FROZEN - Areal Snowmelt Infiltration into Frozen Soils

November 21, 2011

Abstract

A previously developed algorithm for estimating areal snow melt infiltration into frozen soils (FROZEN) is included into the MESH modelling system (a Regional Atmospheric-Hydrologic-Land-Surface Model) to attain a more comprehensive physical description of cold regions processes in the Canadian Prairies. Different levels of the improved MESH model complexity are applied to a typical Prairie watershed to quantify improvements in predicting spring stream flows. Results confirmed that at the selected model resolution of 0.125°by 0.125°significant improvements of stream flow predictions in the Prairie region can be achieved by including the areal snow melt infiltration into frozen soils which usually is ignored in most land surface schemes (LSSs).

1 Background information

Over the last 15 years there has been a systematic attempt within the Mackenzie GEWEX Study (MAGS) in Canada as part of a strong global research effort to couple atmospheric and hydrological models using the LSS as the common link (Pietroniro and Soulis, 2003; Soulis et al., 2004; Snelgrove, 2005; Soulis and Seglenieks, 2007). Additionally, to facilitate coupling between models that focus on different components of the earth system, the numerical weather prediction research group at Environment Canada (RPN) has developed a community environmental modelling system known as MEC (Modélisation Environmentale Communautaire) using a general and computationally efficient coupler (Pellerin et al., 2004). A conceptual framework for model development was initiated using different degrees of model coupling that range from a linked model which requires separate calibration of the atmospheric model and the hydrological model to a complete two way coupled model (Pietroniro and Soulis, 2003; Soulis et al., 2004). The MAGS approach has been to first combine LSS models with hydrological streamflow models to provide stand-alone hydrology-land-surface schemes (H-LSS) that were later used as a basis for coupling with both weather and climate atmospheric models. The MAGS H-LSS named as the WATCLASS model (Verseghy, 1991; Verseghy et al., 1993; Soulis et al., 2000) is based on the Canadian Land Surface Scheme (CLASS), a physically based model that can simulate the energy and water balances of vegetation, snow and a minimum of three soil layers. This was accomplished by designing a two-way interface to WATFLOOD (Kouwen et al., 1993), a distributed hydrologic model developed at the University of Waterloo.

There is an increasing interest in using (and improving) LSSs for stream flow simulations at a relatively finer scales than the resolution of the global circulation models (GCM) (Lu et al., 2008; Nasonova and Gusev, 2008; Nasonova et al., 2009; Music and Caya, 2009; Wang et al., 2009). And recent advances on LSSs include effect of soil moisture initialization (Lo and Famiglietti, 2011) in improving model predictions and effect of groundwater dynamics on the LSS hydrologic memory (Lo and Famiglietti, 2010). Although LSSs have a complete representation of the land surface hydrologic calculation particularly the vertical fluxes, the quality and the complexity of the soil moisture and runoff parameterizations are generally crude (Koster et al., 2000; Bastidas et al., 2006; Livneh et al., 2010). In LSSs small-scale horizontal processes and landscape heterogeneity were either ignored or aggregated (Dornes et al., 2008).

(Soulis et al., 2000) included physically based lateral flow algorithms into WATCLASS to enhance the elementary hydrology of CLASS. Refer to Mekonnen et al 2011 for the details of the elementary hydrology of CLASS as well as for the details of enhanced runoff components. To attain a more comprehensive physical description of cold regions processes within predictive models and with lessons learned from the MAGS experience, the IP3 network (Improved Processes and Parameterization for Prediction in

Cold Regions), through funding from the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS) and starting from the year 2006, has been extensively engaged in:

1. Improving understanding of the surface water and weather systems in cold regions, particularly Canada's Rocky Mountains and western Arctic,
2. Developing effective parameterizations of the cold regions processes for incorporation into hydrological/meteorological models, and
3. Enhancing the predictive capability of coupled atmospheric-hydrologic-land surface models.

The prediction team of the IP3 network converted WATCLASS into a configuration of MEC that is currently known as "MEC − Surface and Hydrology" or MESH. MESH development efforts continue to include more cold regions hydrological process algorithms that are developed and evaluated by the process and parameterization teams of the IP3 network using the Cold Regions Hydrological Model (CHRM) (Pomeroy et al., 2007). The CRHM model has been used as a testing ground to develop and evaluate mathematical descriptions of the cold regions processes. Recently an advanced frozen soil infiltration algorithm, named as the 'FROZEN' module in CRHM, is adapted into the MESH modelling system. In the previous version of the MESH model the snow melt is assumed to percolate through the snow pack and to finally infiltrate into the soil. The assumption, however, gets crude as the model resolution becomes finer.

2 FROZEN algorithm

The FROZEN algorithm, proposed by (Zhao and Gray, 1999), is base on a general parametric expression for estimating snowmelt infiltration into different-textured frozen soils from measurable physical parameters. Numerical results from the HAWTS (physically based model for Heat And Water Transport in frozen Soils, (Zhao and Gray, 1997)) are used to derive a general functional relationship between infiltration, total soil saturation (water + ice) and temperature at the start of snow ablation, the soil surface saturation during melting, and infiltration opportunity time (the time that meltwater is available at the soil surface for infiltration) for sandy loam, silt loam, silty clay loam, and clay soils. The relationship is calibrated for estimating snowmelt infiltration into frozen mineral soils in boreal forest and prairie environments using field measurements. According to the FROZEN algorithm the infiltration potential of frozen soils is grouped into the following three groups depending on the surface entry conditions:

- Restricted - water entry is impeded by surface conditions such as ice lens formations and the melt water becomes direct runoff,
- Limited - capillary flow predominates and water entry is primarily influenced by soil physical properties, and
- Unlimited - gravity flow predominates and most of the melt water infiltrates.

The parametric equation is required for the limited soils to partition the snowmelt into direct runoff and infiltrated water. For limited soils, cumulative infiltration over time is estimated by the parametric equation that describes cumulative infiltration into frozen unsaturated soils of limited infiltrability as:

$$INF = C * {S_0}^{2.92} * (1 - S_I)^{1.64} * \left(\frac{273.15 - T_I}{273.15}\right)^{-0.45} * {t_0}^{0.44} \qquad T_I \leq 273.15 \tag{1}$$

where INF is the potential infiltration capacity (mm), S_0 is soil surface saturation, S_I is the average soil saturation (water + ice) of 0 - 40 cm soil layer at the start of infiltration, T_I is initial soil temperature (K), t_0 is infiltration opportunity time (hr), and C is the parametric equation constant and is found to be 2.10 and 1.14 for the prairie soils and forest soils, respectively (Gray et al., 2001). $S_I = \frac{\theta_i}{\phi}$ where θ_i is the average volumetric soil moisture (water + ice) at start of infiltration (mm^3/mm^3) and ϕ is soil porosity (mm^3/mm^3).

The infiltration opportunity time can be estimated or accumulated from preliminary model runs such as analyzing the CLASS outputs. It can also be estimated from the snow water equivalent, SWE, using the following empirical correlation reported by (Zhao and Gray, 1997):

$$t_0 = 0.65 * SWE - 5 \tag{2}$$

where t_0 is in hours and SWE in mm of water.

The FROZEN algorithm constrains total infiltration into limited soils by the available water storage capacity. The maximum amount of snow water a frozen soil of limited class can infiltrate, the water storage potential $W_{sP}(mm)$, is constrained as:

$$W_{sP} = 0.6 * \phi(1 - S_I)z_p \tag{3}$$

where $z_p(mm)$ is the depth of the highly permeable surface layer (e.g. thickness of organic layer and depth of surface-connected cracks).

3 Implementation into the MESH modelling system

The FROZEN.F90 program included in this document is thoroughly commented to clarify the FROZEN algorithm computation procedure. The FROZEN module includes five parameters into the MESH model (name of variables is in reference to the FROZEN.F90 program): $SOIL\_POR\_MAX$ - Maximum soil porosity, $SOIL\_DEPTH$ - Depth from surface to bottom of rooting zone to compute the maximum water holding capacity of the frozen soil (equivalent of $0.6 * z_p$ in Eqn (3)), $S0$ - Surface saturation during melting, C - Coefficient for the frozen soil infiltration parametric equation, and T_ICE_LENS - Overnight minimum temperature to cause ice lens after major melt.

The whole computational procedure can be summarized as follows:

1. As the soil freezes and snow starts to accumulate on a given land scape unit:
   - FROZEN is initiated,
   - The initial infiltration type is assumed as unlimited infiltration, and
   - FROZEN saves the current soil saturation and temperature values as initial soil saturation and initial temperature values.
2. At each consequent time step:
   - CLASS provides snow melt rate, soil saturation and temperature values to the FROZEN algorithm,
   - FROZEN checks for any ice lens formation (if ice lens is formed the infiltration type becomes restricted. Otherwise the infiltration type is set as limited),
   - For limited soils FROZEN estimates potential infiltration based on the parametric equation. The actual infiltration depends on the:
     - the amount of snow melt,
     - the infiltration potential of the frozen soil,
     - the available water storage capacity of the frozen soil, and
     - the actual and potential cumulative infiltration.
   - FROZEN returns direct runoff and snowmelt minus direct runoff back to CLASS, and
   - SNINFLM (modified SNINFL subroutine that allows snowmelt to be partitioned into direct runoff and infiltrated water) adds direct runoff to overland flow and to total runoff.

4 Testing

The Upper Assiniboine River Basin (UARB) was used to test the different levels of model complexity. The UARB model domain is vertically divided in to 6 soil layers (with layer thickness of 0.10m, 0.25m, 0.75m, 1.00m, 1.00m and 1.00m from top to bottom) and is horizontally discretized using 0.125°by 0.125°. The model configuration with flat CLASS (complete representation of the vertical mass and energy transfers at the land surface together with simple hydrology processes) is set as the baseline model. All parameter values of the baseline model are fixed to literature based values and the soil representation is set the same as the geophysical field used in the GEM model. The baseline model setting in essence is a top-down approach. In this study the results obtained from such baseline configuration are termed as out-of-the-box results. Physically based algorithms (bottom-up approach) are step by step by activated till the soil moisture budget is properly represented to satisfactorily reproduce the observed stream flow records. A combination of a priori parameter sets and calibrated parameter values are used for parameters of the included algorithms (than the baseline model components).

The currently available gridded meteorological forcing data of the 2004 to 2009 CaPA and GEM archive was used to calibrate and validate parameter values. Historical hydrometric data (HYDAT) is taken from Water Survey of Canada. There are three stream flow stations as shown in Figure **??** and Table 1 that have records during the selected time period. Utmost efforts were made to base parameter estimation on streams within the UARB where flows are not regulated, the entire drainage area is effective (contribute to stream flow), all GRUs are represented (when all the selected sub-basins are considered). Accordingly, sub-basin 05MC001 was used to calibrate model parameters whereas sub-basins 05MB003 and 05MD004 were used to spatially validate parameter values.

Table 1: Location and drainage area of the head water sub-basins used for calibration of parameter values

Station ID	Station Name	Location (Lat, Lon)	Area [km^2] Gross	Area [km^2] Effective	Mean flow [m^3/s]
05MB003	WHITESAND RIVER NEAR CANORA	51.64°, -102.37°	8740	2000	4.96
05MC001	ASSINIBOINE RIVER AT STURGIS	51.94°, -102.55°	1930	1140	3.09
05MD004	ASSINIBOINE RIVER AT KAMSACK	51.57°, -101.92°	13000	4320	10.74

The Dynamically Dimensioned Search (DDS) algorithm (Tolson and Shoemaker, 2007) was used to construct a global optimum parameter set for the different levels of model configuration than the baseline configuration. The objective function was set to minimization of the sum of absolute value of differences between observed and simulated stream flow records of basin 05MC001. The model calibration-validation strategy also takes advantage of the MESH model's capability to run simulations on selected sub-basins, without having to run the model over the entire UARB. And for the final rating of calibrated model performance, the recommended statistics used are based on the guidelines developed by (Moriasi et al., 2007), who recommend the Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970), percent bias (PBIAS) and RMSE-observations standard deviation ratio (RSR).

Out-of-the-box simulation results (i.e. using the baseline configuration of the model where advanced hydrological processes are not included or activated) are shown in Figure 1.

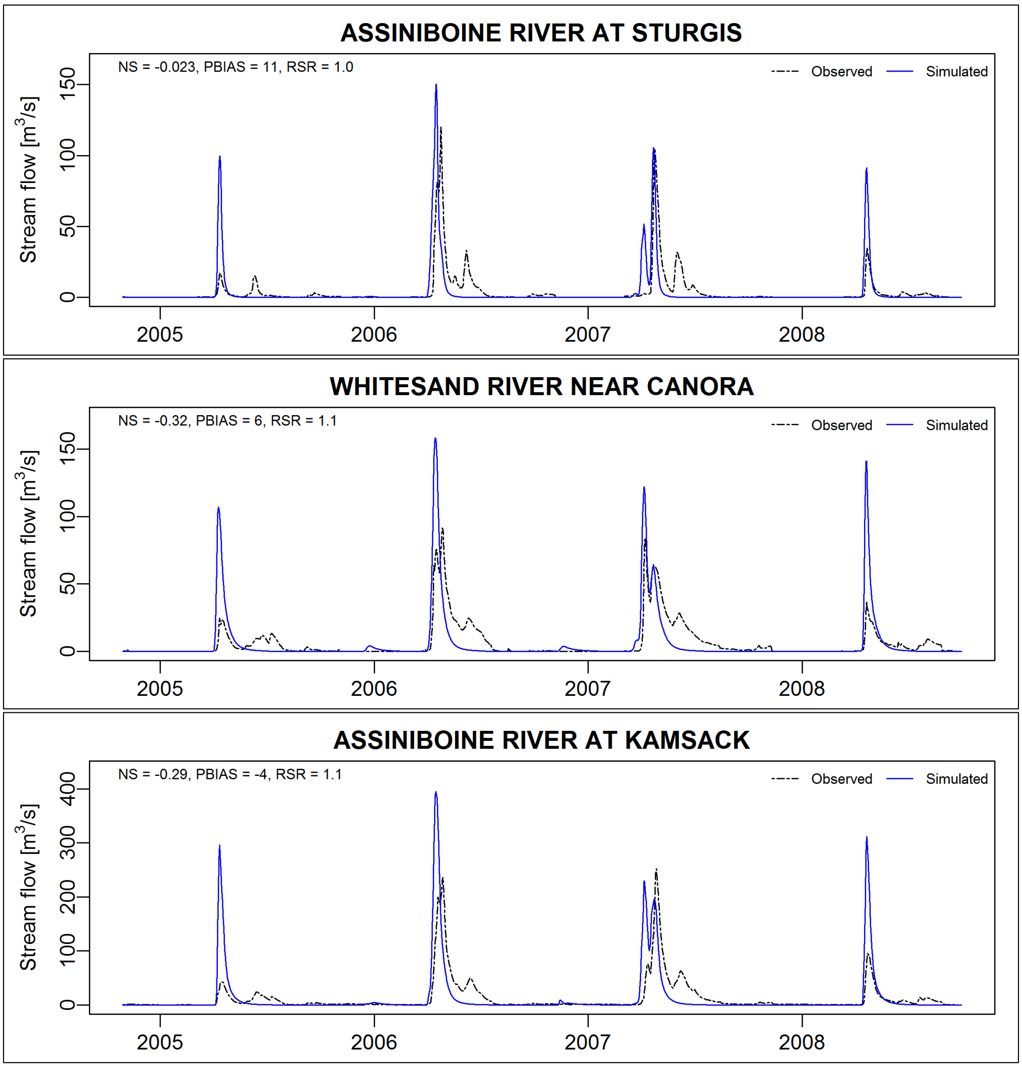

Figure 1: Out-of-the-box simulation results for selected sub-basins.

The hydrographs for out-of-the-box results are not that bad but it is clear that there needs to be more processes that will spatially and temporarily redistribute the water budget. Hence, advanced overland and lateral flow processes (Verseghy, 2000)) are activated and the parameters that affect the included processes were identified to be used for calibration.

Parameter values shown in Tables 2 and 3 are calibrated based on sub-basin 05MC001. Only river roughness values are optimized for sub-basins 05MB003 and 05MD004. Results are shown in Figure 2. Though the calibration results matched well with the observation, the time wise validation on the same sub-basin turned out to be unsatisfactory (Table 4). Inconsistency of parameter values were clearly manifested in the spatial validation results of sub-basin 05MB003 and sub-basin 05MD004 (Table 5).

Table 2: Calibrated parameter values

	GRU_1	GRU_2	GRU_3	GRU_4
XSLOPE	0.08980	0.04620	0.06850	0.01100
Ks	0.00412	0.01451	0.01027	0.01968
XDRAINH	0.07600	0.02000	0.06800	0.02600
$\%SAND_1$	44.56	31.65	46.94	59.42
$\%CLAY_1$	25.59	45.18	53.06	39.58
$\%SAND_2$	8.59	11.90	46.94	70.00
$\%CLAY_2$	83.19	64.36	53.06	29.00
$\%SAND_3$	23.52	24.65	79.69	38.38
$\%CLAY_3$	29.99	16.19	20.31	3.48

Table 3: River roughness values for the selected sub-basins

	05MC001	05MB003	05MD004
WF_R2	0.724	0.450	0.200

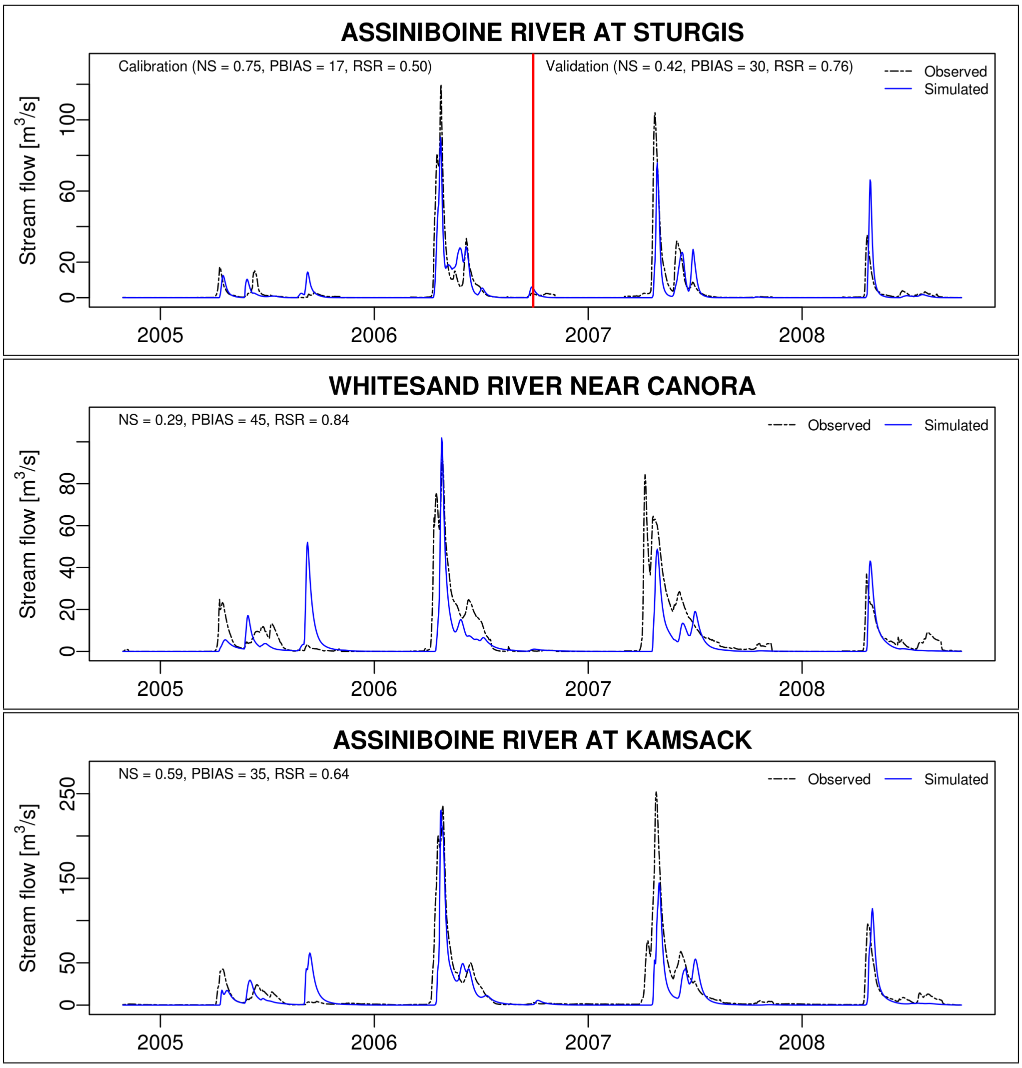

Figure 2: Top: Model calibration and validation in the time dimension. Middle and bottom plots: Spatial validation using independent sub-basins.

Table 4: Performance ratings for calibration and validation (time wise) using sub-basin 05MC001

	NSE		PBIAS		RSR	
	calibration	validation	calibration	validation	calibration	validation
05MC001	0.75 (very good)	0.42 (unsatisfactory)	17 (satisfactory)	30 (unsatisfactory)	0.50 (very good)	0.76 (unsatisfactory)

Table 5: Performance ratings for spatial validation

	NSE	PBIAS	RSR
05MB003	0.29 (unsatisfactory)	45 (unsatisfactory)	0.84 (unsatisfactory)
05MD004	0.59 (good)	35 (unsatisfactory)	0.64 (satisfactory)

As shown in Figure 2 there is a consistent pattern in that simulated spring stream flows lag behind the observed stream flows most probably due to the assumption that snow melt infiltrates into the soil and comes out as inter flow. The frozen soil infiltration algorithm is then activated using field measured value of 2.1 for the parametric equation constant (C in Eq. (1)). Only one extra parameter, the surface saturation (S_0), is optimized as shown in Table 6.

Table 6: Selected parameters, parameter description and specified parameter ranges.

Parameter name	Parameter description	Parameter range
WF_R2	River roughness	0.0200 - 2.00
XSLOPE	Average overland slope	0.0001 - 0.10
Ks	Saturated Horizontal conductivity at surface	0.0001 - 0.02
XDRAINH	Horizontal conductivity at a depth of 1 m divided by Ks	0.0010 - 1.00
$\%SAND_1$	Percentages of sand content of layer 1	0.0000 - 90.00
$\%CLAY_1$	Percentages of clay content of layer 1	0.0000 - 90.00
$\%SAND_2$	Percentages of sand content of layer 2	0.0000 - 90.00
$\%CLAY_2$	Percentages of clay content of layer 2	0.0000 - 90.00
$\%SAND_3$	Percentages of sand content of layer 3	0.0000 - 90.00
$\%CLAY_3$	Percentages of clay content of layer 3	0.0000 - 90.00
S_0	Surface saturation	0.7500 - 1.00

Parameter values shown in Tables 7 and 8 are calibrated based on sub-basin 05MC001. Only river roughness values are optimized for sub-basins 05MB003 and 05MD004.

Table 7: Calibrated parameter values

	GRU_1	GRU_2	GRU_3	GRU_4
XSLOPE	0.05730	0.04350	0.06690	0.00530
Ks	0.00568	0.01353	0.02580	0.02975
XDRAINH	0.07400	0.05000	0.01900	0.06100
$\%SAND_1$	68.13	48.48	8.46	73.47
$\%CLAY_1$	27.36	23.46	5.59	25.53
$\%SAND_2$	53.35	59.99	67.81	58.03
$\%CLAY_2$	46.65	39.01	32.19	15.74
$\%SAND_3$	16.52	59.99	47.79	65.15
$\%CLAY_3$	83.48	16.43	35.60	25.02
S_0	0.80	0.80	0.80	0.80

Table 8: River roughness values for the selected sub-basins

	05MC001	05MB003	05MD004
WF_R2	1.170	0.600	0.200

Results are shown in Figure 3. The results were significantly, as shown in Figure 3 and Table 8, improved as the frozen soil infiltration algorithm was activated. The consistency of parameter values in the spatial validation is very interesting as shown in the spatial validation results of sub-basin 05MB003 and sub-basin 05MD004 (Table 9).

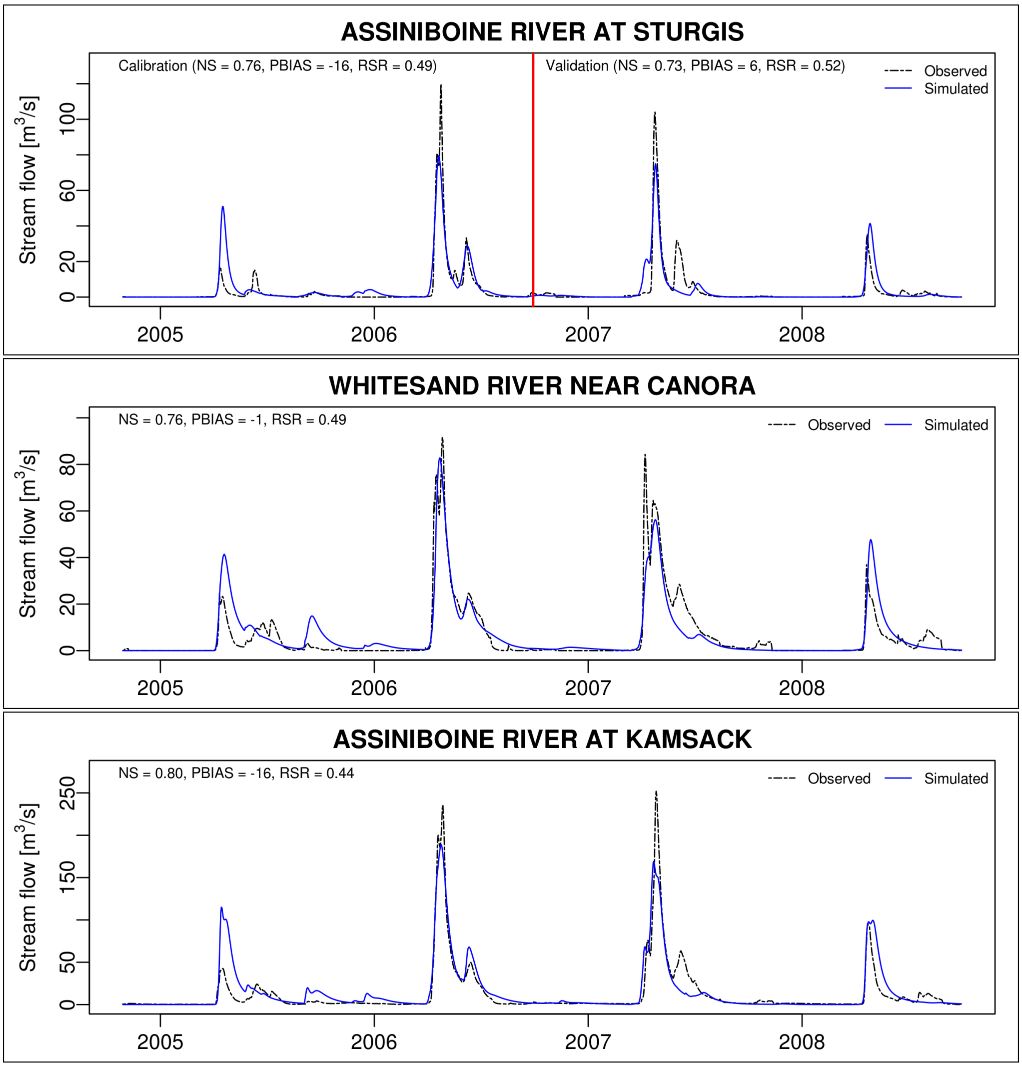

Figure 3: Top: Model calibration and validation in the time dimension. Middle and bottom plots: Spatial validation using independent sub-basins.

Table 9: Performance ratings for calibration and validation (time wise) using sub-basin 05MC001

	NSE calibration	validation	PBIAS calibration	validation	RSR calibration	validation
05MC001	0.76 (very good)	0.73 (good)	-16 (satisfactory)	6 (very good)	0.49 (very good)	0.52 (good)

Table 10: Performance ratings for spatial validation

	NSE	PBIAS	RSR
05MB003	0.76 (very good)	-1 (very good)	0.49 (very good)
05MD004	0.80 (very good)	-16 (satisfactory)	0.44 (very good)

```
SUBROUTINE FROZEN(FI, SNOWMELT, TS, SOIL_MOIST, SWE,                    &
                  SOIL_POR_MAX, SOIL_DEPTH, S0, T_ICE_LENS,             &
                  t0_ACC, C, DELT, NCOUNT, ILG, IL1, IL2,               &
                  SI, TSI, INFILTYPE, SNOWMELTD, SNOWMELTD_LAST,        &
                  MELTRUNOFF, SNOWINFIL, CUMSNOWINFIL)

!>=========================================================================

!>                 December 20, 2010 - M.A. Mekonnen
!>=========================================================================

!> DESCRIPTION: For a frozen soil the frozen module partitions snow melt
!>              runoff into infiltration and runoff using Gray et al,
!>              2001. The subroutine is adapted from the FROZEN module
!>              of the Cold Regions Hydrological Model (CRHM).
!>=========================================================================

!> REFERENCES:
!> 1. Pomeroy et al, 2007 - The cold regions hydrological model: a
!>                          platform for basing process representation
!>                          and model structure on physical evidence,
!>                          Hydrological Processes 21: 2650 - 2667

!> 2. Gray et al, 2001 - Estimating areal snowmelt infiltration into
!>                       frozen soils, Hydrological Processes 15: 3095
!>                       - 3111

!> 3. Zhao and Gray, 1999 - Estimating areal snowmelt infiltration into
!>                          frozen soils, Hydrological Processes 13:
!>                          1827 - 1842

!> 4. Zhao and Gray, 1997 - A parameteric expression for estimating
!>                          infiltration into frozen soils, Hydrological
!>                          Processes 11: 1761 - 1775
!>=========================================================================

!> Incoming variables

!> FROZENSOILINFILFLAG - Flag for frozen soil infiltration calculation
!>                        choices.
!>                     - 0 (Default value) - do not use FROZEN
!>                         algorithm. This corresponds to unlimited
!>                         infiltration.
!>                     - 1 - use FROZEN algorithm.

!> FI                  - Fractional area
!> DELZ1               - Top soil layer depth (m)
!> SNOWMELT            - Melt rate at the bottom of snowpack (m/sec)
!> TS                  - Temperature of top soil layer (řk)
!> SWE                 - Snow water equivalent (mm)
!> SOIL_MOIST          - Frozen soil moisture (mm^3/mm^3)
!> DELT                - Model time step (sec)
!> NCOUNT              - Number of counts in a day [1 to 48]

!> Outgoing variables:

!> t0_ACC              - Accumulated opportunity time (hr)
!> TSI                 - Initial soil temperature (řC)
!> SI                  - Initial soil moisture (mm^3/mm^3)
!> INFILTYPE           - Infiltration type
!> SNOWINFIL           - Melt infiltration rate (m/sec)
!> CUMSNOWINFIL        - Cumulative melt infiltration (m)
!> MELTRUNOFF          - Melt runoff (m/sec)
!> CUMMELTRUNOFF       - Cumulative melt runoff (m)
!> SNOWMELTD           - Daily snow melt (m)
!> SNOWMELTD_LAST      - Yesterday's snowmelt (m)

!> Parameters:
!>
!> SOIL_POR_MAX        - Maximum soil porosity (mm^3/mm^3) [ 0 - 1]
!> SOIL_DEPTH          - Depth from surface to bottom of rooting zone for
!>                       maximum water holding capacity (m)
!> S0                  - Surface saturation during melting (mm^3/mm^3)
!>                       [0 - 1]
!> C                   - Coefficient for the frozen soil infiltration
!>                       parameteric equation. Ranges vary from 1 to 3
!>                       Prairie value = 2.1, Boreal Forest value =1.14
!> T_ICE_LENS          - Overnight minimum temperature to cause ice lens
!>                       after major melt (žC)

!> Local temporary variables:
!>
!> t0                  - Opportunity time (hr)
```

```fortran
!> INF                    -   Cumulative frozen soil infiltration (mm)
!> INF0                   -   Frozen soil infiltration rate (m/sec)
!> CAPACITY               -   Maximum top frozen soil water holding capacity
!>                            (m/sec)
!>=============================================================================

USE FLAGS

IMPLICIT NONE

!> INCOMING
INTEGER NCOUNT, ILG, IL1, IL2
REAL    DELT, t0_ACC, SOIL_POR_MAX, SOIL_DEPTH, S0, T_ICE_LENS
REAL    FI(ILG), SWE(ILG), SNOWMELT(ILG), TS(ILG), SOIL_MOIST(ILG), C(ILG)

!> OUTGOING
INTEGER INFILTYPE(ILG)
REAL    SI(ILG), TSI(ILG), SNOWMELTD(ILG), SNOWMELTD_LAST(ILG),               &
        SNOWINFIL(ILG), CUMSNOWINFIL(ILG), MELTRUNOFF(ILG)

!> LOCAL
INTEGER, PARAMETER :: RESTRICTED = 1
INTEGER, PARAMETER :: UNLIMITED  = 2
INTEGER, PARAMETER :: LIMITED    = 3

INTEGER I
REAL    t0, INF, INF0, INF1, INF2, INF3, INF4, CAPACITY

!>-----------------------------------------------------------------------------
!> Initialize snow infiltration and melt runoff.
!>-----------------------------------------------------------------------------
SNOWINFIL  = SNOWMELT
MELTRUNOFF = 0.0

!>-----------------------------------------------------------------------------
!> Loop through active elements (GRUs).
!>-----------------------------------------------------------------------------
DO I = IL1, IL2

!>-----------------------------------------------------------------------------
!>  Check if GRU snow cover fraction is greater than 1% and if FROZEN
!>  module is activated for the specific GRU.
!>-----------------------------------------------------------------------------
    IF(FI(I) > 0.01 .and. C(I) > 0.0)THEN

!>-----------------------------------------------------------------------------
!>      Restricted infiltration due to ice lens formation can occur if
!>      soil temperature is less than some specified value and that there
!>      was a significant amount of snow melt (at least 5 mm).
!>-----------------------------------------------------------------------------
        IF(TS(I)              <= T_ICE_LENS  .AND.                            &
           INFILTYPE(I)       == LIMITED     .AND.                            &
           SNOWMELTD_LAST(I) >   0.005            )INFILTYPE(I) = RESTRICTED

!>-----------------------------------------------------------------------------
!>      Compute daily snow melt.
!>-----------------------------------------------------------------------------
        SNOWMELTD(I) = SNOWMELTD(I) + SNOWMELT(I)*DELT

!>-----------------------------------------------------------------------------
!>      Store end of day's snow melt as yesterday's snow melt and reset
!>      daily snow melt to zero.
!>-----------------------------------------------------------------------------
        IF(NCOUNT == 48)THEN
           SNOWMELTD_LAST(I) = SNOWMELTD(I)
           SNOWMELTD(I)      = 0.0
        ENDIF

!>-----------------------------------------------------------------------------
!>      Snow is melting.
!>-----------------------------------------------------------------------------
        IF(SNOWMELT(I) > 0.0)THEN
           IF(INFILTYPE(I) == UNLIMITED)INFILTYPE(I) = LIMITED

!>-----------------------------------------------------------------------------
!>          Partition snow melt into infiltration and runoff.
!>-----------------------------------------------------------------------------
           SELECT CASE(INFILTYPE(I))

!>-----------------------------------------------------------------------------
!>              Unlimited infiltration category.
!>-----------------------------------------------------------------------------
              CASE(UNLIMITED)
```

```
!>------------------------------------------------------------------------
!>          All snow melt infiltrates.
!>------------------------------------------------------------------------
            SNOWINFIL(I)       = SNOWMELT(I)
            CUMSNOWINFIL(I)  = CUMSNOWINFIL(I) + SNOWINFIL(I)*DELT

!>------------------------------------------------------------------------
!>        Restricted infiltration category.
!>------------------------------------------------------------------------
        CASE(RESTRICTED)

!>------------------------------------------------------------------------
!>          All snow melt becomes direct runoff.
!>------------------------------------------------------------------------
            MELTRUNOFF(I)       = SNOWMELT(I)

!>------------------------------------------------------------------------
!>        Limited infiltration category.
!>------------------------------------------------------------------------
        CASE(LIMITED)

!>------------------------------------------------------------------------
!>          Actual infiltration is limited by the available water
!>          holding capacity and the potential infiltration rate.
!>------------------------------------------------------------------------

!>------------------------------------------------------------------------
!           Compute water holding capacity of the frozen soil.
!>------------------------------------------------------------------------
            CAPACITY = (SOIL_POR_MAX-SOIL_MOIST(I))*SOIL_DEPTH/DELT

!>------------------------------------------------------------------------
!>          If there exists some more space for further infiltration.
!>------------------------------------------------------------------------
            IF(CAPACITY > 0.0)THEN

!>------------------------------------------------------------------------
!>              Compute potential infiltration rate using the
!>              parameteric equation.
!>------------------------------------------------------------------------

!>------------------------------------------------------------------------
!>              Opportunity time (user specified or computed).
!>------------------------------------------------------------------------
                IF(t0_ACC > 0.0)THEN

!>------------------------------------------------------------------------
!>                  User provided opportunity time.
!>------------------------------------------------------------------------
                    t0 = t0_ACC

                ELSE

!>------------------------------------------------------------------------
!>                  Compute opportunity time [hours] based on the empirical
!>                  equation by Zhao and Gray, 1997.
!>------------------------------------------------------------------------
                    t0 = MAX(DELT/3600.0, 0.65 * SWE(I) - 5)

                ENDIF

!>------------------------------------------------------------------------
!>              Compute potential frozen soil infiltration.
!>------------------------------------------------------------------------
                INF1  = C(I) * (S0**2.92)
                INF2  = (1.0 - SI(I))**1.64
                INF3  = (-TSI(I) / 273.15)**(-0.45)
                INF4  = t0**0.44
                INF   = INF1 * INF2 * INF3 * INF4 / 1000.0

!>------------------------------------------------------------------------
!>              Potential infiltration rate in m/sec
!>------------------------------------------------------------------------
                INF0 = INF/(t0*3600.0)

!>------------------------------------------------------------------------
!>              All snow melt infiltrates if there is sufficient
!>              frozen soil water holding capacity and actual melting
!>              rate is less than the potential infiltration rate.
!>------------------------------------------------------------------------
                IF(SNOWMELT(I) <= INF0  .AND.                          &
                   SNOWMELT(I) <= CAPACITY)THEN
```

```
                  SNOWINFIL(I)    = SNOWMELT(I)
                  MELTRUNOFF(I)  = 0.0

!>-----------------------------------------------------------------------
!>              Snow melt infilitration limited by potential
!>              infiltration rate.
!>-----------------------------------------------------------------------
               ELSEIF(SNOWMELT(I) >  INF0  .AND.                        &
                      INF0         <= CAPACITY)THEN

                 SNOWINFIL(I)    = INF0
                 MELTRUNOFF(I)  = SNOWMELT(I) - INF0

!>-----------------------------------------------------------------------
!               Snow melt infilitration limited by available capacity.
!>-----------------------------------------------------------------------
               ELSE

                  SNOWINFIL(I)    = CAPACITY
                  MELTRUNOFF(I)  = SNOWMELT(I) - CAPACITY

               ENDIF

!>-----------------------------------------------------------------------
!>              Compute cummulative infiltration.
!>-----------------------------------------------------------------------
               CUMSNOWINFIL(I) = CUMSNOWINFIL(I) + SNOWINFIL(I)*DELT

!>-----------------------------------------------------------------------
!>              Check mass conservation and adjust infiltration
!>              category.
!>-----------------------------------------------------------------------
               IF(CUMSNOWINFIL(I)   > INF)THEN

                  CUMSNOWINFIL(I)   = INF
                  INFILTYPE(I)      = RESTRICTED

               ENDIF

!>-----------------------------------------------------------------------
!>            All snow melt becomes runoff if frozen soil water holding
!>            capacity is exhausted.
!>-----------------------------------------------------------------------
            ELSE

               MELTRUNOFF(I)      = SNOWMELT(I)

            ENDIF

         END SELECT

      ENDIF

   ELSE

!>-----------------------------------------------------------------------
!>       Snow melting just started. Initialize soil moisture and
!>       temperature.
!>-----------------------------------------------------------------------
         SI(I)      = SOIL_MOIST(I) / MAX(SOIL_MOIST(I), SOIL_POR_MAX)
         TSI(I)     = MIN(-0.10, TS(I))

   ENDIF
ENDDO

RETURN

END
```

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