CGU HS Committee on River Ice Processes and the Environment
14th Workshop on the Hydraulics of Ice Covered Rivers
Quebec City, June 19 - 22, 2007

Modelling anchor ice presence-absence in gravel bed streams

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In this study, we analysed the meteorological and hydraulic conditions conducive to anchor ice formation in three gravel bed streams of southern Québec (Beauport, Duberger and York rivers). The first objective was to model the occurrence of anchor ice events at the river reach scale. The data set included the dichotomous response variable presence-absence of anchor ice in a river reach at 7:00 am on each sampling day and five continuous predictors related to air temperature: freezing degree-hours cumulated over the preceding 6 hours (FDH-6), 8 hours (FDH-8), 12 hours (FDH-12), 24 hours (FDH-24) and 48 hours (FDH-48). Only the logistic regression model using FDH-12 was found significant according to the Wald test. Calculation of the correct classification rate (CCR) indicates that this model correctly classified 80.9% of the observed anchor ice presence-absence events at the river reach scale. The second objective was to model the spatial distribution of anchor ice within the study reaches of the Beauport and Duberger rivers for the events where anchor ice occurred. At each site, 54 parcels of 0.25 m^2 were used to evaluate the spatial distribution of anchor ice between 7:00 am and 8:30 am on each sampling day. Covariates common to all parcels within a river section (air and water temperature) and hydraulic variables specific to each parcel (flow velocity V, water depth D, Froude number $V/(gD)^{1/2}$) were used as explanatory variables. The results of a hierarchical logistic regression analysis indicates that once the air temperature reached the critical value for anchor ice formation, the Froude number was the unique parameter controlling the spatial distribution of anchor ice within a reach. The model correctly classified 67.5% of the presence-absence observations of anchor-ice on the parcels. This logistic model is one of the first attempts to predict the spatial distribution of anchor ice despite numerous other field and laboratory work.

1. Introduction

Anchor ice is a phenomenon common to most northern rivers. It generally forms by the accretion of frazil ice crystals on the streambed (Beltaos *et al.*, 1993; Hammar *et al.*, 1996; Kerr *et al.*, 1997) where it can reach thickness sufficient to modify local flow and sediment transport processes. For example, anchor ice accumulations have been shown to cause water stage increases, to divert the flow to other portions of the channel and to cause flow concentration capable of inducing local erosion of stream bed material (Beltaos *et al.*, 1993). Anchor ice also has important ecological consequences for fish inhabiting rivers during the winter season. For example, it may affect the survival of incubating salmonid eggs by reducing the intragravel flow supplying the oxygen to the eggs (Walsh and Calkins, 1986; Calkins, 1989; Power *et al.*, 1993). It may also be detrimental to juvenile salmonids by flooding or dewatering entire stream sections (Chisholm *et al.*, 1987; Beltaos *et al.*, 1993; Prowse, 2001a), thereby forcing them to move to find a more suitable habitat in a period of the year where spending critical energy reserve may induce mortality (Cunjak, 1996; Brown, 1999).

However, despite the considerable physical and biological importance of anchor ice, the study of the conditions leading to its formation has received less attention than other forms of river ice. Because anchor ice is formed of frazil ice crystals entrained toward the bed by turbulent flow eddies, its initiation is closely related to the production of frazil ice. Such frazil ice is produced when atmospheric conditions promote large and rapid radiative losses from the water mass causing water temperature to drop slightly below 0ºC. These conditions are generally optimally attained during clear windy nights (Parkinson, 1984) with air temperature below -10ºC (Beltaos, 1993; Forest, 1994; Yapa and Shen, 1986). Not surprisingly, nights where air temperature drops below approximately -10ºC have also been reported to be conducive to anchor ice (Parkinson, 1984; Terada *et al.*, 1998) but there currently exists no statistical model to predict the presence of anchor ice on a river reach from meteorological conditions.

Once frazil ice crystals are produced, anchor ice does not form everywhere along the wetted perimeter of the channel. Field observations by Terada et al. (1998) and Yamazaki et al. (1996) showed that anchor ice tend to form in shallow, fast flowing sections having Froude number values ranging between 0.2 and 1.5. Hiramaya et al. (1997) suggested that the critical Froude number at which anchor ice will form should be positively related to air temperature. However, there exist to date no statistical relationship to support the field observations relating anchor ice formation to water depth and flow velocity.

The general objective of this study was to develop a predictive model of anchor ice formation in natural gravel bed rivers from meteorological and hydraulic conditions. The first specific objective was to determine the meteorological conditions leading to anchor ice formation in gravel bed rivers. Once the conditions for anchor ice formation at the river reach level were established, the second objective was to determine the separate and combined effects of hydraulic conditions on the spatial distribution of anchor ice.

2. Methodology

The general approach was to document, at the beginning of winter, the daily presence and spatial distribution of anchor ice on the streambed of three gravel bed rivers of southern Québec (Canada): the York, the Beauport and the Duberger Rivers. Field work was conducted in

November and December 2005 before the ice completely covered the rivers and halted the formation of anchor ice.

2.1 Study sites

York River

The York River is located in the Gaspé Peninsula on the south shore of the St-Lawrence River (48°52' N, 65°05' W). The source of the river is located in the Notre-Dame mountain range in the Appalachian Mountains. The main stem is 98 km long and ends in the Baie of Gaspé, draining a watershed of 659 km^2 mostly located in forested land. The mean air temperature in November and December is -3.0°C and -9.8°C respectively (Environment Canada weather station # 7055380).

Beauport and Duberger Rivers

The Beauport River is located on the north shore of the St-Lawrence River near Québec City (46°51' N, 71°11' W). It takes its origin from two small lakes and ends its course after 12.5 km into the St-Lawrence River where it drains an area of 22.5 km^2 mostly located in urban landscape. The Duberger River (46°49' N, 71°18' W) is also located in the urban area of Québec City, approximately 15 km west of the Beauport River. It is a tributary of the St-Charles River and flows over 8 km. For both rivers, the mean November and December monthly air temperature is respectively -0.7°C and -9.1°C (Jean-Lesage International Airport weather station # 7016294).

2.2 Anchor ice measurements

York River

On the York River, four sites were selected to determine the meteorological conditions leading to anchor ice formation at the river level. Two of these sites were pool-riffle sections, one was a rapid and one was a pool. Each site was approximately 100 m long and 25 m wide. Data on the York River were collected between November 10 and November 18 during a daily visit at 7:00 a.m. A total of 12 presence and absence events were evaluated on the four sites during this 8-days period. On four occasions, two sites per day were assessed. During these visits, a lack of anchor ice was noted as an absence while any amount of anchor ice within a site was noted as a presence of anchor ice.

Beauport and Duberger rivers

On the Beauport River, data were collected between December 2 and December 7 when the formation of a complete ice cover stopped data collection for 6 days. On December 14, the cover melted and field work resumed until December 21 when the ice cover reestablished over the entire reach. On the Duberger River, data were collected during 4 days from December 4 to December 7. The ice cover formed permanently on December 8 and no supplementary field work was conducted on this river. A total of 14 events were evaluated on both sites.

The study sites on the Duberger and Beauport rivers were approximately 150 m long by 5 m wide and comprised several pool-riffle units. At each site, 54 parcels of 0.25 m^2 were used to evaluate the presence or absence of anchor ice. The parcels were located on 18 transects perpendicular to the flow and equally distributed between riffles and pools to include a large range of potential anchor ice formation conditions (Figure 1).

Presence and absence of anchor ice was determined for every parcel during a daily visit between 7:00 a.m. and 8:30 a.m. It was assumed that anchor ice formation and decay was negligible during the 1.5 hour window during which both sites were assessed. Once all parcels had been evaluated, all existing anchor ice was manually removed from each parcel to allow new anchor ice to form during the following event. It was assumed and latter confirmed by field observations, that anchor ice formation was negligible during the daytime period comprised between successive assessments.

These presence-absence evaluations of each parcel on both sites were used twofold. Firstly, a lack of anchor ice on all parcels of a site was classified as an absence of ice on the entire site while presence of anchor ice on any number of parcels was classified as a presence of anchor ice on the site. These data were used in combination with the data collected on the York River to determine the meteorological conditions leading to anchor ice formation at the river level (n = 30 events). Secondly, the presence-absence evaluations or each parcel were used individually to determine the effect of hydraulic conditions and air temperature on the spatial distribution of anchor ice at the parcel level (n = 448 parcels assessed during 10 events).

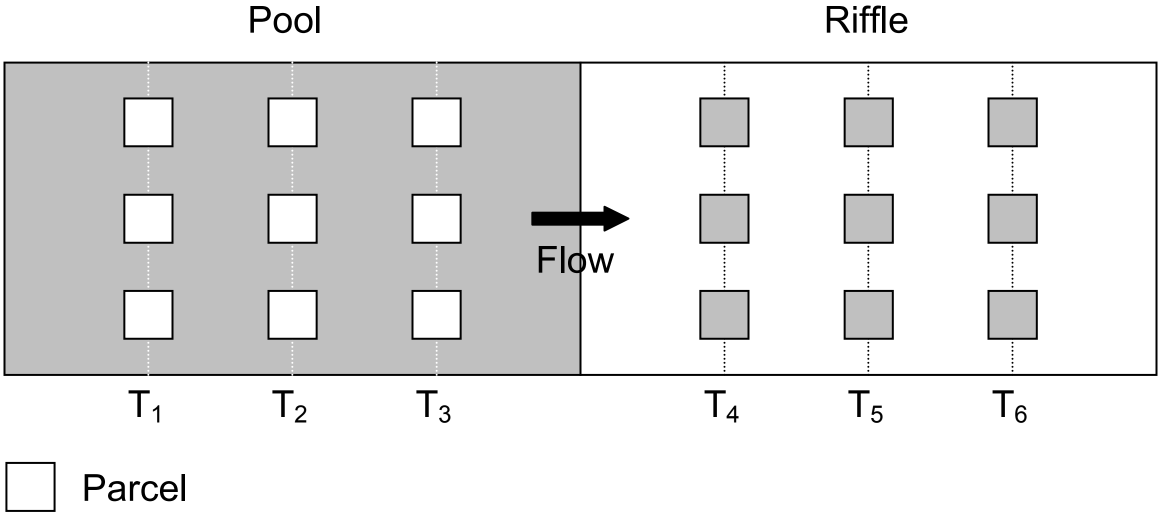


Figure 1 Schematic representation of the sampling procedure on the Beauport and Duberger rivers. Transects (T_i) were evenly distributed between pools and riffles. Three parcels were equally spaced on each transect for anchor ice presence-absence evaluation.

2.3 Climatic and hydraulic variables

Air temperature on the York River was recorded hourly at each site with Optic StowAway temperature data loggers (Onset Computer Corp., ±0.5°C precision). Air temperature on the Beauport and Duberger rivers were obtained from the nearest Environment Canada weather station (Jean-Lesage International Airport weather station # 7016294). From these data, cumulated freezing degree-hours indices were calculated for periods of 6, 8, 12, 24 and 48 hours preceding anchor ice assessment at 7:00 a.m. These indices were denoted *FDH-6*, *FDH-8, FDH-12*, *FDH-24* and *FDH-48* respectively and were used to estimate the heat flux from the atmosphere to the water mass (Ashton, 1986).

Water temperature was measured hourly on the three rivers using StowAway TidBit data loggers (Onset Computer Corp., ±0.2°C precision). On the Beauport and Duberger rivers, a data logger was installed at each end of the study sections while only one data logger per study section was used on the York River. On the Beauport and Duberger rivers, water temperatures recorded by the two data loggers located at each sites were averaged. From these data, water temperature was averaged for each river site during periods of 6, 8, 12, 24 and 48 hours preceding anchor ice assessment at 7:00 a.m. These variables were denoted *W-6*, *W-8, W-12*, *W-24* and *W-48* respectively.

On the Beauport and Duberger rivers, mean flow velocity and water depth were measured on each parcel at every visit. These measurements were made at the center of the parcel in late afternoon and used to evaluate formation conditions for the following night. Flow velocity was measured using an electromagnetic current meter (Flow-Mate 2000, Marsh-McBirney Inc.) at 0.4 of the depth from the streambed and averaged during 60 seconds. In addition, the Froude number ($Fr = v/(gd)^{1/2}$) was calculated from velocity (v) and depth (d) measured at each parcel.

2.4 Logistic modeling of anchor ice formation

Predictive model of anchor ice presence at the river reach level

The objective of this analysis was to elaborate a predictive model of anchor ice presence on a river from air and water temperature data. A logistic regression model was used to analyze and predict the presence-absence of anchor ice. Logistic regression is a statistical approach that predicts the probability of occurrence of a dichotomous response variable based on explanatory variables (Hosmer and Lemeshow, 2000). The logit transformation of the probability of presence (p) produces a linear function according to the equation:

$$Logit(p) = \log\frac{p}{1-p} = \beta_0 + \sum_{1}^{k}\beta_{1i}x_i \qquad [1]$$

in which β_0 and β_1 are the regression constants and x_i the explanatory variables (Hosmer and Lemeshow, 2000). The predicted values in each case have a value between 0 and 1.

The data set describing the presence-absence of anchor ice at the river section level was used for the analysis. The dataset included the dichotomous response variable presence-absence of anchor ice at a river section, and ten continuous predictors related to air *(FDH-6*, *FDH-8*, *FDH-12, FDH-24* and *FDH-48*) and water temperature (*W-6*, *W-8*, *W-12, W-24* and *W-48*).

Predictive model of the spatial distribution of anchor ice at the parcel level

The objective of this analysis was to assess the probability of anchor ice formation on a parcel across rivers, meteorological conditions and hydraulic conditions using the presence-absence data collected at the parcel level on the Beauport and Duberger rivers. The model estimated the dichotomous response variable presence-absence of anchor ice on a parcel. Covariates common to all parcels on a river section, such as air and water temperature, and hydraulic variables specific to each parcel (water velocity, depth and Froude number) were used as the explanatory variables. To appropriately model river-level and hydraulic-level covariates, a two-level hierarchical logistic regression model was developed (Wong and Mason, 1985). Hierarchical regression models are useful for understanding relationships in hierarchical data structures (Sullivan *et al*., 1999) such as sampled parcels nested within a river.

The observations were classified into two hierarchical levels. The micro-level accounted for the hydraulic conditions and the macro-level accounted for a specific day on a specific section of a river. Each macro level unit J included n_j micro-level units (i.e. n_j parcels in the jth river site). Separate micro-level models were developed for each of the J macro-level units. The response variable (*Pres*) was a dichotomous variable distinguishing between presence (1) or absence (0) of anchor ice on a parcel. The micro-level model for a single predictor or covariate (x_1) was in the form (Wong and Mason, 1985; Sullivan *et al.*, 1999):

$$Logit(\mathrm{Pres}_{ij}) = \beta_{0j} + \beta_{1j}x_1 + \varepsilon_{ij} \qquad [2]$$

where $Pres_{ij}$ is the dependent variable on the ith level unit (i.e. sampling plots) nested within the jth macro-level unit (i.e. river-date), β_{0j} is the intercept for the jth macro-level unit, x_1 is the micro-level predictor, β_{1j} is the regression coefficient associated with the micro-level predictor and ε_{ij} is the random error associated with the ith micro-level unit nested within the jth macro-level unit.

The hierarchical model is composed of J models using the micro-level variables. These models are in the form shown in equation 1 and each one has a different intercept and slope coefficient (β_{0j} and β_{1j}). In the macro-level model, the regression coefficients were considered as dependent variables and related to appropriate macro-level covariates. For the analysis of two macro-level covariates (z_1 and z_2), the macro-level models were in the form (Wong and Mason, 1985; Sullivan *et al.*, 1999):

$$\beta_{0j} = \gamma_{00} + \gamma_{01}z_1 + \gamma_{02}z_2 + \upsilon_{0j} \qquad [3]$$

$$\beta_{1j} = \gamma_{10} + \gamma_{11}z_1 + \gamma_{12}z_2 + \upsilon_{1j} \qquad [4]$$

where β_{0j} and β_{1j} are the intercept and the slope for the jth macro-level unit, γ_{00} and γ_{10} are the overall mean intercept and slope adjusted for z, respectively z_j is the macro-level predictor, γ_{01} and γ_{11} are the regression coefficients associated with the macro-level predictor z relative to the macro-level intercept and slopes, respectively and υ_{0j} and υ_{1j} are the random effect on the intercept and slope respectively adjusted for z. The hierarchical model combining the micro-level and macro-level models was in the form (Wong and Mason, 1985; Sullivan *et al.*, 1999):

$$Logit(\mathrm{Pres}_{ij}) = \gamma_{00} + \gamma_{01}z_1 + \gamma_{02}z_2 + \gamma_{10}x_1 + (\gamma_{11}z_1 + \gamma_{12}z_2)x_1 + \upsilon_{0j} + \upsilon_{1j}x_1 + \varepsilon_{ij} \qquad [5]$$

2.5 Model assessment and validation

Assessment of the goodness-of-fit of each model was obtained from the Hosmer and Lemeshow test (Hosmer and Lemeshow, 2000). This test is effective to evaluate the fit of a model for data set having different covariate patterns, as typically occurs if one of the predictor is continuous such as air and water temperature (Hosmer and Lemeshow, 2000).

The receiver-operating characteristics curve (ROC) procedure was used to assess the model performance at all possible probability threshold at which anchor ice presence might be accepted ($0 < p < 1$) (Manel *et al.*, 2001). The curve was obtained by plotting the sensitivity (percentage of true presence correctly predicted) vs. 1-specificity (percentage of true absence correctly predicted) over all the probability of anchor ice formation. Good model performances are characterized by a curve that maximizes sensitivity for low value of specificity and are indicated by large areas under the ROC curve (AUC).

While the AUC measured from the ROC curve is considered useful for comparing the performance of presence-absence models in a threshold independent fashion, truly predictive modeling might require some probability at which to accept the presence of anchor ice (Fielding and Bell, 1997). The optimum probability threshold can be identified using the ROC curves by reading the point on the curve at which the sum of sensitivity and specificity is maximized (Manel *et al.*, 2001). This optimal threshold was used instead of the normal threshold of $p = 0.05$ to predict the presence or absence of anchor ice and to equalize the cost of misclassifying anchor ice as present (sensitivity) and absent (specificity) (Fielding and Bell, 1997).

The modeling procedure was tested on independent cases which were derived by partitioning data into a training set and a test set. The leave-one-out cross validation procedure allowed the separation of one or more events from the entire dataset (Efron, 1982). The cross-validation was performed on both analyses, each time leaving out one case at a time. For example, for the multilevel hierarchical logistic regression, J-1 macro-level units formed the training set and the presence was predicted for the isolated macro-level site and compared with the true value. The process was iterated for all of the J macro-level units.

Once the optimal threshold was identified from the ROC procedure and the models validated, the correct classification rate (percentage of all cases correctly predicted, CCR), the sensitivity and the specificity were obtained from the confusion matrices to evaluate the model accuracy.

3. Results

3.1 Predictive model of anchor ice presence at the river reach level

Examination of anchor ice presence-absence data from York, Beauport and Duberger rivers shows that, as expected, anchor ice formed only when water temperature was equal or inferior to 0°C (Figure 2). Of the 30 presence-absence events analyzed, 9 had water temperature superior to 0°C and 21 had water temperature equal or inferior to 0°C. A closer examination of the events having subfreezing water temperature indicates that anchor ice formed in a wide range of cumulated freezing degree-hours. For instance, using *FDH-12* as an example, the data indicate that anchor ice formed at values ranging between 59.3°C-h and 300.0°C-h, but also that it was absent at values as high as 111.5°C-h, showing that even during cold nights, anchor ice did not always form.

Only presence-absence events having subfreezing water temperature ($n = 21$) were used in the analysis since anchor ice formation is impossible when water temperature is greater than 0°C (Table 1). Five different models using freezing degree-hours cumulated during six hours (*FDH-6*), 8 hours (*FDH-8*), 12 hours (*FDH-12*), 24 hours (*FDH-24*) and 48 hours (*FDH-48*) were tested to predict the occurrence of anchor ice. Analysis of the parameter estimates indicates that among the five models independently tested, only the one using *FDH-12* was significant according to the Wald test. The intercept was non significant and removed from the model.

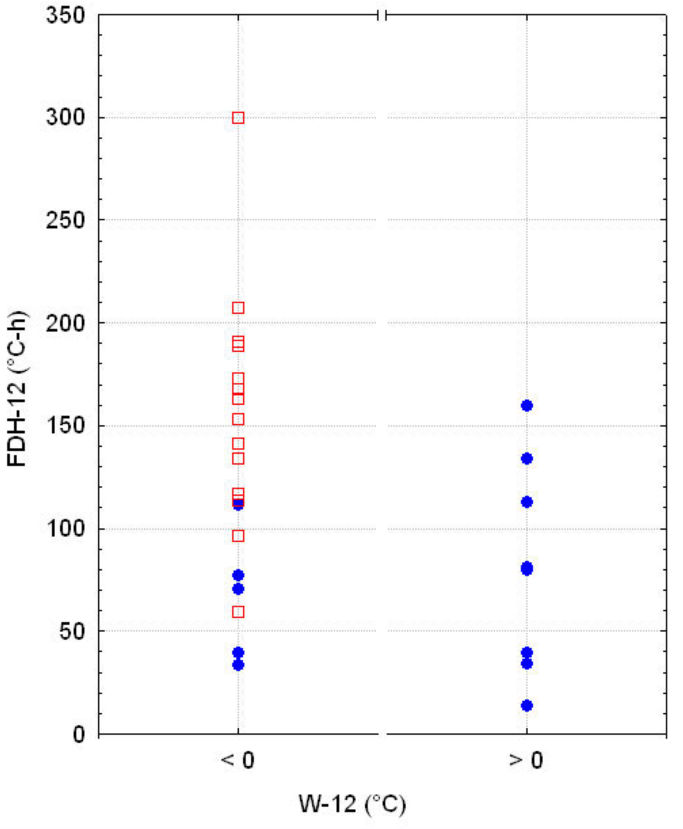


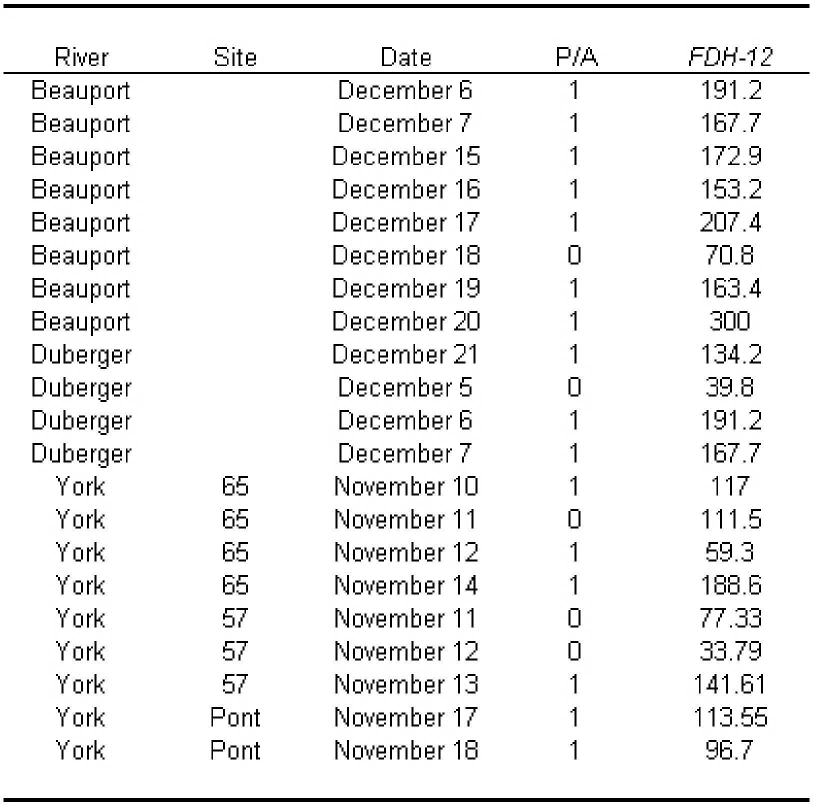
Figure 2 Presence (□) and absence (●) of anchor ice as a function of cumulated freezing-degree-hours during 12 hours (*FDH-12*) and water temperature averaged during 12 hours (*W-12*).

The result of the Hosmer-Lemeshow test was not significant ($p > 0.5$) and suggests that the model significantly fits the data (Table 2) (Hosmer and Lemeshow, 2000). The analysis of the regression diagnostic statistics (Deviance delta and Pearson Chi-2 delta) did not reveal the presence of outliers, suggesting that the model support the entire set of data, which is consistent with the Hosmer-Lemeshow and ROC curve tests. The area calculated under the ROC curve was 0.95 indicating that the model is highly accurate in discriminating event of anchor ice formation independently of any specified threshold

The optimal decision threshold selected to equalize the cost of misclassifying events as presence or absence of anchor ice using the ROC plot was 0.82. Any predicted event with a probability of occurrence superior to 0.822 was classified as a presence of anchor ice, otherwise it was classified as an absence. The threshold also indicates that at least 111.7°C-hr cumulated during

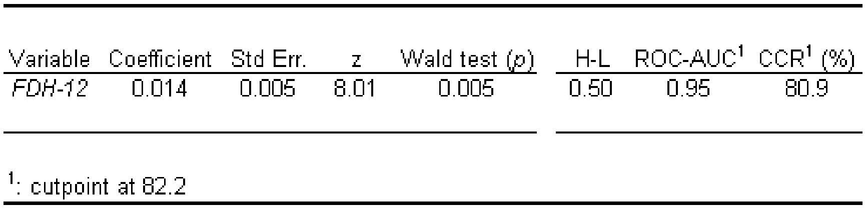
12 hours was necessary for anchor ice to form which is equivalent to -9.3°C averaged over 12 hours. Using this threshold, the confusion matrix from the validated model provided three measures to evaluate the accuracy of the model. The sensitivity and the specificity indicate that respectively 81.3% of the presence events and 80.0% of the absence events were correctly classified. The third measure, the correct classification rate (CCR), indicates that the model correctly classified 80.9% of the anchor ice presence-absence events.

Table 1 Presence (1) and absence (0) of anchor ice on the Beauport, Duberger and York rivers and associated freezing degree-hour cumulated during 12 hours (*FDH-12*) when water temperature was equal or inferior to 0°C.



River	Site	Date	P/A	*FDH-12*
Beauport		December 6	1	191.2
Beauport		December 7	1	167.7
Beauport		December 15	1	172.9
Beauport		December 16	1	153.2
Beauport		December 17	1	207.4
Beauport		December 18	0	70.8
Beauport		December 19	1	163.4
Beauport		December 20	1	300
Duberger		December 21	1	134.2
Duberger		December 5	0	39.8
Duberger		December 6	1	191.2
Duberger		December 7	1	167.7
York	65	November 10	1	117
York	65	November 11	0	111.5
York	65	November 12	1	59.3
York	65	November 14	1	188.6
York	57	November 11	0	77.33
York	57	November 12	0	33.79
York	57	November 13	1	141.61
York	Pont	November 17	1	113.55
York	Pont	November 18	1	96.7

Table 2 Estimated coefficient, Standard error (Std. Err.), z-score (z), two-tailled p-value (p > Chi-2), Hosmer-Lemeshow test (H-L), Area under the ROC curve (ROC-AUC), and the correct classification rate (CCR) for the final logistic regression model for the presence and absence of anchor ice. n = 21.



Variable	Coefficient	Std Err.	z	Wald test (*p*)	H-L	ROC-AUC[1]	CCR[1] (%)
FDH-12	0.014	0.005	8.01	0.005	0.50	0.95	80.9

[1]: cutpoint at 82.2

3.2 Predictive model of the spatial distribution of anchor ice at the parcel level

Presence and absence data collected on the parcels located on the Beauport and Duberger rivers were used to elaborate a predictive model of anchor ice spatial distribution. Of the 14 presence-absence events characterized on both sites, anchor ice was present on at least one parcel of a site during 10 events. For these 10 events, a total of 448 parcels were characterized and used in the analysis (Table 3).

Table 3 Number of parcels sampled on each river sites (n), cumulated freezing degree-hours during 12 hours (*FDH-12*) for the events with anchor ice formation on at least one parcel per site.

River	Date	n	*FDH-12*
Beauport	December 6	50	191.2
Beauport	December 7	30	167.7
Beauport	December 15	50	172.9
Beauport	December 16	32	153.2
Beauport	December 18	36	207.4
Beauport	December 20	37	163.4
Beauport	December 21	8	300
Duberger	December 4	53	134.2
Duberger	December 6	46	191.2
Duberger	December 7	20	167.7

A comparison of the hydraulic conditions prevailing on parcels with and without anchor ice showed that parcels where anchor ice was present had significantly higher mean flow velocities (t-test, n = 448, $p < 0.001$) (Figure 3a) and were significantly shallower (t-test, n = 448, $p < 0.05$) (Figure 3b) than parcels where anchor ice was absent. The combined effect of flow velocity and water depth was captured by calculating the Froude number of each parcel. Comparing parcels with and without anchor ice showed that those where anchor ice was present had a significantly higher Froude number (mean = 0.22) than those where it was absent (mean = 0.10) (t-test, n = 448, $p < 0.0001$) (Figure 3c).

For the hierarchical logistic model, the Froude number was selected as the micro-level variable to characterize the hydraulic conditions on the parcels since it combines the effects of water depth and velocity. The macro-level variables included in the model were the freezing degree-hours cumulated over 12 hours (*FDH-12*) and the water temperature averaged over 12 hours (*W-12*). The variable *FDH-12* was selected because the results of the analysis of anchor ice formation at the river level indicated that *FDH-12* significantly described and predicted the formation of anchor ice. The variables included in the full hierarchical logistic model were therefore *Froude*, *FDH-12* and *W-12,* and the interaction terms between the micro-level and the macro-level variables were *Froude***FDH-12* and *Froude** *W-12*.

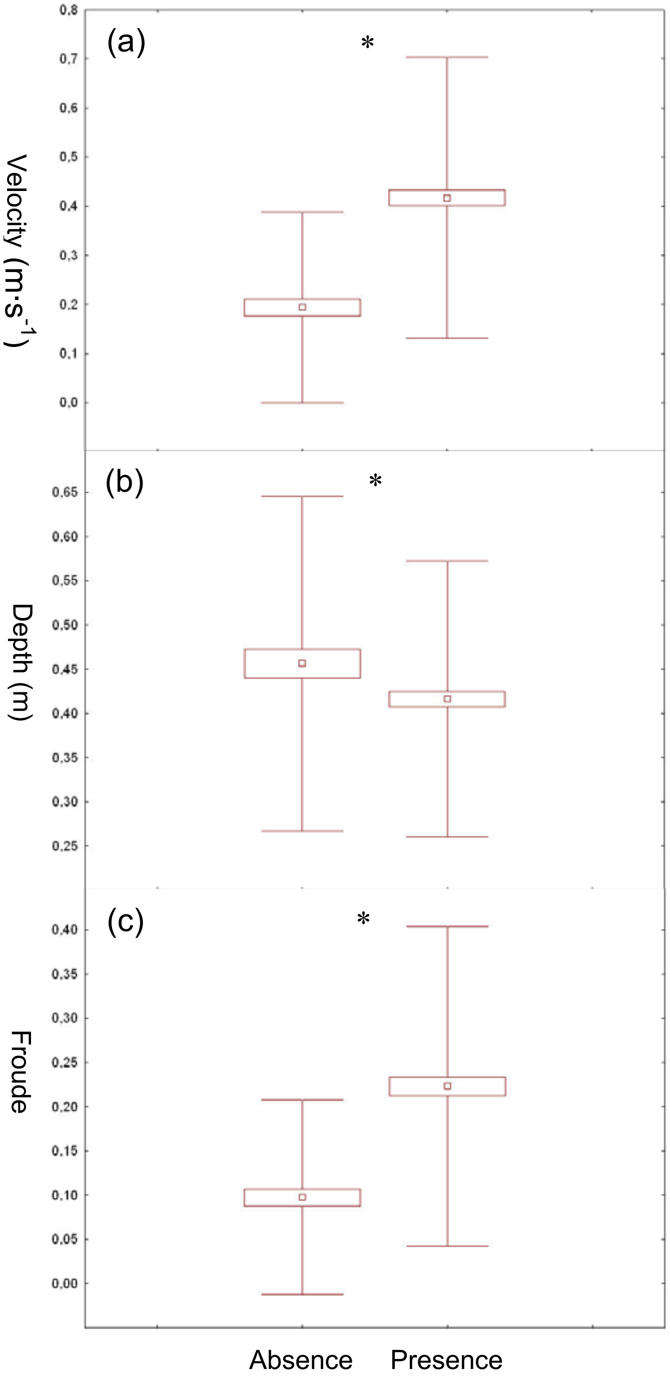


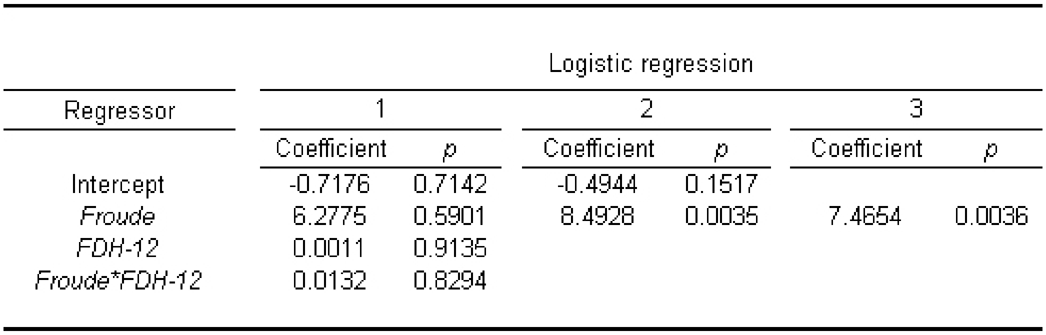
Figure 3 Velocity (a), Depth (b) and Froude number (c) (mean, standard error, standard deviation) as a function of presence and absence of anchor ice on a parcel, * indicates significant differences at $p < 0.05$ (t-test).

The final model was obtained using a backward removal logistic regression procedure. The results of this procedure showed that only the micro-level variable, *Froude*, was significant according to the Wald test (Table 4). The final model indicated that the macro-level variable *FDH-12* had no significant effect on the presence of anchor ice on a parcel. In addition, there was no interaction between the macro-level variable *FDH-12* and the micro-level variable *Froude*, suggesting that the Froude number conducive to anchor ice formation on a parcel was not significantly affected by air temperature. The intercept was not significant and excluded from the final model. The final logistic model indicated that only the Froude number significantly controlled spatial distribution of anchor ice on the streambed during anchor ice events (Table 4).

The Hosmer-Lemeshow test was not significant ($p > 0.38$) and indicated that the model significantly fitted the data. The analysis of the regression residuals (Pearson Chi-2 residuals) did not reveal any outliers, signifying that the model support the entire set of data, a result consistent with the one of the Hosmer-Lemeshow test. The area calculated under the ROC curve was 0.78, suggesting that the model was moderately accurate in discriminating presence or absence of anchor ice on a parcel (Table 5) (Hosmer and Lemeshow, 2000).

The optimal decision threshold selected to equalize the cost of misclassifying events as presence or absence of anchor ice using the ROC plot was 0.62. This threshold value corresponds to a Froude number of 0.1 which signifies that anchor ice formation is likely to occur over this critical value. The results of the leave-one-out validation indicated that the average CCR predicted by the cross-validated model was 67.5%. On average, the validated model was better at predicting the presence (CCR of 71.5%) than the absence (CCR of 51.3%) of anchor ice.

Table 4 Estimates for the hierarchical logistic regression of anchor ice presence as a function of micro (*Froude*) and macro variables (*FDH-12*) and their interactions.



	Logistic regression					
Regressor	1		2		3	
	Coefficient	*p*	Coefficient	*p*	Coefficient	*p*
Intercept	-0.7176	0.7142	-0.4944	0.1517		
Froude	6.2775	0.5901	8.4928	0.0035	7.4654	0.0036
FDH-12	0.0011	0.9135				
*Froude*FDH-12*	0.0132	0.8294				

Table 5 Estimated coefficient, Standard error (Std. Err.), F-score (F), two-tailled p-value ($p >$ F), Hosmer-Lemeshow test (H-L), Area under the ROC curve (ROC-AUC), and the correct classification rate (CCR) for the final logistic regression model for the spatial distribution of anchor ice. n = 10.

Variable	Coefficient	Std Err.	F	Wald test (*p*)	H-L	ROC-AUC[1]	CCR[1] (%)
Froude	7.47	1.91	3.9	0.004	0.38	0.78	67.5

[1]: cutpoint at 62.5

4. Discussion

4.1 Predictive model of anchor ice presence at the river level

The results of the logistic regression analysis at the river level confirm the importance of air temperature as a key variable controlling the formation of anchor ice. Of the five freezing degree-hours indices used in the analysis (*FDH-6, FDH-8, FDH-12, FDH-24* and *FDH-48*) only *FDH-12* was found to be significantly related to the presence-absence of anchor ice, with an 80.5 percentage of correct predictions.

This result differs from the observations of Terada et al. (1998) on a river in Japan who found that anchor ice formation was correlated with freezing degree-hours cumulated over 6 hours. Both results suggest the importance of the night period preceding the formation of anchor ice. However, our results suggest that the beginning of the night is also important for anchor ice formation.

The analysis also indicates that when more than 111.7°C-h are cumulated over 12 hours, anchor ice was likely to form on the York, the Duberger and the Beauport rivers. This cumulated value is equivalent to an average of -9.3°C over the entire night. This result is consistent with the work of Terada et al. (1998) who observed that the threshold temperature for anchor ice formation was approximately -10°C.

The logistic model did not perform perfectly in predicting the presence-absence events. Approximately 20% of the events were misclassified by the model which, in our study, corresponds to 3 presence-absence events. Examination of the misclassified events revealed that on November 11, anchor ice did not form on the York River when the model predicted that it would. Further analysis of the atmospheric conditions during the night of that particular event (Environment Canada station # 7016294) revealed that the sky was cloudy, which may have reduced radiative losses to the atmosphere and impede the formation of anchor ice despite relatively cold air temperature (111.5°C-h FDH-12).

In addition, two events that occurred on November 12 and 18 on the York River, were wrongly classified as an absence of anchor ice by the model. During these events, anchor ice was present despite low *FDH-12* values (59.3°C-h and 96.7°C-h FDH-12 respectively). During both events, air temperature dropped sharply in the last half of the night presumably initiating anchor ice formation during a short period. These results suggest that even if *FDH-12* was shown to be a good predictor of anchor ice formation, only few consecutive hours of cold air temperature may be sufficient to produce anchor ice. This supports the observations of Terada et al. (1998) that freezing degree-hours cumulated over 6 hours is a good predictor of anchor ice formation. However, their index was calculated for the last 6 hours of the night (1:00 a.m. to 7:00 a.m.) while our analysis of the misclassified events suggests that cold air temperature occurring over any consecutive period of 6 hours during the night could be conducive to the formation of anchor ice.

4.2 Predictive model of the spatial distribution of anchor ice at the parcel level

The results of the analysis of the spatial distribution of anchor ice on the parcels located on the Beauport and the Duberger rivers indicated that the cross-validated hierarchical logistic model correctly predicted 67.5% of the events. This logistic model is the first attempt to predict the spatial distribution of anchor ice on the streambed despite numerous other field and laboratory works (Arden and Wigle, 1972; Parkinson, 1984; Tsang, 1992; Terada *et al.*, 1998). Since the Froude number of the flow is the only variable included in the model, it could be easily combined with any 2-D hydrodynamic model of the flow to produce a predicted map of the spatial distribution of anchor ice in a river. However, more work remains to be done in order to improve the predictive power of the model especially when predicting the absence of anchor ice on a parcel.

Indeed, a closer examination of the results indicated that the model performed better at predicting the presence (71.5%) than the absence (50.0%) of anchor ice on a parcel. The discrepancy may be caused by the classification method used in the analysis. The correct classification rate always favor the group having the most numerous events (Hosmer and Lemeshow, 2000). The presence events were almost 3 times more frequent compared to the absence events which may have skewed the classification. The use of a different classification method may have solved the problem of group size sensitivity. However, other variables such as sediment size and the relative submergence may also control the formation of anchor ice on the streambed. Anchor ice generally forms on coarse sediments because they offer more surface for the frazil ice crystals to adhere and accumulate (Hammar *et al.*, 1996; Shen, 2003a). In addition, coarse sediments increase turbulent mixing which promotes frazil ice deposition on the streambed and anchor ice formation (Hammar *et al.*, 1996). Coarse sediments are also less influenced by the geothermal heat flux from the bed and are supercooled faster than finer sediments (Tsang, 1982; Ashton, 1986; Prowse, 1994). The addition of a variable describing the contribution of sediment size to anchor ice formation could probably improve the performance of the model.

The hierarchical logistic model indicates that the Froude number was an important factor controlling the spatial distribution of anchor ice. In our study, the critical Froude number over which anchor ice formed was 0.1, which is close but slightly lower than the value of 0.148 obtained by Kerr et al. (1997) and the value of 0.2 reported by Terada et al. (1998). On the Beauport and the Duberger rivers, anchor ice was occasionally observed on parcels composed of fine sediments with low Froude number which may seems unusual compared to the observations reported in the literature (Arden and Wigle, 1972; Terada *et al.*, 1998). However, formation of anchor ice on these parcels may have been caused by the accretion of frazil ice crystals to anchor ice already formed instead of adhesion of frazil crystals to the substrate. Field observations accomplished during this study indicate that these parcels were usually located directly upstream of a riffle. Continuous accretion of frazil ice crystals on the upstream front of anchor ice located at the beginning of the riffle could have thus resulted in its upstream progression. Despite the weak bonds between anchor ice and fine sediments, the bonds between the ice crystals could compensate and support the progression of the anchor ice front. However, anchor ice on these parcels is not likely to accumulate substantially because the buoyancy of the ice will eventually be greater than the bounds between the ice crystals.

Our results also showed that air temperature did not influence the spatial distribution of anchor ice. When air temperature reached the critical temperature for anchor ice formation, the hydraulic conditions were the sole parameters controlling the distribution of anchor ice on the streambed of the Beauport and Duberger rivers. These results do not support the suggestion of Terada et al. (1998) that cold air temperature would reduced the critical Froude number for anchor ice formation.

Acknowledgements

Financial support was provided by a NSERC research grant to Normand Bergeron. The authors are thankful to Patricia Johnston for field assistance.

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