Appendix A

Ice Module Formulation

A.1 Open-Water Condition

As previously documented, under the open-water conditions, the net energy flux passing the air-water interface, H_N, for water temperature simulation is given by the following equation:

$$H_N = H_{SN} + H_{AN} - H_B - H_E - H_C \tag{A1}$$

where H_N = net energy flux passing the air-water interface into water (W/m^2)
H_{SN} = Net solar or short-wave radiation influx (W/m^2)
H_{AN} = Net long-wave atmospheric radiation flux (W/m^2)
H_B = back radiation from the water surface to atmosphere (W/m^2)
H_E = heat loss by evaporation from water to atmosphere (W/m^2)
H_C = heat loss by conduction from water to atmosphere (W/m^2)

Note that in RMA11 heat transfer rates are calculated as kJ/m^2/hr. Units are shown above and throughout this appendix in W/m^2 for reader convenience.

A.2 Ice-Cover Condition

The heat flux to ice from the warm water below, q_w, is empirically estimated using equations A2 and A3 as suggested by Ashton (1986) as follows:

$$q_w = \alpha_1 \frac{(T_w - T_m)}{d^{0.2}} \qquad \text{if } u \le u_c \tag{A2}$$

$$q_w = \alpha_2 \frac{u^{0.8}(T_w - T_m)}{d^{0.2}} \qquad \text{if } u > u_c \tag{A3}$$

where: q_w = heat loss to ice from the warm water underneath the ice cover (W/m^2)

u = average current velocity in the water column (m/s)

u_c = velocity criterion for switching formulation between Eqs. A2 and A3.

d = water depth (m)

T_m = temperature at the ice/water interface (default value = 0 °C)

T_w = average water temperature in the water column (^{0}C)

α_1, α_2 = calibration parameters

Under the ice-cover conditions, the net energy flux into water, H_N, as shown in Eq. (A1) is set to be equal in magnitude to q_w in Eqs. (A2) and (A3), but in the opposite direction:

$$H_N = -q_w \tag{A4}$$

The value of H_N determined in Eq. A4 is then be applied in RMA11 for water temperature simulation.

A.3 Simulation of Ice-Cover Thickness

Under the ice and snow cover conditions, the factors that affect the amount of heat loss to atmosphere include ice thickness, snow thickness and air temperature. As indicated in Figure A1, heat exchanges take place at the water/ice, ice/snow, and snow/air interfaces. Heat fluxes at the different interfaces can be expressed as follows:

$$q_a = H_a (T_S - T_a) \tag{A5}$$

$$q_s = \frac{K_a}{h_S}(T_{S1} - T_S) \tag{A6}$$

$$q_i = \frac{K_i}{h}(T_m - T_{S1}) \tag{A7}$$

where q_a = heat flux from snow surface to air (W/m^2)

q_s = heat flux through the snow cover (W/m^2)

q_i = heat flux through the ice cover (W/m^2)

h = Ice cover thickness (m)

T_{s1} = temperature at the ice/snow interface

T_s	=	temperature at the snow/air interface
T_a	=	air temperature (°C)
k_i	=	thermal conductivity of ice (W/m/°C), defined by Eq. A8 below
k_s	=	thermal conductivity of snow (W/m/°C) defined by Eq. A9 below
H_a	=	heat transfer coefficient accounting for the thermal resistance between the uppermost surface and air (W/m^2/°C)
h_s	=	thickness of snow cover (m)
h	=	thickness of ice cover (m)

The thermal conductivity of ice, k_i, as suggested by Ashton (1986), is calculated using:

$$k_i = (2.21 - 0.11T_i) \tag{A8}$$

The thermal conductivity of snow, k_s, as suggested Woo and Heron (XXXX), is calculated using:

$$k_s = 2.84x10^{-6}\rho_s^2 \tag{A9}$$

where ρ_s is the density of snow (default value = 300 kg/m$^{3)}$.

The total difference between water temperature at the water/ice interface, T_m, and air temperature, T_a, can be expressed as follows:

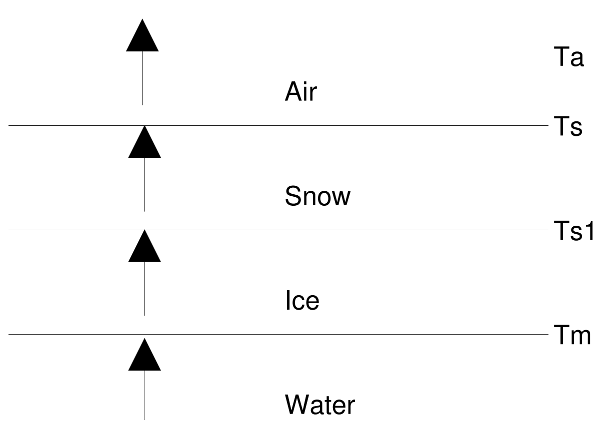

Figure A1 Different interfaces in heat conductance from water to the air under the ice and snow cover condition.

$$T_m - T_a = (T_m - T_{s1}) + (T_{s1} - T_s) + (T_s - T_a) \tag{A10}$$

Assuming that the heat flux through the different interfaces is equal in magnitude, and is equal to the net heat flux to atmosphere, q, i.e. $q_a = q_s = q_i = q$, then substitution of Eqs. A5 to A7 into Eq. A10 yields:

$$q = \alpha_3 (T_m - T_a)\left(\frac{h}{k_i} + \frac{\alpha_4 h_s}{k_s} + \frac{1}{H_a}\right)^{-1} \tag{A11}$$

where α_3 is a calibration parameter, and α_4 is the correction factor for the thickness of snow cover to account for the effects of wind, sublimation and radiation.

Under the assumption that radiation only affects snow cover thickness, the heat input to ice, q_n, is the summation of the heat flux from the water below and the latent heat release as a result of ice formation. It is formulated as follows:

$$q_n = \rho L \frac{dh}{dt} + q_w \tag{A12}$$

where: ρ - density of ice (default value 917 kg/m^3),

L - latent heat of fusion of ice (default value 333.4 J/g)

q_w - heat flux from the warm water below (W/m^2), defined by Eqs. A2 and A3

Using the principle of mass balance, the heat loss from ice to atmosphere is equal to the heat input to ice, an equation for computing ice thickness can be obtained by combining Eq. A11 and Eq. A12 as follows:

$$\rho L \frac{dh}{dt} = \alpha_3 \left(T_m - T_a\right)\left(\frac{h}{k_i} + \frac{\alpha_4 h_s}{k_s} + \frac{1}{H_a}\right)^{-1} - q_w \qquad \text{(A13)}$$

A brief flow chart is shown in Figure A2 to indicate the use of different equations for open-water and ice-cover conditions, respectively, in the ice module.

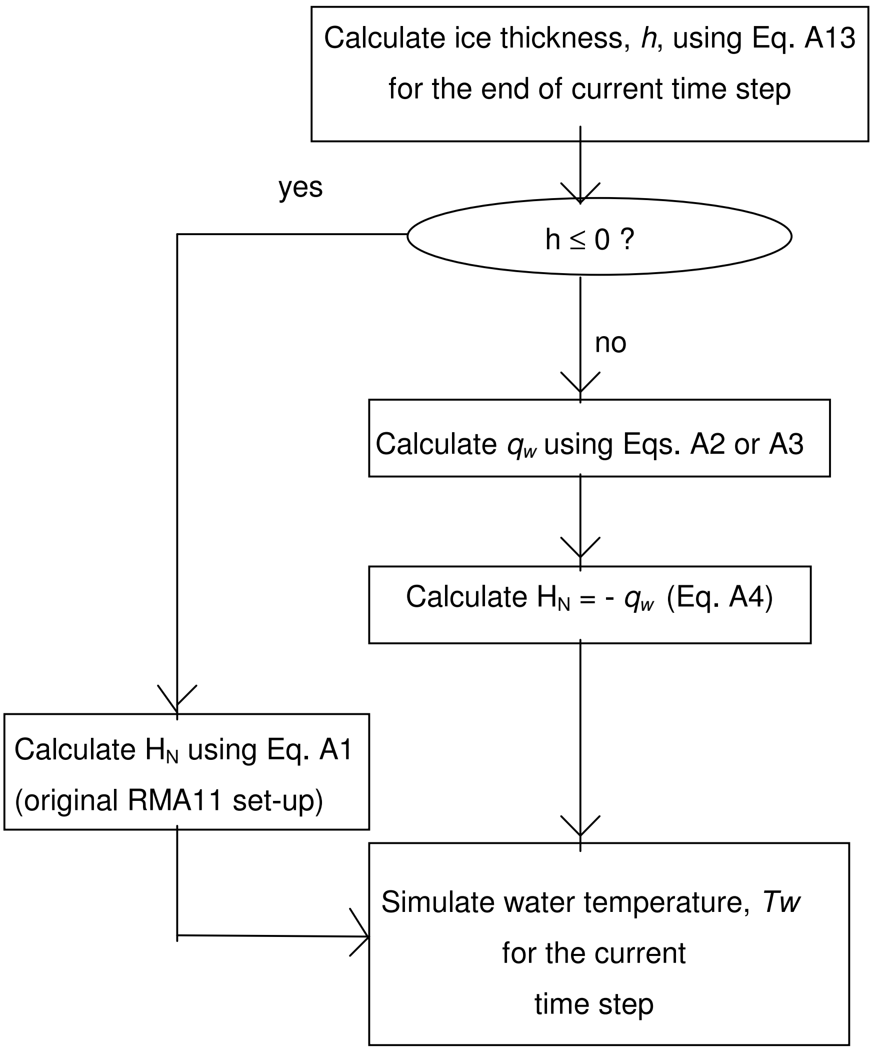

Figure A2 Flow chart for incorporation the ice module into the RMA11 model

Appendix B

Implementation of the Revised Sand Transport Algorithm in RMA-11

B.1 INTRODUCTION

Modification of some and the addition of several new subroutines to RMA-11 have been undertaken to implement the revised algorithm. This document will briefly describe each of the affected subroutines including how the revised method has been adapted and discuss the structure of the required additional data.

B.2 SUBROUTINE CHANGES AND ADDITIONS

"FILELAH.FOR" has been changed to allow definition of the wave data input file. The exact structure of this data file will be described in a later section. Initial nodal values of all wave-related parameters are all set to zero.

"GETWAVE.FOR" is a new subroutine developed to allow linear interpolation from the wave data file to the exact simulation time for values of wave height, period and direction on a node by node basis. Thus the wave data file does not have be created to match the time steps used in the RMA-11 simulation. An additional decoding option in GETWAVE allows the user to input a wave data file where values are constant over time (but vary from node to node).

"INCON.FOR" has been changed to output a line that indicates that a revised transport algorithm has been selected. An additional change has been made to compute the settling velocity for sand if the input value is set equal to zero.

"RMA11.FOR" has been changed so that GETWAVE is called for each time step.

"SEDIMENT.FOR" has been changed so that the nodal values of current direction, wave height, period and direction are transferred to local variables and a call made to WAVECM when the new option is selected.

"WAVECM.FOR" is a new subroutine that has been created to compute the sand transport potential for each node for the new option. The subroutine uses the revised sand transport algorithm documented earlier to compute the net sand transport rate given the current velocity and direction and the wave height, period and direction. This transport rate is then converted to a transport potential in the form of a concentration using the following relationship.

$$C_p = Q_{tot}/(v * d)$$

Where

C_p	=	sand potential (kg/m^3)
Q_{tot}	=	sand transport rate (kg/sec/m)
v	=	current velocity (m/sec
d	=	water depth (m)

BLK1.COM is a set of “include” data that has been modified by the addition of a WAVEDAT common block that contains all the wave-related data.

During the process of computation of sand transport the bed roughness Δ_t is computed from the wave forcing parameters. In order to use this method for systems without wave forcing an alternate method for calculation of Δ_t is required. Following Van Rijn (1990), a system is assumed to be classified based on values of the bed shear stress parameter T and the particle parameter D_*. The following forms for the bed shape and resulting bed roughness have been used:

For $1 < D_* < 10$	and $0 < T < 3$	Ripples
For $1 <: D_* < 10$	and $3 < T < 25$	Dunes
For $1 < D_* < 10$	and $25 < T$	Plane bed
For $10 <: D_*$		Dunes

The following equations for Δ_t are then applied

Ripples $\quad \Delta_t = 150 * d_{50}$ (m)

Dunes $\quad \Delta_t = 0.11*(d_{50}/h)^3*(1.0 - e^{-0.5*T})*(25.0 - T)*h$ (m)

Plane bed $\quad \Delta_t = 0.002$ (m)

B.3 CHANGES TO INPUT DATA FILE

Two changes to the input data structure are required to execute this option.

(1) If a wave data file is to be used an identifier and a filename must be added to the main input file in the files section.

(2) The water quality file must be amended to select option 4 for the sand transport method.

Complete documentation of the input requirements are included in the chapter 6 of the user document.

B.4 TEST CASES

Since the primary impact of the changes to RMA-11 are the input of wave data and the computation of the sand transport potential, testing can be best carried out by comparing the sand transport potential for three cases.

(1) The previous implementation of the Van Rijn algorithm
(2) The new Van Rijn algorithm with no wave influence
(3) The new Van Rijn algorithm with waves included.

The test case consisted of a straight section of channel with the following parameters a depth of 10.0 metres, a water velocity

Water Depth	10 (m)
Water Velocity	0.484 (m/sec)
D50 for sand particle	0.0003 (m)
D90 for sand particle	0.0005 (m)
Wave height	0.5 (m)
Wave period	3.0 (s)
Wave direction	0.0
Sand density	2650 (kg/m^3)

Results for sand transport potential are as follows

Case	Sand transport potential	Roughness height
1	0.29	N/A
2	0.21	0.000450 (m)
3	0.17	0.000155 (m)