

Tracers

HYPE can simulate tracers in addition to water flows, nutrients and organic carbon. Tracers are simulated as a substance given in [info.txt](#) and follow the water as a concentration. Two tracers are implemented;

- T1 is a general tracer that can have different characteristics that is governed by model parameters
- T2 is water temperature

General tracer (T1)

T1 is the substance name for a general tracer. It can be used to simulate different substances, e.g. pathogens or O18 isotope. The tracer is simulated as a concentration in HYPE's water bodies, e.g. snow, soil water, surface water. In addition T1 can be simulated as adsorbed to soil, as a store above ground, and in river sediments.

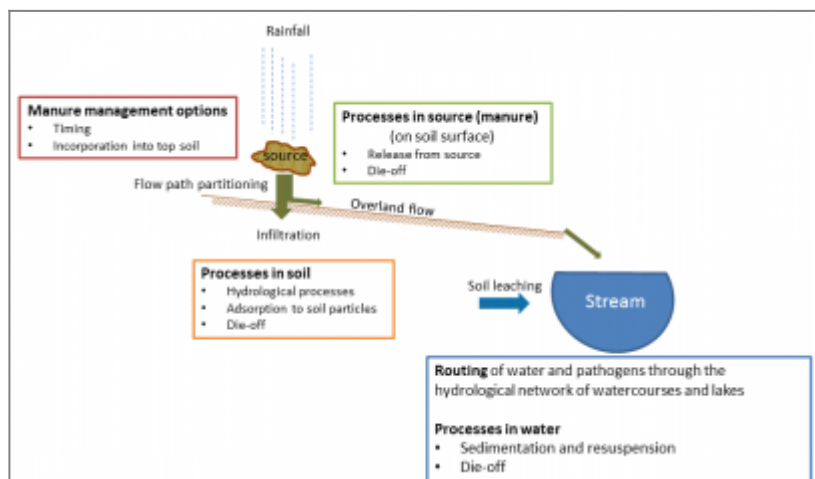


Figure 1: Example of T1 model used for simulating pathogens.

The following table shows how the unit of different tracers relates to each other and how they are related to input and output parameters and variables. The general unit (U) is used in tables of parameters and input data where the substance is not defined.

Variabel/parameter	General unit (U)	Weight (kg)	Number of pathogens (#)
Amount in manure/residuals (<i>t1amount</i>)	U/ha	kg/ha	#/ha
Point source concentration (<i>ps_t1</i>)	mU/m3 or μ U/L	mg/L	thousandth part/m3 or millionth part/L
Concentration of water as incoming source (<i>cpt1</i> , <i>t1leaksoil</i> / <i>t1leakluse</i>)	mU/m3 or μ U/L	mg/L	thousandth part/m3 or millionth part/L
Initial concentration parameters (<i>init1</i> , <i>init1sw</i>)	mU/m3 or μ U/L	mg/L	thousandth part/m3 or millionth part/L
Simulated amount T1 in or above soil (<i>aT11</i> , <i>aT12</i> , <i>aT13</i> , <i>sT11</i> , <i>sT12</i> , <i>sT13</i> , <i>T1sf</i>)	U/km2	kg/km2	#/km2

Variabel/parameter	General unit (U)	Weight (kg)	Number of pathogens (#)
Simulated amount T1 in river sediment (<i>Tsmr</i> , <i>Tslr</i>)	U	kg	#
Simulated concentration of water (<i>coT1</i> , <i>ceT1</i> , <i>csT1</i> , <i>ccT1</i> , <i>clT1</i> , <i>Tcr1</i> , <i>Tcr2</i> , <i>Tcr3</i> , <i>Tcrd</i> , <i>Tcrs</i>)	mU/m ³ or µU/L	mg/L	thousandth part/m ³ or millionth part/L
Observed concentration (<i>reT1</i>)	mU/m ³ or µU/L	mg/L	thousandth part/m ³ or millionth part/L

Sources

There are four different ways to introduce the tracer T1 to the model:

1) T1 may be added as a concentration in precipitation (*cpt1*). This concentration is added as a time series in [Xobs.txt](#).

2) Point sources may be a source of T1 to surface waters. Point sources of tracer T1 can be added to the local stream, the local lake, the main river or the outlet lake.

3) A pool laid down on land can be a source of the tracer. The pool is defined similar to the manure for nutrients (*t1amount*). It can be added at a specific point in time or equally distributed over a period of time. The pool may be tilled down into the top soil layers also in similar fashion as manure.

4) The tracer can be introduced to HYPE in the form of typical concentrations for leakage from different land-uses and/or soil types. The concentration of the runoff from a class (*conc*) is calculated as the product of two model parameters:

$$conc = t1leakluse \times t1leaksoil$$

One parameter is land use dependent (*t1leakluse*) and one is soil type dependent (*t1leaksoil*).

The source of tracer by a typical concentration (introduction way 4) is not compatible with the sources concentration of precipitation (introduction way 1) and pool on the ground (introduction way 3).

Processes

In its basic state, T1 act as a tracer passively following the water through the model (except for evaporation). By supplying input data and parameter values this behaviour may be changed to simulate a non-conservative substance, e.g., a patogen.

Evaporation

As default T1 do not follow evaporating water. This is an exception from the basic assumption that T1 is a conservative tracer if no parameters are set. The tracer will follow evaporating water (with same concentration as the water it is evaporating from) if the model parameter *t1evap* is set to one. Default is zero. It is possible to set a value between zero and one so that the tracer partly follows evaporating water.

Release from above ground storage

T1 can be released from a storage above ground (e.g. manure) by rain and snowmelt (flow q (mm/day)). The released tracer will follow the flow, as a concentration, and depending on the fate of the flow, the tracer may follow surface runoff, infiltration or other path ways. The release is governed by the model parameter $t1rel$ (1/mm). A fraction (a_{rel}) of the total amount of tracer in the store above ground is released and follows the flow according to equation:

$$a_{rel} = 1 - e^{-t1rel \times q}$$

Exponential decay

Patogens grow and die over time. To simulate this, HYPE supplies a process for the combined effect as an exponential decay. The process is governed by the model parameter $t1expdec$, which denote the half life time of the tracer in days. Exponential decay is applied to tracer T1 in most forms; in soil water, river, lakes, the above ground storage, tracers adsorbed to soil and tracers in river sediment.

Adsorption/desorption

Tracer adsorption/desorption to/from soil particles is calculated based on an equilibrium concentration (c_{eq} (e.g. number of pathogens/L or U/L)) of soil water. The equilibrium concentration is assumed to be reached within one time step of the model, typically one day, and this gives the amount of tracer adsorbed or desorbed during the time step is calculated. The equilibrium concentration (c_{eq}) is calculated from the amount of tracers and soil characteristics. The equation is:

$$c_{eq} = \frac{t1freuc \times Atot}{\left(v + t1freuc \times b_{density} \times d \right)}$$

where $Atot$ is the sum of tracer adsorbed and solved in soil water of the soil layer (U/km²), v the volume of water in the soil layer (mm), $b_{density}$ is soil density (1300 kg soil/m³), and d is the thickness of the soil layer (m). The general model parameter $t1freuc$ is an equilibrium concentration coefficient. In the case of pathogens, the model parameter describes the number of pathogens adsorbed to one kg of soil per pathogens in one litre of soil water (or in general unit (U/kg soil)/(U/L)).

Sedimentation/resuspension in river

Sedimentation or resuspension of tracers in rivers is calculated the same way as particulate phosphorus (described [here](#)). The process depends on the current flow (q) in the river in relation to bankful flow (q_{bank}) and the general model parameter $t1sedexp$. Bankful flow is the flow when the river is filled to the brim. This flow is calculated as the second largest simulated flow in the last year. The fraction of the tracer that is resuspended or sedimented is determined by the equation:

$$a_{sres} = \max \left(-1, \min \left(1, \frac{q_{bank} - q}{q_{bank}} \frac{t1sedexp}{t1sedexp} \right) \right)$$

For low flow, the fraction (a_{sres}) is positive and sedimentation (F_{sed} (U/day)) occur, for high flow the fraction is negative and there will be resuspension from the sediments instead (F_{resusp} (U/day)):

$$F_{sed} = a_{sres} \times c_{river} \times v_{river}, a_{sres} > 0$$

$$F_{resusp} = -a_{sres} \times A_{sed}, a_{sres} < 0$$

where c_{river} is the concentration of T1 in river (U/m3), v_{river} is the volume of river (m3), and A_{sed} is amount of tracer T1 in the sediment (U).

Sedimentation in lakes

Sedimentation of tracer T1 in lakes is calculated the same way as e.g. particular phosphorus. The sedimentation is goverend by sink velocity (m/d), which is given by the general model parameter *t1sedvel*.

Links to file reference

Section	Symbol	Parameter/Data	File
General tracer (T1)		<i>init1, init1sw</i>	par.txt
Sources		<i>cpt1</i>	Xobs.txt
		<i>ps_t1</i>	PointSourceData.txt
		<i>t1amount</i>	CropData.txt
	<i>t1leakluse, t1leaksoil</i>	<i>t1leakluse, t1leaksoil</i>	par.txt
Processes	<i>t1rel, t1sedexp, t1freuc</i>	<i>t1rel, t1sedexp, t1freuc</i>	par.txt
		<i>t1evap, t1expdec, t1sedvel</i>	
	<i>d</i>		GeoClass.txt

Links to relevant procedures in the code

Modules (file)	Procedures
tracer_processes (t_proc.f90)	add_tracer_point_source_to_river
	add_tracer_point_source_to_lake
	soil_tracer_processes
	tracer_processes_in_river
	tracer_processes_in_lake
	decay_of_tracer
	decay_of_tracer_sorbedphase
	sorption_of_tracer
	sedimentation_resuspension_of_tracer
	T1_crop_sources
	T1_incorporation
	release_from_source

Water temperature (T2)

Water temperature can be simulated by HYPE with the substance/tracer called T2. Water temperature is suitable to be simulated in a catchment model, because it relates to the hydrology and the landscape. The substance follows the water paths in HYPE and is calculated in degree Celsius.

Sources

There are different ways to introduce heat into the water of HYPE.

Initial value of water temperature of HYPE's water bodies can be set by model parameters. The general parameter *iniT2* is used for some water bodies, i.e. soil, rivers and lakes. Aquifer temperature is given in [AquiferData.txt](#) (*temp*).

Snow and glacier melt water is assumed to hold zero degrees.

Precipitation

Temperature of precipitation on land is set to air temperature (but limited to zero).

For water surfaces the temperature setting is more complex. Temperature of rain on water is set to air temperature (but limited to zero). Snowfall are assumed to have the average temperature of the water (uppertemp for lakes, mean temperature for rivers) for ice conditions, i.e. not to influence the temperature of the water. For snowfall on open water the temperature is calculated as dependent on sensible heat content and latent heat of freezing, taken into account different specific heat capacity of ice and water. Temperature of precipitation is a weighed average of these three components.

Point source

Point sources influence the water temperature T2. Point sources may have a constant temperature set from indata (*ps_t2*) or otherwise the water is assumed to be zero degrees. Point sources of tracer

T2 can be added to the local or main river, or internal or outlet lake.

Local diffuse source

The water of local diffuse source is not allowed to influence the water temperature of the receiving water body (soil or local river).

Soil processes

The primary process for changing water temperature is exchange of heat over a water surface. Apart from that, surface water temperature is determined by mixing water of different temperature. Exceptions have been made for some processes not to influence the water temperature. This because their effect on water temperature has not yet been included in full.

Soil temperature

In addition to the “concentration” of T2 in soil water, the (solid) soil layer has their own temperature state variables. Temperature of soil, i.e. solid material, is calculated separately from the T2 temperature of soil water. The temperature of a soil layer depends on the air temperature and the deep soil layer temperature to different degree. Deep soil layer temperature is calculated separately. See Chapter [Soil temperature and snow depth](#).

Temperature T2 of soil water is not yet developed and is simply set to the temperature of soil. Still, snow melt are assigned the temperature T2 zero. Evaporation of soil water is not affected by T2 or affecting soil water T2.

Runoff

Soil runoff temperature is set from soil layer temperatures. Tile drainage temperature is set to the temperature of the soil layer it originates from. Surface runoff gets the temperature from soil layer one (saturated overland flow) or rainfall, snowmelt and glaciermelt (excess infiltration).

Lake and river ice

The river ice routines are performing best if the special classes for local and main river is set. The routines then use the forcing data and snow parameters defined for these classes. If the river classes is not set, forcing and snow parameters for lakes are used as a replacement. If no lake classes are provided, forcing and snow parameters are taken from slc class one, whatever that is.

Floating snow covered ice sheet model

Lake and river ice is simulated with a simple thermodynamic ice model driven by air temperature and precipitation. It is to a large extent adopted from the models presented by Leppäranta (1983, 1993),

in which lake and river ice is represented by a floating snow covered ice sheet characterized by three layers of frozen water: black ice, snow ice, and snow (Figure 2, left). If the top of the ice layer is submerged under water, the depth of a slush layer (wet snow) is also defined (Figure 2, right).

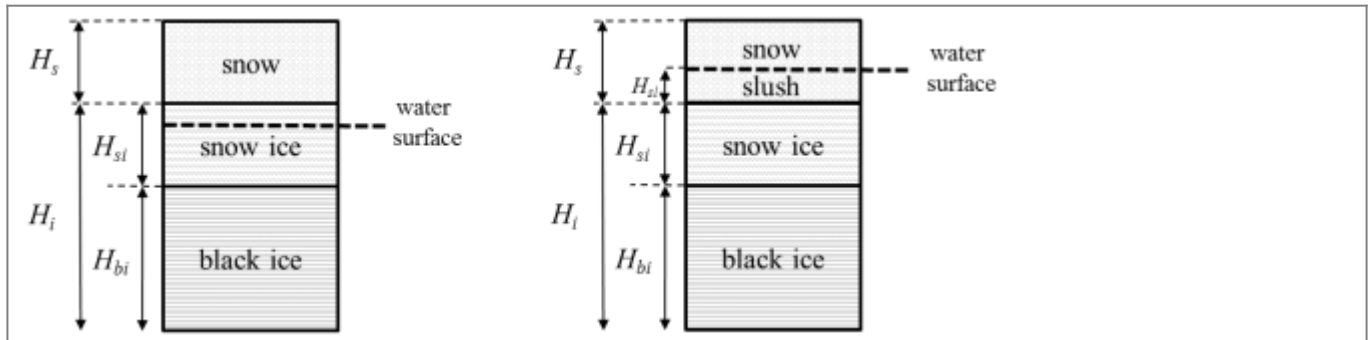


Figure 2: A floating snow covered ice sheet with (left) three layer of frozen water black ice, snow ice and snow and (right) with a slush (wet snow) layer formed when the top of the ice is sub-merged under water due to the load of the snow pack.

Influence of the ice model on lake and river evaporation and water temperatures

It should be noted that in the current version of the HYPE model, the ice mass balance is independent from the mass balance of the lakes and rivers. No water is removed from lake or river water to form the ice cover and no water is added to the lake and river when the ice is melting. This simplification is reasonable only for rivers and lakes large enough to never freeze to the bottom. The ice model influences lake and river water only through its' impact on water temperatures and evaporation:

- evaporation from lakes and rivers is set to 0 in the presence of ice
- heating and cooling of lakes and rivers through surface heat exchange with the air is set to 0 in the presence of ice
- lake and river water temperature is adjusted to take into account the inflow of 0°C melt water during ice melt

Water temperature is also adjusted to take into account the heat needed to melt snowfall on ice-free lakes and rivers.

Black ice growth

Black ice growth ($\frac{dH_i}{dt}$ (cm/s)) is derived from the modified Stefan's equations as described by Leppäranta (1983):

$$\frac{dH_i}{dt} = \frac{k_i}{\rho_i \times L_f} \times \frac{(T_f - T_a)}{\left(H_i + H_s \times \frac{k_i}{k_s} + \frac{k_i}{k_a} \right)}$$

The first part is constant in HYPE. k_i is thermal conductivity of ice (0.022 J/°C/cm/s), ρ_i is density of ice (0.917 g/cm³), and L_f is latent heat of freezing (334 J/g).

T_f is freezing temperature of lake or river water (°C), a parameter. T_a is air temperature (°C). H_i is ice

depth (cm) and H_s is snow depth on the ice (cm). k_a is heat exchange coefficient with atmosphere ($\text{J}/^\circ\text{C}/\text{cm}^2/\text{s}$). k_s is thermal conductivity of snow ($\text{J}/^\circ\text{C}/\text{cm}/\text{s}$). It is calculated from thermal conductivity of ice and snow and ice density, and a parameter k_{exp} :

$$k_s = k_i \times \left(\frac{\rho_s}{\rho_i} \right)^{k_{\text{exp}}}$$

where ρ_s is density of snow (g/cm^3). Snow density changes over time depending on a change parameter (*sndens*).

The heat released when the black ice is formed at the bottom of the ice layer ($\rho_i \times L_f \times \frac{dH_i}{dt}$) is conducted through the ice and the overlaying snow layer to the atmosphere. This heat flow is driven by the temperature gradient between the air above the ice or snow surface and the freezing temperature of the water assumed at the bottom of the ice layer, and is governed by the depths and thermal conductivities in the ice and snow layers, and the heat exchange coefficient in the air. It should also be noted that a term representing the heat flow from the water has been neglected compared to Leppäranta (1983).

The black ice growth equation is only used if the ice surface is above the water surface (in other words, if there is no slush layer on top of the ice to be frozen first) and if air temperature is below the freezing temperature T_f .

Snow ice growth

If the mass of the snow layer exceeds the floating capacity of the ice, the bottom of the snow layer will be submerged in lake water, and a slush layer (H_{sl}) will form with a depth according to:

$$H_{sl} = \frac{H_s \times \rho_s - H_i (1 - \rho_i)}{\rho_s / \rho_i}$$

As pointed out by Leppäranta (1993), the freezing of slush into snow ice releases less heat compared to black ice growth since the slush already consists of frozen snow particles, and this heat only need to be conducted through the snow pack. The growth of snow ice can thus be calculated by the following equation from Leppäranta (1993):

$$\frac{dH_{bi}}{dt} = \frac{k_s}{\left(\rho_i \times L_f \left(1 - \frac{\rho_s}{\rho_i} \right) \right)} \times \frac{(T_f - T_a)}{\left(H_s + \frac{k_i}{k_a} \right)}$$

where all variables are defined above for black ice growth.

Ice melt and final ice break-up

Snow and ice melt is calculated with a simple temperature index model when air temperature is above 0°C. The snow on the ice has to be completely melted before any ice melt is calculated:

$$\frac{dH_i}{dt} = -p_m \times T_a$$

Ice can be melted from below if the water contain enough heat. This process is limited by a melt efficiency parameter (me).

Final ice break-up is defined as the time step when $H_i=0$. Although it is well known that ice tend to fall apart before it is completely melted, this is not considered by the present model.

Initiation of ice growth

Ice growth is initiated when the solution of the surface heat balance for the open water results in a water temperature below the freezing point. The fraction of the water surface with new ice formation is then estimated by reducing the open water surface area until the surface heat balance solution results in a water temperature equal to the freezing point. The transition from fully ice-free to fully ice-covered conditions is thus smoothed by the gradual increase in fractional ice cover. For deep lakes, the temperature of an upper layer (EPI, Figure 3 below) is used for the onset of ice growth, whereas for shallow lakes and rivers, the mean water temperature is used.

Surface water processes

Temperature T2 of a river is not affected by irrigation withdrawal, abstractions, rural households or point source additions, constructed wetlands, or water returning from aquifers.

Lake basic assumptions

For substances the lake volume is divided into two parts FLP and SLP (see Chapter [Rivers and lakes - Basic assumptions](#)). In addition to simulating temperature as the substance T2 in the two lake parts, states of lake temperature in a hypothetical epilimnion and hypolimnion (*uppertemp*, *lowertemp*) is handled in the model. The average temperature of FLP+SLP is equal to the average temp of the EPI+HYPO. The size of volumes related to the upper and lower temperatures are determined by the thermocline which is estimated for each lake.

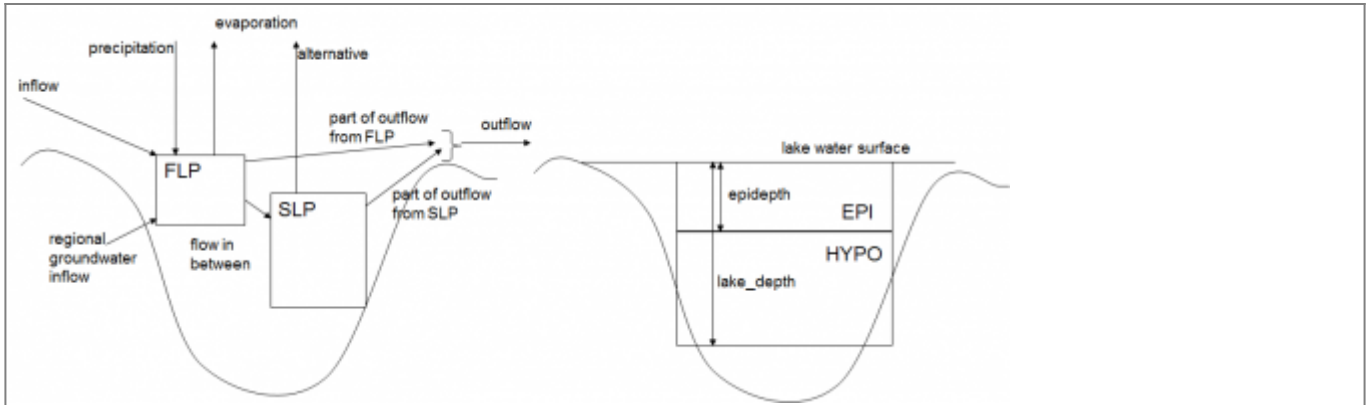


Figure 3: Two different divisions of a lake. Left: two parts signifying fast flows (FLP) and slow flows (SLP). Right: epilimnion (EPI) and hypolimnion (HYPO).

Thermocline depth is estimated from lake area (Hanna, 1990). This average depth is adjusted for current changes by adding precipitation (*prec*) and inflow (*qin*) to the lake, and remove evaporation (*evap*).

$$epidepth = 6.95 \times lakearea^{0.185} + prec - evap + qin$$

where *lakearea* is (km²) and *epidepth* is in m below lake surface. Precipitation, evaporation and inflow is also in meter.

The adjusted depth (*epidepth*) is then used as the division of the lake volume into upper and lower if the lake water depth is larger than the *epidepth*. Otherwise the lake is treated as one single mixed volume in regard to T2 calculations.

Evaporation

Lakes and rivers with given class area may have evaporation. The actual evaporating area is reduced if it is ice covered. Evaporation is not changing the T2 temperature of the river or lake. The latent heat is assumed to be taken care of by the water - atmosphere T2 exchange routine. River evaporation is removed proportionally from the water stores making up the river volume. Lake evaporation may be removed from one or both lake parts (FLP and SLP).

Evaporation from flooded floodplain of rivers or lakes also keep the temperature of the flooded water unchanged.

Water - atmosphere T2 exchange

River and lake water atmosphere exchange is calculated during ice free conditions. Water surface heat balance is calculated based on a model by Piccolroaz et al (2013), with modifications for fractional ice cover, and calculation of fractional freezeup area. This equation depends on four general parameters; *tcf*-temperature difference coefficient, *scf* - solar radiation coefficient, *ccf* - constant coefficient and *lcf* - linear coefficient. The parameters comes in one set for rivers (*tcfriver*, *scfriver*, *ccfriver*, *lcfriver*) and one set for lakes (*tcflake*, *scflake*, *ccflake*, *lcflake*).

A simpler T2 exchange model based only on the temperature difference between air and water is also available. It has two general heat transfer parameters (*t2trlake*, *t2trriver*, unit J/m²/s/degree).

For rivers with no specified river area as a class, a river area is calculated for use in the water - atmosphere T2 exchange and ice processes. The river area is calculated as described in Section [Nitrogen and phosphorus processes in rivers and lakes](#). In addition the river area may be reduced at low volume/flow. This is controlled with parameters (see [River and Lakes - Evaporation](#)).

T2 stratification

At spring and autumn circulation, T2 temperature is averaged out between upper and lowertemp. During periods with stratification a heat transfer between the uppertemp and lowertemp is assumed. This heat transfer depend on the general parameter *upper2deep* (J/m2/s/degree).

Lake outflow

Lake outflow T2 temperature may be determined by the T2 of the lake parts (FLP and SLP) contributing to outflow (see Figure 2). To use this method set parameter *t2mix*. For ilakes the *t2mix* method is always used.

For outlet lakes another method for determining lake outflow temperature is the default method. This method assigns uppertemp to outflow water if the lake is stratified and the thermocline is deeper than the lake threshold (*thres*). For other conditions a mixture of upper and lowertemp is used to set the outflow temperature (*t2out*).

$$t2out = fraction \times uppertemp + (1 - fraction) \times lowertemp$$

$$fraction = \frac{epidepth}{(lakewst - thres)}$$

where *lakewst* is the current depth of the lake.

References

- Hanna 1990. Evaluation of models predicting mixing depth, Can. J. Fish. Aquat. Sci., 47:940-947.
- Leppäranta, M. 1983. A Growth Model for Black Ice, Snow Ice and Snow Thickness in Subarctic Basins. Nordic Hydrology, 14(2):59-70.
- Leppäranta, M. 1993. A review of analytical models of sea-ice growth, Atmosphere-Ocean, 31(1):123-138.
- Piccolroaz, S., M. Toffolon, and B. Majone 2013. A simple lumped model to convert air temperature into surface water temperature in lakes, Hydrol. Earth Syst. Sci., 17:3323-3338, doi:10.5194/hess-17-3323-2013.

Links to file reference

Section	Symbol	Parameter/Data	File
Sources		<i>iniT1</i>	par.txt
		<i>temp</i>	AquiferData.txt
		<i>ps_t2</i>	PointSourceData.txt
Lake and river ice	T_f	<i>ricetf, licetf</i>	par.txt
	k_a	$k_i k_a = \frac{k_i}{k_a}$ calculated from <i>ricekika, licekika</i> ,	
	k_{exp}	<i>ricekexp, licekexp</i>	
	<i>sndens</i>	<i>ricesndens, licesndens</i>	
	p_m	<i>ricetmelt, licetmelt</i>	
	<i>meff</i>	<i>ricewme, licewme</i>	
Surface water processes	<i>tcf</i>	<i>tcfriver, tcflake</i>	par.txt
	<i>scf</i>	<i>scfriver, scflake</i>	
	<i>ccf</i>	<i>ccfriver, ccflake</i>	
	<i>lcf</i>	<i>lcfriver, lcflake</i>	
		<i>t2trlake, t2trriver, upper2deep, t2mix</i>	
	<i>thres</i>	<i>lake_depth</i>	GeoData.txt or LakeData.txt or DamData.txt

Links to relevant procedures in the code

Modules (file)	Procedures	Section
tracer_processes (t_proc.f90)	add_tracer_point_source_to_river	point source
	add_tracer_point_source_to_lake	
npc_surfacewater_processes (npc_sw_proc.f90)	add_point_sources_to_main_river	
npc_soil_processes (npc_soil_proc.f90)	set_class_precipitation_concentration_and_load	precipitation
surfacewater_processes (sw_proc.f90)	add_T2_concentration_in_precipitation_on_water	evaporation
	calculate_river_evaporation	
	calculate_lake_epilimnion_depth	lake basic assumptions
	calculate_T2_transfer_upper2lower	T2 stratification
	T2_processes_in_river	water - atmosphere T2 exchange
	T2_processes_in_lake	
	calculate_watersurface_heatbalance	Lake and river ice
	ice_processes_in_river	
	ice_processes_in_lakes	
	calculate_icedepth	
	calculate_snow_on_ice	
	riverice_riverwater_interaction	
	calculate_lakeice_lakewater_interaction	
	calculate_snowmelt	
soil_processes (soil_proc.f90)	calculate_snowdepth	
	calculate_snow	sources

Modules (file)	Procedures	Section
regional_groundwater (regional_groundwater.f90)	initiate_aquifer_state	
soilmodel_default (soilmodel0.f90)	soilmodel_0	soil temperature and runoff
glacier_soilmodel (glacier_soilmodel.f90)	soilmodel_3	
soilmodel_4 (soilmodel4.f90)	soilmodel_4	