LAVSED-II—A model for predicting suspended load in northern streams

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Received November 5, 1984

Revised manuscript accepted October 24, 1985

The model LAVSED-II (LAVal SEDimentological model number II) has been developed to evaluate the suspended load in northern streams that results from rainfall and snowmelt erosion on upslope areas. The most important parameters are (1) the physical characteristics involved in soil erosion processes and (2) the climatic parameters on a month-to-month basis. Two fundamental relationships are obtained from the governing physical processes and empirical relationships describing snowmelt and sediment transport. The model has been applied to four large watersheds, tributaries of the St. Lawrence River. The computed sediment yield compares very well with the measured suspended load (mostly wash load) in the rivers. The magnitude of the peak during spring is particularly well predicted. The computed sediment yield is shown to be very sensitive to meteorological data. In the case of ungaged watersheds, the model can be applied to estimate the sediment yield.

Le modèle LAVSED-II (second modèle SEDimentologique de l'Université LAVal) a été développé pour évaluer la charge solide en suspension dans les cours d'eau nordiques à partir de l'érosion superficielle pluviale et nivale à l'échelle de grands bassins versants. Deux relations fondamentales sont obtenues en considérant les principales caractéristiques physiques rattachées à l'érosion des sols ainsi que la variabilité des paramètres climatiques sur une base mensuelle. Le modèle a été appliqué sur quatre bassins versants, tributaires du fleuve St-Laurent, dont la charge solide provient essentiellement de l'érosion superficielle. L'apport solide calculé par le modele est comparable à celui observé. La pointe sédimentologique lors de la crue printanière est particulièrement bien définie et l'analyse démontre l'importance des données météorologiques régionales. Pour les bassins non jaugés, la charge solide peut également être estimée par le modèle.

Can. J. Civ. Eng. 13, 162–170 (1986)

Introduction

Sediment transport in streams can be classified in different ways according to the mode of transport and the origin of sediments. The part of the total sediment load composed of particles finer than the sediment bed mixture is commonly referred to as the wash load. The total number of particles transported as suspended load or wash load depends mostly on the upslope supply rate of particles from sheet and rill erosion on the watershed.

Two mathematical models (LAVSED-I and LAVSED-II) have been developed at Laval University for predicting sediment yield from large watersheds. The model LAVSED-I (Frenette and Julien 1986) is based on the universal soil loss equation and an empirical sediment transport equation. Whereas the model LAVSED-I is intended for mapping soil erosion on a mean annual basis, the model LAVSED-II is used to obtain monthly predictions of the sediment yield. This paper briefly describes the principal components of the model LAVSED-II and illustrates its predictive capabilities as applied to large northern watersheds.

First the physical processes are summarized; then the equations are presented for sediment yield due to rainfall and snowmelt. The equations are used in a quasi-stochastic model that calculates the mean monthly sediment yield from stochastic rainfall and deterministic physical characteristics. Finally, the computed yields are compared with the observed sediment load in the four rivers shown in Fig. 1.

Physical processes

Most of the suspended sediment load in northern streams under investigation originates from soil erosion by overland flow. There is snow accumulation on the frozen ground from December to March. The snow cover usually melts over a relatively short period of time, generally in March, and the sediment load peaks during spring floods. From May to November, the sediment load in streams is limited by the rainfall erosion supply.

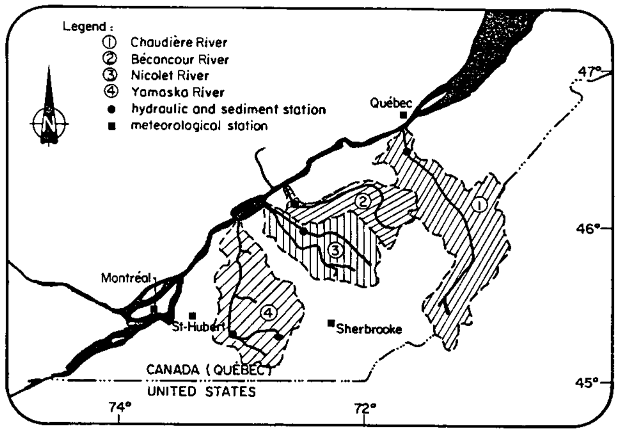

FIG. 1. Location of watersheds.

As shown in Fig. 2, soil erosion through the action of raindrop impact and runoff is a complex process of detachment and transport of soil particles. In most cases, soil detachment by raindrop impact does not control the supply of sediment to overland flow. Most soil particles are moved downslope by surface runoff. For this reason, runoff is a better variable than rainfall to describe soil erosion.

Early in spring, the snowmelt water percolates through the unsaturated zone of the snowpack. As the percolating meltwater reaches the ground, the water in excess of the infiltration rate flows downslope in the saturated layer. Early in the season, the flow in the saturated layer is similar to flow in porous media. As the melting season progresses, however, micro-

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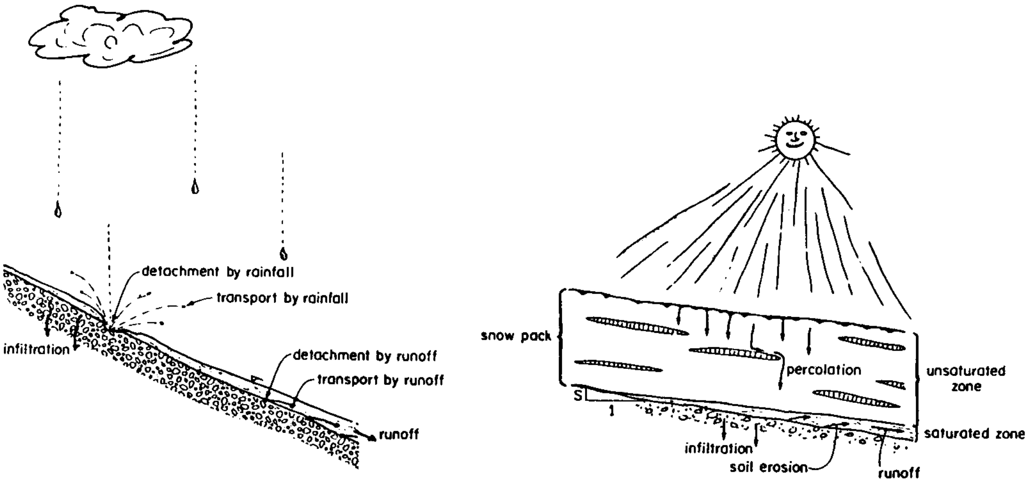

FIG. 2. Soil erosion processes during rainfall and snowmelt.

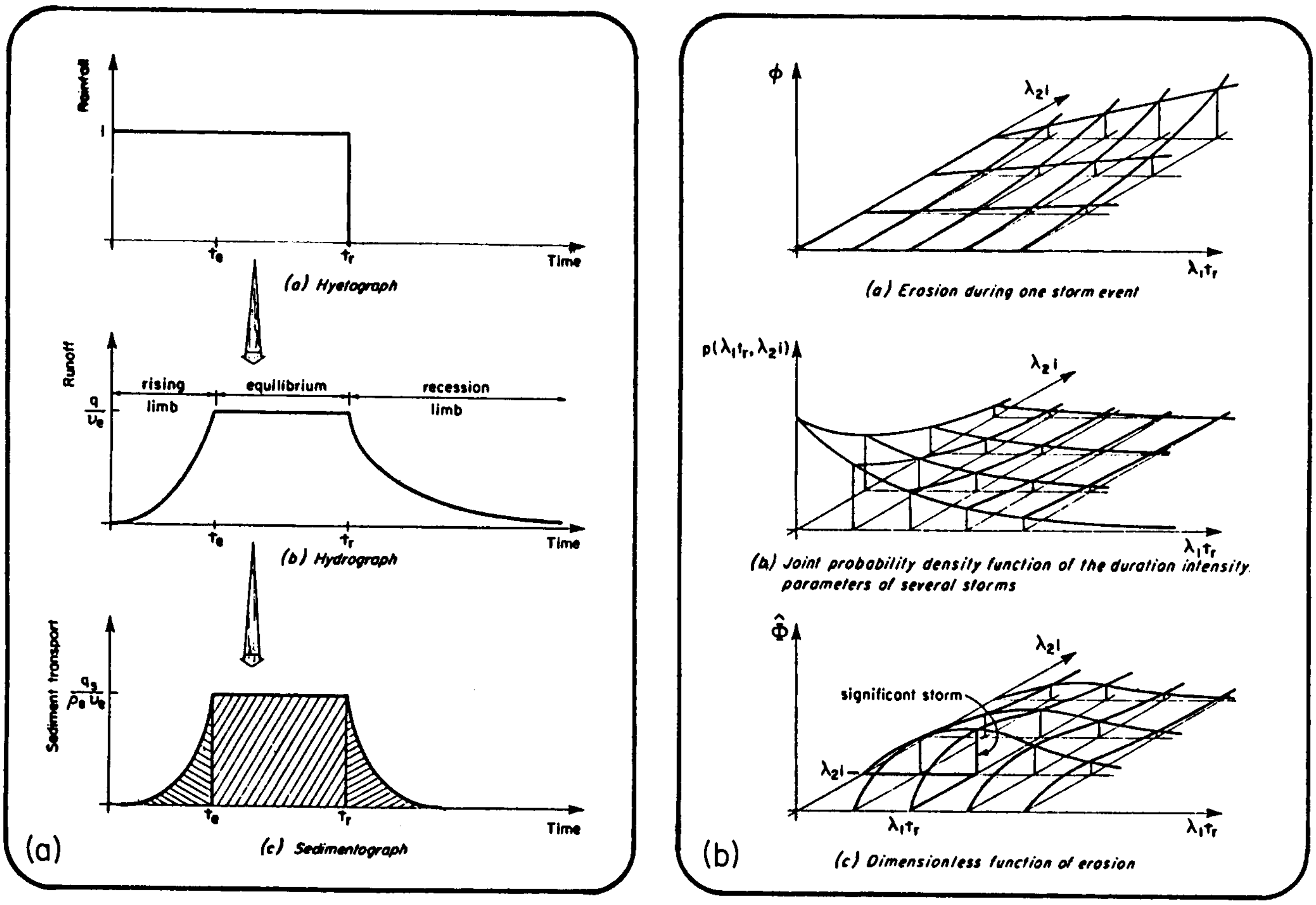

FIG. 3 (*a*). Rainfall erosion analysis. (*b*) Computation of the dimensionless function of erosion.

channels develop in the snowpack and flow conditions gradually degenerate into open channel flows.

Sediment yield during rainfall

As suggested by Todorovic (1968) and Eagleson (1978), point rainfall can be described as a random series of discrete storm events of finite duration and constant intensity. The two principal variables are the storm duration t_r and intensity i. These two variables have been shown by Eagleson (1978) and Julien (1982) to be nearly independent and distributed exponentially, with probability density functions $p(t_r)$ and $p(i)$ written as

[1] $p(t_r) = \lambda_1 \, e^{-\lambda_1 t_r}$

and

[2] $p(i) = \lambda_2 \, e^{-\lambda_2 i}$

The parameters for rainfall duration λ_1 and intensity λ_2 are evaluated for each month.

The problem of rainfall erosion on a small plot is then considered. Surface runoff is a complex phenomenon involving sheet flow and rills depending on geometry and soil conditions. For modeling purposes, it is assumed that the runoff occurs in a thin-sheet layer over an impervious surface area A_e of given length L and slope S. The resulting hydrograph is subdivided into three parts: the rising limb, the equilibrium, and the falling limb. A detailed evaluation of soil erosion for complete and partial equilibrium hydrographs schematized in Fig. 3 has been conducted at Laval University. A series expansion solution was theoretically derived (Julien 1982) and a first-order approximation is obtained when the first term of the series is considered. When applied to field problems, the authors found that the first-order approximation generally gives less than 5% discrepancy between the two computed results. Hence, the specific discharge q to calculate soil erosion is given in terms of the length L and intensity i by

$$[3] \quad q = iL$$

Dimensional analysis supports the following sediment transport capacity relationship q_s as a power function of slope S, discharge q, rainfall intensity i, and four coefficients (α, β, γ, δ):

$$[4] \quad q_s = \alpha S^{\beta} q^{\gamma} i^{\delta}$$

Julien and Simons (1985) discussed the evaluation of the coefficients α, β, γ, and δ using different approaches. From experimental data, Kilinc and Richardson (1973) obtained a regression-type equation and the following coefficients are recommended: $\alpha = 25\,500$, $\beta = 1.66$, $\gamma = 2.035$, and $\delta = 0$ (note q_s in t/(m·s) and q in m^2/s). The total soil erosion by a single rainfall event $\bar{m}$ is obtained by the following equation:

$$[5] \quad \bar{m} = \frac{A_e}{L} q_s t_r$$

In this equation, the soil erosion $\bar{m}$ is a function of the surface area A_e and the duration of rainfall t_r. After substitution of [3] and [4], [5] gives

$$[6] \quad \bar{m} = A_e \alpha S^{\beta} L^{\gamma - 1} i^{\gamma + \delta} t_r$$

This equation estimates the mass of potential soil erosion provided the rainfall duration and intensity are known.

For any rainfall event, the expected value of soil erosion is determined with regard to the variability of the rainfall intensity and duration:

$$[7] \quad M = \int_0^{\infty} \int_0^{\infty} \bar{m} p(t_r) p(i) \, dt_r di$$

After substitution of [1], [2], and [6], the integration of [7] leads to

$$[8] \quad M = A_e \frac{\alpha S^{\beta} L^{\gamma - 1}}{\lambda_1 \lambda_2^{\gamma + \delta}} \Gamma(\gamma + \delta + 1)$$

where $\Gamma(\gamma + \delta + 1)$ is the gamma function.

The expected value of potential soil erosion for one rainfall event is a function of the distributions of rainfall duration and intensity respectively through the parameters λ_1 and λ_2. When compared with the complete series expansion solution, [8] has been shown by Julien (1982) to give accurate evaluation of soil erosion when the following criterion between physical and rainfall characteristics is verified:

$$[9] \quad \left(\frac{8gS}{K\nu_e L}\right)^{1/3} \gg \lambda_1 \lambda_2^{2/3}$$

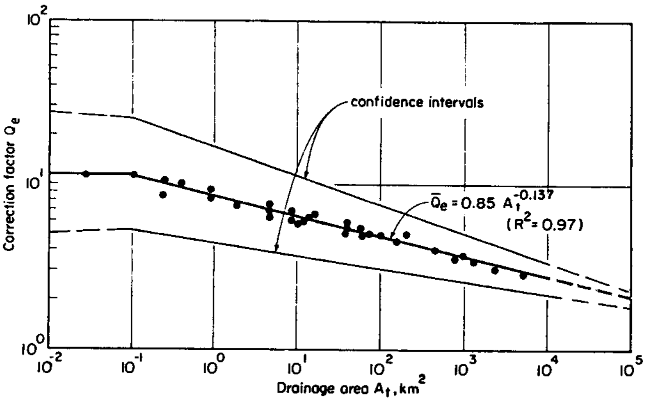

FIG. 4. Mean value and confidence limits (95%) of the correction factor Q_e vs. drainage area.

where g = gravitational acceleration, K = friction coefficient, and ν_e = kinematic viscosity of water. This criterion is largely satisfied for most conditions encountered in the field. For a given month, the expected value of the potential soil erosion $M_{\bar{\nu}}$ is proportional to the mean number of storms $\bar{\nu}$ during that period:

$$[10] \quad M_{\bar{\nu}} = M\bar{\nu}$$

The cropping management factor C of the well-known universal soil-loss equation (Wischmeier and Smith 1978) is used to reduce the potential erosion given by [10] to account for the effects of vegetation. The runoff coefficient C_r, computed from the ratio of runoff to rainfall for a given period of time allows for water losses due to interception, evapotranspiration, and infiltration. A sensitivity analysis involving the following three hypotheses has been undertaken: (1) no infiltration; (2) the runoff coefficient reduces the effective duration of rainfall; and (3) the runoff coefficient reduces the effective intensity of rainfall (or discharge). From application on four watersheds, it was concluded that the best results were obtained with the second hypothesis, and therefore the soil erosion is proportional to the runoff coefficient.

When dealing with large watersheds ($A > 500$ km^2), Julien (1979) introduced the concept of characteristic values for slope length $\bar{L}$, slope $\bar{S}$, and cropping factor $\bar{C}$. A correction factor Q_e was defined as the ratio of soil erosion computed with the characteristic parameters, to the soil erosion computed using the tedious process of subdividing the watershed into small units. Several thousand values of the correction factor were determined and the relationship shown in Fig. 4 ($Q_e = 0.85 A_t^{-0.137}$ is recommended (Julien 1979; Frenette and Julien 1986).

The sediment yield is, by definition, equal to the product of total erosion and the sediment–delivery ratio C_s. Further discussion on the evaluation of the parameters $\bar{L}$, $\bar{S}$, $\bar{C}$, and C_s is given in the section on Applications. The monthly sediment yield Q_{sp} in kt is

$$[11] \quad Q_{sp} \simeq 994 C_s \bar{C} C_r A_t \frac{\bar{\nu} \alpha \bar{S}^{\beta} \bar{L}^{\gamma - 1}}{Q_e \lambda_1 \lambda_2^{\gamma + \delta}} \Gamma(\gamma + \delta + 1)$$

This equation is used in the model LAVSED-II for predicting the sediment yield from large watersheds during the rainfall season.

Sediment yield during snowmelt

The relationship of sediment yield to runoff was investigated

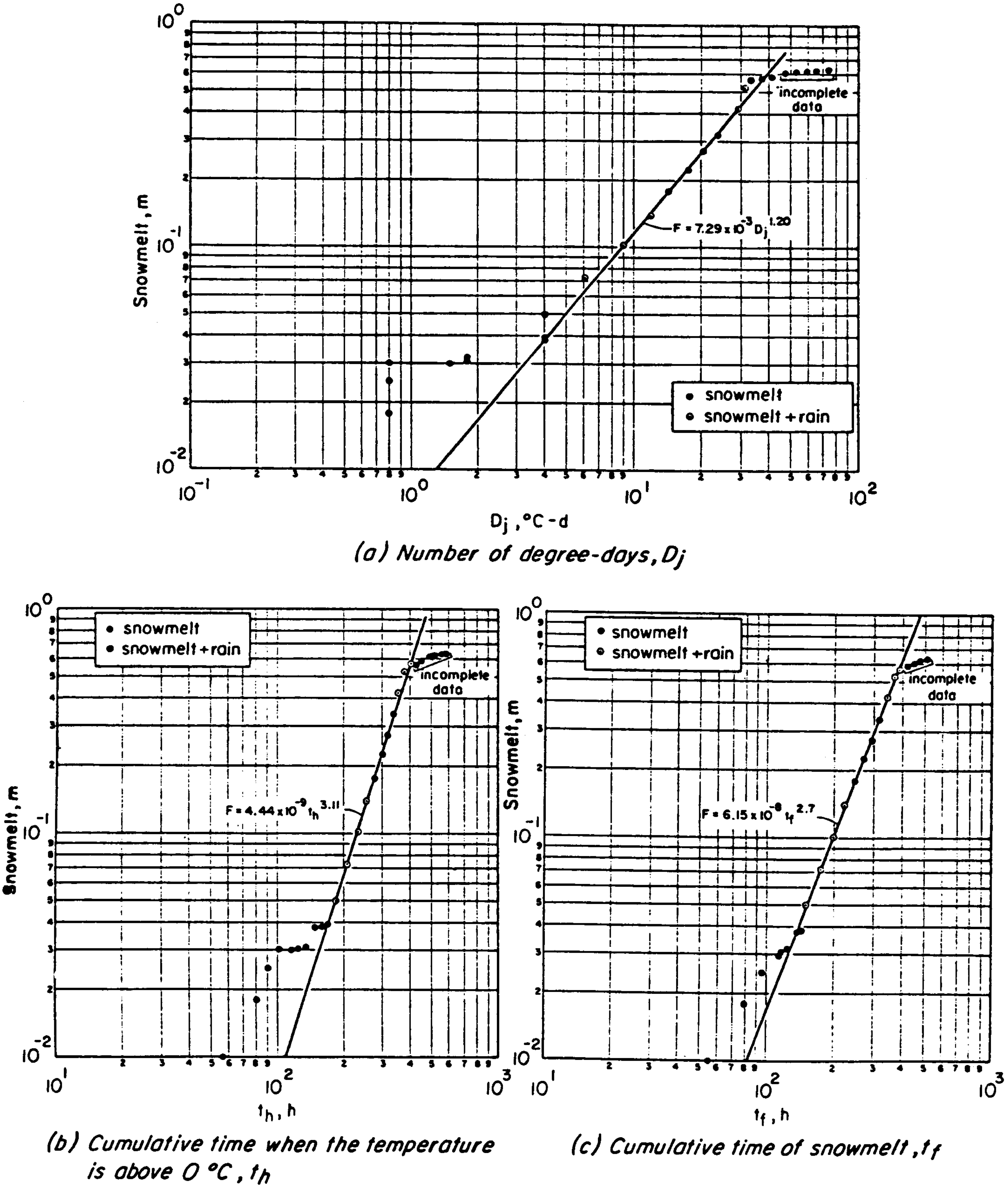

FIG. 5. Cumulative snowmelt as a function of three parameters.

for large watersheds during the snowmelt period. Snowmelt data from a small experimental plot were available for the analysis. Hourly data of runoff intensity were scrutinized, and the cumulative snowmelt F was successfully correlated to three factors (see Fig. 5): (1) the cumulative number of degree-days D_j in °C·d; (2) cumulative time when the temperature is above 0°C, t_h in h; and (3) cumulative time of snowmelt t_f in s:

[12] $F = 7.29 \times 10^{-3} D_j^{1.2}$

[13] $F = 4.44 \times 10^{-9} t_h^{3.11}$

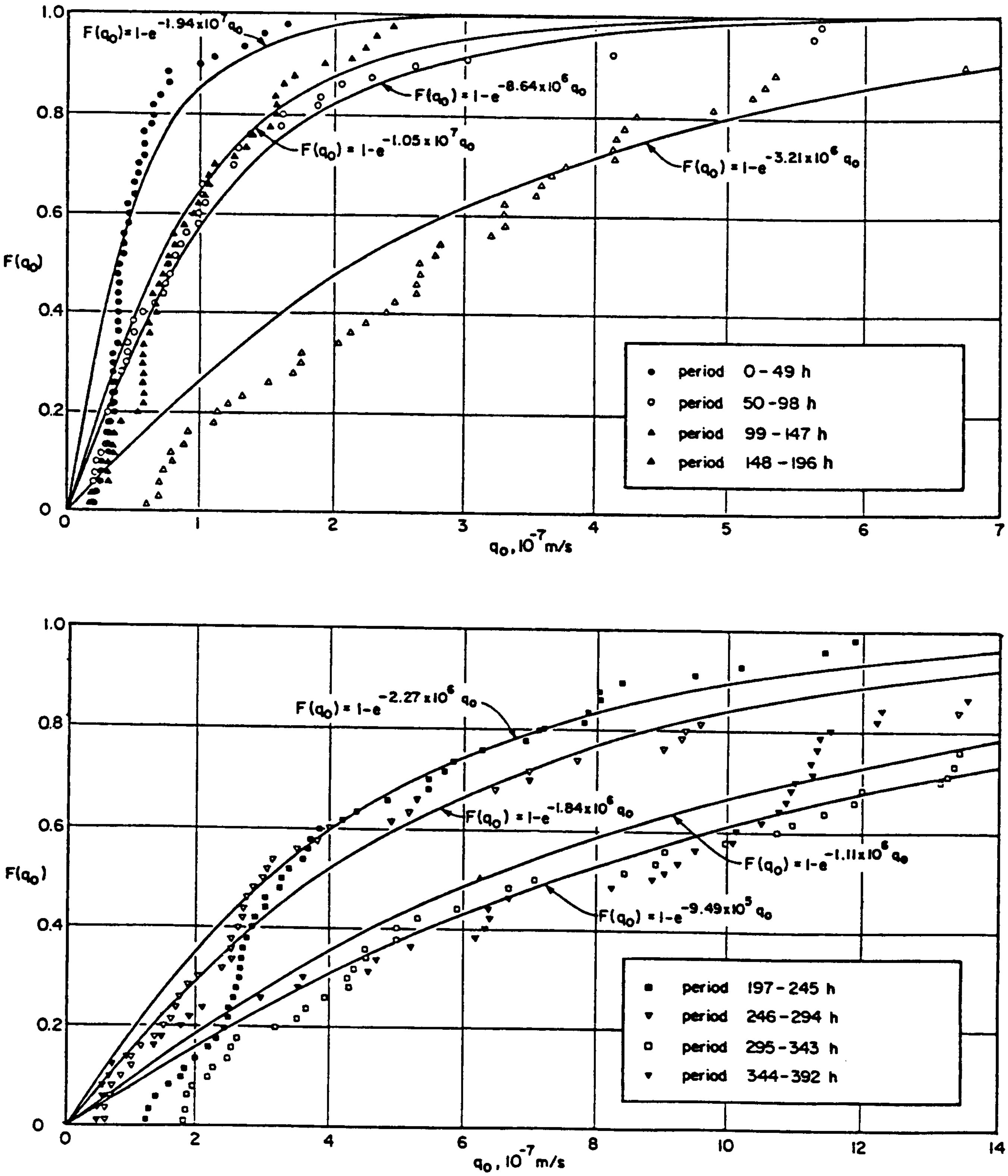

FIG. 6. Runoff distribution during snowmelt.

[14] $F = \alpha_f t_f^{\beta_f} = 1.54 \times 10^{-17} t_f^{2.7}$

where α_f, β_f are the snowmelt parameters.

Equation [14] should be given preference since it is physically sound. Either [12] or [13] is best suited to obtain F when data for t_f is not available. The first derivative of [14] gives the mean runoff intensity, which is also a function of t_f. Consequently, the two variables are not independent. The distribution functions $F(q_0)$ of the hourly runoff intensity q_0 are shown in Fig. 6. The observed data fit an exponential probability density function reasonably well, which can be written as

[15] $F(q_0) = \int_0^{q_0} p(q_0)\, dq_0 = \int_0^{q_0} \lambda_{2f}\, e^{-\lambda_{2f} q_0}\, dq_0$

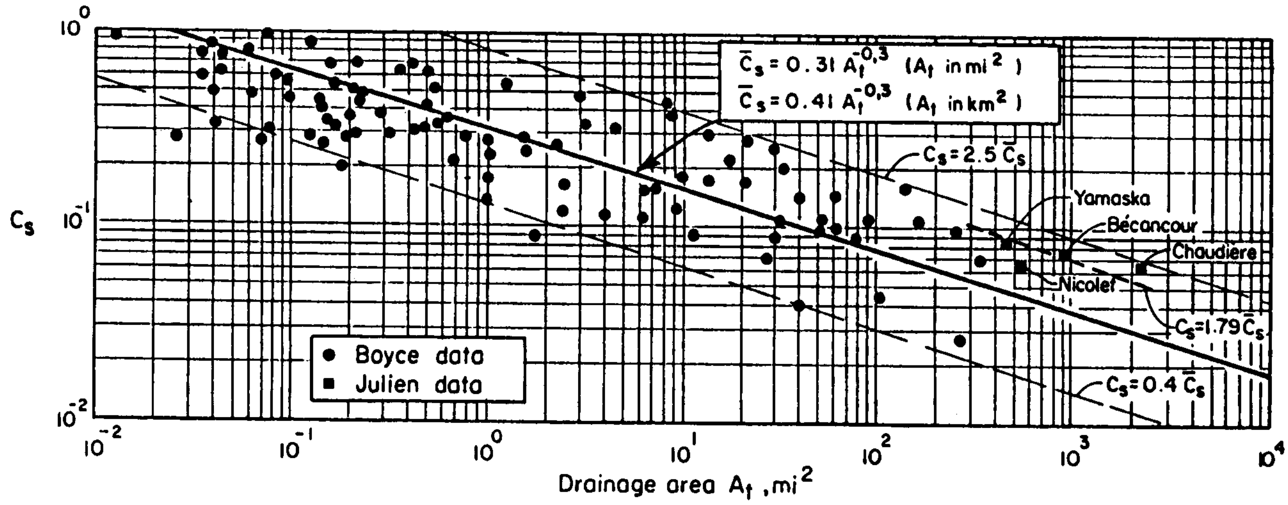

FIG. 7. Sediment–delivery ratio versus drainage area (modified after Boyce 1975).

TABLE 1. Principal characteristics of watersheds

Watershed	Area A_t (km²)	Cropping factor $\bar{C}$	Characteristic slope $\bar{S}$	Runoff length $\bar{L}$ (m)
Chaudière	5830	0.35	0.0156	91.5
Bécancour	2340	0.40	0.0134	91.5
Nicolet	1530	0.65	0.0164	91.5
Yamaska	1260	0.15	0.0216	91.5

and

$$[16] \quad \lambda_{2f} = \frac{dt_f}{dF}$$

When [14] is substituted into [16], the snowmelt parameter λ_{2f} decreases as the melting period progresses. The influence of thawing of the frozen ground has been included in the equations. The effective surface on which soil erosion occurs is assumed to be proportional to the relative time of melting defined as follows:

$$[17] \quad A_f = A_e \left(\frac{t_f}{T_f}\right)^{\gamma_f}$$

in which t_f = time of melting, T_f = total time of melting, and γ_f = thawing parameter (assumed equal to unity). Sensitivity analysis showed that soil erosion is not very sensitive to γ_f. The cumulative soil erosion during snowmelt M_f is

$$[18] \quad M_f = \int_0^{t_f}\int_0^{\infty} \frac{A_f}{L}\,\alpha S^{\beta} q_0^{\gamma} L^{\gamma} \lambda_{2f}\, e^{-\lambda_{2f} q_0}\, dq_0\, dt_f$$

After integration, this equation transforms to

$$[19] \quad M_f = \frac{A_e \alpha S^{\beta} L^{\gamma-1} (\alpha_f \beta_f)^{\gamma}}{\gamma_f + \gamma\beta_f - \gamma + 1} \left(\frac{F}{\alpha_f}\right)^{(\gamma\beta_f - \gamma + 1)/\beta_f} \times \left(\frac{F}{F_t}\right)^{\gamma_f/\beta_f} \Gamma(\gamma + 1)$$

in which F_t is the total snowmelt.

Analysis of erosion on large watersheds indicates that the cumulative erosion E_f can be estimated when the vegetation $\bar{C}$ and the parameters $\bar{S}$, $\bar{L}$, and Q_e are considered:

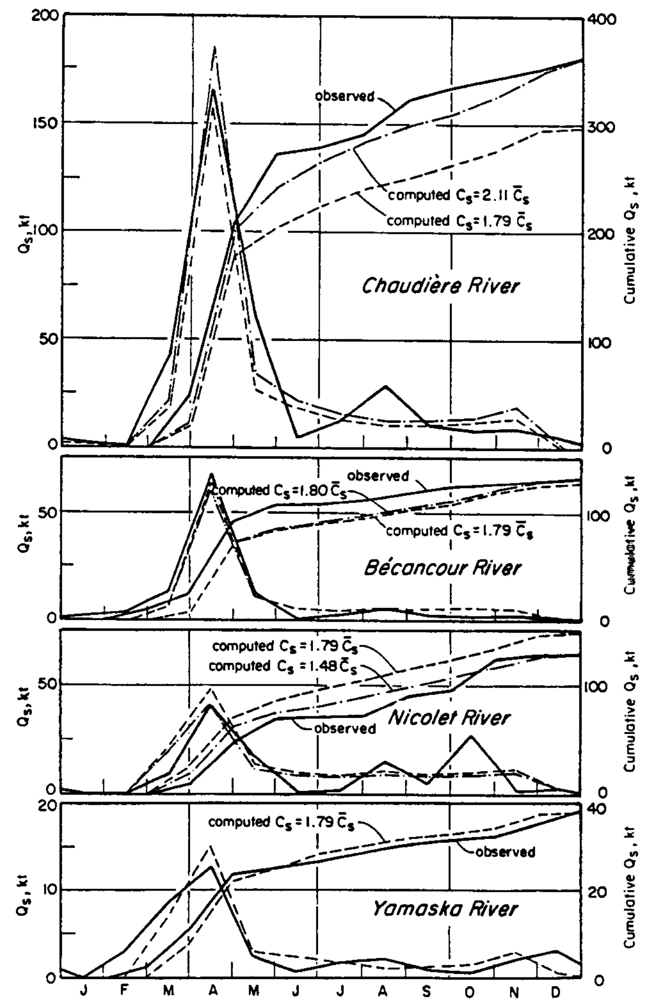

FIG. 8. Computed sediment yield and observed suspended load.

$$[20] \quad E_f \simeq 1000\,\frac{\bar{C}}{Q_e}\,\frac{A_t \alpha \bar{S}^{\beta} \bar{L}^{\gamma-1} (\alpha_f \beta_f)^{\gamma}}{\gamma_f + \gamma\beta_f - \gamma + 1} \times \left(\frac{F}{\alpha_f}\right)^{(\gamma\beta_f - \gamma + 1)/\beta_f} \left(\frac{F}{F_t}\right)^{\gamma_f/\beta_f} \Gamma(\gamma + 1)$$

After substitution of the parameters α, β, γ, α_f, β_f, γ_f, and

TABLE 2. Data required for the model LAVSED-II

Item	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
	(a) Meteorological data at Québec											
Rainfall (mm)	12.4	9.2	22.4	57.6	80	101.8	107.8	102.6	105.6	78.2	66.6	25.4
Percent time of rainfall	0.9	1	2.2	10.5	11.5	11.8	9.8	12.1	12.1	13.1	12.9	3.3
Snowfall (mm of water)	75.2	70.2	48	16.8	1	0	0	0	0	4.4	33.2	78
Percent time with temperature above 0°C	2.9	3	24.8	77.1	98	100	100	100	99.4	91.2	52.5	10.9
	(b) Runoff and sediment yield from the Chaudière River											
Runoff (mm)	20.4	13.6	48.7	184.6	112.5	42.3	26.2	27.2	25.5	42.5	49	42.9
Sediment yield* (kt)	2.6	0.2	42	167	63	4.9	14	30	12	10	10	6.9

*The sediment yield data were used for the validation of the model LAVSED-II but are not required for simulation of the sediment yield.

TABLE 3. Comparison of precipitation data between Montréal and Québec

Location	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
	(a) Rainfall (mm)											
Montréal	22.8	14.8	34.2	64.0	65.6	83.0	85.0	86.6	79.8	73.6	65.8	31.8
Québec	12.4	9.2	22.4	57.6	80.0	101.8	107.8	102.6	105.6	78.6	66.6	25.4
	(b) Snowfall (cm)											
Montréal	54.8	58.2	35.0	8.6	1.6	—	—	—	0.2	1.6	22.2	57.4
Québec	75.2	70.2	48.0	16.8	1.0	—	—	—	—	4.4	33.2	78.0

Q_e, one thus obtains

$$[21] \quad E_f \simeq 30.7 A_t^{1.137} \bar{C} \bar{S}^{1.66} \bar{L}^{1.035} F^{1.65} \left(\frac{F}{F_t}\right)^{0.37}$$

Finally, the cumulative sediment yield during snowmelt Q_{sf} is obtained from the total erosion E_f and the sediment–delivery ratio C_s as:

$$[22] \quad Q_{sf} \simeq 30.7 C_s A_t^{1.137} \bar{C} \bar{S}^{1.66} \bar{L}^{1.035} F^{1.65} \left(\frac{F}{F_t}\right)^{0.37}$$

Equations [22] and [11] are used in the model LAVSED-II to estimate the average sediment yield in northern streams from the main physical characteristics of the watersheds and the variable parameters of rainfall and snowmelt.

Applications

Four watersheds, tributaries of the St. Lawrence River, were analyzed for validation. The principal characteristics of these watersheds are shown in Table 1. The drainage area was obtained from topographic maps (1:250 000). The cropping factor $\bar{C}$ was determined from topographic maps (1:50 000) and from forest and agricultural maps (1:250 000). The characteristic slope was computed from the relationship $\bar{S} = \Delta H/1000\sqrt{A_t}$, in which ΔH is the difference of level between extreme elevations obtained from topographic maps. The runoff length $\bar{L}$ is the length of sheet and rill flow on upland areas. Based on topographical maps and field observations, this length was estimated to be ~300 ft (the value $\bar{L} = 91.5$ m was used for the computations), and was assumed constant for these watersheds. The determination of these parameters ($\bar{C}$, $\bar{L}$, $\bar{S}$) is straightforward and they were not optimized.

The data from 22 meteorological stations on the Chaudière watershed were analyzed to conclude that the data at Quebec Airport shown in Table 2 were representative of the average meteorological conditions on the Chaudière watershed. These data are obtained from the hourly data summaries for the period 1943–1970. The runoff and sediment yield data for the Chaudière watershed are also given in the same table. The runoff data extend from the period 1915–1978 while the sediment data are obtained from the measured suspended load from 1968–1976.

The computer model LAVSED-II based on [11] and [22] predicts monthly sediment yield. The sediment–delivery ratios are computed from the total soil erosion and the observed sediment yield in the river. In Fig. 7, the sediment–delivery ratios are plotted as a function of the drainage area. These results are in good agreement with those from smaller watersheds and a regional trend $C_s = 1.79\bar{C}_s$ is expected to provide a better estimate than $\bar{C}_s$ for these watersheds.

The computed and observed sediment yields are shown in Fig. 8. The data from the nearest meteorological station (namely Québec for Chaudière and Bécancour, and Sherbrooke for Nicolet and Yamaska) were considered. Two values of the sediment-delivery ratio were used: (1) the individual value of C_s for each watershed and (2) the mean regional value given by $C_s = 1.79\bar{C}_s$. Except for the value of C_s, which is calibrated from observed data, the other parameters were not optimized. The model LAVSED-II gives very good prediction of the peak sediment yield during spring. The predicted values during the rainfall season remain within the fluctuation range; and during winter, the sediment loads are shown to be negligible.

Two watersheds were selected (Nicolet and Yamaska) for a sensitivity analysis focused on different meteorological condi-

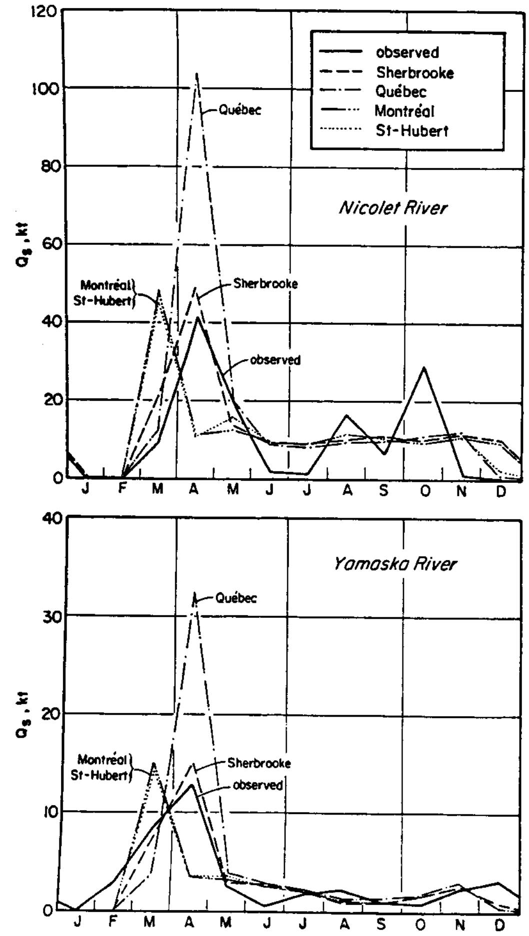

FIG. 9. Sensitivity analysis with different meteorological conditions.

tions summarized in Table 3. The regional value of C_s was used, and from the results shown in Fig. 9, the data of the nearest station give the best results for simulation, namely, the magnitude and the time of occurrence of the peak. Simulations with meteorological data from a warmer statio n (Montréal) produce an earlier peak in sediment yield while the data from a colder region (Québec) give a much higher peak in sediment yield due to the larger accumulation of snow during winter.

Conclusion

The model LAVSED-II described in this paper is well-suited for month-to-month prediction of sediment yield from northern watersheds. The model is based on the most significant physical processes of rainfall, overland flow, snowmelt runoff, soil erosion, and sediment yield. The model LAVSED-II has been successfully applied to several watersheds and the results are shown in Figs. 8 and 9. The model is also applicable to watersheds for which no suspended data are available. In this case the order of magnitude of the sediment yield can be predicted from physical parameters and meteorological and runoff data. Further developments on watershed modeling of snowmelt erosion and sediment yield are currently under preparation at Laval University.

Acknowledgments

This paper is based on studies carried out at the Department of Civil Engineering at Laval University. The authors wish to thank D. M. Hartley, Dr. D. B. Simons, Dr. R. M. Li, G. O. Brown, and J. S. O'Brien from Colorado State University for their helpful and constructive comments in the revision of this paper.

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List of symbols

A_e	surface area of a plot
A_f	effective surface area during snowmelt
A_t	drainage area of a watershed
C	cropping management factor
$\bar{C}$	characteristic cropping factor of a watershed
C_r	runoff coefficient
C_s	sediment–delivery ratio
D_j	cumulative degree-days, °C·d
E_f	cumulative erosion over a large surface
F	cumulative snowmelt
F_t	total snowmelt
$F(q_0)$	distribution function of snowmelt runoff
g	gravitational acceleration
i	rainfall intensity
K	friction coefficient
L	plot length
$\bar{L}$	characteristic slope length of a watershed
$\bar{m}$	soil erosion during a single rainfall event of intensity i and duration t_r
M	expected value of soil erosion by a rainfall event
M_f	cumulative soil erosion during snowmelt
$M_{\bar{\nu}}$	expected value of soil erosion during a given period
$p(i)$	probability density function of rainfall intensity
$p(q_0)$	probability density function of hourly snowmelt intensity
$p(t_r)$	probability density function of rainfall duration
q	overland flow discharge
q_0	hourly snowmelt intensity

q_s	potential sediment discharge
Q_e	correction factor for grid size
Q_{sf}	cumulative sediment yield during snowmelt
Q_{sp}	monthly rainfall sediment yield
S	slope of a plot
$\overline{S}$	characteristic slope of a watershed
t	time
t_f	cumulative time of snowmelt
t_h	cumulative time when the temperature is above 0°C
t_r	rainfall duration
T_f	total time of snowmelt
$\alpha, \beta, \gamma, \delta$	coefficients of the erosion equation
$\alpha_f, \beta_f, \gamma_f$	snowmelt parameters
λ_1	rainfall duration parameter
λ_2	rainfall intensity parameter
λ_{2f}	snowmelt intensity parameter
ν_e	kinematic viscosity of water
$\bar{\nu}$	average number of storms during a period