A. and T. Rosenberg. 2003. Simulating the thermal dynamics of Lake Kinneret. *Ecol. Model.,* 162: 69-86.

Gill A.E., 1982. Atmosphere-ocean dynamics. Academic Press, London.

Gu, R. and Stefan H.G., 1993. Validation of cold climate lake temperature simulation. *Cold Reg. Sci. Technol*., 13(2): 99-104.

Hamilton, D.P. & Schladow, S.G. 1997. Water quality in lakes and reservoirs. Part I Model description. *Ecol. Model*., 96: 91–110.

Haario, H., Laine, M., Mira, A. and Saksman, E., 2006. DRAM: Efficient adaptive MCMC, *Statistics Comput.,* 16: 339-354.

Harvey, L.D., 1990. Testing alternative parameterizations of lateral melting and upward basal heat flux in a thermodynamic sea ice model. *J. Geophys. Res*., 95: 7359-7365.

Imberger, J., 1985: The diurnal mixed layer. *Limnol. Oceanogr.*, 30, 737–770.

Imberger, J. and Patterson, J.C., 1981. A dynamic reservoir simulation model - DYRESM. *In "Transport Models for Inland and Coastal Waters."* H.B. Fisher (ed). Academic Press, New York. 310-361pp.

McCord, S.A., Schladow, S.G. and Miller, T.G., 2000. Modeling artificial aeration kinetics in ice covered lakes. *J. Environ. Eng.-ASCE,* 126: (1) 21-31 Jan. 2000.

Patterson, J.C. and Hamblin, P.F., 1988. Thermal simulation of a lake with winter ice cover. *Limnol. Oceanogr*., 33: 323-338.

Sherman, F.S., Imberger, J. and Corcos, G.M., 1978. Turbulence and mixing in stably stratified waters. *Annu. Rev. Fluid Mech*. 10: 267-288.

Spigel, R. H., J. Imberger, and K. N. Rayner, 1986: Modeling the diurnal mixed layer. *Limnol. Oceanogr.*, 31, 533–556.

Read J.S., Hamilton, D.P., Jones, I.D., Muraoka, K., Winslow, L.A., Kroiss, R., Wu, C.H., Gaiser, E., 2011. Derivation of lake mixing and stratification indices from high-resolution lake buoy data. *Environ. Model. Softw*., 26: 1325-1336.

Rogers, C.K., Lawrence, G.A. and Hamblin, P.F. 1995. Observations and numerical simulation of a shallow ice-covered mid-latitude lake. *Limnol. Oceanogr*., 40: 374-385.

Trolle, D., Hamilton, D.P., Hipsey, M.R., Bolding, K., Bruggeman, J., Mooij, W. M., Janse, J. H., Nielsen, A., Jeppesen, E., Elliott, J. E., Makler-Pick, V., Petzoldt, T., Rinke, K., Flindt, M. R., Arhonditsis, G.B., Gal, G., Bjerring, R., Tominaga, K., Hoen, J., Downing, A. S., Marques, D. M., Fragoso Jr, C. R., Søndergaard, M. and Hanson, P.C., 2012. A community-based framework for aquatic ecosystem models. *Hydrobiol.*, 683(1): 25-34.

Vavrus, S.J., Wynne, R.H., Foley, J.A., 1996. Measuring the sensitivity of southern Wisconsin lake ice to climate variations and lake depth using a numerical model. *Limnol. Oceanogr.,* 41: 822–831.

Wu, J. 1973. Wind induced entrainment across a stable density interface. *J. Fluid Mech.*, 61: 275-287.

Yeates, P.S. and Imberger, J. 2004. Pseudo two-dimensional simulations of internal and boundary fluxes in stratified lakes and reservoirs. *Int. J. Riv. Basin Res.*, 1: 1-23.