

# Introducing KHIONE – (Eulerian) Part I of the ice modelling component of TELEMAC

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**Abstract** — With a view to expand the applicability of the TELEMAC system to cold waters around the world, EDF R&D and HR Wallingford jointly financed the development of a new ice modelling component in collaboration with the ice modelling experts from Clarkson University, USA. This collaboration has seen years of experience and ice modelling capabilities of the Clarkson's team introduced into the TELEMAC system.

Various ice processes can occur in cold regions during winter periods. These include complex interactions between thermal-ice processes and ice dynamics coupled with hydrodynamics. This Part I article introduces those based on the Eulerian assumption. Part II will later introduce processes based on the Lagrangian assumption. Some of the validation cases developed to demonstrate KHIONE's capabilities are presented.

## I. INTRODUCTION

The state of the art knowledge and modelling capabilities in ice processes resides in northern countries that have major infrastructures recurrently subject to ice for long periods of time. To name only a few, several industries in Canada, the USA, Northern Europe and Russia, Japan, and China are influenced by ice processes over water bodies. The presence of ice in waters affects the design and operation of coastal and riverine infrastructure and projects in addition to impacts on ecological and environmental conditions of water bodies. For instance, the St. Lawrence River is a major transportation route between the Atlantic and the Great Lakes for both the USA and Canada. It also serves the hydropower industry in those countries. Great portions of the St. Lawrence River freeze-up during the winter months. Similarly, the Yellow River is essential for China's very existence while being the cause of devastating floods. Amongst those floods, the breakup of ice jams in Inner Mongolia has caused extreme loss of life and property in the past century.

With a view to expand the use of the TELEMAC system to these waters and other cold regions around the world, EDF R&D and HR Wallingford jointly financed the development of a new ice modelling component in collaboration with the experts of the Department of Civil and Environmental Engineering, Clarkson University, USA. Years of experience and of development of ice

modelling capabilities within the Clarkson's team were introduced into the TELEMAC system to produce KHIONE.

Somewhat in line with the naming tradition of TELEMAC, the new component was named KHIONE, from the Greek goddess of snow and ice, daughter of Borea (god of the northern wind), and who had a son with Poseidon (god of the sea).

This article is Part I of two parts, focusing on the ice processes based on the Eulerian assumption. Part II, anticipated for the XXVI<sup>th</sup> TELEMAC User Conference will later introduce processes based on the Lagrangian assumption. These processes have been integrated in the version v8p0 (released later in 2018) and are therefore documented and available in parallel.

## II. POSITIONING OF KHIONE

### A. ... within the ice modelling history

Numerical modelling studies have played an important role in river and coastal engineering, even more so when related to ice modelling. The requirement to work in an environment with air temperature below freezing to accurately represent exchanges at the air-ice-water interfaces has restricted physical modelling studies to idealised experiments in relatively small flumes in frigorific rooms. Additionally, it is very difficult to scale ice dynamic processes (see [1] and [2]) rendering the growth of frazil ice or the formation and evolution of an ice cover and their interaction with the hydrodynamics, the bathymetry, and the banks or any manmade structures virtually impossible.

Contrarily, numerical models can be a useful tool to investigate the numerous processes that interact under different flow, level, weather, and operational conditions. Thermal-ice processes have been considered in numerical models with increasing complexity in the past couple of decades (see [2]). For instance, in 1991, [2] developed a 1D river ice model, RICE, further improved by [3] and [4], capable of simulating unsteady flow and ice processes in channel networks over a long winter period. In 2000, [6] developed a 2D river ice dynamics model, DynaRICE, enable the modeling of the formation of ice jams, which could not be done with the conventional static ice jam theory (see [2] and [11] for instance). The DynaRICE models were further extended in 2006 by [6] to incorporate thermal-ice processes. Simulation of water temperature with super-cooling, frazil ice concentration, surface ice transport, ice cover

progression, undercover ice transport, thermal growth and decay of ice covers, and ice-cover stability were included. Later this was further refined to include the treatment of trans-critical flows and wetting and drying bed transitions [9].

### B. ... within the TELEMAC system

The KHIONE component is now part of TELEMAC, an open source suite of scientific codes enabling mathematical modelling of all free surface hydraulics including water levels, currents, waves, transport of tracers and sediments as well as geomorphology and water quality.

Because ice processes are intertwined with hydrodynamic processes, a simulation using KHIONE is carried out through TELEMAC-2D (coupling with TELEMAC-3D to be completed at a later stage). KHIONE cannot be run in standalone mode. Furthermore, since ice processes are also dependent upon temperature and heat exchanges with the atmosphere, a coupling with the water quality component WAQTEL is also necessary. This is done through the TELEMAC-2D keyword `COUPLING WITH = "KHIONE;WAQTEL"`.

Once coupling is activated, individual ice processes are triggered by setting the keyword `ICE PROCESSES` to a multiplicative combination of prime numbers, with each prime number being associated to a particular process. For instance, `ICE PROCESSES = 2` turns on the surface heat exchanges with the atmosphere, and only that process. When water is allowed to cool slightly below freezing temperature, super-cooling can produce frazil ice. With `ICE PROCESSES = 14` (where 14 is 7 times 2), not only the surface heat exchange process is turned on, but the formation of static border ice is also made possible. The effect of surface ice dynamics and ice cover on the hydrodynamics uses the prime number 3, thus setting `ICE PROCESSES = 42` (where 42 is 7 times 3 times 2) would trigger a combination of all 3 processes. It is noted that 1 is not a prime number and would switch off all processes.

For consistency and possible interaction between KHIONE and WAQTEL, a number of changes were also implemented in WAQTEL. In particular, the TELEMAC-2D keyword `WATER QUALITY PROCESS` is now also based on a combination of prime numbers, with 1 switching all water quality processes off.

## III. THEORETICAL ASPECTS

This section presents the first part of the theoretical aspects of the developments made for KHIONE. These include modules relating to the heat budget, the interaction between water temperature and frazil concentration, the freeze up processes and the formation of static and dynamic border ice cover, in addition to the effects ice has on the hydrodynamics or on structures such has clogging of frazil ice on intake grids or undercover flows. Surface ice dynamics and evolution, ice jam and breakup will be presented at a later stage.

### A. Energy Budget (exchange with the atmosphere)

A dominant part of the heat exchanges occurs at the surface in contact with the atmosphere and includes short and long wave radiation, evaporation / condensation, sensible heat exchange, and precipitation (see [1] and [7]). There are two options provided to the user depending on the availability of atmospheric data: a linearized formulation, the parameters of which should be calibrated and a comprehensive thermal budget

(based on humidity, winds, solar radiation, precipitation, cloud cover, etc.).

For the linearized option, the total surface heat loss rate,  $\phi^*$ , may be written:

$$\phi^* = -\phi_R + \alpha' + \beta'(T_s - T_a) \quad (1)$$

in which,  $\alpha'$  and  $\beta'$  are user defined parameters and  $\phi_R$  is the net short wave radiation, the difference between the incoming solar radiation and the solar radiation reflected back to the atmosphere, a function of the cloud cover, the optical air mass, the day of the year and the solar latitude and declination, the atmospheric pressure, the eccentricity correction factor of the earth's orbit the albedo and a solar constant of 1,300 [W/m<sup>2</sup>]. These are detailed in the user manual. If  $\alpha'$  and the solar constant are set to zero, then the total surface heat loss rate is a direct function of the difference between the surface and the air temperature.

For the comprehensive option, the total surface heat loss rate,  $\phi^*$ , may be written:

$$\phi^* = -\phi_R + \phi_B + \phi_E + \phi_H + \phi_P \quad (2)$$

in which,  $\phi_B$  is the effective back radiation or terrestrial radiation, also the net balance of the atmospheric long-wave radiation reaching the surface water, the fraction of the atmospheric radiation reflected back by the surface water, and the long wave radiation emitted by the surface water,  $\phi_E$  is the evaporation heat transfer,  $\phi_H$  is the conductive or sensible heat transfer, and  $\phi_P$  is the heat transfer due to precipitation. Saturated vapour pressure, wind, emissivity, relative humidity, air and surface temperatures, cloud cover, visibility or even the snow or rain fall make up the principal parameters of these additional fluxes. These are detailed in the user manual.

### B. Supercooling and suspended frazil concentration

When the water is super-cooled, suspended frazil ice particles start to form. The continuous heat loss from the water body promotes the increase in size and concentration of the frazil ice. Depending on the turbulent intensity, the entrained frazil ice may either float to the water surface contributing to the surface ice sheet or remain entrained in the fast flows.

The change of suspended frazil ice concentration can be caused by both creation of particles (thermal growth) and by settling (mass exchange with surface ice). Separating the two terms, the source / sink term of the frazil equation is:

$$\frac{DF}{Dt} = \frac{DF^g}{Dt} + E \quad (3)$$

in which  $F$  is the frazil concentration and  $E$  represents the mass exchanges (settling) with the surface ice. Ice production due thermal growth of frazil can then be computed as:

$$\frac{DF^g}{Dt} = -\frac{1}{\rho_i L_i} \frac{N_u^f K_w}{d_e} \alpha_0 T_w N_f \quad (4)$$

in which  $\rho_i$  is the mas density of ice,  $L_i$  is the latent heat of fusion,  $d_e$  is the frazil crystal thickness,  $N_u^f$  is the Nusselt number,  $K_w$  is the thermal conductivity of water,  $\alpha_0$  is the surface area of a frazil particle normal to the a-axis of frazil crystal,  $N_f$  is the number of crystal per unit volume, and  $T_w$  is the water temperature.

With that said, we note that the conservation of the thermal energy of the ice-water mixture is solved (as opposed to the conservation of frazil concentration) and is written:

$$\frac{De_T}{Dt} = (\phi_{ss} - \phi_{sk}) + \rho_i L_i E \quad (5)$$

where the thermal energy  $e_T = \rho_w C_p (1 - F) T_w - \rho_i L_i F$

in which  $\phi_{ss}$  and  $\phi_{sk}$  are the rates of heat gain and loss respectively. Combining the above equations and re-arranging in an effort to extract the source and sink terms for the water temperature equation, leads to:

$$\frac{DT_w}{Dt} = \frac{(\phi_{ss} - \phi_{sk})}{\rho_w C_p (1 - F)} - \frac{T_w E}{(1 - F)} + \frac{\rho_i L_i}{\rho_w C_p (1 - F)} \frac{DF^g}{Dt} + \frac{T_w}{(1 - F)} \frac{DF^g}{Dt} \quad (6)$$

in which, on the right side of the above equation the first term denotes the water temperature change due to the heat loss and gain through the water surface; the second term denotes the water temperature change due to mass exchange of suspended frazil between the suspended layer and the surface ice layer; and the third and fourth terms denote the water temperature changes due to the heat transfer from suspended frazil to water or due to frazil thermal growth. The first term is included in the water temperature conservation equation, the second term is an order of magnitude smaller than the other terms and can be neglected. Additional details are provided within the user manual.

### C. Border ice cover formation

Border ice can be divided into two types: static border ice and dynamic border ice. Static border ice is usually the first ice to appear on the surface. It is essentially the skim ice formation along the banks. Dynamic border ice is due to the accumulation of surface ice floes along the edge of static border ice. The growth of dynamic border ice is subjected to a mechanical condition where the adherence of the surface ice floes balances the drag and gravity component on the ice floes. The formulation for the static and dynamic border ice growth in KHIONE is detailed in [3].

#### 1) Static border ice

Static border ice growth is computed by proximity to border edges of the finite element mesh (either mesh boundaries or by accumulation of border ice where border ice has formed already). If the thermal and hydrodynamic conditions for static border ice growth are met on a node adjacent to the border ice boundary, ice growth will proceed from the boundary toward that node. The growth continues from node to node until the conditions exceed the thresholds for static border ice growth.

The following thresholds for static border ice formation follow the work of [7]:

- The water surface temperature (computed from the depth-averaged water temperature based on [7] and [8]) is less than a critical value for static border ice formation (set by default to  $-1.1^\circ\text{C}$  based on data from River Ohre, Germany);
- The buoyant velocity of frazil is greater than the vertical turbulence velocity (including the effect of wind-generated turbulence) computed by [3]; and
- The local depth-averaged velocity is less than the critical velocity for static border ice formation.

Additional details are provided within the user manual.

#### 2) Dynamic border ice

The formulation implemented within KHIONE follows the work of [2], with modifications on the value of the critical velocity. A dimensionless relationship for the lateral growth rate of dynamic border ice is expressed as:

$$\rho_w L_i \frac{\Delta W}{\Delta \phi} = 14.1 V_*^{-0.93} C_a^{1.08} \quad (7)$$

in which  $\Delta W$  is the growth rate of dynamic border ice,  $\Delta \phi$  the heat loss through the water-air interface,  $V_* = u/V_c$  is the velocity criteria for dynamic border ice growth with  $u$  the flow velocity and  $V_c$  the maximum flow velocity where ice parcels can adhere to existing border ice, and  $C_a$  the surface ice area.

The critical velocity for dynamic border ice formation was found to be (see [12])  $V_c = 0.4$  [m/s] for the upper St. Lawrence River. Additionally, [2] found that equation (7) is valid for  $0.167 < V_* < 1.0$ . When  $V_* < 0.167$  static border ice or skim ice will grow and  $1.0 < V_*$  no border ice will grow. The lower limit is used for the limiting condition for static border ice growth, where  $u \leq V_* V_c = 0.167 * 0.4 = 0.07$  [m/s]. Dynamic border ice growth is also limited by areal concentration of surface ice (see [2]). Only static border ice can grow if  $C_a < 0.1$  and only equation (7) should be used for dynamic border ice growth otherwise.

### D. Ice cover impact on the hydrodynamics

The conventional St. Venant equations for free surface flow have been extended to include the surface ice effects (see [10]).

#### 1) The continuity equation

The continuity equation for the total water discharge can be written as:

$$\frac{\partial \eta}{\partial t} + \frac{\partial q_{tx}}{\partial x} + \frac{\partial q_{ty}}{\partial y} = \frac{\partial}{\partial t} (C_a t'_i) \quad (8)$$

in which  $q_{tx} = q_{lx} + q_{ux}$  and  $q_{ty} = q_{ly} + q_{uy}$  are the components of total unit width water discharge,  $q_{lx}$  and  $q_{ly}$  are the components of unit width water discharge beneath the ice layer (lower),  $q_{ux} = q_{ix} + q_{sx}$  and  $q_{uy} = q_{iy} + q_{sy}$  are the components of unit width water discharge in the upper layer,  $q_{ix} = u_i(\eta - \eta')(1 - C_a)$  and  $q_{iy} = v_i(\eta - \eta')(1 - C_a)$  are the components of unit width water discharge carried by the ice,  $q_{sx}$  and  $q_{sy}$  are the components of unit width water discharge in the ice layer relative to the moving surface ice, or seepage discharge through the ice cover,  $\eta$  the water surface elevation and  $\eta'$  the bottom of the ice cover,  $C_a$  is the surface ice area.

#### 2) The momentum equations

The momentum equations are modified as follows:

$$\left\{ \begin{array}{l} \frac{\partial q_{tx}}{\partial t} + \frac{\partial}{\partial x} \frac{q_{tx}^2}{H_t} + \frac{\partial}{\partial x} \frac{q_{tx} q_{ty}}{H_t} = \\ \quad \frac{1}{\rho} (\tau_{sx} - \tau_{bx}) + \frac{1}{\rho} \left( \frac{\partial T_{xx}}{\partial x} + \frac{\partial T_{yx}}{\partial y} \right) - g H_t \frac{\partial \eta}{\partial x} \\ \frac{\partial q_{ty}}{\partial t} + \frac{\partial}{\partial x} \frac{q_{tx} q_{ty}}{H_t} + \frac{\partial}{\partial y} \frac{q_{ty}^2}{H_t} = \\ \quad \frac{1}{\rho} (\tau_{sy} - \tau_{by}) + \frac{1}{\rho} \left( \frac{\partial T_{xy}}{\partial x} + \frac{\partial T_{yy}}{\partial y} \right) - g H_t \frac{\partial \eta}{\partial y} \end{array} \right. \quad (9)$$

in which one can write  $T_{xy} = \epsilon_{xy}(\partial q_{tx}/\partial y + \partial q_{ty}/\partial x)$  and  $\epsilon_{xy}$  are the eddy viscosity coefficients,  $\tau_s$  and  $\tau_b$  are the shear stresses at the ice-water interface and the bed respectively,

and  $H_t$  is the water depth underneath an equivalent ice-water interface computed from  $H_t/H = (q_t/q_l)^{3/5}$ , with  $H$  the water depth beneath the ice layer.

#### E. Frazil ice clogging on a set of bars

Figure 1 below shows the anticipated stages of frazil ice clogging on a rack made of regularly spaced bars. First, one observes the initial frazil ice adhesion, followed by the frazil ice deposition on the leading edge. Then the accumulated ice bridges between bars and start blocking the flow. Still ice accumulates between bars due to the head difference across the rack and carry on pilling up for as long as there is frazil ice in suspension in the water.

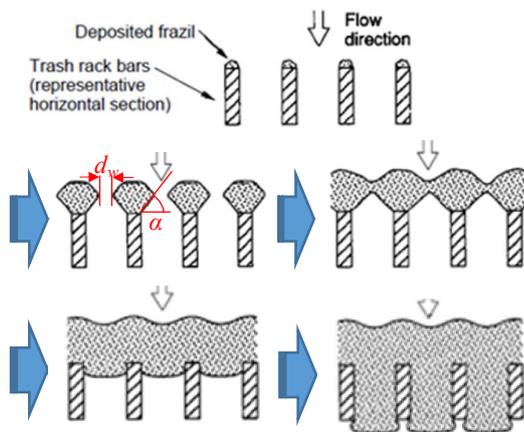


Figure 1 - Stages of frazil accretion on a rack of vertical bars

It is estimated from (see Figure 1) that the angle  $\alpha$  between the edge of frazil accumulation and the transverse direction is about 55 deg. The width of the gap between two bars with gradual ice accumulation is noted  $d_w$  and is computed by KHIONE as a function of frazil ice concentration, the discharge through the bars, a deposition coefficient and the porosity of ice, assumed to be 0.67 (see [1]).

## IV. EXAMPLES OF APPLICATIONS

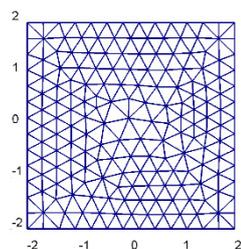
In this section, a few of the validation test cases developed through the collaborative research project are presented to highlight practical applications of the theoretical aspects presented in the previous section. Again, these cases focus on the Eulerian part of KHIONE, with other validation test cases being currently tested for the Lagrangian part of KHIONE.

### A. Energy Budget (contact with the atmosphere)

This first test case compares various uses of the two heat exchange models implemented within KHIONE, namely the full thermal budget model and a linearized model, with and without solar radiation.

#### 1) Model setup

The domain is a simple square box (4x4 m) surrounded by solid boundary with no hydrodynamics, no friction and no diffusion of tracer. The still water depth is initially set to 1 m and the water temperature set at 10.59°C. The model is run for 288 steps of 300 s



(i.e. a duration of 1 day).

Although only one tracer is used (temperature), frazil is also activated by KHIONE when `ICE PROCESSES = 2`, and would appear if the air temperature was sufficiently cold.

#### 2) Model drivers

There are no external drivers to the model other than the atmospheric exchanges. This is where the four variations of the same test case differ, with values of  $\alpha'$  and  $\beta'$  of (1) set through the keywords `WATER-AIR HEAT EXCHANGE CONSTANT` and `WATER-AIR HEAT EXCHANGE COEFFICIENT` respectively. By default,  $\alpha' = 50$  and  $\beta' = 20$ . These values are unrealistic in the test case provided and only serve for illustrative purpose.

- Linear model: the model is first driven by a constant air temperature and no solar radiation nor any other atmospheric heat fluxes.

The essential keywords for KHIONE are:

```
AIR TEMPERATURE = -6.0
WATER-AIR HEAT EXCHANGE COEFFICIENT = 14.0
SOLAR CONSTANT = 0.
```

The essential keyword for WAQTEL is

```
ATMOSPHERE-WATER EXCHANGE MODEL = 3
```

- Linear model with solar radiation: second, the linear model driven by a constant air temperature and the solar radiation is left default.

The essential keyword for KHIONE is:

```
AIR TEMPERATURE = -6.0
WATER-AIR HEAT EXCHANGE CONSTANT = 70.0
```

The essential keyword for WAQTEL is

```
ATMOSPHERE-WATER EXCHANGE MODEL = 3
```

- Linear model with varying air temperature: third, the linear model driven by a varying air temperature and the solar radiation is left default.

The essential keyword for KHIONE is:

```
AIR TEMPERATURE = -6.0
WATER-AIR HEAT EXCHANGE CONSTANT = 0.0
WATER-AIR HEAT EXCHANGE COEFFICIENT = 25.0
```

The essential keyword for WAQTEL is

```
ATMOSPHERE-WATER EXCHANGE MODEL = 3
```

The essential keyword for TELEMAT-2D is:

```
ASCII ATMOSPHERIC DATA FILE = 't2d_meteo.lqd'
```

- Full thermal budget model: last but not least, variations in air temperature, cloud cover, dew temperature, visibility, snow, rain and wind speed are provided through the ASCII file within the TELEMAT-2 D steering file. The heat exchange model is now set to 4, one of two options available within KHIONE.

The essential keyword for WAQTEL is

```
ATMOSPHERE-WATER EXCHANGE MODEL = 4
```

The essential keyword for TELEMAT-2D is:

```
ASCII ATMOSPHERIC DATA FILE = 't2d_meteo.lqd'
```

The input dataset for the full thermal budget model (also used with varying air temperature) is taken from the Wanjiazhai reservoir, China, on the Yellow River.

#### 3) Model results

Figure 2 shows the resulting water temperature in the box under the influence of the atmospheric conditions for all four approaches, whether weather data are provided or not. On a

secondary axis (right) it also shows the air temperature (red dots).

This test case shows the importance of calibrating the  $\alpha'$  and  $\beta'$  parameters of equation (1), corresponding to the keywords `WATER-AIR HEAT EXCHANGE CONSTANT` and `COEFFICIENT` respectively.

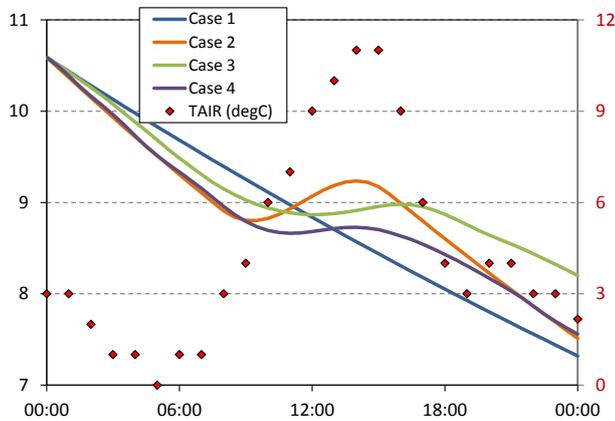


Figure 2 – Water temperature under atmospheric drivers

Comparing results for case 3 and 4, Figure 2 also shows the importance of the other weather parameters (cloud cover, humidity, wind, etc.).

**B. Supercooling and suspended frazil concentration**

Frazil ice forms in supercooled turbulent water whenever the water temperature is slightly below zero, usually only a few hundredths of a degree. This second test case demonstrates KHIONE ability to represent the typical evolution of the water temperature with time, as frazil develop.

**1) Model setup**

The domain is 10 km long flume, 150 m wide, with a mild slope of 1:10,000 between the elevation 5 m (upstream boundary) and 4 m (downstream boundary). Figure 3 below shows the bottom elevation as coloured contour and the mesh.

A hydrodynamic-only simulation is carried out first to reach steady state conditions based on a constant discharge of 300 m<sup>3</sup>/s at the upstream boundary and a constant water level set to 6.6265 m at the downstream boundary (water depth of 2.6265 m). A Manning's n value of 0.025 is used.

Subsequently, a second simulation is carried out with both water temperature and frazil concentration, with the activation of the surface heat exchange (`ICE PROCESSES = 2`). Initial and upstream boundary temperature are set to 0.05°C and the frazil concentration to 0. The model is run for 10 hours, or 18,000 steps of 2 s.

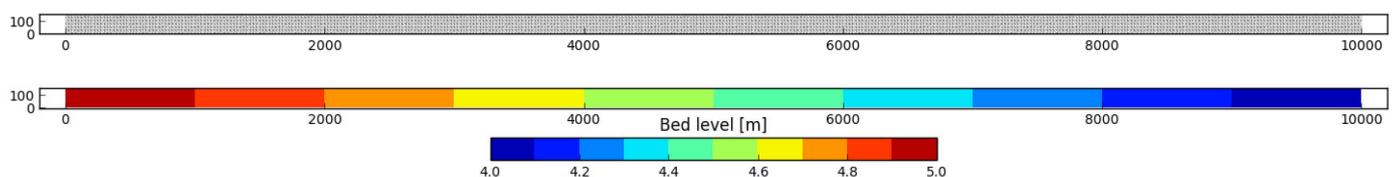


Figure 3 – Model geometry (bathymetry and mesh) for the supercooling and frazil growth test case

**2) Model drivers**

There are no external drivers to the model other than the atmospheric exchanges. This is where the four variations of the same test case differ. The linear model is used based on a constant air temperature and no solar radiation nor any other atmospheric heat fluxes.

The essential keywords for KHIONE are:

```
WATER-AIR HEAT EXCHANGE CONSTANT = 200.
WATER-AIR HEAT EXCHANGE COEFFICIENT = 0.0
SOLAR CONSTANT = 0.
```

The essential keyword for WAQTEL is

```
ATMOSPHERE-WATER EXCHANGE MODEL = 3
```

**3) Model results**

Profiles of water temperature and frazil concentration are extracted along the length of the flume. These also represent how long the upstream water (entering the domain at 0.05°C) has been in contact with the atmosphere. These are shown in Figure 4, with temperature on the primary axis (left) and frazil concentration on the secondary axis (right, x10<sup>-3</sup>).

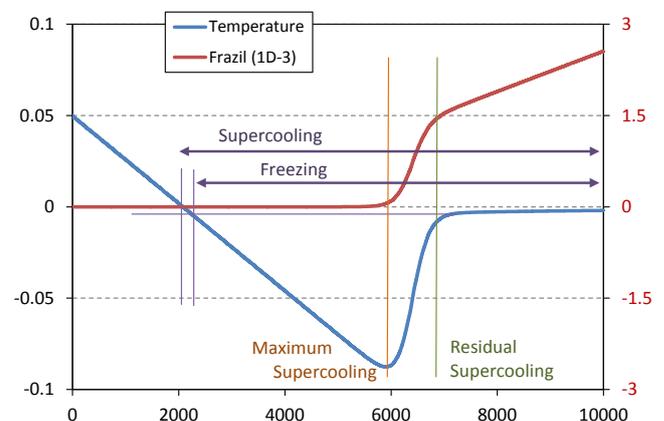


Figure 4 – Frazil growth as temperature gets supercooled

For a constant rate of heat loss, the temperature decreases linearly and reaches the freezing point. Further atmospheric cooling results in supercooling and frazil ice begins to form – although not visible here because of small amount. This process is accompanied by a release of latent heat due to frazil production. The maximum amount of supercooling is then reached and a balance between released latent heat and heat loss through the water surface occurs at that time. Where the frazil growth is faster with the increase in frazil concentration, the release of latent heat is larger than the heat loss to the atmosphere. The temperature thus increases until thermal equilibrium is reached. After that, the temperature is virtually constant, and if the temperature is less than 0° C, residual supercooling take place.

### C. Border ice cover formation

As described in the previous section, static border ice will form in areas where both the thermal and hydrodynamic threshold conditions are met, including in calmer areas of river bends, for instance.

#### 1) Model setup

For this reason, the domain used in this case has been build based on a meandering channel following a sine curve, the cross section of which is of trapezoidal shape. The whole channel also follow a gentle slope of 1:10,000. The length of the meandering channel is about 400 m, while its width is about 25 m. The top inset of Figure 5 below shows the bottom elevation of the model.

A hydrodynamic-only simulation is carried out first to reach steady state conditions based on a constant discharge of  $5 \text{ m}^3/\text{s}$  set at the upstream and downstream boundary with an initial

water level set at 2.5 m (water depth ranging from 0.5 m on the banks to 4.5 m in the middle of the channel). The simulation is first run without any friction. The second inset of the Figure 5 below shows the resulting current speed. The flow tends to overshoot each bend creating areas of calmer waters.

Subsequently, a second simulation is carried out, coupled with KHIONE, activating the surface heat budget, the effect of the ice cover on the hydrodynamics and the formation of border ice: `ICE PROCESSES = 42, (=2x3x7)`.

Initial and upstream boundary temperature are purposefully set to  $-0.05^\circ\text{C}$ , already in the range of supercooling, and the frazil concentration to 0.005. The model is run for 2 hours, or 7,200 steps of 1 s. A Manning's n value of 0.025 is used, so as to gradually change the steady state solution within this second simulation.

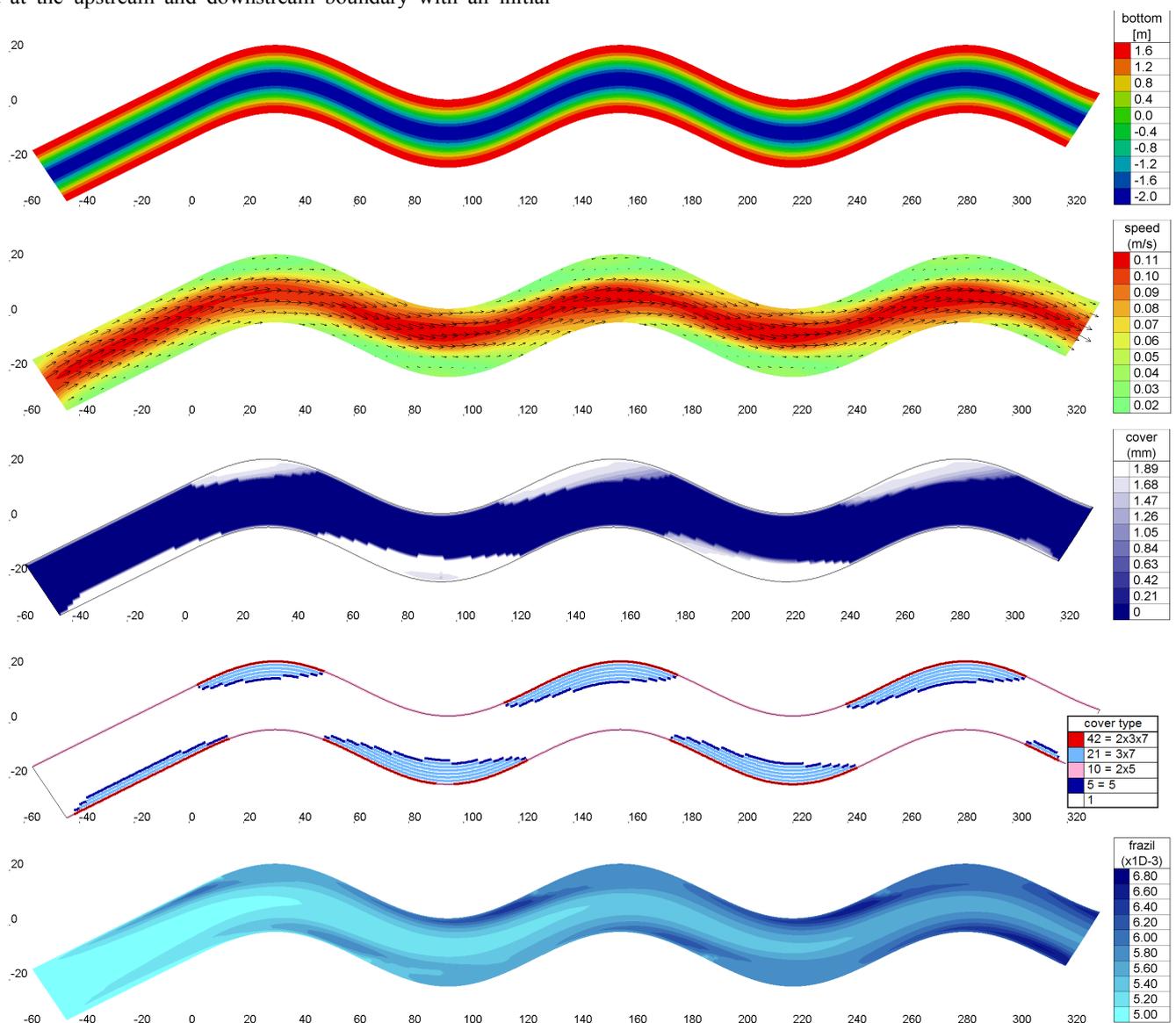


Figure 5 – Formation of static and dynamic border ice cover within a meandering channel (bottom, speed, ice cover, ice type)

## 2) Model drivers

There are no external drivers to the model other than the atmospheric exchanges. The linear model is used based on a constant air temperature and no solar radiation nor any other atmospheric heat fluxes.

The essential keywords for KHIONE are:

```
AIR TEMPERATURE = -10.0.
WATER-AIR HEAT EXCHANGE CONSTANT = 0.0
SOLAR CONSTANT = 0.
```

The essential keyword for WAQTEL is

```
ATMOSPHERE-WATER EXCHANGE MODEL = 3
```

## 3) Model results

The middle inset of Figure 5 above shows the ice cover formed after 2 hours. While it may only be a few millimetres thick (floating above the water), border ice forms extremely rapidly. Additionally, it prevents the water from being in direct contact with the atmosphere, providing an insulation layer where it forms. This is shown in the bottom inset of Figure 5, with darker blue area of frazil production, frazil is simply transported (and gradually melted) under the patches of ice cover.

The last inset of Figure 5 (second from the bottom up) shows a variable used by KHIONE to manage the various states and properties of the ice cover. This (integer) variable is set as a multiplicative combination of prime numbers, with each prime number associated to a particular ice cover type. It also shows that border ice expands from the border, while thickening from the surface down. Additional details can be found in the user manual.

### D. Ice cover impact on the hydrodynamics

This test case demonstrates KHIONE's ability to affect the hydrodynamics – hence the coupling with TELEMAC-2D – in particular when an ice cover is produced. Four variations of the same test case are presented, each based on a different ice cover configuration.

#### 1) Model setup

The model geometry is identical to the supercooling test case (see Section IV-B). The hydrodynamic regime is only different in its downstream boundary conditions, raised to 7.535 m (water depth of 3.535 m). A Manning's n value of 0.025 is used.

An ice cover is installed above the water surface at the start of the simulation, allowing TELEMAC-2D to adapt to its presence in term of static pressure and shear stress. Ice cover impact is activated with `ICE PROCESSES = 3`. It is noted that surface heat fluxes are not included here.

The model is run for 10 hours, or 7,200 steps of 5 s.

#### 2) Model drivers

There are no external drivers to the model other than the initial cover, which is set through the keyword for KHIONE:

```
PREVIOUS ICE COVER COMPUTATION FILE = 'cv4.slf'
```

We note that KHIONE can have initial conditions distinct from the TELEMAC-2D initial conditions. Four variations are presented, whether the ice covers the entire flume, a portion of the upstream or the downstream, or represents an actual ice jam situation.

## 3) Model results

Steady state is reached fairly rapidly. Figure 6 below shows a cross sectional profile along the 10 km flume of the bed elevation (black), the top of the ice cover (red) the bottom of the ice cover (blue, also the interface with water) and the equivalent water surface level.

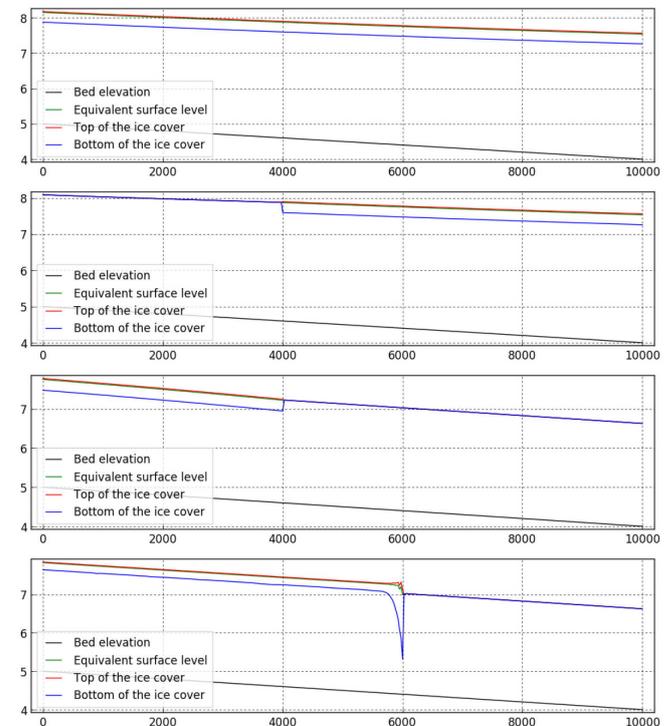


Figure 6 – Water surface affected by ice cover

This test case demonstrates the ability of KHIONE and TELEMAC-2D to interact with one another, with ice cover reaching either types of boundary conditions (imposed or free).

### E. Frazil ice clogging on a set of bars

Ice formation on structures can cause serious difficulties in regions with cold climates, particularly so through frazil ice accretion. Frazil ice often blocks intakes to hydro or nuclear power plants, for instance.

#### 1) Model setup

The model geometry is identical to the supercooling test case (see Section IV-B) except that the bottom elevation has a milder slope at 1:100,000 (from 4.0 m to 4.1 m). The hydrodynamic regime is slower with a prescribed upstream discharge value of 30 m<sup>3</sup>/s and a downstream water elevation of 6.6265 m (water depth of 2.6265 m). A Manning's n value of 0.025 is used.

Surface heat fluxes is used to produce a supercooling within the channel, hence the formation of frazil ice, to which the clogging process is added. Both processes are activated with `ICE PROCESSES = 10`, (=2x5).

#### 2) Model drivers

The linear model is used based on a constant air temperature and no solar radiation nor any other atmospheric heat fluxes.

The essential keywords for KHIONE are:

```
AIR TEMPERATURE = -5.0
```

```
SOLAR CONSTANT = 0.
```

The essential keyword for WAQTEL is

```
ATMOSPHERE-WATER EXCHANGE MODEL = 3
```

Additionally, clogging is set at the downstream boundary as if it was an intake to a power station (150 m entrance width). The physical characteristics of the rack is defined through the thickness of the bars and the distance between two bars (from their centre axis). Either or both horizontal and vertical bars are allowed but only vertical bars are here tested to slow down the clogging process.

The essential keywords for KHIONE are:

```
CLOGGING RESULTS FILE = 'clg.prn'
```

```
CLOGGED BOUNDARY NUMBERS = 1
```

```
POROSITY OF ACCUMULATED ICE = 0.67
```

```
ANGLE OF ACCUMULATED ICE = 35.
```

```
PHYSICAL CHARACTERISTICS OF THE INTAKE RACK =  
0.2; 0.00; 0.2; 0.01
```

with an absence of transverse bars is set with the 0.00 value.

The model is run for 5 hours, or 600 steps of 30 s, which highlights the usually very rapid blockage of the intake once frazil ice are in suspension in the incoming water.

### 3) Model results

KHIONE writes a number of quantities to its ASCII result file, amongst which the remaining open area through which water continue to pass through and the total mass of ice accumulated on the grid. These are shown on Figure 7 below.

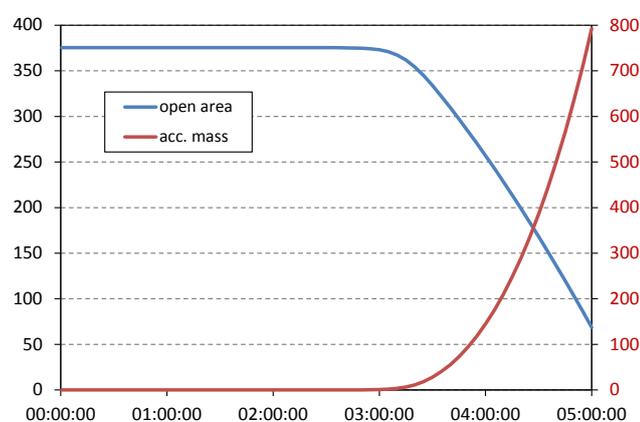


Figure 7 – Frazil ice accumulation on an intake

At this stage, KHIONE does not feedback the blockage of the rack to the hydrodynamics and assumed a uniform accumulation of ice throughout the length of the intake. HR Wallingford is currently expanding the clogging code to correct these.

### CONCLUSIONS

Thanks to the important and sustained effort of the Department of Civil and Environmental Engineering of Clarkson University, technically and financially supported over the last two years by EDF R&D and HR Wallingford, ice modelling capabilities have now been added to the TELEMAC system, in the name of the Greek goddess KHIONE.

While this article presents, in this Part I, the capabilities of the Eulerian part of this ice modelling component, a Lagrangian part also exists to model the dynamics of surface / floating ice, ice jams and breakup phases. This second part will be presented at a future conferences.

KHIONE comes with its latex documentations, including a comprehensive user manual with extensive theoretical description and a validation manual based on a growing number of test cases. Of course, as it is always the case with scientific code, KHIONE is bound to be evolving rapidly in the next few years, and the TELEMAC consortium welcomes any feedback the open source community may have.

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