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# ANALYSE HYDRO-CLIMATIQUE ET GÉOMORPHOLOGIQUE DES DÉGLACEMENTS MÉCANIQUES DE LA RIVIÈRE NECOPASTIC AU QUÉBEC NORDIQUE

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# Résumé

Cette thèse de doctorat constitue une analyse hydro-climatique et géomorphologique des déglacements mécaniques d'un petit cours d'eau du Haut-Boréal québécois : la rivière Necopastic. L'étude de la variabilité spatiale et temporelle dans l'intensité et la fréquence de ces événements a été permise grâce à l'analyse dendrochronologique des cicatrices d'abrasion glacielle échantillonnées sur les arbres le long du cours principal de la rivière.

Dans le cadre de cette thèse, les problèmes liés à l'échantillonnage des arbres et à la construction de chronologies glacielles en milieu fluvial ont été identifiés et solutionnés en accord avec les principes de base en dendrochronologie (i.e., la sélection des sites, la sensibilité des enregistreurs et la réplication). Une chronologie construite selon cette nouvelle méthode a permis l'analyse du contexte hydro-climatique dans lequel se déclenchent les épisodes de déglacement mécanique à l'intérieur du bassin-versant de la rivière Necopastic. En croisant les variations dans l'intensité des déglacements mécaniques aux variables hydro-climatiques régionales (période 1950-2003) et en incorporant ces variables dans un modèle prédictif (arbre de classification et de régression), il a été démontré que les déglacements mécaniques intenses se produisent surtout en présence d'un couvert de glace dont les propriétés physiques ne sont pas dégradées au moment de la crue printanière. Des crues régionales hâtives et soudaines combinées à des printemps froids et neigeux (lorsque l'indice d'Oscillation Arctique est positif) favorisent le déclenchement d'épisodes de déglacements mécaniques intenses. Enfin, l'impact de ces événements sur la géométrie et la géomorphologie des chenaux dépend de leur fréquence. Lorsque les déglacements mécaniques surviennent plus souvent qu'une fois à tous les cinq ans, les

chenaux apparaissent élargis et présentent une morphologie érodée à deux niveaux. Ces variations dans la largeur et la forme des chenaux ne peuvent pas être décrites adéquatement par des courbes de géométrie hydraulique.

# Abstract

This thesis relates to the hydro-climatic and geomorphological analysis of mechanical breakups in a high-boreal watercourse: the Necopastic River. Spatio-temporal variations in ice-flood intensity and frequency in this small ungauged watershed were investigated through the use of a detailed dendrochronological analysis of ice-scars.

In this thesis, a dendrochronological procedure to construct chronologies of hydro-climatically significant discrete events was developed. Problems relating to the field sampling and to the construction of an ice-scar chronology were identified and solutioned. A chronology was constructed following these recommendations to analyse the hydro-climatic conditions triggering river ice breakups in the Necopastic watershed. By relating tree-ring reconstructed variations in the intensity of breakup to regional hydrological and climatological variables and by incorporating these variables into a predictive model (Classification and Regression Tree) it was demonstrated that intense mechanical breakups form when river ice is not degraded at the time of flooding. Conditions of early and flashy regional spring floods combined to cold and snowy springs (in a positive Arctic Oscillation index) favour intense mechanical breakups. The severity of impacts on channel geometry and geomorphology however depend on the frequency of these events. When mechanical breakups occur more often than once every five years, channels become enlarged and present a “two-level” ice-scoured morphology. These variations cannot be adequately described by hydraulic geometry curves.

# Avant-Propos

Cette thèse est composée de trois articles scientifiques rédigés directement en anglais par l'étudiant. Ces articles sont accompagnés d'une introduction générale et d'une conclusion. L'étudiant a récolté (avec assistance) toutes les données de terrain présentées dans cette thèse. Il a lui-même réalisé toutes les analyses de laboratoire, a conçu toutes les figures et toutes les illustrations. L'étudiant est l'auteur principal des trois contributions. Le directeur de la thèse, Dr Yves Bégin (Institut National de la Recherche Scientifique, centre Eau-Terre-Environnement), et le co-directeur Dr Dominique Arseneault (Université du Québec à Rimouski) ont tous deux contribué à enrichir le contenu et la langue de ces ouvrages par leurs révisions. Ils sont tous deux co-auteurs des trois articles scientifiques.

Le premier article (chapitre 2) porte sur le développement d'une méthode dendrochronologique permettant la construction de chronologies d'événements discrets hydro-climatiquement interprétables. Le second article (chapitre 3) porte sur l'analyse hydro-climatique de la chronologie développée au chapitre 2. Le dernier article (chapitre 4) constitue une analyse de l'impact des événements d'embâcles sur la géomorphologie d'un petit cours d'eau du Haut-Boréal québécois.

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*Janvier, de glace, fait le point, -Février, qui passe, le rompt! – (dicton)*

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# Chapitre 1. Introduction générale

## 1.1 Problématique

À chaque printemps, la plupart des rivières des milieux froids passent d'un régime hydrologique influencé par un couvert de glace à un régime d'eaux libres. Cette période transitoire dans le cycle hydrologique annuel des cours d'eau nordiques dure entre quelques heures et plusieurs semaines en fonction des processus hydro-climatiques qui contrôlent le déglacement. Dans un contexte de déglacement thermique (« *thermal breakups* »), le couvert de glace se détériore lentement et sur place en raison des échanges de chaleur entre l'eau, l'atmosphère et la glace (Prowse et Marsh, 1989; Beltaos, 1997). Durant ces épisodes, le risque d'embâcle est minimal puisque la glace perd progressivement ses propriétés mécaniques jusqu'à ce qu'elle soit emportée par le courant sous la forme d'une glace visqueuse. Par opposition, les épisodes de déglacement mécanique (« *mechanical breakups* ») surviennent lorsque les forces hydrodynamiques sont suffisamment importantes pour morceler et mobiliser le couvert de glace avant même sa détérioration printanière (Beltaos, 1997, 2003). Les radeaux de glace noire mis en mouvement lors de ces événements s'amoncellent souvent, sous forme d'embâcle, dans les sections de cours d'eau plus étroites, sinueuses ou dans les tronçons situés en aval des ruptures de pente.

Les embâcles formés durant les épisodes de déglacement mécanique menacent sérieusement les écosystèmes fluviaux, les communautés humaines qui habitent la zone riveraine et les infrastructures qui s'y retrouvent. Premièrement, la hausse de niveau derrière un embâcle peut être plus importante, à débit équivalent, que le niveau atteint lors d’une crue générée dans des conditions d’eau libre (Smith, 1980; Ashmore et Church, 2001), ce qui mène inévitablement à des inondations plus sévères. Deuxièmement, cette hausse de niveau est habituellement soudaine, ce qui complexifie grandement la mise en place et l’application des mesures de mitigation telles que l’évacuation des résidents et le déblocage du chenal. Troisièmement, les risques d’érosion du lit et des berges sont accrus durant ces événements en raison de la présence de glace flottante, un agent géomorphologique important dans les milieux nordiques. Au Canada seulement, les estimés les plus récents (i.e. 1990), chiffrent le coût annuel des pertes et dommages associés aux embâcles de glace à près de 60 millions de dollars (Gerard et Davar, 1996).

En raison des impacts économiques, sociaux et environnementaux qu’ils occasionnent, la prédiction du mode de déglacement est un enjeu crucial pour les scientifiques et les gestionnaires du milieu fluvial. L’identification et la hiérarchisation des principales variables hydro-climatiques exerçant une influence sur la formation d’embâcles printaniers pourraient entre-autres permettre d’allonger le temps de réaction et ainsi éviter d’importants dommages et pertes en vies humaines (White, 2002). Par ailleurs, l’incorporation de ces variables dans un modèle prédictif rendrait possible une meilleure anticipation des effets potentiels des changements climatiques sur le mode, l’intensité et la sévérité du déglacement en rivière (Ashmore et Church, 2001; Prowse et Beltaos, 2002).

Afin d’obtenir des prédictions aussi justes que possibles, une approche de modélisation déterministe devrait idéalement être envisagée afin de caractériser, d’un point de vue quantitatif, les relations fonctionnelles qui existent entre les facteurs climatiques, hydrologiques, hydrauliques et géomorphologiques qui contrôlent l’occurrence et l'intensité des embâcles (Beltaos 1997, 2003; Beltaos et Burrell, 2003). Cela permettrait, entre autres, de produire des modèles prédictifs qui ont la particularité d'êtres transférables entre les sites et entre les cours d'eau (Mahabir *et al*., 2007). Or, les mécanismes de fracturation, de mobilisation, de transport et d'amoncellement de la glace dans les cours d'eau sont extrêmement complexes et variables spatialement. De surcroît, aucun modèle analytique permettant l'intégration simultanée de toutes ces variables n'a pu, à ce jour, être formulé.

À l'heure actuelle, les meilleurs succès de prédiction sont obtenus à partir de modèles statistiques (White, 2002; Mahabir *et al*., 2007). Ces modèles doivent être calibrés sur des données historiques et cherchent à caractériser, en utilisant une approche de type « boîte noire », la relation qui existe entre les variables hydro-climatiques d'une part, et l'occurrence et l'intensité des embâcles d'autre part. La puissance de ces analyses (i.e., leur capacité d'effectuer des prédictions justes) est donc forcément tributaire de la longueur et de la qualité des historiques d'embâcles sur lesquelles ces relations statistiques sont calibrées (White, 2002; Beltaos et Burrell, 2003). Ces historiques sont habituellement construits à partir de registres instrumentaux (stations de jaugeages).

Les registres instrumentaux produisent des historiques dont la qualité doit toutefois d'être discutée. Dans un premier temps, il faut rappeler que la calibration des modèles statistiques doit se faire à partir d'un nombre suffisant d'événement. Cela permet entre-autres d'apprécier les multiples combinaisons de variables qui sont associées au déclenchement de ces phénomènes. Or, les embâcles sont, par leur nature extrême, des événements relativement rares. Par conséquent, peu de registres instrumentaux permettent de constituer ne serait-ce qu'un petit échantillon utile pour l'analyse statistique. La rareté des événements d'embâcles dans les registres hydrométriques est aussi exacerbée par le fait que l'instrumentation est habituellement installée (sauf exceptions) dans des sections où les embâcles surviennent peu fréquemment. Enfin, même lorsque les registres instrumentaux couvrent une période suffisante, l'historique qu'ils livrent n'est que partiel dans la mesure où les événements qui se produisent en amont ou en aval des stations d'enregistrement risquent de ne pas être perceptibles dans les archives (**figure 1.1**).

Dans un deuxième temps, l'utilisation des registres instrumentaux restreint la modélisation des processus de déglacement aux régions pour lesquelles de telles séries sont disponibles. Au Québec par exemple, la plupart des stations de jaugeage sont concentrées dans la portion australe de la province (http://www.cehq.gouv.qc.ca/suivihydro/default.asp). Dans cette zone tempérée, les épisodes de déglacement les plus sévères surviennent généralement lors des redoux hivernaux (Beltaos et Burrell, 2003). Plus particulièrement, l'épaisseur des couverts de glace qui se forment sur ces cours d'eau semble fortement influencée par les variations de température hivernale (Beltaos et Burrell, 2003). Ainsi, lors des hivers plus cléments, seule une mince couche de glace se forme sur ces cours d'eau. Par conséquent, cette glace perd rapidement ses propriétés mécaniques lorsque s'amorce la fonte. Or, cette situation n'est pas représentative des processus de déglacement qui ont cours sous de hautes latitudes. Dans les régions froides, les redoux hivernaux sont pratiquement inexistants. La glace est donc plus épaisse et les variations dans la température hivernale n'affectent pas significativement les propriétés physiques du couvert (Beltaos et Burrell, 2003). Par conséquent, il faut s'attendre à ce que les conditions hydro-météorologiques printanières aient une plus grande importance dans ces régions froides. Ces différences mettent en évidence le fait qu'il pourrait y exister une certaine variabilité latitudinale dans les mécanismes hydro-climatiques régissant les déglacements. Afin de modéliser ces aspects, d'autres sources d'information permettant de reconstituer l'historique des embâcles en milieu froid devront être explorées.

Ultimement, ces limites du réseau hydrométrique empêchent l'évaluation précise de la fréquence des embâcles dans les cours d'eau non-jaugés. Cela nuit entre-autres à l'évaluation adéquate du rôle de la glace en tant qu'agent d'érosion dans ces environnements. Il existe actuellement un débat parmi les géomorphologues à savoir dans quelle mesure le mode de déglacement modifie les propriétés géométriques et les caractéristiques géomorphologiques des cours d'eau nordiques. Par exemple, Smith (1979; 1980) soutient qu'à partir du moment où les embâcles surviennent à l'intérieur d'un bassin versant, les chenaux apparaissent systématiquement élargis et présentent une morphologie à deux niveaux témoignant de l'érosion glacielle. À l'image de nombreux ouvrages anecdotiques décrivant des formes de terrain sculptées par l'action des glace (Dionne, 1974; Mackay *et al.*, 1974; Dionne, 1976, 1978; Hamelin, 1979; Koutaniemi, 1984; Prowse et Gridley, 1993; Dyke, 2000; Prowse, 2001b; Smith et Pearce, 2002; Walker et Hudson, 2003), Smith (1979; 1980) ne présente aucune donnée sur la fréquence des événements nécessaires à l'entretient de telles morphologies. Au contraire, ces travaux impliquent plutôt l'existence d'une dichotomie fondée sur la présence (chenaux élargis et érodés) et l'absence (chenaux normaux) d'embâcles printaniers (**figure 1.2**). Étant donné que, dans ces systèmes dynamiques, la notion même d'entretien géomorphologique renvoie implicitement à la fréquence des événements formatifs (Wolman et Miller, 1960), le fait de réduire la dynamique d'embâcle à sa seule occurrence constitue une simplification à outrance d’un phénomène hautement plus complexe sous l’angle fréquentiel. Sachant que la récurrence des embâcles printaniers est très variable le long du continuum fluvial et à travers les cours d’eau d’une même région physiographique (Beltaos, 1996), ne serait-il pas plus juste d’envisager un certain gradient dans l’intensité et la nature des impacts géomorphologiques associés aux variations dans la fréquence des événements d’embâcles?

En terminant, il importe de rappeler que les données historiques sur l’occurrence et l’intensité des déglacements sont cruciales pour l’avancement de la connaissance dans le domaine de l’hydrogéomorphologie nordique. Toutefois, ces données sont généralement rares et lorsqu’elles existent, leur qualité est douteuse. Il est donc clair que de nouvelles sources de données permettant d’allonger l’historique et de connaître la fréquence des embâcles devront être explorées afin de faire progresser la connaissance des ces régions. Ces données devraient permettre de préciser le contexte hydro-climatique dans lequel se déclenchent les embâcles et de documenter, dans une perspective historique, le rôle de la glace en tant qu’agent géomorphologique. Dans la présente thèse, nous nous attaquerons à ces problématiques en mettant à profit l’information historique contenue dans les arbres riverains.

## 1.2 La dendrochronologie : un accès à l’historique des événements d’embâcles

La dendrochronologie est fréquemment utilisée pour reconstituer l’intensité et la fréquence des événements extrêmes (Schweingruber, 1996). Parmi les techniques les plus courantes, la datation de cicatrices produites sur les troncs d’arbres permet de reconstituer l’historique des crues glacielles en milieu fluvial (Henoch, 1971; Parker et Jozsa, 1973; Payette, 1980; Smith et Reynolds, 1983; Hupp, 1988) et en milieu lacustre (Bégin and Payette, 1988;

Tardif et Bergeron, 1997; Bégin, 1999; Lemay et Bégin, 2008) mais aussi d'interpréter l'intensité et la fréquence des avalanches (Johnson, 1987; Germain *et al.*, 2005) et des éboulis rocheux en milieu forestier (Stoffel, 2005; Stoffel et Perret, 2006). Cette méthode est fondée sur le fait que le nombre, la forme et la hauteur relative des cicatrices datant d'une année donnée sont des indicateurs de l'intensité des événements discrets ayant perturbé le milieu.

À ce jour, peu de chronologies construites à partir d'arbres cicatrisés par la glace ont servi à l'analyse des conditions hydro-climatiques gouvernant le déglacement en rivière. Au Québec boréal et subarctique, l'analyse des chronologies glacielles construites en milieu lacustre a mis en évidence une augmentation dans l'intensité des crues glacielles durant la dernière moitié du XX$^{e}$ siècle (surtout depuis les années 1930) attribuable principalement à une augmentation des précipitations nivales et à l'apparition de conditions de forte hydraulicité printanière (Bégin et Payette, 1988; Tardif et Bergeron, 1997; Bégin, 2000b; Lemay et Bégin, 2008). Toutefois, comme le font remarquer Lemay et Bégin (2008), ces résultats sont difficilement transférables au contexte fluvial étant donné les importantes différences du point de vue des processus de mobilisation et de fracture de la glace entre les deux environnements.

Les environnements lacustres et fluviaux se distinguent notamment par le rôle que joue la glace lors du déglacement printanier. En rivière, la glace joue un rôle « actif » puisque le déglacement résulte d'une interaction entre les forces hydrauliques qui tendent à déloger le couvert de glace et celles qui tendent à le maintenir en place (e.g. température, précipitation nivales, radiation solaire, etc) (Beltaos, 1997, 2003). En lac, le rôle de la glace est « passif » puisque le couvert fond sur place (déglacement thermique) et est porté au contact de la végétation par le vent lors des hauts-niveaux printaniers (Bégin et Payette, 1988; Tardif et Bergeron, 1997; Bégin, 2000b; Lemay et Bégin, 2008). Une autre différence fondamentale est que la hauteur des cicatrices en milieu lacustre est intuitivement interprétable puisqu'elle témoigne de la hauteur atteinte par la crue, une variable hydro-climatiquement significative dans ces environnements (Lemay et Bégin, 2008). En rivière, les plus importantes inondations ont lieu derrière les embâcles (Gerard et Karpuk, 1979). Les cicatrices produites lors de ces événements ne renvoient pas aux caractéristiques de la crue régionale, mais plutôt à la hauteur atteinte par l'inondation derrière l'embâcle, une variable fortement liée aux conditions de site et à la présence de glace obstruant le chenal en aval du barrage (Beltaos, 1996). Enfin, en lac, une seule masse d'eau porte les radeaux de glace au contact de la végétation alors qu'en rivière, l'emplacement des embâcles est variable et imprévisible (sinon aléatoire), si bien que les événements enregistrés dans une section de cours d'eau peuvent différer considérablement de ceux enregistrés dans une section avoisinante.

Enfin, en milieu fluvial, les chronologies glacielles ont souvent été construites afin de fournir un cadre chronologique à l'interprétation des processus géomorphologiques (Sigafoos, 1964; Alestalo, 1971; Shroder, 1980; Schweingruber, 1996), mais rarement pour des fins d'analyse du contexte hydro-climatique gouvernant le déglacement. En conséquence, les étapes menant à la construction de telles chronologies demeurent non-standardisées et mal adaptées au contexte fluviatile. Afin d'aborder correctement la complexité et la particularité des milieux fluviaux, le choix des sites et des arbres à échantillonner, des indicateurs à privilégier, de même que la stratégie et l'évaluation de la représentativité de l'échantillonnage dendrochronologique devront être précisés.

## 1.3 Objectif principal

L'objectif principal de cette thèse de doctorat est de documenter, au moyen d'indicateurs dendrochronologiques, les mécanismes hydro-climatiques qui gouvernent la formation d'embâcles de glace ainsi que les impacts géomorphologiques que ces événements ont à l'intérieur d'un petit bassin versant du Haut-Boréal Québécois.

## 1.4 Objectifs spécifiques

Les objectifs spécifiques poursuivis par cette thèse sont :

1- D'établir un cadre méthodologique pour la construction de chronologies destinées à l'étude du contexte hydro-climatique dans lequel se déclenchent les événements d'embâcles en milieu fluvial.

2- D'analyser, à partir d'une telle chronologie, le contexte hydro-climatique dans lequel les embâcles sont survenus à l'intérieur d'un bassin versant non jaugé du Nord du Québec.

3- D'évaluer, dans une perspective hydrographique et fréquentielle, l'impact des embâcles sur les caractéristiques géométriques et sur la géomorphologie d'un petit cours d'eau caractéristique de la région de la Baie de James, dans le Nord du Québec.

**1.5 Site à l’étude : le bassin versant de la Necopastic**

La rivière Necopastic constitue un cours d’eau idéal pour répondre aux objectifs de cette thèse, notamment en raison : 1) de son accessibilité; 2) de l’homogénéité climatique de son bassin versant; 3) de son régime d’écoulement permettant les déglacements mécaniques; 4) de la présence de végétation permettant l’enregistrement des événements discrets; et 5) de l’homogénéité géologique de son bassin.

Accessible par la route, le bassin versant de la rivière Necopastic est situé à une quarantaine de kilomètres au sud-ouest de la localité de Radisson, sur le territoire de la baie de James au Moyen-Nord québécois (**figure 1.3**). La rivière Necopastic intercepte la Grande Rivière entre les centrales hydroélectriques LG-2 et LG-1 et n’a pas été affectée par la mise en eau des réservoirs dans cette région. Ce petit bassin de forme dendritique draine une superficie d’environ 250 $km^2$ à l’exutoire. Le cours principal de la rivière équivaut à un ordre cinq, selon la méthode de hiérarchisation de Strahler. La pente des tronçons est généralement assez faible et l’écoulement y est tranquille, bien que certains seuils caractérisés par un écoulement turbulent et une pente forte entrecoupent ces sections. L’altitude maximale est de 120 m alors que l’altitude minimale à l’embouchure est de 30 m.

Étant donné sa faible taille et son relief peu accentué, le bassin de la rivière Necopastic peut être considéré comme relativement homogène d’un point de vue climatique. Cela signifie que les changements longitudinaux dans les processus hydrologiques ne sont pas attribuables à des conditions climatiques particulières sévissant sur une portion isolée du cours d'eau. La température moyenne annuelle (aéroport La Grande, 7093715) est de -3,4°C, avec des moyennes mensuelles minimales et maximales atteignant -23,2°C et 13,7°C en janvier et en juillet, respectivement (Environment Canada, 2008). De plus, les mois de décembre, janvier et février présentent en moyenne moins d'une journée par mois avec des températures au-dessus du point de congélation. Les précipitations annuelles moyennes dans cette région sont évaluées à 680 mm, avec plus de 40 % du volume tombant sous forme de neige.

La crue printanière est de loin l'événement le plus important dans ce petit bassin, non seulement en raison de l'important volume d'eau qui transige durant cette période, mais aussi en raison de la formation de fréquents embâcles qui obstruent l'écoulement et causent d'importantes hausses de niveau. La crue printanière survient généralement entre la mi-avril et la mi-mai. En raison du réseau de drainage dendritique, la pointe est atteinte assez rapidement et est généralement de courte durée en raison de la faible taille du bassin. Les courts enregistrements disponibles (2004-2005) permettent d'évaluer que la rivière Necopastic atteint un débit d'environ 25 $m^3$ /s à plein-bords (en eaux libres). D'autres événements estivaux et automnaux peuvent aussi générer des crues importantes.

La végétation arborescente et arbustive bordant la rivière Necopastic présente d'abondantes cicatrices témoignant d'une activité glacielle récurrente. Les événements cicatrisant les arbres ne semblent toutefois pas être suffisamment puissants pour faucher ou causer la mortalité massive de tiges riveraines comme cela a été observé dans d'autres environnements (Smith et Pearce, 2000). La rivière Necopastic est située au Nord de la taïga québécoise, un biome dominé par l'épinette noire [*Picea mariana* (Mill.) BSP.] et le pin gris [*Pinus banksiana* Lamb.]. Les incendies forestiers sont fréquents et sévères dans cette région, si bien que les espèces se régénérant difficilement après feu telles que le mélèze laricin (*Larix laricina* [Du Roi) K. Koch] et le sapin baumier [*Abies balsamea* (L.) Mill] sont reléguées dans les environnements qui brûlent plus rarement, comme les bordures de lacs, les rives des cours d'eau et les tourbières (Sirois, 1997). En plus des quatre espèces conifériennes mentionnées ci-haut, les rives de la rivière Necopastic, comme celles de la plupart des cours d'eau du Haut-Boréal, sont colonisées par le saule à feuilles plates [*Salix planifolia* Pursh.], l'aulne crispé [*Alnus viridis* ssp *crispa* (Ait.)] et le bouleau glanduleux [*Betula glandulosa* Michx.], des espèces tolérantes à la submersion et résistantes à l'abrasion glacielle.

Le cours principal de la rivière Necopastic est incisé dans des dépôts limono-sableux homogènes d'un point de vue granulométrique, ce qui implique que les changements longitudinaux dans les processus géomorphologiques et les caractéristiques géométriques ne peuvent pas être attribués à des changements lithologiques. Ces dépôts homogènes forment de vastes plaines deltaïques mises en place à l'embouchure de rivières ou d'estuaires qui se jetaient dans la mer de Tyrrell (Vincent, 1985). On retrouve aussi dans le bassin, quoi qu'en plus faible abondance, des dépôts argilo-limoneux mis en place en eau profonde lors de la transgression marine. Les dépressions sont comblées par des accumulations tourbeuses dont la profondeur peut varier entre 1 et 6 m et dont l'accumulation a débuté dès le retrait de la mer entre 7000 et 6000 ans BP (Payette, 2001). Pour leur part, les affleurements rocheux composés de gneiss-granitique précambriens occupent près de 30% de la superficie du bassin.

### 1.6 Structure de la thèse

La présente thèse se divise en cinq chapitres. Le corps de la thèse (chapitres 2-3-4) est constitué de trois articles scientifiques rédigés en anglais.

L'introduction générale constitue le premier chapitre et débute par un survol de la problématique de recherche. Cette section est divisée en deux parties dans lesquelles les enjeux fondamentaux et méthodologiques sont présentés. Les objectifs généraux et particuliers de la thèse sont spécifiés. Le chapitre d'introduction générale se termine par une brève description et une justification du choix du site d'étude.

Le deuxième chapitre s'intitule "*Constructing hydro-climatically significant tree-ring chronologies of discrete events: the example of river ice-floods*". Ce chapitre met au point une méthode pour la construction de chronologies destinées à l'étude du contexte hydro-climatique dans lequel se déclenchent les crues glacielles. Cet article a été élaboré sous l'angle de l'identification et de la résolution de problèmes rencontrés lors de la construction d'une chronologie de cicatrices glacielles sur la rivière Necopastic. La possibilité d'appliquer ces méthodes dans d'autres environnements est discutée.

Le titre du troisième chapitre est: « *Hydro-Climatic Analysis of Mechanical Breakups Reconstructed from Tree-Rings, Necopastic Watershed, Northern Québec, Canada"*. La chronologie glacielle construite d'après la méthode présentée au chapitre deux est appliquée à l'étude du contexte hydro-climatique déclenchant les crues glacielles sur la Necopastic. Dans un premier temps, les relations statistiques qui existent entre les données hydrologiques et climatiques régionales et les variations dans l'intensité des crues glacielles sont établies. Dans un deuxième temps, un modèle d'arbres de classification et de régression (CART ®) est construit afin de prédire l'intensité des crues glacielles sur la rivière Necopastic, à partir d'un jeu de données hydro-climatique.

Le quatrième chapitre s'intitule : "*Impacts of Recurring Ice-jams on Channel Geometry and Geomorphology in a Small High-Boreal Watershed, Northern Québec, Canada*". Ce chapitre vise à évaluer dans un cadre fréquentiel l'impact des crues glacielles sur les propriétés géométriques et géomorphologiques à travers le bassin versant de la rivière Necopastic. Les données fréquentielles ont été obtenues à partir de l'échantillonnage dendrochronologique décrit au chapitre deux.

Le cinquième chapitre constitue la conclusion générale. Dans cette section, une synthèse des principaux résultats de même qu'une discussion portant sur l'importance de la contribution scientifique de la thèse sont proposés. Enfin, les possibilités de recherches futures découlant de ce travail sont discutées.

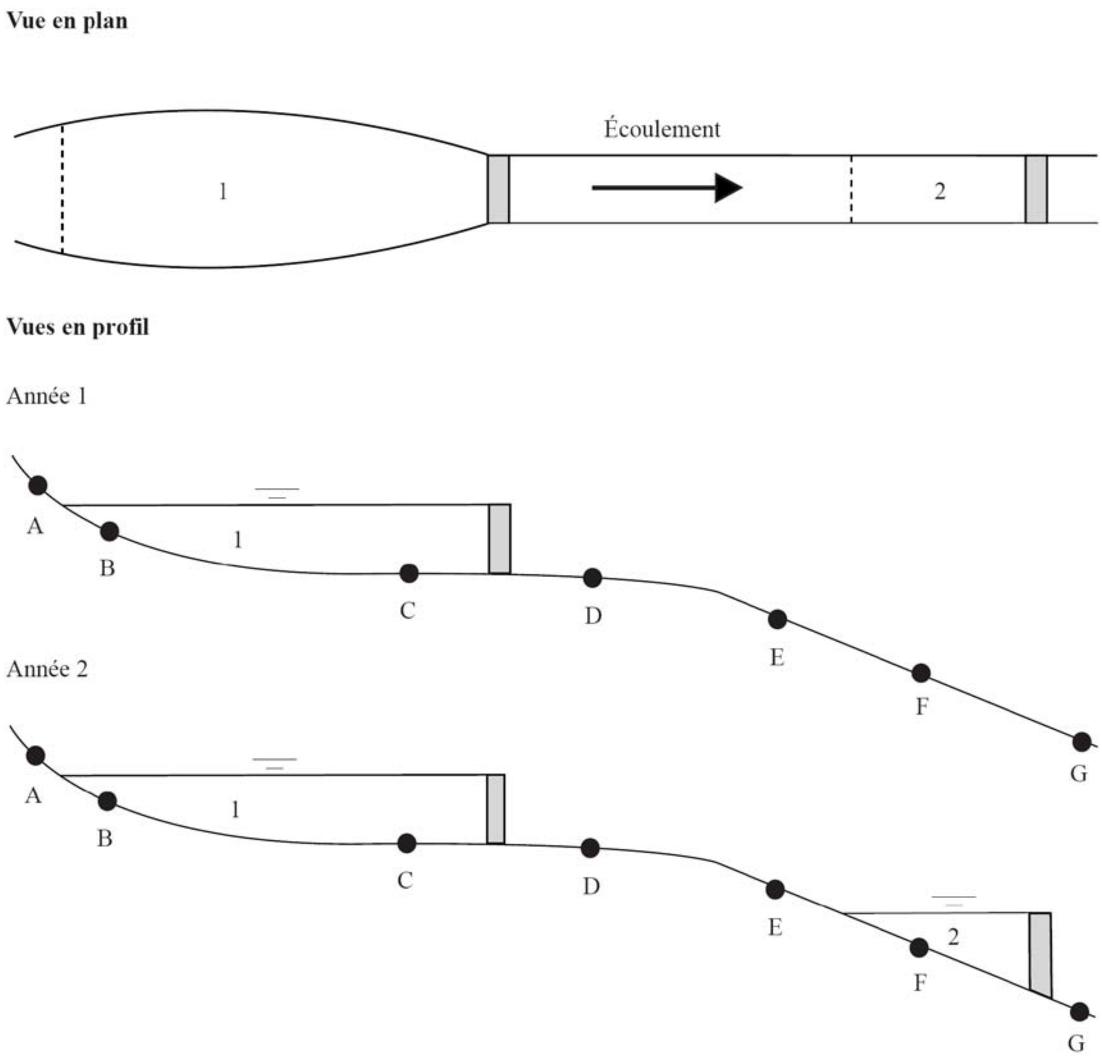


**Figure 1.1** Vues en plan et en profil d’une section typique d’un cours d’eau jaugé (A-G) affecté par de fréquents embâcles (barrages gris).

Lors de l’année 1, l’embâcle se produit dans un site propice à la formation d’embâcles (vue en plan). En dépit des variations dans la hauteur d’eau, l’événement sera perceptible dans les archives aux stations B et C. Lors de l’année 2, seules les stations B, C et F enregistrent des événements. À noter que les stations A, D, E et G n’ont enregistré aucun embâcle durant ces deux années, bien que des événements se soient produits ailleurs sur le cours d’eau

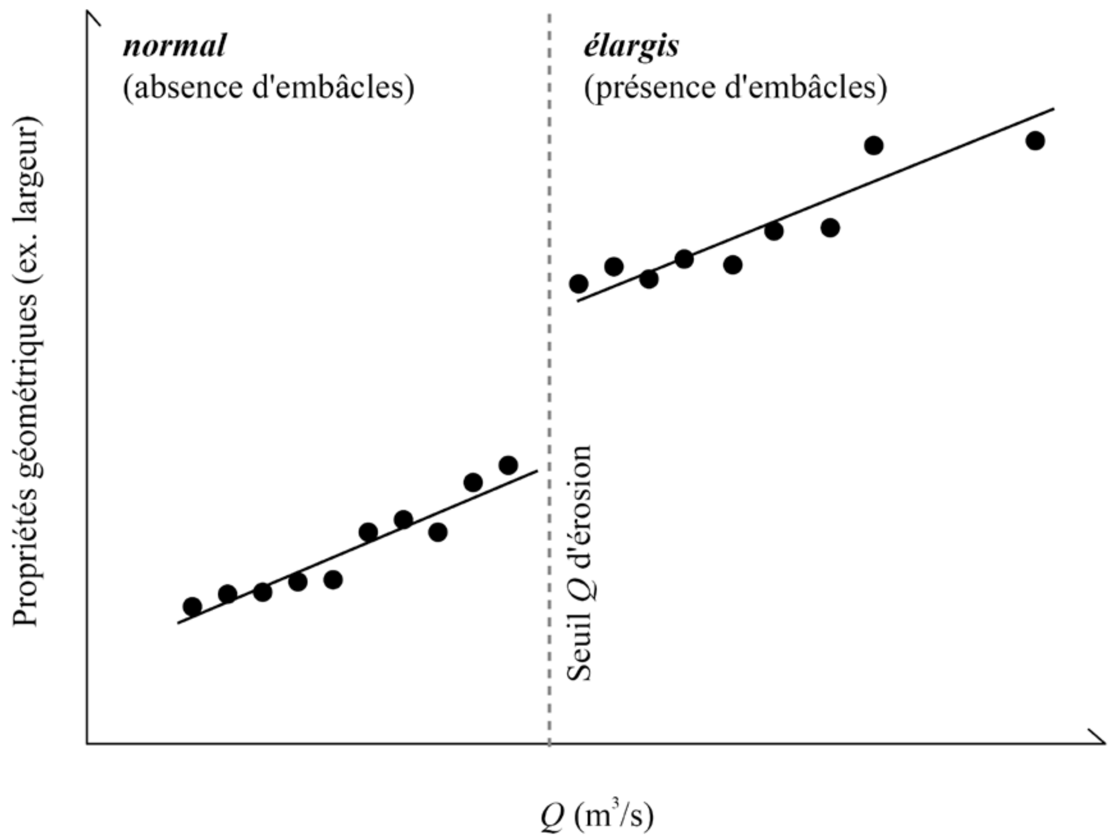


**Figure 1.2** Évolution longitudinale des propriétés géométriques (exemple de la largeur) d'un cours d'eau affecté par des embâcles

Au-dessus du seuil *Q*, le cours d'eau développe la capacité de fractionner et de mobiliser son couvert de glace au printemps, ce qui résulte en de sévères embâcles. Ces événements (dont la fréquence est inconnue) contribuent à maintenir une forme de chenal élargie par rapport aux cours d'eau non-affectés par les embâcles. Adapté de Smith (1980).

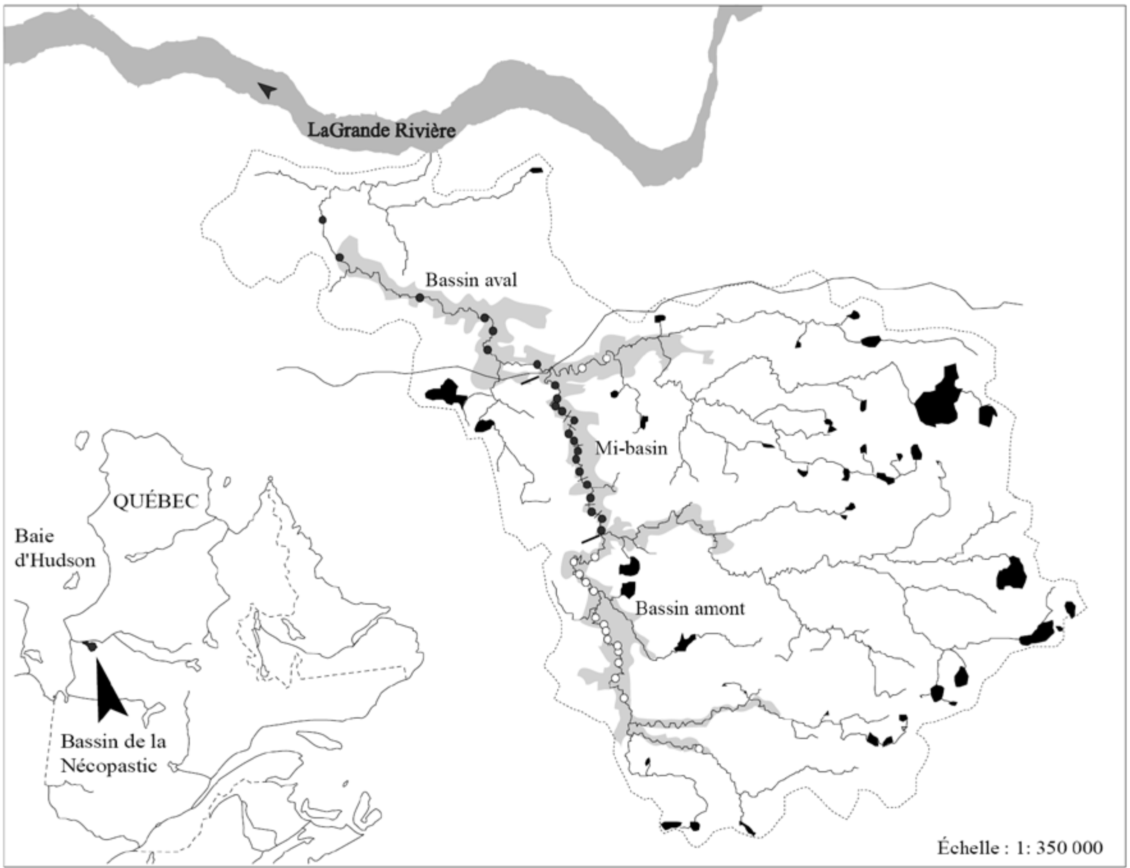


**Figure 1.3** Localisation et hydrographie du bassin versant de la Necopastic, à la Baie de James.

Les lacs sont en noir. Les cercles sur le cours principal représentent les sites d'échantillonnage. Les cercles blancs et les cercles noirs représentent respectivement l'absence ou la présence d'activité glacielle (indiquée par la présence ou l'absence de cicatrices sur les arbustes et les arbres riverains). La zone grise bordant le cours principal de la rivière Necopastic constitue une zone de dépôts meubles d'origine fluvio-glaciaire. Ces dépôts sont constitués d'une matrice fine limono-sableuse (Vincent, 1985).

# Chapitre 2. Constructing hydro-climatically significant tree-ring chronologies of discrete events: the example of river ice-floods

## Abstract

In this study, we present a method allowing to use ice scars born by trees in order to investigate the hydro-climatic context into which mechanical breakups are triggered in fluvial environments. The proposed method is based on three dendrochronological principles 1) site selection 2) sensitivity of trees and 3) replication. Problems encountered during fieldwork and during the construction of a chronology for the Necopastic River are identified and solutioned. First, it is demonstrated that ice-flood intensity is best evaluated at the scale of a climatically homogeneous watershed and from the proportion of sites recording the event. Second, flexible and small diameter stems should be removed from the chronology because they are considered insensitive to ice-scouring. In order to construct a chronology from equally sensitive stems, all rings formed under the modal Radius at the First Scar (RFS) should be eliminated. Third, sampling should be sufficient to uncover the most important events occurring in each site. To evaluate this, an Iterative Sampling with Replacement (ISR) algorithm was developed. The algorithm evaluates the chronology's saturation by calculating the amount of new events each time a randomly drawn tree is added to the chronology. The sampling is regarded as sufficient when each tree adds less than 5% of new events. Fourth, patterns of stem mortality and regeneration in the landscape should not influence the recording of ice-flood events. Non-parametric tests (e.g., Kolmogorov-Smirnov) are suggested to fulfill this purpose.

**Résumé**

Dans le présent article, nous décrivons une méthode permettant d'utiliser les cicatrices d'abrasion glacielle afin d'étudier le contexte hydro-climatique dans lequel se déclenchent les épisodes de déglacements mécaniques en milieu fluvial. Cette méthode se base sur trois grands principes dendrochronologiques 1) la sélection des sites 2) la sensibilité des enregistreurs 3) la réplication. Les problèmes liés à l'échantillonnage des arbres et à la construction d'une chronologie glacielle sur la rivière Nécopastic ont été identifiés et solutionnés. Dans un premier temps, il est démontré que l'évaluation de l'intensité d'un épisode de déglacement mécanique doit se faire à l'échelle d'un bassin homogène sur le plan climatique et en fonction de la proportion de sites ayant enregistré un événement. Dans un deuxième temps, les tiges flexibles et de faible diamètre doivent être retirées de la chronologie puisqu'elles sont de mauvais enregistreurs. Afin que la chronologie soit constituée d'individus ayant la même capacité d'enregistrement, il est conseillé d'éliminer tous les cernes dont le rayon est inférieur au rayon modal à la première cicatrice (Radius at the First Scar). Dans un troisième temps, on doit s'assurer de la représentativité de l'échantillonnage dendrochronologique en chaque site. Pour ce faire, un algorithme d'échantillonnage itératif avec remise (*Iterative Sampling-with Replacement*, ISR) été développé. Cet algorithme évalue la saturation de l'échantillonnage en calculant la quantité d'événements nouveaux ajoutés par chaque arbre tiré au hasard. Enfin, il importe de s'assurer que les phases de mortalité et de régénération à l'échelle du paysage n'influencent pas la structure d'âge des cicatrices. Afin de déterminer sir les deux populations sont différentes, des tests de comparaison de distribution (e.g., Kolmogorov-Smirnov) sont utilisés.

## 2.1 Introduction

Many discrete extreme events such as floods, avalanches or rockfalls are climate-sensitive. These events are triggered either through a complex interaction between driving hydro-climatic variables or through the exceedence of some thresholds conditions (IPCC, 2007). In cold areas for example, hydro-climatic conditions prevailing during winter and spring determine the continuum between mechanically and thermally induced river ice breakups (Beltaos, 2003). Extreme spring ice-jams are generally produced during mechanical breakup events following large and rapidly rising runoff prior to ice melt (Prowse and Beltaos, 2002). These conditions are opposed to thermal breakup events where the ice cover largely "melts *in situ*" under the effect of various atmospheric and hydrothermal heat fluxes (Prowse and Marsh, 1989).

However, in most fluvial systems, specific hydro-climatic conditions triggering mechanical breakups remain largely unquantified because long-term and high-resolution archives relating these phenomenons are rare and scattered. First, hydrometric records often cover short periods of time yielding small datasets that are unhelpful to the study of these complex and multivariate processes. Second, gauging stations provide only site-specific data on ice-jam formation. Events occurring upstream or downstream may not be visible in the archives (Bégin, 2000a; Beltaos, 2000).

In the absence of adequate instrumental readings, discrete extreme events are often reconstructed using dendrochronological techniques (Alestalo, 1971; Shroder, 1980). Among the potential methods, the tree-ring dating of corrasion scars represents an interesting avenue to reconstruct the frequency and stage of extreme ice-scouring events disturbing riverbanks (Henoch, 1971; Parker and Jozsa, 1973; Payette, 1980; Smith and Reynolds, 1983; Payette and Delwaide, 1991) and lake shores (Bégin and Payette, 1988; Tardif and Bergeron, 1997; Bégin, 1999; Lemay and Bégin, 2008). Corrasion scars have also been employed to reconstruct major periods of snow avalanches (Johnson, 1987; Germain *et al.*, 2005) and rockfall activity (Stoffel, 2005; Stoffel and Perret, 2006). The general idea behind this method (Sigafoos, 1964; Alestalo, 1971; Shroder, 1980; Schweingruber, 1996) is to inventory trees in a disturbed area and to interpret the magnitude of past discrete events using indicators such as height and frequencies of injuries dating from a same year. Although, this method has been repeatedly used in various geomorphological and ecological settings, it has never been employed as a proxy to investigate the hydro-climatical context triggering extreme discrete events in fluvial environments. Despite the great potential of such methods, some important methodological pitfalls must be underlined and solutioned.

This methodological paper focuses on problems arising when ice-scar chronologies are constructed to investigate Hydro-Climatic Conditions Triggering Mechanical Breakups (HCCTMB) in rivers. The aim of this study is to yield a methodological framework for constructing chronologies that are sufficiently robust and noiseless to investigate the possible teleconnections with regional hydro-climatic variables. To reach this objective, we will exemplify the problems encountered during the construction of an ice-scar chronology on the Necopastic River, a small stream located in the James Bay area, northern Québec. We will insist on : 1) the choice of an adequate dendrochronological indicator, 2) the appropriate spatial scale to deliver the information, 3) the identification of trees that are insensitive to the process under study, 4) the representativeness of the dendrochronological sampling, 5) the interference between the hydro-climatic signal and forest structural aspects. Then, we will provide solutions inspired from key dendrochronological concepts (Fritts, 1976; Shroder, 1980) and from studies conducted in lakes (Bégin and Payette, 1988; Tardif and Bergeron, 1997; Bégin, 2000b, a; Lemay and Bégin, 2008) where considerable efforts were deployed to develop meaningful ice-flood chronologies. Finally, we will discuss the applicability of our methods to the analysis of discrete events in various settings.

### 2.2 Dendrochronological principles guiding the construction of discrete event chronologies

Discrete tree-ring chronologies aim to reconstruct variations in the magnitude of past extreme events. To construct such chronologies, dendrochronological techniques should agree with the key concepts of this discipline (Fritts, 1976; Shroder, 1980). Here, we list some of these concepts and briefly describe how they apply to the construction of hydro-climatically significant tree ring chronologies of discrete events.

-*Site selection*: Sites should be selected in order to maximize the chances that variations in the chronology are attributable to the environmental process under study. Sites that are overly responsive to undesirable processes or to phenomenon occurring only locally should be avoided.

-*Sensitivity*: The manner trees respond to a disturbance (e.g. their mechanical properties) varies with their age, size, and height. To construct hydro-climatically significant chronologies, all included individuals should be equally sensitive to the process under study, unless important bias can occur.

-*Replication*: Sampling many trees in a site and many sites within a given area is a way to maximize the environmental signal in a chronology and to attenuate the undesirable, tree-specific or site specific “noise”.

**2.3 Study area**

The Necopastic River (53’73’’N 78’28’’W) is a high-boreal watercourse located 40 km west from the town of Radisson, James Bay, northern Québec. Its small South-North oriented watershed drains an area of 250 km². The main stream is an affluent of LaGrande River well-known for the major hydroelectrical projects conduced by Hydro-Québec along its course (**figure 2.1 a,b**). The Necopastic River intercepts LaGrande River between the LG-1 and LG-2 hydroelectric centrals but only the lower part of the studied stream was affected by the inundation of the LG-1 reservoir. The Necopastic River watershed was chosen because of its accessibility and due to the fact that the major part of its basin remains not affected by the presence of man.

Climate normals (1971-2001) at the *La Grande Rivière A* station displays a typical high-boreal continental climate with mean annual temperatures around -3,14°C (Environment_Canada, 2008). Minimum (-23.2°C) and maximum (13,2°C) monthly averages are reached in January and July, respectively. The total annual precipitation is 684 mm, with 37% (248 mm) falling as snow.  Climate records also show that the months of December, January and February have an average of less than one day per month with a temperature over 0°C. In contrast with rivers of the cold-temperate climate where extreme ice-jams events frequently occur during winter warm spells (Beltaos and Prowse, 2001; Beltaos and Burrell, 2003), ice-jamming is most frequent during the spring-flood on the Necopastic River.

Regional vegetation is characterized by the co-dominance of fire-adapted species such as black spruce [*Picea mariana* (Mill. BSP)] and Jack pine [*Pinus banksiana* (Lamb)] (Arseneault and Sirois, 2004). In riparian area where fire frequency is lower, black spruce shares its dominance with eastern larch [*Larix laricina* (Du Roi) K. Koch] and balsam fir [Abies balsamea (L.) Mill] (Arseneault and Sirois, 2004; Bouchon and Arseneault, 2004; Boucher *et al.*, 2006; Arseneault *et al.*, 2007). Ice-scouring tolerant shrubs such as *Alnus viridis* ssp *crispa* (Ait.) Turrill, *Salix planifolia* Pursh. and *Betula glandulosa* Michx cover the riverbanks and floodplains of most streams in the area, and those of the Necopastic River in particular.

## 2.4 Material and methods

### 2.4.2 Dendrochronological sampling

Trees used to construct the preliminary ice-scar chronology were sampled in 15 sites (**figure 2.1c**). The sampling was restricted to the upstream portion of the Necopastic River (**figure 2.1b**). Site selection was made from the analysis of 1:10 000 aerial photographs (Hydro-Québec) prior to the field campaigns of summers 2005 and 2006. Our objective was to eliminate sites with a configuration that favours ice-jam formation independently of hydro-climatic forcings (i.e., sinuous reaches, channel constrictions, obstructions). Selected sites are relatively linear segments of the Necopastic River, have a stream-length of about 100 m and present similar coniferous densities (**figure 2.2**). Hydrographic sills (**figure 2.1c**) limit backwater effects between sites.

A total of 181 individuals and 888 scars (with about 75% opened) were sampled, with the intent of sampling at least 10 trees at each site (**table 2.1**). Individuals were identified as black spruce (72%) and eastern larch (28%). It was not possible to sample 10 trees in all sites due to logistical constraints in remote sites (sites 6,8,9,10,14) or because less than 10 scarred trees were present (sites 7,11). Living and dead trees to sample were randomly chosen within the population, but trunks under 10 cm of diameter were never sampled to avoid collecting scars produced on flexible stems. Both riverbanks were sampled. Individual trees located within a tree-length distance were not sampled to attenuate sampling redundancy. When ice-marks were well defined on a tree bole, cross-sections were taken in the middle of the scar. Otherwise, cross-sections were taken at multiple heights in order to date every possible scar on the tree. Scar minimal and maximal heights relative to bankfull elevation were measured using a metric tape. Bankfull stage was identified at each site following the procedure described by Williams (1978). Additionally, one cross-section was taken at the base of each tree to obtain an approximate age of tree establishment. **Table 2.1** summarizes the sampling in each site. Five fire-scarred trees were sampled on well-drained terraces adjacent to the Necopastic River in order to date past fires in the watershed (**figure 2.1c**).

In the laboratory, cross-sections were finely sanded and tree-rings counted from the last year of growth (2005 or 2006) to the center. Samples from dead trees were cross-dated with master chronologies existing in the area. Each ice-scouring event was dated with the precaution of not replicating events found at multiple heights on the same tree. Scars after AD 2003 were excluded from the chronology because newly formed damages are difficult to observe in the field. Finally, the Radius at the First Scar (hereafter named RFS, in cm) was measured on each cross-section on each tree. Statistical analyses were performed using MATLAB R14 and SPSS 13.0 for Windows.

### 2.5 Methodological problems encountered while reconstructing mechanical breakups from ice scars

***Problem 1) Classical indicators may not be well suited for the study of HCCTMB***

The analysis of HCCTMB relies on finding an adequate tree-ring indicator of past mechanical breakup intensity and on delivering the information at the appropriate spatial scale. Classical dendrochronological indicators such as maximal scar heights or relative frequencies[1] of ice scarred trees (Shroder 1978) are not always relevant to the study of HCCTMB in rivers.

First, maximal scar heights reflect post-breakup conditions instead of HCCTMB. Backwater flood stage is physically linked to the resistance at the ice-jam toe and to the rapidity at which reaches located downstream get ice-free (Beltaos, 1997). Second, scars produced during high water levels may result from ice piling up or sliding on trees. Lemay and Begin (2008) evaluated that scars longer than 50 cm probably result from such a process. On the Necopastic River, more than 20% of all scars are longer than 50 cm (**figure 2.3a, 2.3b**) suggesting that this process may be important in our basin. Third, scar shapes produced by recent events may be biased by previous marks. On the Necopastic River, trees are heavily scarred between 50 and 150 cm above bankfull (**figure 2.3c).** At these heights, cambial activity on exposed-to-drift-ice trunk sections (**figure 2.3d**) is almost completely interrupted, leaving no space available for the formation of new marks.

Furthermore, at-a-site relative frequencies of ice-scarred trees are not representative of the magnitude of ice-jams occurring within the watershed. To illustrate this, relative scar frequencies were calculated for each of the 15 sites in the Necopastic basin. A comparison of the three most important events between 1950 and 2003 at each site depicts considerable variability between the segments (**figure 2.4**). For example, although the ice-flood event of 1987 is well replicated between sites, it does not correspond to one of the three most

[1] the ratio of the number of trees bearing a scar of year "*t*" to the number of trees available for recording at year "*t*".

important years in four sites. Sampling in one of these four sites would lead to an inaccurate interpretation of the real magnitude of past ice-floods occurring in the entire basin that year. Additionally, events of years 1975, 1976, 1983, 1989 and 1992 appear in the top-three events in two sites or less. Unlike the former situation, sampling in these sites would overestimate the importance of locally important events.

***Solution***

We put forward the idea that HCCTMB should be analysed at the scale of the watershed. We hypothesize that hydro-climatically induced mechanical breakups should be observed in many sites in contrast with events resulting from locally favourable stream morphologies. Thus, well replicated events should indicate highly favourable conditions. Accounting for the mortality of trees throughout the watershed involves slightly modifying the formula introduced by Shroder (1978) so that :

$$I_T\ (\%) = \sum_{1}^{t} R_t \Big/ \sum_{1}^{t} A_t \cdot 100 \qquad (2.1)$$

where $I_T$ is a weighted chronology of the magnitude of mechanical breakups events during time period $T = (1\ldots t)$. $I_t$ corresponds to the ratio of the number of sites recording an event at time $t$ ($R_t$) to the number of sites available for recording at time $t$ ($A_t$). Events are considered “recorded” when at least one scar is found at time $t$. As argued by Bégin (2000a), the at-a-site replication of an ice scar simply increases the level of confidence in the verification of events occurring locally, but a single date should be considered the same way. Similarly, sites were considered “available” when at least on tree was installed at time *t*. The **equation 2.1** was applied on the Necopastic River and the resulting ice-scar chronology is presented in **figure 2.5a.**

***Problem 2) Small trees may be insensitive to ice-scouring***

Large stems are more reliable recorders than smaller ones. Small stems bend easily under the impact of drift-ice (Payette, 1980) and are often covered with snow leaving them undamaged during ice-scouring events. However, to analyse HCCTMB from tree rings, the recording capacity of trees must not markedly change through time and sampled individuals must have had an equal chance of recording all events during a defined time period. To our knowledge, no work has been done on finding the minimal size over which trees have equal chances of recording ice-flood events.

***Solution***

An empirical manner to quantify the minimal size of equally sensitive recorders is to report the RFS measures in a frequency histogram (**figure 2.6**) and to locate the modal size class. Trees larger than the modal size have a similar recording potential. On the Necopastic River, the distribution of RFS measures is bimodal; the smallest mode corresponds to the 2-3 cm size class (**figure 2.6**). All tree rings formed under 3 cm were discarded to exclude less sensitive stems from the chronology. This implied that 1) trees became available for recording when their smaller radius became larger than the modal RFS and 2) sites became available for recording when at least one tree became larger than the modal RFS. Incorporating these modifications and reusing **equation 2.1** produces a new chronology of mechanical breakups for the Necopastic River (**figure 2.5b).** The exclusion tree-rings formed on small stems reduced the importance of events pertaining to the pre-1910 and to the 1940-1980 periods by about 10% (**figure 2.5d**). Additionally, the number of years without any scars passed from 17 to 18 (**figure 2.5b).**

***Problem 3) Are there enough trees in the chronology?***

If replication between sites is an adequate proxy of the magnitude of mechanical breakups (see problem 1), then the sampling should be sufficiently extensive to reveal the most important events in each site. In order to uncover these events, field dendrochronologists too often assume that they have no other choice than sampling each and every tree bearing scars so that no events remain unsampled. This pragmatic solution is not realistic when budgetary and time constraints exist or when the study is conducted in protected areas. Moreover, sampling the complete population is unnecessary when similar trends can be detected from fewer trees. Taking this into account, dendrochronologists need to determine if a sample size is sufficiently large to insure that 1) most important events occurring in a site are uncovered and 2) the chronology would not change dramatically if a few more trees were added.

***Solution***

A solution to this problem is to take advantage of modern computer-intensive techniques to determine if chronologies are constructed from saturated sampling. “Oversaturated” sampling refers to situations where each new tree incorporated to the chronology uncovers few new events. On the contrary, the sampling can be considered “undersaturated” when each new tree adds a significant amount of new events that were not discovered by previous trees. In the following section, we describe and apply an Iterative Sampling-with-Replacement (ISR) algorithm that can help dendrochronologists evaluate if the sampling saturates the event-chronology. The ISR algorithm can be summarized as follows, but the mathematical expression and the algorithm’s flowchart are described in detail in **annexes 1 and 2**, respectively. The ISR algorithm iteratively samples (e.g. 1000 times) with replacement *k* trees (starting with *k*=1) in the sample data set. Once all iterations are completed, it computes the mean number of events that are discovered. Then, it repeats the same procedure, but with *k*+1 trees and so on, until the value of *k* equals the number of trees sampled at that site. A new mean number of events is calculated at the end of each iteration.  Finally, the ISR algorithm determines that the sampling oversaturates when a new tree adds less than 5 % of new events.

We applied this procedure to evaluate saturation of the sampling in sites of the Necopastic River. The results are summarized in **table 2.1** but are illustrated only for sites 5 and 9 to avoid redundancy (**figure 2.7**). At site 5, the sampling oversaturates when only 11 trees are incorporated. 29 trees were sampled and 45 events were uncovered (see **table 2.1** for details). Trees had 5.2 scars in average and the oldest tree dates back to 1914 AD. By comparison, site 9 still looks undersaturated when all eight trees are incorporated to the chronology (**figure 2.7**). Trees uncovered an average of 2.5 events and the oldest tree dates back to 1796 AD. In addition to the fact that the number of trees sampled in site 5 was higher, its shorter record and better replication of events between trees contributed to the saturation of the sampling.

Overall, the ISR algorithm revealed that the sampling at sites 8, 9 and 15 was not sufficiently extensive (**table 2.1**). Also, each tree probably uncovered different ice-jam events. On the Necopastic River, a final chronology was produced after removing these undersaturated sites (**figure 2.5c**). This resulted in a decreased importance of events dating from the pre ~1910 and 1960s periods and an increased importance of events in the 1950s and after ~1980 (**figure 2.5d**). The number of years with no ice-scouring evidences increased from 18 (**figure 2.5b**) to 20 (**figure 2.5c**).

***Problem 4) Does tree survival and establishment affect the hydro-climatic signal?***

The analysis of HCCTMB implies that variations in the final tree-ring chronology (**figure 2.5c**) do not simply reflect patterns of stem recruitment and tree mortality in the area. Disturbances such as forest fires and insect outbreaks in the boreal environment may often lead to important mortality and subsequent massive regeneration along streams (Bouchon and Arseneault, 2004; Arseneault *et al.*, 2007). For example, on the Necopastic River, the brief survey of fire scars on adjacent terraces revealed two fire dates: 1922 and 1941 (**figure 2.1c**). Although the extent of these fires could not be determined precisely, stem recruitment following these events are visible in the cumulative distribution of tree availability in the watershed (**figure 2.8a**). It is important to determine whether or not these phases of stem recruitment influenced the ice scar record.

***Solution***

Several authors used the statistical comparison of both ice-scar and tree installation age structures using a nonparametric Kolmogorov-Smirnov (K-S) test (Bégin and Payette, 1988; Tardif and Bergeron, 1997). The K-S procedure tests the null hypothesis that both cumulative distributions have similar shapes. In the absence of a statistically significant difference between the two curves, one may suspect that the recording of discrete events is influenced by forest structure. Transposing this technique to the study of HCCTMB in fluvial environments forces us to make slight modifications to the method in order 1) to agree with the principle of equal sensitivity and 2) to incorporate the solutions described earlier in this paper. First, cumulative distributions of site replication and site availability should also be compared using a K-S test since these variables relate to forest structural aspects. Second, tree rings and scars formed under the modal RFS should be removed (see problem 2) to ensure that events were recorded on equally sensitive stems. Third, only sites characterized by oversaturated sampling must be included as soon as one tree overgrows the modal RFS (problem 3). When applied in our watershed, this procedure revealed that variations in the ages of trees are significantly different ($p<0.001$) from the ages of scars (**figure 2.8a**). Similarly, variations in the ages of sites are significantly different ($p<0.001$) from the cumulative amount of replication throughout the watershed (**figure 2.8b**) Thus, it can be assumed that population dynamics do not influence the recording of ice-scouring events within the Necopastic basin.

## 2.6 Discussion

All solutions enumerated earlier have a common objective: producing a noiseless ice-scar chronology from which HCCTMB can be analysed. We will now discuss the usefulness of these solutions in different fluvial systems and also in various environments where field studies focus on linking the occurrence of discrete events (e.g., avalanches, rockfall activity) to regional hydro-climatic conditions.

### 2.6.1 The watershed signal: a new paradigm in the construction of hydro-climatically significant mechanical breakup chronologies.

Spring ice-jams and subsequent backwater flooding resulting from mechanical breakups are spatially unpredictable (Ashton, 1978; Kellerhals and Church, 1980) on a year to year basis. Accordingly, we argue that obtaining a “watershed signal” is preferable in comparison to a more localized one, even at the detriment of a finer scale analysis.

Although this sampling strategy can be applied in other fluvial systems, not all watersheds are appropriate. The ideal watershed should be small enough to be hydro-climatically homogeneous. Thus, variations in breakup magnitude cannot be attributed to site-specific climatic conditions. Due to its small size (250km$^2$) and its low relief, the hydro-climatic homogeneity of the Necopastic River basin can be assumed.  However, basins should be large enough to generate a flow sufficient to mobilize the ice cover during spring. An additional criteria is that basins should be large enough to allow adequate spacing between sampling sites in order to avoid pseudoreplicating the events (Hurlbert, 1984). Pseudoreplication can occur when events recorded in a site are affected by the release of jams recorded upstream or through backwater effects from downstream. Upstream jam releases affecting sites in the whole watershed would be rare on the Necopastic River. We observed that, due to its small-sized channel and the alternance between straight and incurved sections, ice rafts cannot move over long distances. Backwater effects would be more problematic in the Necopastic River, but the alternance of regularly spaced sills (**figure 2.1**) and gently sloping segments is likely to restrict propagation of backwaters to one or two sites, at most. Ultimately, the orientation of the basin must also be considered. Large northward flowing basins such as the Mackenzie River basin should be avoided since mechanical breakups occurring in the lower part of the watershed are often caused by a rapidly increasing discharge from upstream (Kellerhals and Church, 1980).

The strategy of avoiding sites prone to jams is similar to the methodology proposed by Bégin (2000a; 2000b) and Lemay and Bégin (2008) for the sampling of discrete ice-flood events in lakes. These authors argued that chronologies constructed in moderately exposed shore segments are more easily hydro-climatically interpretable than those produced in highly exposed sites characterized by geomorphic instabilities, heterogeneous tree densities and that appear very sensitive to minor events. In rivers, we propose to construct chronologies from trees sampled in moderately exposed sites characterised by linear channel sections of constant depth, width and cross-sectional area.

### 2.6.2 Attenuating the sources of noise: a prerequisite to the hydro-climatic analysis of discrete events

Reducing the sources of noise affecting the quality of tree-ring records is an important step in the production of hydro-climatically interpretable discrete events chronologies. In our study, we identified four potential sources of noise that interfere with mechanical breakup chronologies. These sources of noise are 1) inconvenient tree-ring indicators 2) inappropriate trees to the process of interest 3) incomplete or unrepresentative sampling and 4) interference between the hydro-climatic signal and forest dynamics. In the following section, we discuss the potential applicability of methodological solutions proposed in this paper to the study of hydro-climatically induced discrete events in different environments (e.g. ice-floods in different environments, rockfall activities, avalanches, gravitational processes on mountain slopes).

#### 2.6.2.1 Scar heights: an imprecise and often inappropriate indicator

Measured scar heights and lengths on the Necopastic River are only poorly translatable in terms of water levels because 1) numerous marks result from ice pile ups on banks (**figure 2.2a,b**) and therefore over-estimate the true water levels attained during ice-jams and 2) shapes and positions of scars depend largely on the space left unscarred by previous events (**figure 2.2c,d**). Similarly, Smith and Reynolds (1983) observed that tree scars overestimated by about 1.4 m the water level recorded by instruments on the Red Dear River (Alberta) and partly attributed this difference to ice blocks sliding up the trees during ice-jams. From a detailed analysis of scarred trees, Payette (1980) also found that injuries dating from two major floods on the Leaf River in northern Québec (i.e. 1979 and 1934) showed considerable variations both in terms of lengths and heights. In this environment, some scars were more than 3.5 m long, resulting in imprecise reconstructions of the water levels attained during these jams. Such inaccuracies are very similar to those documented in other environments. For example, Stoffel and Perret (2006) recognized that high scars resulting from rockfall activity in the Swiss Alps are often produced by material rebounding on stems, and do not indicate more “important” events. Similarly, Germain et al. (2005) reported that scar heights visible in avalanche snow paths reflect more the impact of avalanche-transported stems on standing trees than the volumes of snow moved downslope. Here, it is important to mention that we do not mean that high scars should be left unsampled. On the contrary as argued by Stoffel and Perret (2006), tree-ring reconstructions omitting high scars can be incomplete. We simply underline the fact that, in many environments, scar heights do not provide reliable estimates of the real magnitude of past discrete events. We therefore conclude that the use of such an indicator must be used with great caution.

The fact that scar heights are discarded herein highlights the important difference in research objectives pursued in our study in comparison with earlier studies using tree scars as an indicator of past ice-flood magnitude. Earlier dendrochronological studies conducted in similar environments were not designed to investigate the existing teleconnections between the occurrence of discrete extreme events and the regional hydro-climate. Instead, they aimed to provide data on the frequency and magnitude of past ice-jams regardless of the hydro-climatic conditions causing them. For example, Smith and Reynolds (1983) surveyed the banks of the Red Dear River (Alberta) in order to find high water level marks dating from past ice-jams. An objective was to construct a chronology that extends beyond the available hydrometric record. In our study, the objective of constructing a chronology that extends as far as possible in the past is only secondary. A more important objective is that a hydro-climatically interpretable signal can be extracted from the chronology. This implies eliminating indicators that are not directly related to the phenomenon of interest. The time period required should, on the contrary, be dictated by statistical considerations (e.g., sample size, number of independent variables, etc.).

Scar heights should be considered only when they directly reflect the physical mechanisms triggering discrete events. In fluvial environments, high-water levels recorded as ice scars are not related to the conditions *causing* mechanical breakups. Instead, they must be seen as a *consequence* of an ice-jam and subsequent backwater effects resulting from mechanical breakups. This is radically different from the situation occurring in boreal and subarctic lakes where scar heights were used as a proxy of the magnitude of past ice-floods (Bégin and Payette, 1988; Tardif and Bergeron, 1997; Lemay and Bégin, 2008). Lake ice almost always thermally degrades in situ and most of the work causing riparian tree scarring is accomplished by wind shear during high spring water levels (Bégin and Payette, 1988; Tardif and Bergeron, 1997; Lemay and Bégin, 2008). Moreover, in lakes, a single water body influences all shore segments during breakup such that lateral variation in the number and height of scars mostly reflect the exposition and orientation of the shore (Bégin and Payette, 1988; Tardif and Bergeron, 1997; Bégin, 2000b; Lemay and Bégin, 2008). Consequently, given a series of homogeneous lakeshore segments and a method to eliminate suspect scars resulting from ice pile up, it is possible to estimate water-levels from ice-scars with more confidence.

### 2.6.2.2 Inappropriate trees

The modal RMS is an objective way to determine the minimal size of stems to include in a tree-ring chronology. This method could be used in other environments where stem sensitivity depends on stem size. To circumvent uncertainties associated with small stems, it was proposed that events recorded during the first 20 years of growth should be removed from ice-flood chronologies in lakes (Lemay and Bégin, 2008). On the Necopastic River, all scars formed on stems smaller than three centimetres in radius (modal RFS) were removed from the chronology. This result corresponds grossly to the age criteria proposed by (Lemay and Bégin, 2008) from trees sampled in a nearby area. In avalanches paths, mechanical injuries on stems also depend largely on the stem's stiffness as moving snow masses often leave small bendable stems undamaged (Johnson, 1987). Similarly, Germain (2005) chose not to consider the first 10 years of growth in a reconstruction of past avalanche history from reaction wood sequences. Although such age criterions seem appropriate in their respective field contexts, they are not generalisable to other environments or processes. In contrast, our method, based on the modal RFS is an easy way to select stems empirically according to their mechanical properties.

#### 2.6.2.3 Incomplete sampling

The ISR procedure developed herein can be used in every situation where dendrochronologists need to know if an event-chronology is constructed from a sufficient number of trees. An often recognized problem is the under-representation of events dated from hidden (overgrown) scars (Schweingruber, 1996), biasing the chronology towards visible scars. This is problematic in hydrologic systems (Tardif and Bergeron, 1997; Bégin, 1999, 2000b; Lemay and Bégin, 2008) but it was also noted in reconstructions of rockfall activity on mountain hillslopes (Lafortune *et al.*, 1997; Stoffel and Perret, 2006). In the inspiring methodological paper from Stoffel and Perret (2006), it was argued that without any quantitative data on the number of hidden scars, past frequencies and magnitude of discrete events cannot be adequately described. Here, we put forward the idea that each and every sampled scar must be included in the chronology, whether it is visible or not. Given an adequate replication between events in a site and a quantitative estimation of the minimal number of trees to include in a chronology, there is no reason to remove events dated from hidden scars solely.

An interesting aspect about the ISR procedure is that the minimal number of trees to sample on the Necopastic River (**table 2.1**) is relatively similar between sites with values between 8 and 12 trees. Consequently, we judge that it is safe to sample about 15 trees per site on the Necopastic River to obtain a representative sample. Although this procedure could be applied in other fluvial systems and even to the study of other processes, it is too soon to affirm that 15 trees per site is a sample size that can be generalized. A next step would be to conduct a sensitivity analysis with artificial tree-ring data to quantify the influence of attributes (e.g. age of trees, synchronicity of tree installation, return period of events, number of scar-replicates in a site, total number of events, etc) on the minimal number of trees to sample in various environments. This type of statistical modeling could help estimating the number of trees to include to saturate the chronology, given a few metrics that are easily measurable on the field (e.g. mean age of trees, mean number of opened scars, etc.).

#### 2.6.2.4 Interference with forest dynamics

The K-S procedure presented here can be used in various environments where event chronologies are constructed from trees living in highly disturbed environments. The causes or massive mortality can be external (e.g., forest fires, logging activity, insect outbreaks, etc) or directly related to the discrete event under study. Destructive capacities of extreme discrete events and associated patterns of vegetation recovery were described in many environments such as avalanche corridors (Johnson, 1987; Germain *et al.*, 2005) and ice-jam-prone river segments (Scott *et al.*, 1997; Smith and Pearce, 2000). In these situations, old stems bearing old scars would become rarer while massive post-disturbance regeneration would artificially increase the importance of recent events. In such situations, it is recommended to use a K-S procedure similar to the one used herein to verify that variations observed in the forest structure are different from those observed in the long-term tree-ring record.

## 2.7 Conclusion

This study has exemplified some of the most important problems arising when tree-ring chronologies are used to analyse the hydro-climatic conditions triggering past extreme events. We have focused mainly on river mechanical breakups, but insisted on the fact that the proposed solutions can be used in other environments. When tree-ring chronologies are constructed to analyse HCCTMB in rivers, we recommend that:

Step 1) Sampling sites should be selected in order to minimize site-specific influences on the recording. In rivers, sites should be moderately exposed to ice-jams i.e., they should 1) have a constant width and depth, b) be relatively linear and c) have homogeneous tree densities.

Step 2) The full trunk of trees should be sampled so that no hidden scars remain unsampled. A stem cross section should be taken at the trunk base to approximate tree establishment. We recommend a minimum of 15 trees per site, but this number can vary between settings.

Step 3) Along with scar dating, the Radius at the First Scar (RFS) should be measured on each tree.

Step 4) Tree-rings formed under the modal RFS should be excluded from the chronology. The first year of tree availability should be determined as the first year larger than the modal RFS.

Step 5) The sampling representativeness at each site should be evaluated by determining the minimal number of trees to include in a chronology. The ISR algorithm can be used to evaluate the chronology’s saturation. Undersaturated sites should be excluded from the final chronology.

Step 6) Age structure of scars should be compared to that of tree population using a two-sample Kolmogorov-Smirnov test. The chronology should be judged hydro-climatically interpretable only if patterns of stem mortality and recruitment are not perceptible in the long-term tree-ring record. If the K-S test indicates that both cumulative distributions are similar, sites that exert an important demographic control should be removed. Otherwise, we recommend conducting the hydro-climatic analysis on the post-disturbance part of the chronology.

Step 7) The magnitude of an event should be expressed as a ratio of the number of sites recording an event at time *t* to the number of sites available for recording at time *t.* A site is available if it has a least one tree with a radius larger than the modal RFS.

**Table 2.1** Dendrochronological characteristics of study sites

| Site | Date of site availability* (yr AD) | Number of trees sampled (N) | Mean number of scars / tree* (N) | Number of events (N) | ISR | |
|---|---|---|---|---|---|---|
| | | | | | Type of sampling | Minimal size |
| 1 | 1869 | 18 | 10,9 | 89 | Oversaturated | 12 |
| 2 | 1945 | 15 | 2,6 | 24 | Oversaturated | 8 |
| 3 | 1871 | 11 | 3,5 | 18 | Oversaturated | 9 |
| 4 | 1936 | 20 | 2,5 | 16 | Oversaturated | 10 |
| 5 | 1914 | 29 | 5,2 | 45 | Oversaturated | 11 |
| 6 | 1798 | 9 | 7,9 | 48 | Oversaturated | 8 |
| 7 | 1856 | 7 | 5,85 | 29 | Complete | - |
| 8 | 1890 | 4 | 3 | 12 | Undersaturated | - |
| 9 | 1796 | 8 | 2,5 | 16 | Undersaturated | - |
| 10 | 1865 | 8 | 6,12 | 34 | Oversaturated | 8 |
| 11 | 1917 | 5 | 3,2 | 11 | Complete | - |
| 12 | 1877 | 15 | 3,66 | 29 | Oversaturated | 11 |
| 13 | 1870 | 14 | 3,14 | 24 | Oversaturated | 11 |
| 14 | 1879 | 8 | 5,87 | 28 | Oversaturated | 8 |
| 15 | 1841 | 10 | 3 | 21 | Undersaturated | - |
| Mean | | | | | | |

*Trees become available when ray is larger than RFS (see problem 2)

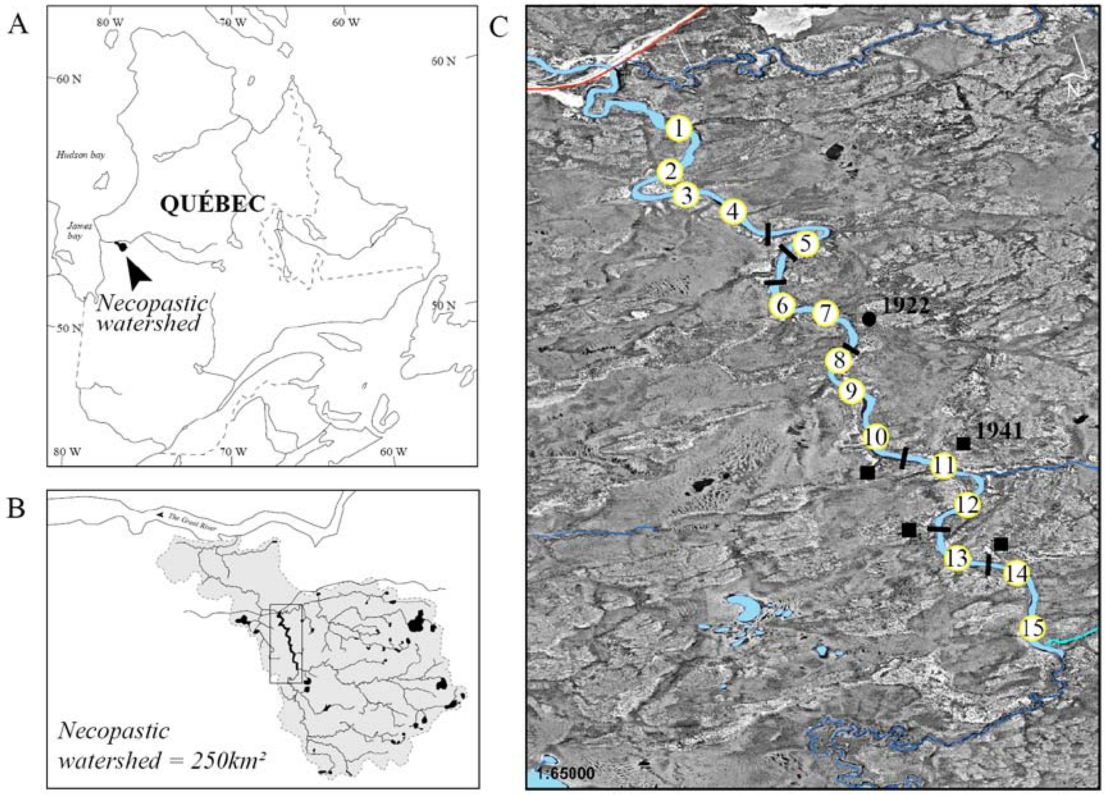


**Figure 2.1** The Necopastic Watershed

A) Location in northern Québec, B) Basin hydrography and delimitation (shaded gray). The black rectangle delineates the section under study, C) Location of study sites. Hydrographic sills are illustrated

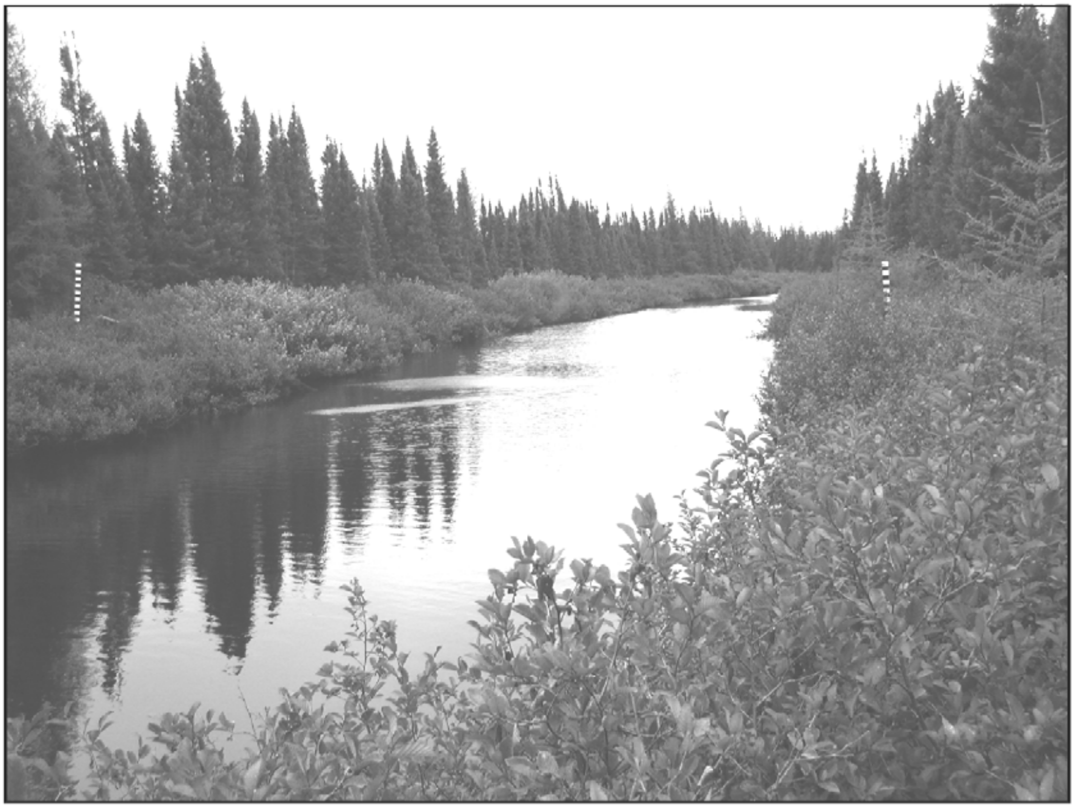

**Figure 2.2** Example of a rectilinear reach of the Necopastic River

Most trees boarding the riverbanks bear ice-scars

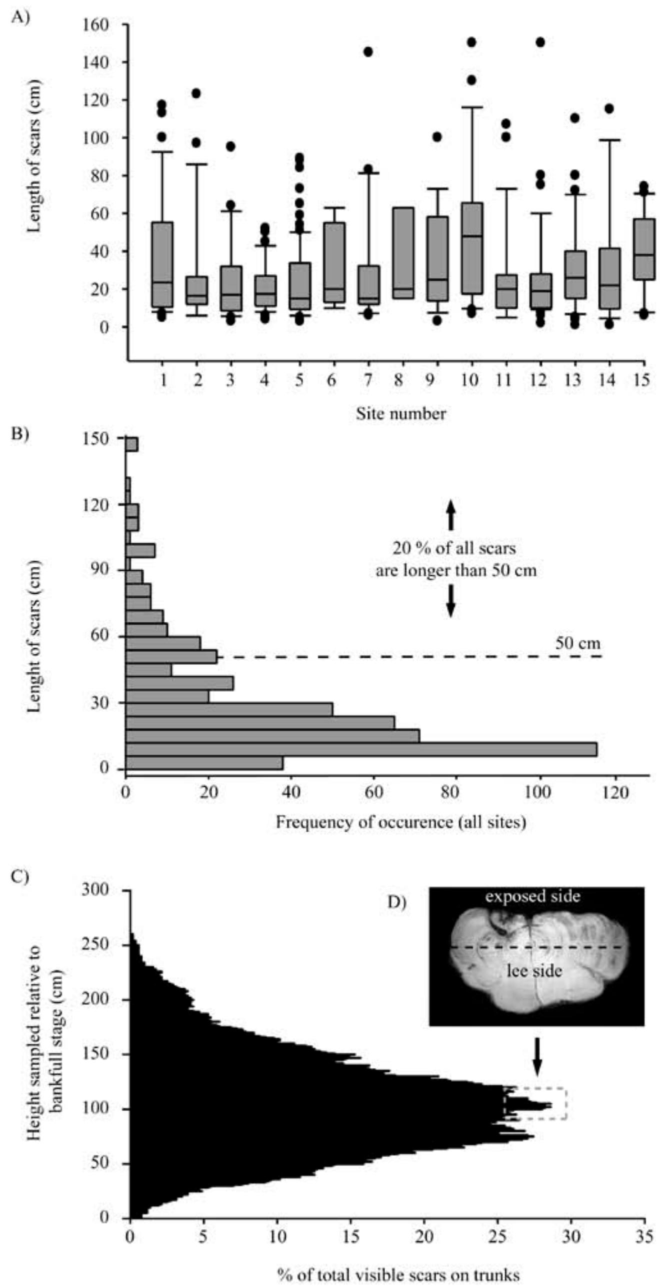


**Figure 2.3** Shape aspects of ice scars

A) Distribution of scar lengths for each site, B) Frequency of scar length classes (each class represents 10 cm). The dotted line represents the scars that are longer than 50 cm. C) Proportion of opened scars (% of the total number of opened scars) as a function of height above bankfull D) Example of a tree (viewed as a cross-section) that was repeatedly scarred on the exposed to drift-ice side.

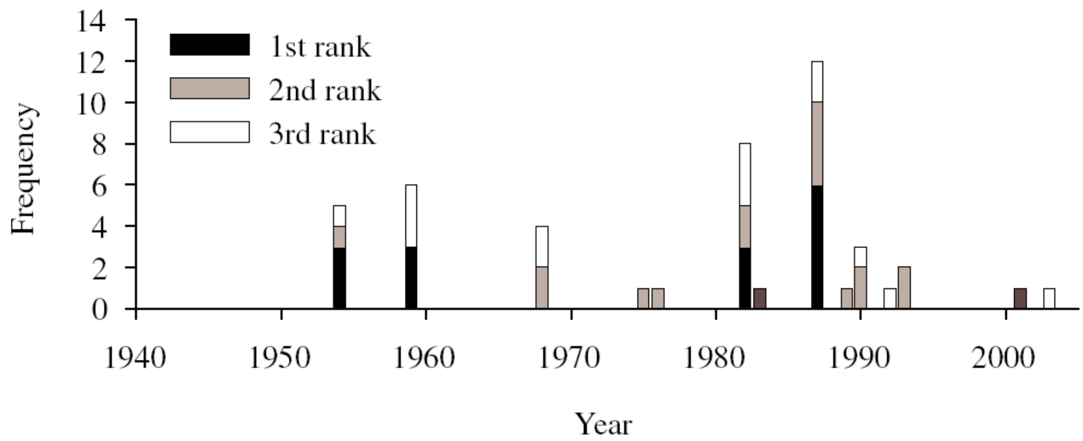


**Figure 2.4:** Time-distribution of the three most important events in each site.

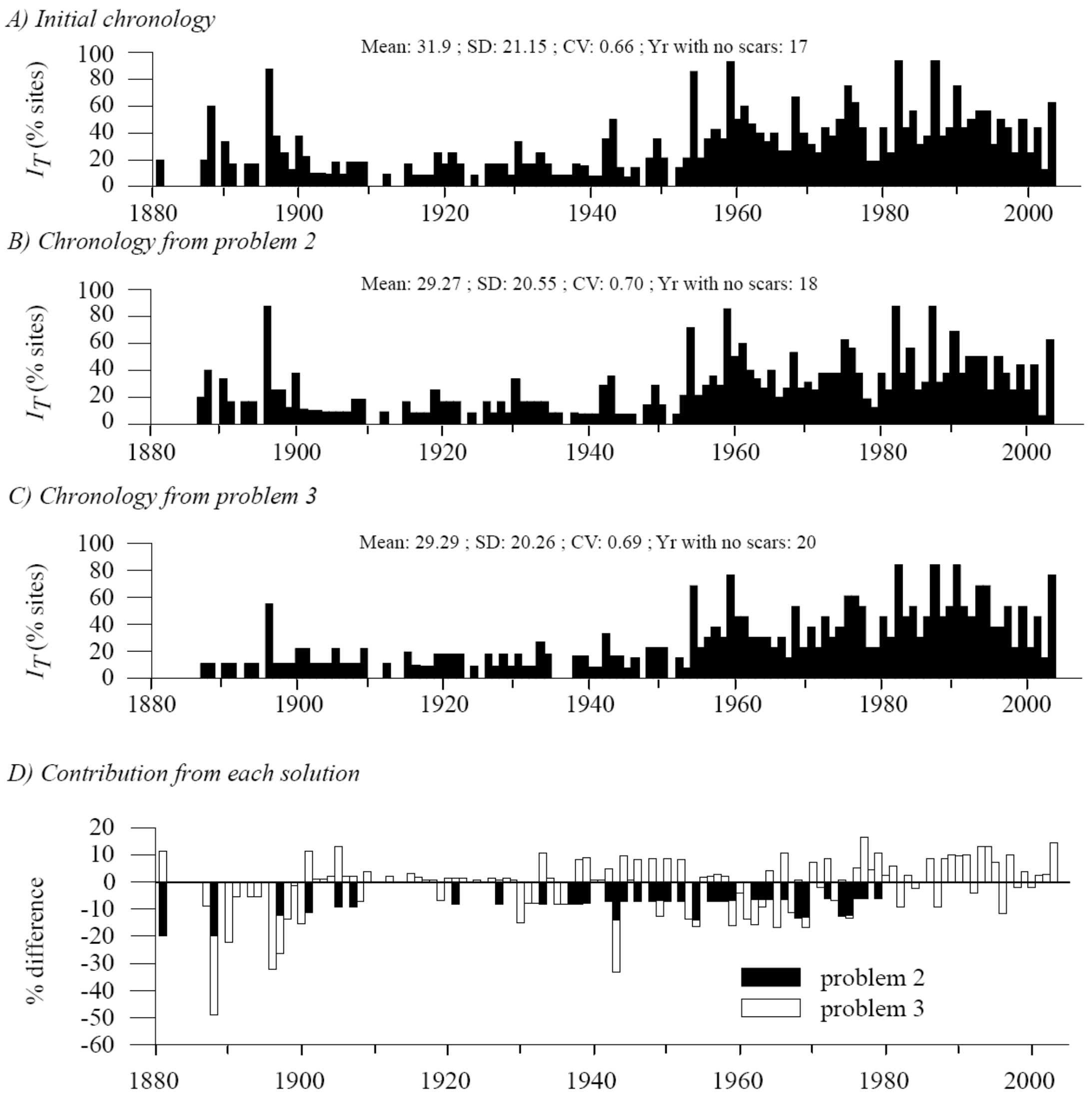


**Figure 2.5**: Evolution of the chronology after the application of each solution proposed in this paper (A-C).

Overall percentage of difference after solving problem 2 (black bars) when compared to the initial chronology and after solving problem 3 (white bars) when compared to problem 2.

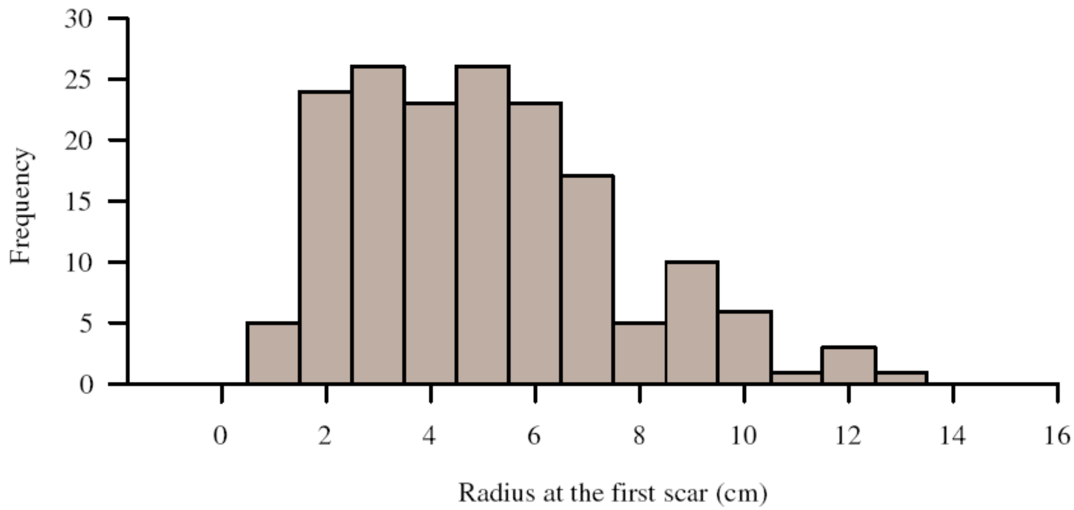


**Figure 2.6** Histogram of the Radius at the First Scar (RFS). Each class represent 1 cm of radius

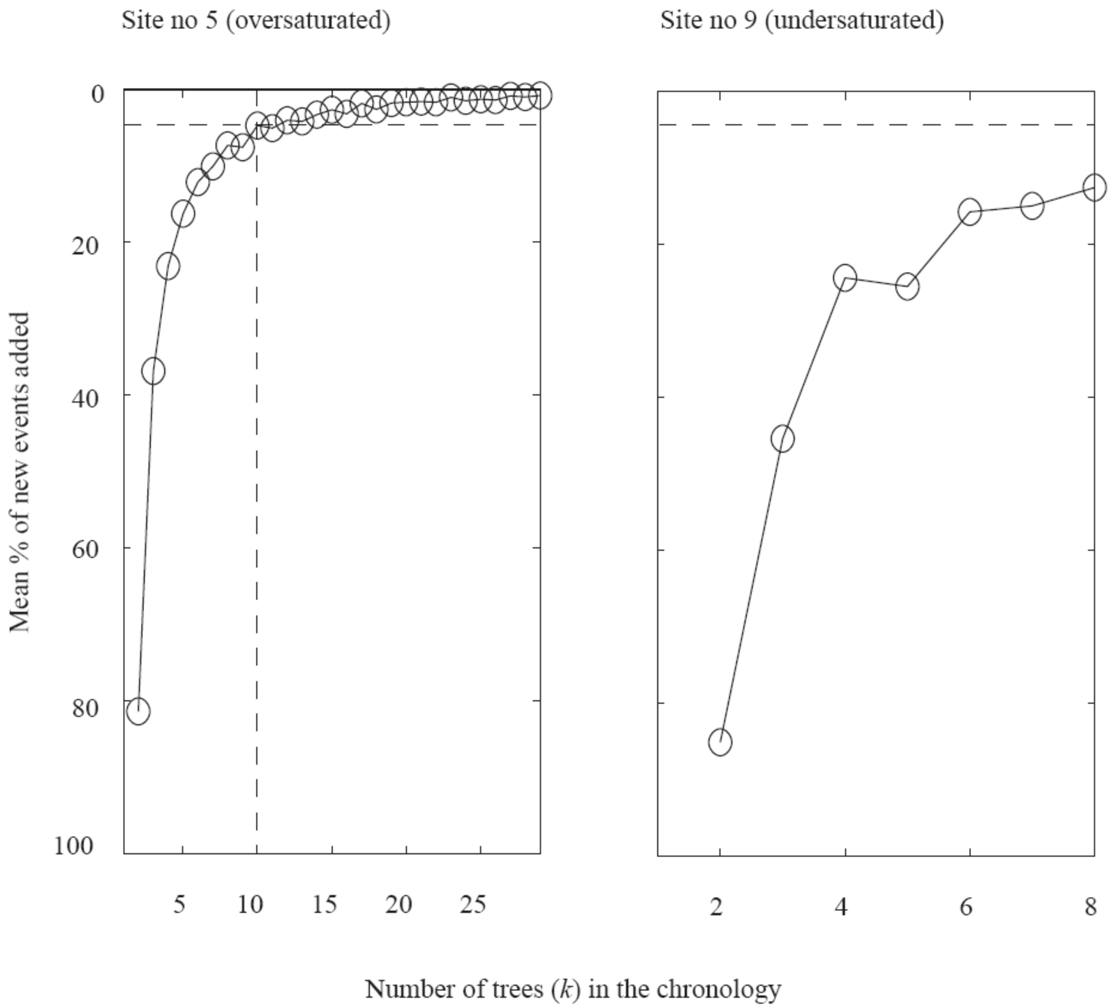


**Figure 2.7** Example outputs of the ISR algorithm.

A) Oversaturated sampling, B) Undersaturated sampling

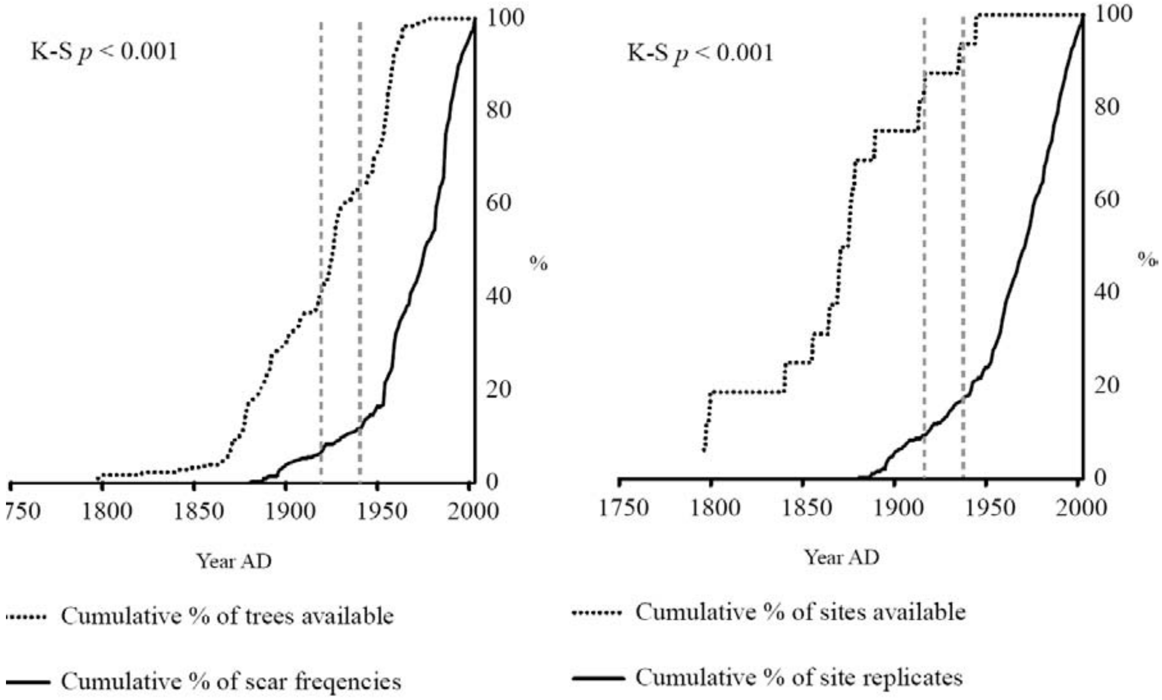


**Figure 2.8** Cumulative distributions of A) Scar frequencies and tree availability B) Site replication and site availability.

Results of the K-S test are presented on the graph. In both graphs, only trees larger than the modal RMS were considered.

# Chapitre 3. Hydro-climatic analysis of mechanical breakups reconstructed from tree-rings, Necopastic Watershed, northern Québec, Canada

**Abstract**

We used a 54-year (1950-2003) ice scar chronology constructed from damaged riparian trees to investigate the possible links between the intensity of mechanical breakups in the Necopastic River watershed (James Bay, northern Québec) and large-scale hydrologic and climatic conditions. Our objectives were 1) to identify hydrologic and climatic variables that explain the variations in mechanical breakup intensity, 2) to organize these variables in terms of importance and 3) to construct a predictive model for ice-floods in the Necopastic watershed. We used parametric correlation analysis to measure the degree of linear association between variables and Classification Trees (CART) coupled with a cross-validation approach to construct the predictive model and to organize variables according to their importance. Our main conclusions are that breakups within the Necopastic watershed are under the influence of large-scale hemispheric annular modes such as the Arctic Oscillation (AO). High spring AO indexes in the James Bay area are associated with important nival precipitations and cold temperatures. We hypothesize that these conditions may delay the thermal degradation of the ice cover. However, the processes driving mechanical breakups are best explained by an interaction between the forces that tend to maintain the ice cover in place and those that tend to dislodge it. In contrast with lakes, the timing and flashiness of the regional flood peak are better

predictors than flood intensity and volume. This highlights the fact that ice-floods in lakes and rivers are driven by different processes.

**Résumé**

Nous avons utilisé une chronologie glacielle (1950-2003) construite à partir d'arbres cicatrisés par la glace pour investiguer la relation entre l'intensité des déglacements mécaniques sur la rivière Nécopastic (baie de James, Québec nordique) et les conditions hydro-climatiques régionales. Nos objectifs étaient 1) d'identifier les variables hydrologiques et climatiques qui expliquent les variations dans l'intensité des déglacements mécaniques 2) d'organiser ces variables en fonction de leur importance et 3) de construire un modèle prédictif de l'intensité des crues glacielles pour la rivière Nécopastic. Nous avons utilisé des analyses de corrélations paramétriques pour mesurer le degré d'association entre l'indice d'intensité des déglacements et les variables hydro-climatiques. Des arbres de classification et de régression (CART) couplés à une approche de validation croisée ont aussi été construits afin d'organiser les variables en fonction de leur importance et de modèle prédictif. Notre analyse montre que le déglacement de la rivière Necopastic est sous l'influence de l'indice d'Oscillation Arctique. Lorsque cet indice est élevé, la région se caractérise par des conditions printanières froides et neigeuses. Nous faisons l'hypothèse que ces conditions permettent de retarder la dégradation du couvert par des processus thermiques. Toutefois, l'intensité des déglacements mécaniques dans ce petit bassin versant est contrôlé à la fois par des forces qui tendent à maintenir le couvert en place et d'autres qui tendent à le déloger.

Contrairement au milieu lacustre, le moment et la rapidité à laquelle la crue régionale se produit expliquent mieux les variations dans l'intensité du déglacement que l'intensité et le volume de la crue printanière. Ceci met en lumière les importantes différences qui existent entre ces deux milieux sur le plan du mécanisme de déglacement.

## 3.1 Introduction

River ice breakup, the annual process by which cold-environment rivers get free of ice, is an important process that is highly dependant on both hydrological and climatic conditions during winter and spring (Beltaos, 1997, 2000, 2003). It is now generally accepted that mild spring temperatures lead to thermal (or ”mature”) breakups characterized by a progressive deterioration of the ice cover (Prowse and Marsh, 1989). Because the ice melts *in situ* during thermal breakups, resulting damages and flooding risks are usually very low. By opposition, during mechanical (or “premature”) breakups, the almost-intact river ice is violently broken by hydrodynamic forces of the flood wave propagating downstream (Beltaos, 1997, 2003). This situation is often aggravated by rain-on-snow events or rapid temperature rises favouring the formation of ice-jams. Ice-jam formation and release are known to interfere with hydropower generation and seriously threaten streamside inhabitants and infrastructures. Additionally, extreme ice-jams and associated backwater flooding are proven to have a considerable impact on channel and floodplain geomorphology (Dionne, 1974; Mackay and Mackay, 1977; Smith, 1979; Prowse, 2001b; Smith and Pearce, 2002), streamflow characteristics (Prowse, 1994; Prowse and Beltaos, 2002) and riparian ecology (Smith and Pearce, 2000; Prowse, 2001a, 2003).

Although the categorization of breakups into thermal or mechanical events may be oversimplistic, it is nevertheless a useful concept for investigating the range of hydro-climatical thresholds triggering breakup in cold environments, as most events usually fall somewhere between these two extremes. However, despite substantial theoretical advances in modeling such thresholds in a deterministic physically-based approach (Beltaos, 1997, 2000, 2003), modeling and predicting the severity of ice-jam events from regional hydrologic and climatic data is still an important challenge for cold-regions hydrologists. Finding adequate and high resolution historical data on the type of breakup is a considerable obstacle to investigate the links between regional hydro-climatic variables and breakup severity. First, the paucity and short time period of gauge records from which data on water levels and discharge during breakup are retrieved limit the possibility of analysis. Second, some extreme ice-jams occurring downstream or upstream of the monitoring station may be imperceptible in the archives.

In the absence of adequate instrumental data, dendrochronological techniques are often used to reconstruct major discrete events such as ice-jam-floods and can provide high resolution data on their past frequency and magnitude. Among dendrochronological techniques, the analysis of ice-scarred trees is an efficient way of investigating the characteristics of past discrete ice-jam-floods. It was extensively used in order to reconstruct the frequency and stage of extreme ice-scouring events disturbing riverbanks (Henoch, 1971; Parker and Jozsa, 1973; Payette, 1980; Smith and Reynolds, 1983; Payette and Delwaide, 1991) and lake shores (Bégin and Payette, 1988; Tardif and Bergeron, 1997; Bégin, 1999; Lemay and Bégin, 2008).

To date, few studies have used ice-scar chronologies to analyze hydro-climatic conditions triggering mechanical breakups in fluvial environments, more particularly in small northern watersheds. In subarctic Québec, chronologies constructed from lacustrine

(Bégin and Payette, 1988; Tardif and Bergeron, 1997; Bégin, 2000b; Lemay and Bégin, 2008) and large river (Payette, 1980) environments have shown that episodes of intense ice-flooding during the last century have typically occurred during years of high spring discharge. It was hypothesized that the increased ice-flood intensity and spring flood discharge since AD 1930 were partly attributable to increased winter and spring precipitations due to the northward displacement of the Arctic front (Bégin, 2000b; Lemay and Bégin, 2008). However, lake and river ice-floods may hardly be compared in terms of breakup processes. In rivers, hydrodynamic forces are generally involved to dislodge and fracture the ice cover whereas lake ice decays in place under the influence of solar radiation and wind activity that provides the necessary shear to break the ice. Consequently, hydro-climatic interpretations obtained from ice-scar chronologies constructed in lakes are poorly transferable to the fluvial context. Case studies in diversified environments are needed to increase our understanding of how regional and hydrologic variables influence ice regimes (Ettema, 2002)

In this study, we propose a hydro-climatic interpretation of an ice-flood chronology reconstructed from scarred trees along a small high-boreal stream (Necopastic River) in the eastern James Bay area. Our main objective is to investigate regional teleconnections between hydrologic and climatic conditions that triggered mechanical breakups and subsequent ice-jamming events in this small stream. A second objective is to investigate whether or not these extreme events are driven by large hemispheric annular modes such as the Arctic Oscillation that control numerous climatic variables in this area. A third objective is to determine the hierarchy of hydro-climatic variables and create a predictive model for ice-flood intensity in the Necopastic watershed.

### 3.2 Study area

The Necopastic River (53'73N 78'28W) is an ungauged high-boreal watercourse that drains an area of about 250 km². The Necopastic River intercepts LaGrande River between the LG-1 and LG-2 hydroelectric centrals, but only the lower part of the studied stream was affected by the inundation of the LG-1 reservoir. The Necopastic River was chosen because its basin remains unaffected by the presence of man.

Climate normals (1971-2001) at the *LaGrande Rivière A* station displays a typical high-boreal continental climate. Mean annual temperatures are around -3.14°C (Environment Canada, 2008) with minimum (-23.2°C) and maximum (13.2°C) monthly averages are reached in January and July, respectively. The total annual precipitation is 684 mm, with 37% (248 mm) falling as snow. The months of December, January and February show an average of less than one day per month with a temperature above 0°C. Thus, in contrast with rivers of cold-temperate climate, ice-jams are not likely to occur during winter warm spells (Beltaos and Prowse, 2001; Beltaos and Burrell, 2003).

Regional vegetation is characterized by the co-dominance of black spruce [*Picea mariana* (Mill. BSP)] and Jack pine [*Pinus banksiana* (Lamb.)] (Arseneault and Sirois, 2004). In riparian areas where fire frequency is lower, black spruce shares its dominance with eastern larch [*Larix laricina* (Du Roi) K. Koch] and balsam fir [*Abies balsamea* (L.) Mill]

(Arseneault and Sirois, 2004; Bouchon and Arseneault, 2004; Boucher *et al.*, 2006; Arseneault *et al.*, 2007). Ice-scouring tolerant shrubs such as *Alnus viridis ssp. crispa* (Ait.) Turrill. *Salix planifolia* Pursh. and *Betula glandulosa* Michx are found along most streams and floodplains in the area.

## 3.3 Methods

### 3.3.1 Tree-scar sampling and construction of the chronology

An ice-scar chronology was constructed according to a method recently developed by Boucher (2008a) to reconstruct hydro-climatically driven ice-floods in fluvial environments. The general assumption behind the sampling procedure is that, given a relatively climatically homogeneous basin, the replication of an ice-flood event between sites indicates the strength to which climate and hydrology affected the onset of mechanical breakups. Field sampling strategy and computational procedures to reconstruct past ice-flood intensity and evaluate the saturation of the chronology are summarized in the following steps:

Step 1) Fifteen homogeneous riverbank segments of constant width, depth and slope were chosen.

Step 2) Trees were sampled on both riverbanks and were spaced by at least a distance equivalent to a tree height. The entire trunk was investigated by prelevating multiple cross-sections so that hidden scars could be sampled. A cross section was taken at the very base of the trunk to approximate the year of tree establishment. The number of trees sampled in each reach varied considerably according to logistical constraints (**table 3.1**).

Step 3) Scars were dated and rings were counted since tree installation.

Step 4) Scars found on small bendable stems were removed from the chronology because these are less sensitive to ice-scouring. To determine the minimal size of recorders, the Ray at the First Scar (RFS) was measured on all trees. All RFS measures were plotted into a frequency plot and the modal RFS frequency class was determined. All tree-rings produced under the modal RFS were withdrawn from the chronology. Likewise, trees were considered available when they had overgrown the modal RFS.

Step 5) Using an Iterative Sampling with Replacement procedure (ISR), the saturation of the chronology evaluated. This procedure involves iteratively sampling into the original sample set and computing the mean percentage of new events added each time a random tree is added to the chronology. All sampling sites were then classified as "undersaturated" (incomplete) or "oversaturated" (i.e., when a new added tree adds less than 5 % of new events, in average). Undersaturated sites were discarded from the final chronology, because it was impossible to know if other important events could have been added by sampling more trees.

Step 6) For each year, the number of sites recording an event was counted along with the number of sites available for recording (i.e., site that has at least one tree available for recording).

Step 7) The intensity of mechanical breakup events at time $t$ ($I_t$) in the Necopastic River, was calculated using the ratio (%) between the number of sites that recorded this events ($R_t$) and the number of sites available for recording ($A_t$).

Step 8) A Kolmogorov-Smirnov (K-S) procedure was used to ensure that variations in $I_t$ are not attributable to forest structural aspects.

### 3.3.2 Regional hydro-climatic data, and large scale teleconnections

Variations in $I_t$ were correlated to regional hydro-climatic data to identify key variables. Harmonized water supplies to LG-1 (1950-2003) were used to construct yearly spring flood hydrographs. Spring flood hydrographs were characterized by eight variables (Gregory and Walling, 1973) (**table 3.2**). To reduce subjectivity in the hydrograph characterization, an algorithm was programmed in MATLAB R14 for the batch computation of these eight variables for each year. If the algorithm did not end the flood by June 30th (i.e. Julian day 181 or 180 for normal or bissextile years, respectively), flood was forced to end because all lakes and streams are free of ice after that date in the area.

Climatic data used in the analysis are monthly means to the LG-1 basin (**table 3.2**). These data were interpolated from nearby meteorological stations using a kriging with external-drift method that include topographic forcing as a factor of regional variability (Tapsoba *et al.*, 2005). Different variables were considered for the analysis, including monthly mean, minimum and maximum air temperatures (°C) (1960-2003), total precipitations (cm), (1950-2003), snow depth (cm), snow water equivalent ($kg/m^2$) and density ($kg/m^3$) (1960-2003). Although covering a shorter period (1977-2003), March and April degree-days of frost (DDF) and degree-days of heat (DDH) were calculated from daily records at the nearby LaGrande meteorological station along with monthly sums of solid and liquid precipitations (**table 3.2**). The monthly mean indexes of the Arctic Oscillation (1950-2007) were available at the U.S. National Weather Service (NWS) of the National

Oceanic and Atmospheric Administration (NOAA). In this paper, we present mean AO indexes for March and April (AO_MA) (**table 3.2**).

### 3.3.3 CART model

The most influential hydrologic, climatic and oscillation variables were incorporated into a classification tree model to predict ice-flood intensity in the Necopastic River. Classification trees were performed using the Classification and Regression Tree (CART ®) software (version 6.0, Salford Systems). The classification tree algorithm originally developed by Breiman *et al.* (1984) consists of using a set of predictor variables (e.g., hydro-climatic variables) to split a “root node” that contains all cases ($I_t$) into two or more child nodes following “if-else” rules that optimize the purity of descendants. In our study, the intensity of ice-floods as estimated from tree rings ($I_t$), was transformed into a binary variable ($I_{t(low,high)}$) for two reasons: 1) the time period for analysis is relatively short (54 years) and 2) there are numerous variables involved in the prediction of ice-flood intensity. The class “high intensity” was attributed to years where $I_t$ was superior to the mean (1950-2003) plus its 95% confidence interval. Tree growth stopped when terminal node size$\leq$ 2 cases. The class with the greatest representation was assigned as the node class.

To avoid statistical overfitting and increase the model parsimony, a tree-pruning algorithm combined to a 10-fold cross-validation approach was adopted. The cross-validation technique involves separating the original dataset into 10 roughly-equal parts. The algorithm then chooses the first nine parts as a learning sample to construct a maximal size tree and reserves the last fraction as a test sample. The misclassification rates are calculated for the maximal size tree and also recalculated for each sub-tree defined by the pruning algorithm. This procedure was repeated until each of the 10 folds were used as a testing sample. The error rates of these 10 test samples were then mapped to the nodes of the original maximal size tree. The “optimal tree” was defined as the one with the smallest cross-validation error-cost. Finally, the optimal tree was scored to evaluate the trends in hydro-climatic conditions triggering mechanical breakups over time. This was done by assigning a new intensity class to each year by re-injecting hydro-climatic variables into the model.

## 3.4 Results

### 3.4.1 General features of the ice-scar chronology

The ice scar chronology depicts a general increasing trend in the intensity of ice-floods during the last century and a particularly abrupt increase since the early 1950s (**figure 3.2a**). The increase in ice-flood intensity during the last fifty years is independent of the variations due to mortality and regeneration in the population (**figure 3.2b**). Although mechanical breakups causing ice-jams have occurred almost each year in the Necopastic watershed, the relative proportion of sites recording these events varied considerably Before 1950, an average of 11 ± 10% of all available sites recorded an ice-flood event. After 1950, this proportion reaches 42 ± 20%. Moreover, highly intense ice-flood events have occurred almost exclusively after 1950. In fact, 1896 was the only highly intense ice-flood occurring before 1950. Conversely, 19 out of the 20 years that did not record an extreme ice-flood event occurred before 1950 and only one (1951) belongs to the second half of the century.

### 3.4.2 Relationships with regional hydrograph

Significant negative correlation were observed between $I_t$ and the date of flood peak (DTE_PEAK, $r$ = -0.39) and the duration of hydrograph rise (DUR_RISE, $r$ = -0.38) (**table 3.3**). Conversely, $I_t$ was positively correlated with the duration of hydrograph recession (DUR_REC, $r$ = .35). Partial correlation coefficients (**table 3.2**, in parentheses) were computed in order to test the significance of these relations while controlling for the effect of regional flood peak discharge (PEAK). Because partial correlation coefficients are significant (**table 3.2**), it can be deduced that DTE_PEAK, DUR_RISE and DUR_REC impact $I_t$ independently of PEAK characteristics. Ice-flood intensity on the Necopastic ($I_t$) is not correlated to the regional flood peak (PEAK), the volume of flood (VOL) and the volume of hydrograph rise (VOL_RISE).

### 3.4.3 Relationships with regional climate and AO

The total amount of precipitation in April (PREC_APR) and mean snow depth in March and April (H_SNOW_MA) are both correlated to the intensity of ice-flooding on the Necopastic River with values of -.38 and -.37, respectively (**table 3.3**). When liquid and solid precipitations are considered separately, only March and April cumulative snowfall (PREC_SNOW) are positively related to $I_t$, whilst spring rainfall (PREC_RAIN) is not.

The mean temperature of March and April (T_MEAN), the Degree-Days of Frost (DDF) and Degree-Days of Heat (DDH) during spring are all unrelated to $I_t$.

The Arctic Oscillation (AO) index is relatively well correlated ($r$ = 0,47) with ice-flood intensity on the Necopastic River (**table 3.4**, **figure 3.3**). In the area, the AO index (expressed as an average index for the months of March and April) is associated mostly to cold and snowy springs. This is illustrated by a strong correlation between the spring AO index and snowfall in April (PREC_SNOW; $r$ = .55) and by a significant negative relationship with cumulative DDF in April ($r$ = -.53). Incorporating these two variables into a multiple regression model to predict values of AO results in a 40% explanation of the index variance ($R^2$ = .39, $p < 0.05$). When the AO index is compared to the total amount of precipitation falling over the area during spring months (1960-2003), correlation coefficients are weaker, but still significant (PREC_TOT; $r$ = .37, H_SNOW; $r$ = .33).

### 3.4.4 CART modeling of ice-flood intensity

By constructing three different classification trees, we were able to determine the hierarchy and combinations of variables that trigger intense mechanical breakups in the Necopastic River watershed. **Figure 3.4a** presents the "optimal tree" constructed from hydrological variables only. The optimal tree contains two splits and three terminal nodes. The terminal node corresponding to high intensity ice-flooding events is determined following DUR_REC > 68.5 days and DUR_RISE ≤ 27.5 days. In the present tree, DUR_REC is the most important splitter (100%) closely followed by

DUR_RISE (~85%) (**figure 3.6a**). DTE_PEAK has only a limited splitting capacity (30%). However, the decision tree constructed from hydrological variables only would give poor prediction accuracy if it was used on an independent dataset (cross-validation relative error cost= 1.11, **figure 3.5**). Although hydrological variables are correlated to the intensity of ice-flooding on the Necopastic River, their capacity to split between high and low events appears to be lower than the "random splitting".

The optimal tree constructed from climatical and oscillation only data has only one split (AO_MA = 0.28) and two terminal nodes **(figure 3.4b)**. The small size of this tree signifies 1) that the split in AO_MA integrates the best splits of other climatical variables and 2) that splits on PREC_TOT and H_SNOW (relative importance of 43% and 13%, respectively; **figure 3.6b**), would have resulted in higher cost trees, probably as a consequence of the small dataset. From the simple tree depicted on **figure 3.4b**, it can be understood that most high intensity ice-flood events occur during high positive AO index (mean for March and April). The cross validation relative error cost of 0,51 (**figure 3.5b**) is fairly better than in the previous model.

Combining hydrological and climatical variables yields an even lower cost tree (0.39, **figure 3.5c**), that portrays in a finer way the complex interactions leading to the occurrence of mechanical breakups and ice-flooding in this river. First, AO is the most important primary splitter (**figure 3.6c**), and similarly to the precedent tree, high intensity ice-floods occur during high positive AO indexes (AO_MA >0.28). Second and third splits are effectuated by PREC_TOT and DUR_RISE (relative importance of 60% and

57%, respectively; **figure 3.6b**). The second split isolates low intensity events if April PREC_TOT are inferior to 6.6 cm (terminal node = LOW I). The third split discriminates between high and low intensity events according to DUR_RISE. Rapid regional flood rise (DUR_RISE <= 20.5 days) lead to high intensity events (terminal node = HIGH I); otherwise events are classified as low intensity (terminal node = LOW II).

The tree constructed from hydrological and climatical variable together (**figure 3.4c**) fits the original data (N=54) quite well. About 86.5% of the low intensity events and 88.2% of the high intensity events were well classified during the learning step (**table 3.5**). In average, 87% of all predictions were accurate with the original dataset. The cross-validated tree also presents good prediction accuracy. If it was used on an independent dataset, the model would be better at classifying with success high intensity events (88.2%) than low intensity events (73%).

Based on the final tree, conditions that favoured the occurrence of extreme ice-floods in the Necopastic River have been more frequent since the 1980s (**figure 3.7**). Although HIGH II (AO_MA >0.28) events distributed evenly since 1950, they combined to HIGH I events (AO_MA >0.28, / PREC_TOT_A >6.6 cm / DUR_RISE ≤ 20.5 days) after 1980. Inversely, conditions triggering low intensity ice-flooding in our watershed have tended to decrease in frequency during the last 50 years. LOW II events (AO_MA≤ 0.28 / PREC_TOT_A / > 6.6 cm / DUR_RISE >20.5 days) were common between 1950 and ~1975 but were replaced by LOW I events (AO_MA≤ 0.28 / PREC_TOT_A / < 6.6 cm) afterwards.

## 3.5 Discussion

River ice breakup results from a complex interaction between forces that tend to dislodge the ice cover and those that maintain it in place (Beltaos, 2003). For the Necopastic River, hydrological variables are related to forces that provide the necessary shear to break and mobilize the ice cover whereas climatical variables (mostly snow precipitations) represent forces that tend to delay its thermal degradation.

Floods generating mechanical breakups must occur before the ice cover completely degrades and looses its mechanical properties (Beltaos, 2003). Whilst slowly rising floods store important amounts of hydrothermal heat favoring the thermal degradation of the ice cover (Prowse and Marsh, 1989), flashy and early floods impact a mechanically intact ice cover, and may result in severe ice-jams. Thus, variables measuring the timing (DTE_PEAK), and the "flashiness" (DUR_RISE) of the regional flood are significantly related to the intensity of ice-flooding (**table 3.3**). Non-significant correlation between flood intensity and the hydrograph start of rise (START) underline that, in the early flood, hydraulic forces necessary to lift, break and mobilize the ice cover cannot be supplied by the stream. The positive correlation between flood intensity and duration of recession (DUR_REC) probably suggest that slowly receding floods maintain hydraulic forces on the degrading ice cover until the mechanical breakup threshold is exceeded (Beltaos, 1997, 2003). DUR_REC is also is linked to DUR_RISE (r=-0.59, not in results) mainly because the algorithm stopped the flood on the 30$^{th}$ day of June (end of ice period) and consequently, by subtraction, both variables are negatively correlated.

Regional flood magnitude seems to be of little importance in determining the onset of mechanical breakups in the Necopastic River in comparison to "when" and "how fast" the peak is reached (**table 3.3**). In contrast with lakes (Bégin and Payette, 1988; Tardif and Bergeron, 1997; Bégin, 1999; Lemay and Bégin, 2007), ice-floods on the Necopastic River do not appear to be triggered in a context of regional high hydraulicity. This is supported by the fact that high hydraulicity variables (flood volume (VOL) and flood peak (PEAK)) are never correlated with flooding intensity. In contrast with rivers, hydraulic forces exert no influence on the process of breakup in lakes. High water levels are nonetheless required to lift the thermally degrading lake ice such that wind can transport large floating ice rafts to the contact of shoreline vegetation (Bégin and Payette, 1988; Tardif and Bergeron, 1997; Lemay and Bégin, 2007).

While timing and flashiness of the regional flood are important variables in the process of breakup, fresh snow falling just before the melt would delay the thermal degradation of the ice cover. Because of its low thermal diffusivity and high albedo, fresh snow insulates and protects the ice cover from rotting (Ashton, 1978). In turn, it increases the probability that a mechanically intact ice cover is present at the time of flooding. In these conditions, even if the regional flood does not attain record peaks, a mechanical breakup can still occur. Although rain-on-snow events are possible, most of the precipitations fall as snow during the early spring in this High-Boreal area and the significance of the correlation between PREC_TOT_A and $I_t$ should be interpreted as such. This is evidenced by the fact that PREC_TOT_A correlates better with April snowfall ($r$ = 0,75, $p$<0.001) than it does with April rainfall ($r$ = 0.52, $p$<0.001).

Climatic variables influencing the process of breakup on the Necopastic River depend largely on yearly variations in the AO index, therefore reinforcing the regional signal detected in our chronology (**figure 3.3**). AO is a cold-seasoned pattern (Serreze *et al.*, 1997) and is well known to influence both precipitations and temperatures at the continental scale (Thompson and Wallace, 1998, 2001; Bamzai, 2003). In northern environments, many components of the hydrological cycle are affected by large scale oscillations (AO, ENSO, NAO), including streamflow (Neal *et al.*, 2002), glacier mass-balance (Nesje *et al.*, 2000; Zeeberg and Forman, 2001), snow cover (Bamzai, 2003) and extreme flooding (Jain and Lall, 2000). In the studied area, high spring AO indexes are clearly associated with conditions that favor the occurrence of severe mechanical breakups, such as snowier and colder springs (**table 3.4**). The influence of AO on climatic variables influencing breakup is substantiated by 1) a significant positive correlation between $I_t$ and AO_MA (**table 3.4, figure 3.3**) and 2) a pruned-to-one-split CART tree (**figure 3.4b**) constructed from climatical and oscillation variables only.

The shift in the type of breakup processes observed in the 1980's (**figure 3.7**) is best explained by a change in the degree of degradation of the ice-cover at the time of flooding. Before 1980, degradation of the ice was probably too advanced when the regional flood peaked. Regional floods raised slowly (**figure 3.8a**) during that period and yielded low intensity events (LOW II). During that period, conditions leading to high intensity events (HIGH II) could exceptionally be attained during years of high positive AO index retarding the ice cover degradation. After 1980, floods became flashier at the regional scale (**figure 3.8a**). During that period, extremely rapid flood rises (HIGH I events) caused high intensity mechanical breakups in 1984, 1987 and 1999. Moreover, years of high spring precipitation also became more common after 1980 (**figure 3.8b**), a phenomenon that is partly triggered by higher positive AO index (**figure 3.8c**). These conditions provided additional insulation to the ice cover therefore preventing its melt. In spite of flashier floods, high intensity events could not be attained when spring precipitations were extremely low (LOW I events) causing the ice to degrade before flooding occurs.

Finally, the analysis and interpretation of the earlier part of our chronology (before 1950) is complicated by the lack of instrumental records. Although it suggests an increased ice-flooding activity after 1950, the hydrological and climatical significance of this shift remains to be documented **(figure 3.2a)**. The ice was probably less degraded at the time of flooding after 1950, but the exact combination of processes leading to this situation cannot be clearly interpreted for the moment. We took a step ahead and found that the relation between $I_t$ and April precipitation is probably valid in the long term (**figure 3.9**) using Climate Research Unit (CRU) reconstructed (1901-2003) precipitation records (http://www.cru.uea.ac.uk/cru/data/, grid no 204,287). This suggests that the process of breakup in the Necopastic River responded to variations in early spring precipitations during the last century. Hence, we hypothesize that the increased amount of April precipitation during the last fifty years might be, at least partly, responsible for the increased ice-flooding activity in our watershed since 1950 (**figure 3.9**). However, we acknowledge that this relation, taken alone, is insufficient to appreciate the full complexity of river ice breakup processes and recommend that other studies should be conducted in different environments to attest the existence of such a trend at the regional scale.

**3.6 Conclusions**

Ice-scar chronologies can be used to investigate hydro-climatic conditions triggering mechanical breakups in river systems when gauging stations cover a too brief period or provide inadequate data on ice-flooding. Using the replication of ice-scars between sites in a climatically homogeneous watershed, we developed an index of ice-flood intensity ($I_t$) that can help clarify the influence of hydro-climatic variables on mechanical breakups.

First, it was observed that mechanical breakups occurred almost every year since 1880 but have been more intense since 1950. Coupling the 1950-2003 period to regional hydrologic and climatic data have led to the following conclusions:

1- For a mechanical breakup to occur on the Necopastic River, the thermal degradation of the ice must not be too advanced when the spring flood develops. Consequently, regional flood timing and flashiness are more important to the onset of mechanical breakups than high hydraulicity variables such as regional flood volume and flood peak intensity. By opposition, early spring snow precipitations tend to delay the thermal degradation of the ice cover by providing additional insulation effect.

2- The AO index (mean for March and April) is well correlated to the intensity of ice-flooding on the Necopastic River. AO is a cold-seasoned pattern and its positive phase is characterized by cold and snowy springs, conditions that favour the occurrence of ice-floods on the Necopastic River.

3- Using CART modeling, we constructed a predictive model for two classes of ice-flood intensity on the Necopastic River: HIGH and LOW. The best predictive accuracy is achieved when both climatical and hydrological variables are used as inputs to the model. This confirms the fact that breakups in river results from an interplay between forces that tend to dislodge the ice-cover and those that tend to stabilize it.

4- Intensity classes were well reproduced when the classification tree was used on the original dataset (87% predictions were good). If applied on an independent dataset, prediction successes would still be acceptable (81%), although slightly better at predicting high intensity events.

5- During the last century, ice-flooding was clearly a non-stationary process. Thus, teleconnections described for the 1950-2003 cannot be transferred to explain the breakup processes in the first part of the century. Our analysis suggest that, since 1950, ice conditions at the moment of breakup probably became more favourable to intense ice-flooding, but the hydro-climatic conditions associated with this regime shift remains to be documented.

**Table 3.1** Tree-ring characteristics of study sites along the Necopastic River

| Site | Date of site availability* (yr AD) | Number of trees sampled (N) | Mean number of scars / tree* (N) | Number of events* (N) | Frequency of events* (N $y^{-1}$) | ISR (sampling effort validation) |
|---|---|---|---|---|---|---|
| 1 | 1869 | 18 | 10,9 | 89 | 0,66 | Oversaturated |
| 2 | 1945 | 15 | 2,6 | 24 | 0,41 | Oversaturated |
| 3 | 1871 | 11 | 3,5 | 18 | 0,14 | Oversaturated |
| 4 | 1936 | 20 | 2,5 | 16 | 0,24 | Oversaturated |
| 5 | 1914 | 29 | 5,2 | 45 | 0,51 | Oversaturated |
| 6 | 1798 | 9 | 7,9 | 48 | 0,23 | Oversaturated |
| 7 | 1856 | 7 | 5,85 | 29 | 0,20 | Complete |
| 8 | 1890 | 4 | 3 | 12 | 0,11 | Undersaturated |
| 9 | 1796 | 8 | 2,5 | 16 | 0,08 | Undersaturated |
| 10 | 1865 | 8 | 6,12 | 34 | 0,25 | Oversaturated |
| 11 | 1917 | 5 | 3,2 | 11 | 0,13 | Complete |
| 12 | 1877 | 15 | 3,66 | 29 | 0,23 | Oversaturated |
| 13 | 1870 | 14 | 3,14 | 24 | 0,18 | Oversaturated |
| 14 | 1879 | 8 | 5,87 | 28 | 0,23 | Oversaturated |
| 15 | 1841 | 10 | 3 | 21 | 0,13 | Undersaturated |
| Mean | | | | | 0,25 ±1.6 | |

*Trees become available when radii is larger than RFS (see method)

**Table 3.2** Hydrological, climatical and oscillation data used in the present study

| Category | Month | Variable | ID | Units | Source | Time period |
|---|---|---|---|---|---|---|
| Hydrological | - | Start of hydrograph rise | START | d | IREQ | 1950-2003 |
| | - | End of hydrograph recession | END | d | IREQ | 1950-2003 |
| | - | Duration of hydrograph rise | DUR_RISE | d | IREQ | 1950-2003 |
| | - | Date of peak | DTE_PEAK | d | IREQ | 1950-2003 |
| | - | Duration of hydrograph recession | DUR_REC | d | IREQ | 1950-2003 |
| | - | Peak discharge | PEAK | $m^3s^{-1}$ | IREQ | 1950-2003 |
| | - | Volume during rise | VOL_RISE | $m^3$ | IREQ | 1950-2003 |
| | - | Flood volume | VOL | $m^3$ | IREQ | 1950-2003 |
| Climatical | J,F,M,A,M | Mean temperature | T | °C | IREQ | 1960-2003 |
| | J,F,M,A,M | Snowpack density | DENS_SNOW | $kg/m^3$ | IREQ | 1960-2003 |
| | J,F,M,A,M | Snow water equivalent | SWE_SNOW | $kg/m^2$ | IREQ | 1960-2003 |
| | M,A,M | Snow depth | H_SNOW | cm | IREQ | 1960-2003 |
| | J,F,M,A,M | Total Precipitation | PREC_TO T | cm | IREQ | 1960-2003 |
| | J,F,M,A,M | Snowfall | PREC_SNOW | cm | Environment Canada | 1977-2003 |
| | J,F,M,A,M | Rainfall | PREC_RAIN | cm | Environment Canada | 1977-2003 |
| | M,A,M | Degree-Days of Heat (>°C) | DDH | °Cd | Environment Canada | 1977-2003 |
| | M,A,M | Degree-Days of Frost (<°C) | DDF | °Cd | Environment Canada | 1977-2003 |
| Oscillation | M,A,M | Arctic Oscillation index | AO_MA | - | NOAA | 1950-2003 |

**Table 3.3** Pearson correlation coefficients (*r*) between ice-flood intensity ($I_t$) and hydrological variables

| | DTE_PEAK | DUR_RISE | DUR_REC | START | END | VOL | VOL_RISE | PEAK |
|---|---|---|---|---|---|---|---|---|
| $I_t$ | -.389[a] (-.362[b]) | -.379[a] (-.338[b]) | .345[b] (.368[b]) | - | - | - | - | - |

[a]: $p<0.001$
[b]: $p<0.05$

**Table 3.4** Pearson correlation coefficients (*r*) between ice-flood intensity ($I_t$) and climatical and oscillation (AO) variables

| | AO | PREC_TOT_A | H_SNOW_MA | T_Mean_MA | PREC_SNOW_A | PREC_RAIN_A | DDF_MA | DDH_MA |
|---|---|---|---|---|---|---|---|---|
| Year | 1950- | 1960- | 1960- | 1960- | 1977- | 1977- | 1977- | 1977- |
| $I_t$ | .470 [a] | .376[b] | .371[b] | - | .411 [b] | - | - | - |
| *AO* | 1 | .373[b] | .330[a] | -.344 [a] | .572 [a] | - | -.533 [a] | - |

[a]: $p<0.001$
[b]: $p<0.05$

**Table 3.5** Prediction accuracies for the final tree

| Intensity Class | Number of years | Learn Sample | | | Test Sample | | |
|---|---|---|---|---|---|---|---|
| | | % Correct | Low $I_t$ | High $I_t$ | % Correct | Low $I_t$ | High $I_t$ |
| Low $I_t$ | 37 | 86.49 | 32 | 5 | 72.97 | 27 | 10 |
| High $I_t$ | 17 | 88.24 | 2 | 15 | 88.24 | 2 | 15 |
| Total: | 54.00 | | 34 | 20 | | 29 | 25 |
| Average: | | 87.36 | | | 80.60 | | |

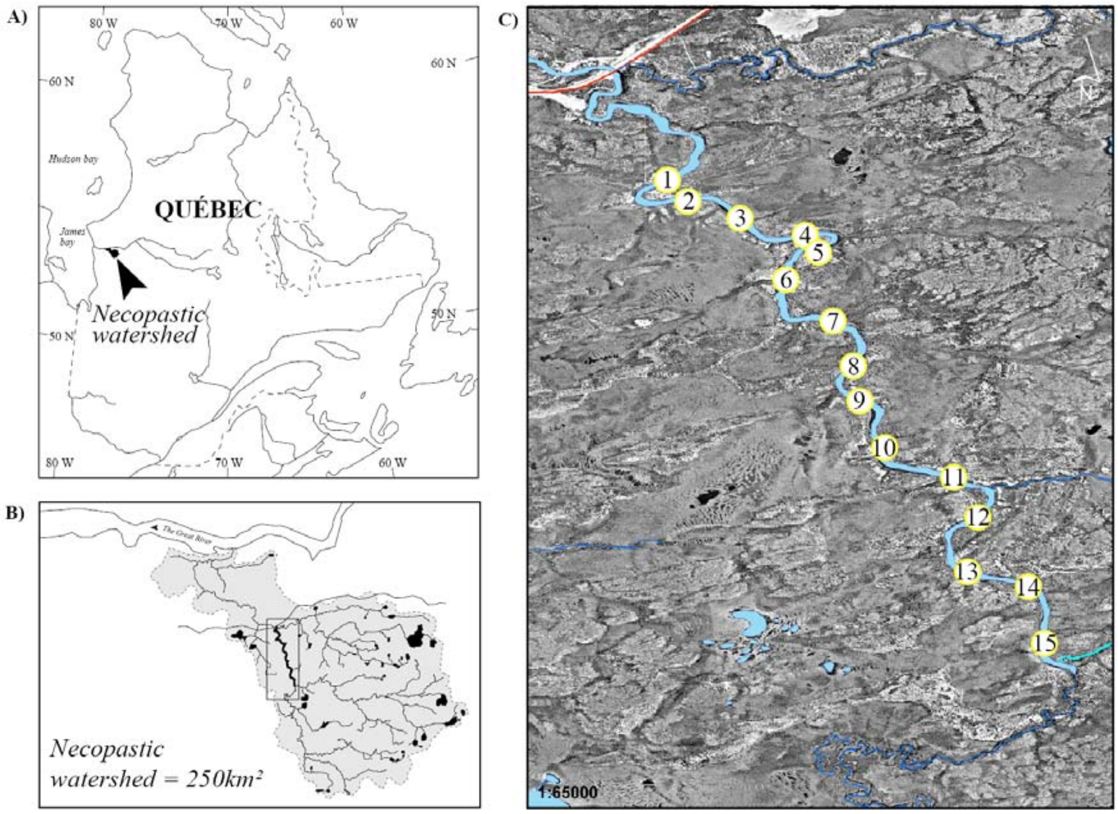


**Figure 3.1** Location and hydrography of the Necopastic watershed

A) Location in northern Québec, B) Basin hydrography and delimitation (shaded gray). The black rectangle delineates the section under study, C) Location of study sites

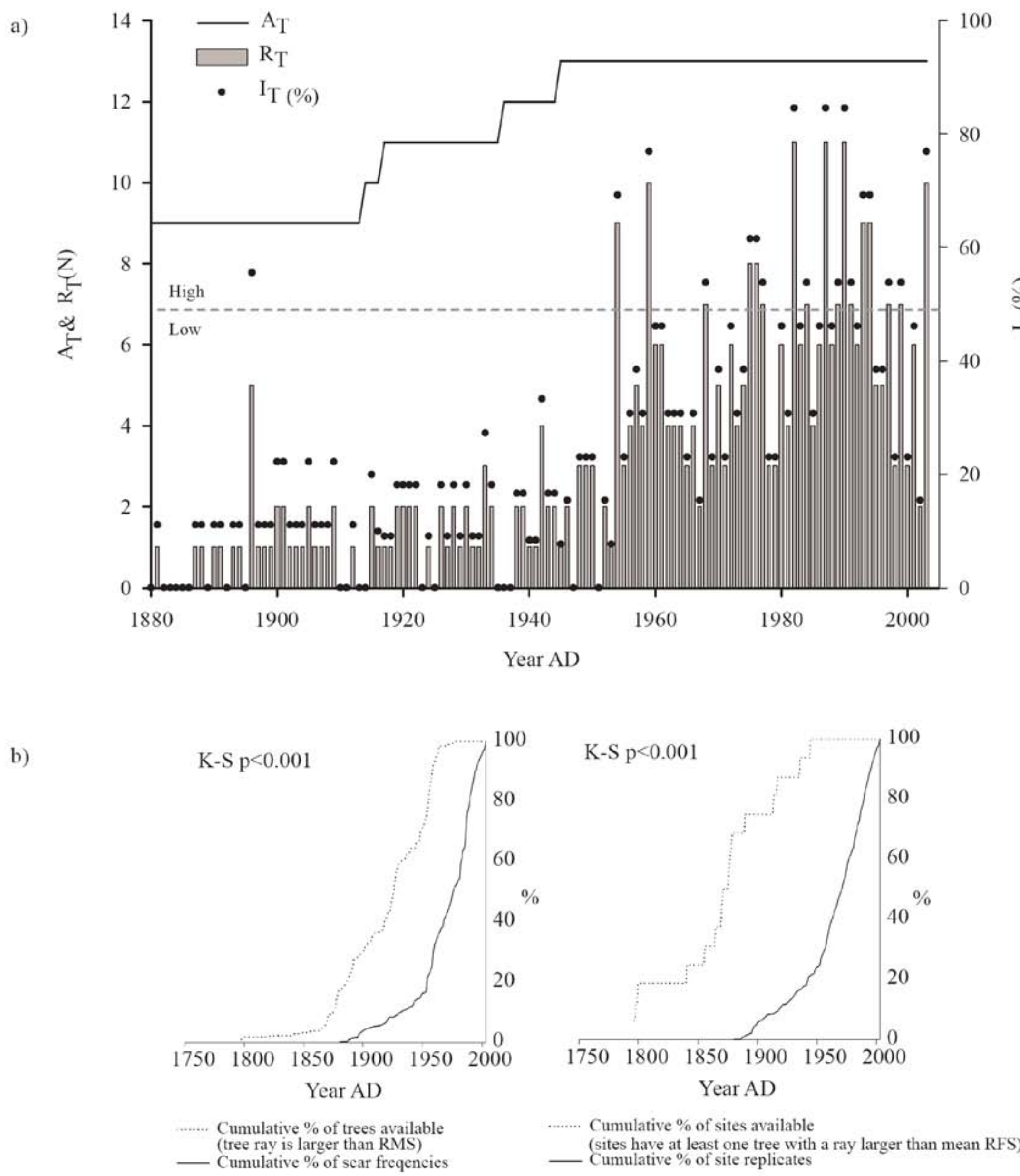


**Figure 3.2** Weighted ice-scar chronology constructed following a methodology proposed in Boucher et al. (2008).

A) The weighted index (IT) (dots) expresses a ratio between the number of sites recording an event (RT) (bars) and the number of sites available for recording (AT) (bold curve). The horizontal dashed line discriminates between high intensity and low intensity events on a mean IT plus its 95% confidence interval criteria B) Cumulative distributions of scar frequencies and tree availability (on the left) and site replication and site availability (on the right). Results of the K-S test are presented on the graph. Only trees larger than the modal RMS were considered.

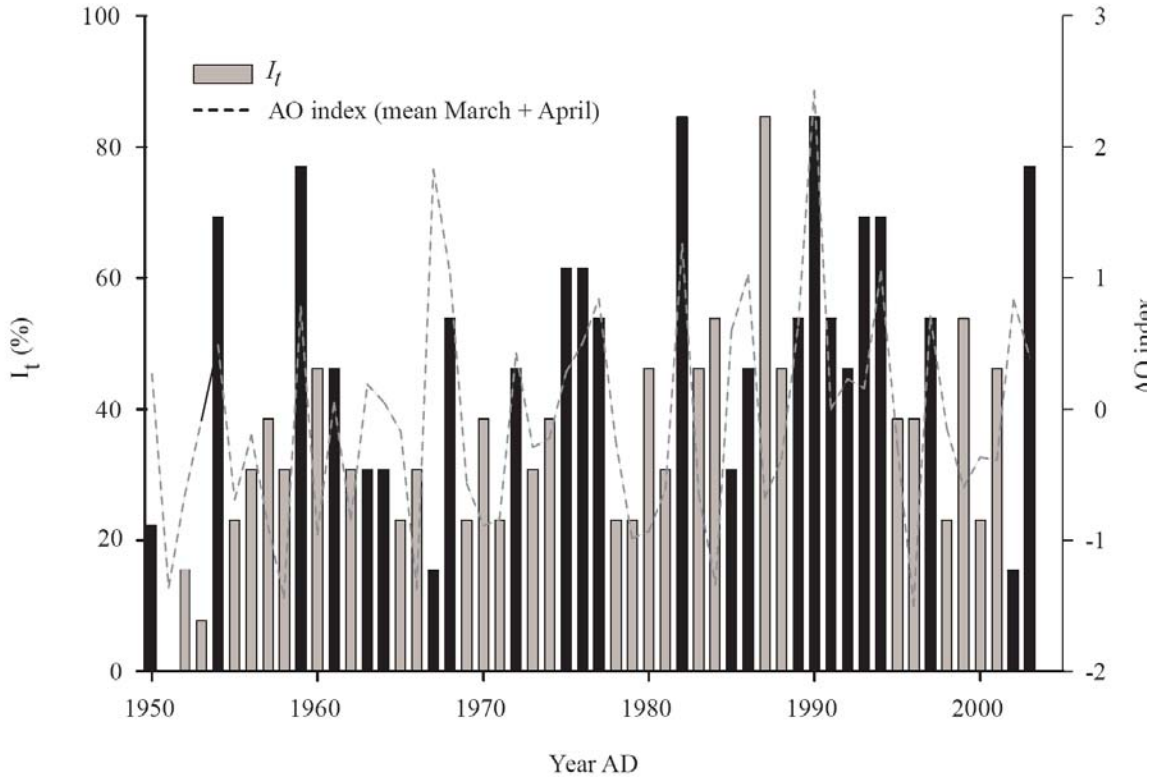


**Figure 3.3** Association between AO_INDEX (mean March-April) (dotted line) and $I_T$ (%) (bars) since 1950.

Black bars refer to years where the AO index is superior to 0.28

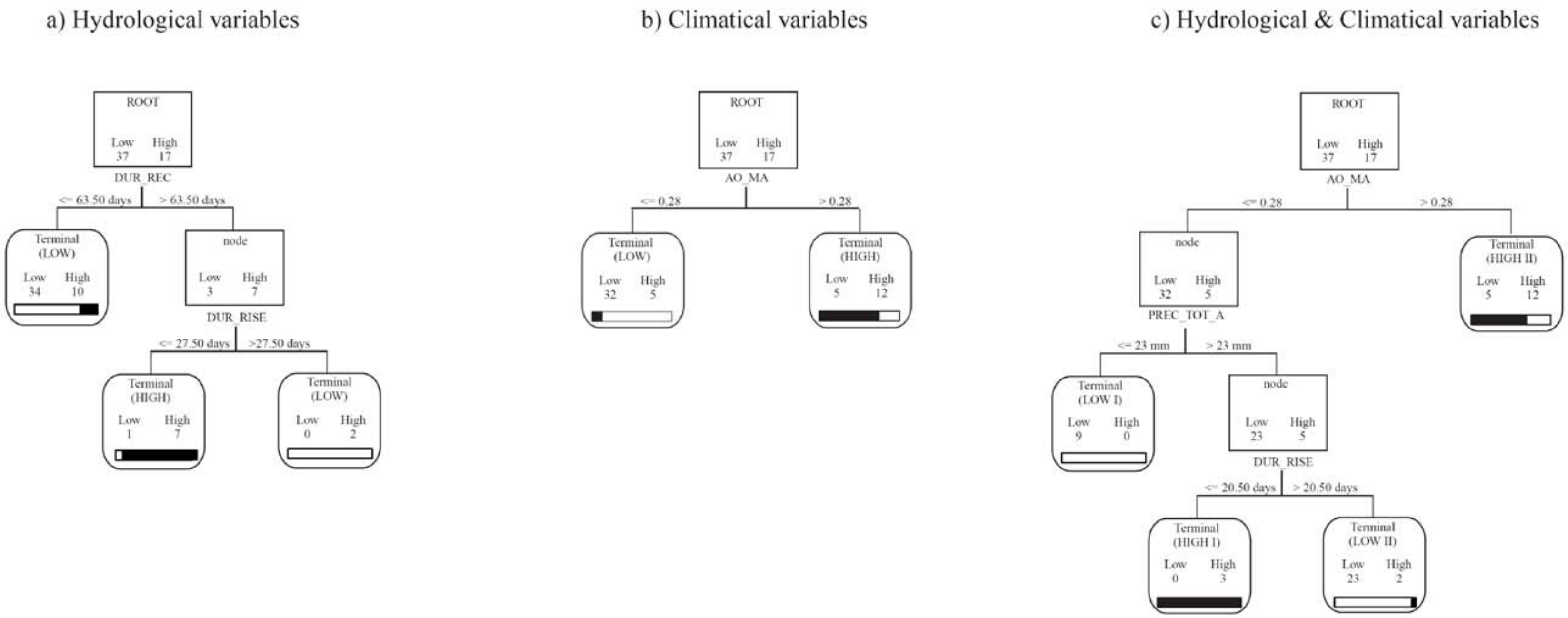


**Figure 3.4** Pruned classification trees

Trees are constructed from A) hydrological variables only B) climatological variables only and C) both hydrological and climatological variables. Trees start by a root node that includes all data (i.e., 17 high intensity events and 37 low intensity events). The root node then splits into two child nodes following rules that are specified directly on the tree. Terminal (leaf) nodes present rounded corners. In each node, the class with the greatest representation was assigned as the node class (in brackets).

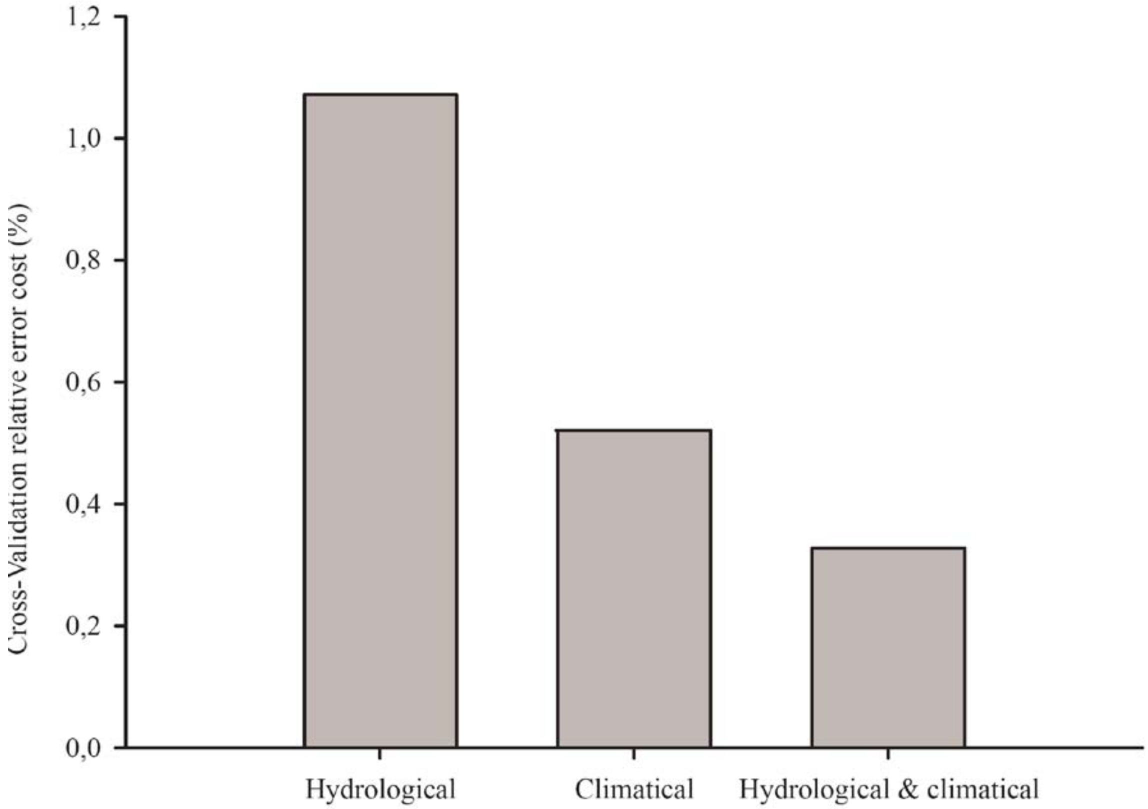


**Figure 3.5** Cross-validation relative errors costs associated with each trees.

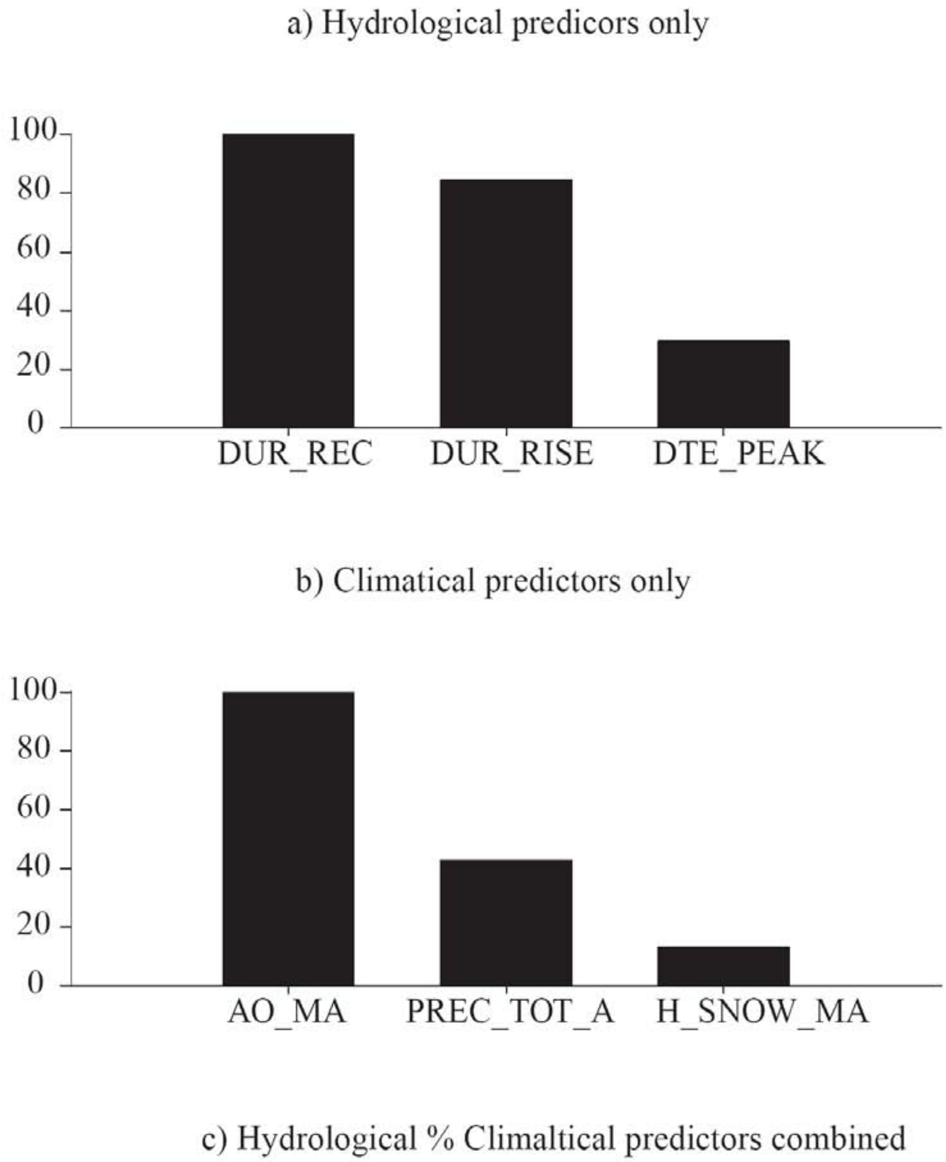


**Figure 3.6** Relative importance of predictors in each trees.

The most important variable is always expressed as 100%.

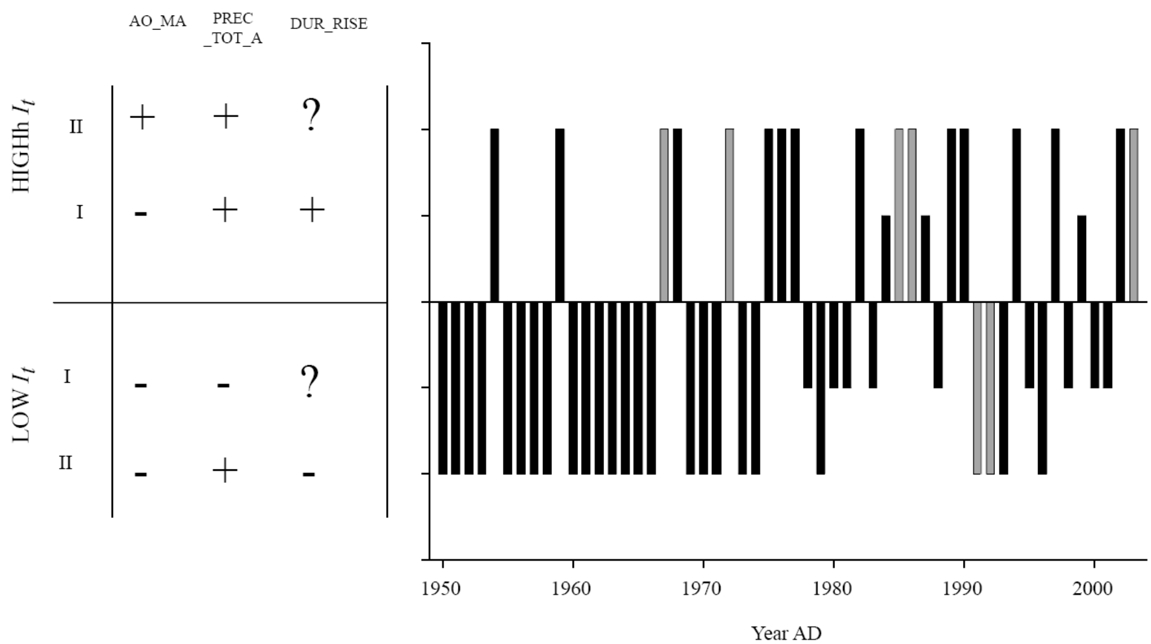


**Figure 3.7** Evolution of the type of processes triggering mechanical breakups in the Necopastic watershed since 1950.

Bars depict predicted classes (LOW I, LOW II, HIGH I and HIGH II) obtained by scoring the classification tree presented in figure 4c (hydrological+climatical variables). Grey bars refer to misclassified intensity classe (e.g. classifying a HIGH as a LOW, or vice-versa). On the left of the graph, the “+” sign indicates that a condition is favourable and “-“ indicates that a condition is not favourable to high intensity mechanical breakups. Whether a condition is favourable or not refers to the original classification rules presented in figure 4C.

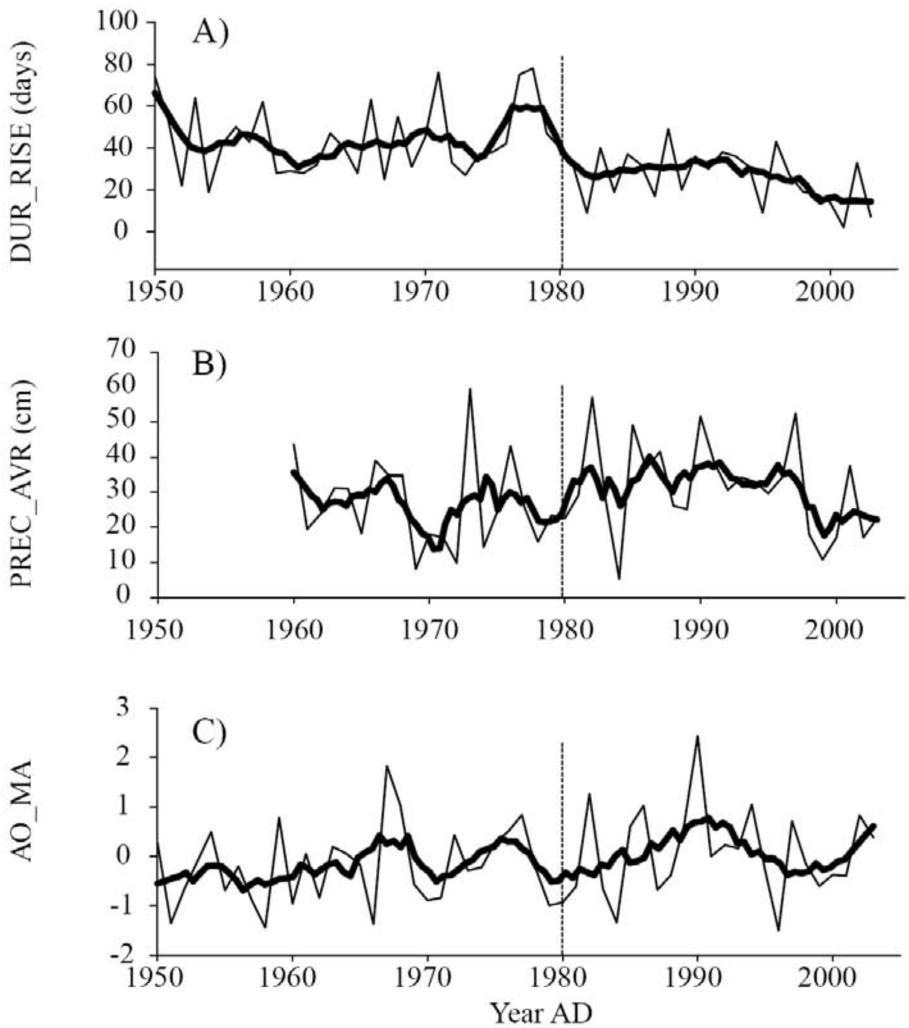


**Figure 3.8** Records of the three most important variables influencing mechanical breakups in the Necopastic

The bold line corresponds to the 5 year running average.

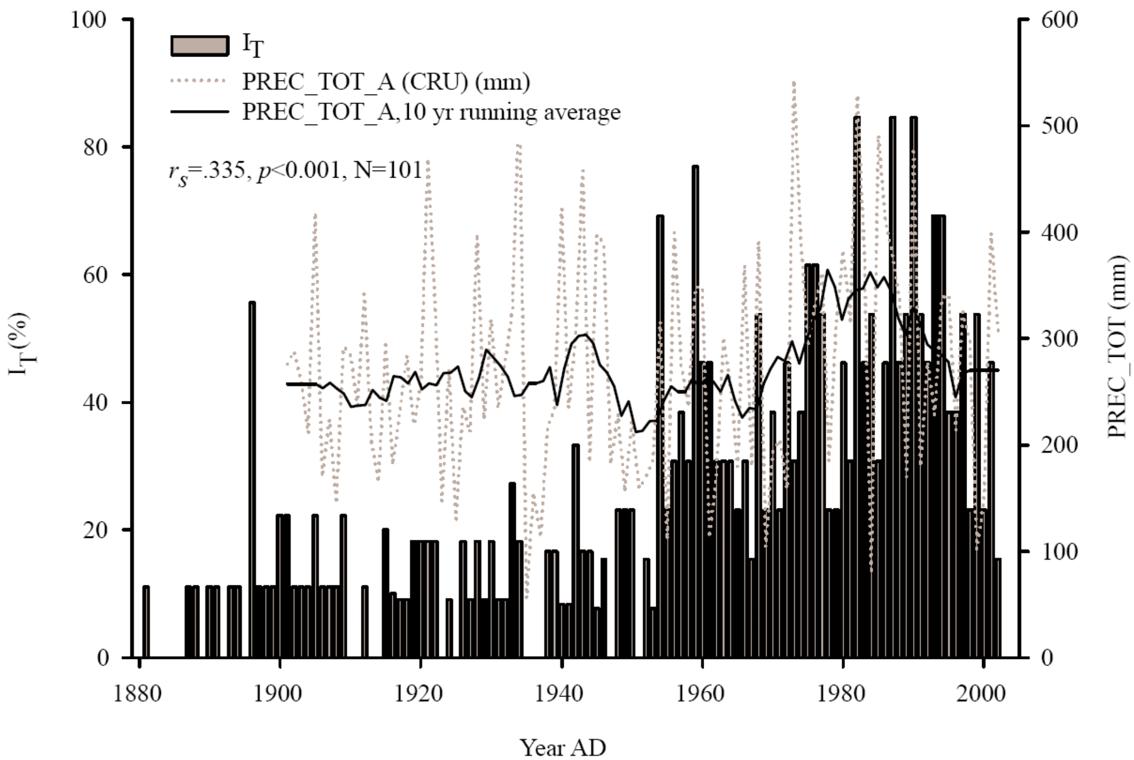


**Figure 3.9** Association between $I_T$ (%) and reconstructed April total precipitation (mm) (PREC_TOT_A) throughout the last century.

PREC_TOT_A is a reconstructed variable obtained from the Climate Research Unit (CRU). The dotted and bold line correspond to the original values and to the 10 yr running average values, respectively

# Chapitre 4. Impacts of recurring ice-jams on channel geometry and geomorphology in a small high-boreal watershed, northern Québec, Canada


## Abstract

River ice-jams are generally perceived as significant erosive events and are well known to impact both channel morphology and geometry. However, the extent of these impacts and the frequency of events required to maintain ice-scoured morphologies remain unexplored. In this study, we investigated downstream variations in geometric and geomorphologic characteristics in a small high-boreal watershed. We coupled these observations to dendrochronological data on ice-jam frequency. It is shown that channels affected by ice erosion experience a rapid retreat of the upper bank and significant deposition on the lower bench. Our results show that channels appear enlarged and present a typical two-level ice-scoured morphology when ice-jams recur more often than once every five years. By contrast, channels appear unaffected by ice when ice-jams are less frequent. We conclude that it can be risky to assume that ice-jams are always important geomorphological agents without considering frequential aspects inherent to these phenomenons.

**Résumé**

Les embâcles de glace sont généralement perçus comme des événements érosifs en milieu fluvial. Leur impact se traduit à la fois sur la géomorphologie du chenal et sur les propriétés géométriques des cours d'eau. Toutefois, l'étendue spatiale de cette érosion et la fréquence des événements glaciels nécessaires au maintien ou à l'apparition des formes d'érosion demeurent méconnus. Dans la présente étude, nous nous intéressons aux variations longitudinales des caractéristiques géométriques et géomorphologiques de la rivière Nécopastic, un petit cours d'eau du Haut-Boréal québécois. Nous couplons ces observations à des données dendrochronologiques nous permettant de connaître la fréquence des embâcles sur ce cours d'eau. Les rives affectées par l'érosion glacielle présentent une morphologie typique caractérisée par un recul rapide de leur partie sommitale et par le dépôt de sédiments sur le replat alluvionnaire. Notre principal constat est que les chenaux apparaissent élargis et présentent cette morphologie particulière lorsque les crues glacielles surviennent au moins une fois à tous les 4-5 ans. En revanche, les chenaux ne semblent pas présenter cette signature géométrique et géomorphologique lorsque les embâcles surviennent moins fréquemment. Nous concluons qu'il peut être risqué d'assumer, en l'absence d'une perspective fréquentielle, que les embâcles de glace sont toujours des événements géomorphologiques importants en milieu fluvial.

## 4.1 Introduction

The size and shape of stream channels and their capacity to contain flows of various size and frequency are usually best seen as a balance between the hydrologic regime and sediment supply (Wolman and Miller, 1960; Harvey, 1969). This useful concept yielded the basis for the hydraulic geometry theory (Leopold and Maddock, 1953) from which the following principles can be drawn: 1) alluvial channels are "maintained" by relatively frequent flows reaching the bankfull stage and 2) downstream changes in alluvial channel characteristics at bankfull are related to changes in discharge attributable to the increase in contributory area. Hydraulic geometry relations (i.e., functions relating discharge and channel characteristics) were extensively used by engineers and geomorphologists to predict channel forms and planning design and management of streams and floodplains of the temperate climate (Singh, 2003).

Whether or not these hydraulic geometry relations hold for cold-regions watersheds is much debated, mainly because of ice effects. From an examination of 24 rivers in Alberta (Canada), Smith (1979; 1980) proposed that repeated episodes of ice abrasion and gouging of the banks during breakup ice-jams could be responsible for the maintenance of enlarged and high capacity bankfull channels. More specifically, these results suggested a region-specific discharge (Q) threshold marking the occurrence of mobile ice and ensuing ice scouring (**figure 4.1)**. Once this threshold is exceeded, ice abrasion on banks and bed causes a step change in geometric properties of channels, such as width, cross-sectional area or depth (Smith, 1980).

However, in a discussion of Smith (1979)'s results, Kellerhals and Church (1980) identified some potential sources of error, such as confounding fluvial terraces and genetic floodplains. These authors insisted on the fact that additional processes such as channel entrenchment, channel icings and backwater effects behind ice-jams may be responsible for the apparent enlargement observed in Albertan rivers. Moreover, Smith (1979)'s study did not include any data describing how frequent ice-jams must be to maintain such enlarged channel forms. Smith (1979)'s results also suggest that, from the moment a stream acquires the capacity to fragment and mobilize its ice cover, enlarged morphologies (quasi) systematically develop. This may be an overly simplistic assumption considering the fact that ice-jam frequencies vary importantly among stream reaches in a watershed (Beltaos, 1996; Boucher, 2008a). Finally, Smith (1979) did not provide any geomorphological description of enlarged channel, so the variety of processes leading to channel enlargement remains unclear.

Despite the important implications of Smith (1979)'s findings for fluvial geomorphology, river management and engineering in the cold environment, very few additional studies intended to investigate how ice processes influence channel morphologies and hydraulic geometry relations. An important part of the literature on river ice impacts presented geomorphological descriptions of fluvial landscapes that have apparently been shaped by ice (Dionne, 1974; Mackay *et al.*, 1974; Dionne, 1976, 1978; Hamelin, 1979; Prowse and Gridley, 1993; Dyke, 2000; Prowse, 2001b; Smith and Pearce, 2002; Walker and Hudson, 2003), but few studies examined the spatial extent of these landforms (Ettema, 2002), a necessary aspect to asses the impact of ice dynamics on hydraulic geometry relations. Recently, McNamara (2000) and Best *et al*. (2005) reinforced Smith (1979)'s hypothesis by reporting a downstream hydraulic geometry anomaly in the Kuparuk watershed, Alaska, that corresponds to a transition from bedfast to floating ice. Nonetheless, there is a need for additional data on bankfull geometry in rivers that undergo significant ice-effects during breakup to verify if hydraulic geometry relations hold in these environments.

In this study, we report downstream hydraulic geometry variations in a small boreal watershed that experiences frequent spring ice-jams. We used cross-section analysis, aerial photographs, detailed geomorphological descriptions and tree-ring chronologies of ice-jam events to determine if geometric and geomorphologic properties of channel relate to variations in the frequency of ice-jam events.

## 4.2 Study area

The Necopastic River (53'73''N 78'28''W) is an ungauged high-boreal watercourse located about 40 km west of Radisson, James Bay, northern Québec. Its small hydro-climatically homogeneous watershed drains an area of 250 km² and the bankfull discharge in the lower reach is about 25 m³ / s (estimated from a rating curve). Climate normals (1971-2001) at the *La Grande Rivière A* station displays a typical high-boreal continental climate with mean annual temperatures around -3.1°C (Environment Canada, 2008). Minimum (-23.2°C) and maximum (13.2°C) monthly averages are reached in January and July, respectively. The total annual precipitation is 684 mm, with 37% (248 mm) falling as snow. The months of December, January and February each have an average of less than one day with a temperature over 0°C. In contrast with rivers of the cold-temperate climate where extreme ice-jam events frequently occur during winter warm spells (Beltaos and Prowse, 2001; Beltaos and Burrell, 2003), ice-jamming is most likely to occur during the spring-flood on the Necopastic River.

Regional vegetation is characterized by the co-dominance of black spruce [*Picea mariana* (Mill. BSP)] and Jack pine [*Pinus banksiana* (Lamb)] (Arseneault and Sirois, 2004). In riparian areas, black spruce shares its dominance with eastern larch [*Larix laricina* (Du Roi) K. Koch] and balsam fir [*Abies balsamea* (L.) Mill] (Arseneault and Sirois, 2004; Bouchon and Arseneault, 2004; Boucher *et al.*, 2006; Arseneault *et al.*, 2007). Ice-scouring tolerant shrubs such as *Alnus viridis ssp. crispa* (Ait.) Turrill. *Salix planifolia* Pursh. and *Betula glandulosa* Michx cover the riverbanks and floodplains of most streams in the area.

## 4.3 Material and methods

### 4.3.1 Studied sites

The Necopastic River watershed can be separated into three classes following major increases in drainage area (upper-basin, mid-basin, lower-basin) and into two groups according to the type of breakup (i.e., thermal versus mechanical breakups) (**figure 4.2**). At each site, ice scars on shrubs (**figure 4.3**) indicated the presence of ice-jams. A total of 39 sites were chosen along the Necopastic River: 16 in the upper basin, 16 in the mid-basin and 7 in the lower basin. All sites are reaches incised into geologically homogeneous Holocene fluvio-glacial deposits (Vincent, 1985) (**figure 4.2**) and correspond to relatively rectilinear stream sections of constant slope, width, depth and cross sectional area. Sites recently flooded by the Canadian beaver (*Castor canadensis* Kuhl.) or located immediately downstream or upstream of a sill were avoided.

### 4.3.2 Geometric and geomorphologic descriptions of sites

During fieldwork, we first identified the bankfull stage that we defined as the height of the relatively flat depositional surface adjacent to the river (Wolman and Leopold, 1957; Williams, 1978). On the Necopastic River, these depositional surfaces in some cases correspond to the height of the valley flat **(figure 4.4a)**. However, with entrenched channels, we carefully distinguished the floodplains from the less frequently flooded terraces. In such sites, genetic floodplains are narrow and form a lower bench that is traceable along the river channel (**figure 4.4b**).

At each site, one representative cross-section was mapped using a Leica TC-705 theodolite (precision = 2 mm ± 2 ppm). These cross-sections were orientated perpendicularly to streamflow direction and encompassed the full valley width. We then computed an algorithm in MATLAB R14 © to interpolate between measurements and calculate bankfull channel widths ($W_{bkf}$), cross sectional areas ($Aw_{bkf}$), depths ($D_{bkf}$) and flat widths ($W_{flat}$) (**figure 4.4).** The theodolite measurements were also used to evaluate the slope of the water surface and the bankfull stage. The slope values in each site were obtained by regressing a minimum of five water-elevation measurements on the distance downstream. The slope gradient was very low (<0.001 m /m) at most sites (**figure 4.5**).

In addition to the field data, supplementary valley-flat width measurements were performed on each Strahler orders using 1: 10 000 aerial photos (Hydro-Québec, 1984). Although multiple lithologies are encountered throughout the basin and might account for some variations, our intention was to get a general portrait of how the flood-prone widths (i.e. valley flats) vary with the recurrence of ice-jams. Flat widths correspond, on aerial photography to the easily recognizable zone colonized by *Alnus viridis*, *Salix planifolia* and *Betula glandulosa* (Bouchon and Arseneault, 2004; Boucher *et al.*, 2006). Three width measurements were averaged in each stream sections of the basin. Overall, 78 averaged widths were calculated in first (n = 57), second (n=15), third (n = 3), fourth (n = 2), and fifth (n = 1) order streams.

All geometric measurements ($W_{bkf}$, $W_{flat}$ $Aw_{bkf}$, $D_{bkf}$) were plotted against the contributive area ($C$), instead of discharge ($Q$) because the Necopastic River is ungauged. Contributive area measurements were made in the software PHYSITEL (Royer *et al.*, 2006) that determines the drainage structure in a basin from a Digital Elevation Model (DEM). A DEM (cell = 20 x 20 m) of the Necopastic River watershed was constructed from SRTM elevation data (http://srtm.usgs.gov/). Hydraulic geometry power functions and equations were computed in SPSS © for Windows.

Geomorphological descriptions features and processes at each site were done using the reconnaissance survey technique (Thorne *et al.*, 1996; Thorne, 1998) to construct a base-line for inter-site comparisons. Data collected include valley description (valley height, shape, angle, coupling to floodplain, valley floor type, surficial geology, number of terraces, extent of flood deposits, channel platform, lateral activity, etc.), channel description (dimensions, flow type, bed sediments, bed armouring, width controls), left and right bank description (bank height, material, slope, shape, vegetation, status and processes of erosion and accumulation, etc.).

### 4.3.3 Tree-ring reconstructed ice-jam frequencies

Trees bordering the Necopastic River present multiple ice-scars (Boucher, 2008b), especially in the mid-basin. These scars form on trees when drift ice raised by jams comes in contact with riparian trees. These marks can be dendrochronologically dated and exhaustive event-chronologies can be constructed (Payette, 1980; Smith and Reynolds, 1983; Hupp, 1988; Boucher, 2008b). On the Necopastic River, scars were sampled in 15 out of the 16 mid-basin sites. None were sampled in the lower basin because this section is part of protected area. The number of trees sampled, the number of events, and the mean age of trees varied considerably between sites (**table 4.1**). To overcome this problem, Boucher *et al.* (2008a) established a robust Iterative Sampling-Resampling (ISR) procedure to determine if the at-a-site sampling effort was sufficient and concluded that three sites do not present these characteristics. Consequently these three sites were not considered in the present study (**table 4.1**).

In the field, when ice marks were well defined, cross-sections were taken in the middle of each scar. Otherwise, when multiple scars were present on the trunk, cross-sections were taken at multiple heights in order to date every possible scar on the tree. Trees with a diameter smaller than 10 cm were never sampled. Individuals were sampled on both banks and were separated by a distance corresponding to a tree height to avoid redundancy in the record. In the laboratory, cross-sections were finely sanded and tree-rings were counted from the last year of growth (2005 or 2006) to the center. Dead samples were cross-dated with master chronologies existing in the area. The year of ice-scouring events were dated with the precaution of not replicating events found at multiple heights on a same individual. Scars that were formed after year 2003 AD were excluded because newly formed damages are difficult to observe in the field.

For each sites, ice-jam frequency was calculated by dividing the number of events recorded by the period available for recording. Sites were considered available for recording when at least one tree has overgrown a radius of three centimeters (Boucher, 2008a). We attributed a frequency of “zero” to one mid-basin site that did not show any geomorphological nor tree-ring evidence of ice scouring.

### 4.4 Results

In the Necopastic River Watershed, an important part (>70%) of the variations in *W* and *Aw* at bankfull is explained by the downstream increase in the contributive area (**figure 4.6a, b**). However, only a weak correlation is observed with channel depth (*Dmax*) (**figure 4.6c**).

Furthermore, from a detailed examination of power functions modeling changes in width and cross-sectional area (**figure 4.6a, b**) throughout the watershed, considerable variability occurs in both these variables at mid-basin (for contributive areas of 100 to150 $km^2$), where mechanical breakups become more frequent (**figure 4.2**). For example, in the upper basin, mean channel widths and cross-sectional areas vary between 7.4 ± 1.6 m and 7.9 ± 3.6 $m^2$ respectively. At mid-basin these values rise to 19.7 ± 4.8 m and 24.2 ± 8.7 $m^2$ approaching values of the lower basin (i.e., 19.3 ± 3.5 m and 23.4 ± 5.7 $m^2$, respectively).

Mid-basin variations in *W* and *Aw* are significantly related to tree-ring reconstructed ice-jam frequencies ($r_s$ = 0.61 and 0.54, respectively; **figure 4.7a, b**), while variations in channel depth are not. Narrow channels are associated with low ice-jam frequencies (0- 0.2 $yr^{-1}$ on the abscises) in comparison with larger channels (0.2 - 0.6 $yr^{-1}$ on the abscises). Furthermore, observed downstream channel geometry variations do not appear to be related to changes in channel gradient ($r_s < 0.2$, $p > 0.05$ with *W*, *Aw*, and *D*).

Valley flats widths ($W_{flat}$) tend to decrease in the downstream direction (**figure 4.8a**). This results contrasts with the previously described tendency of bankfull channels to become “enlarged” at mid-basin (**figure 4.6a, b**). The upstream sites present relatively wide valley flats (11 ±4.7m) that contrast with narrower flood corridors of the mid- (6.7 ±2.5m) and lower- (8 ±2.9m) ice-jam prone sites. The latter situation is also visible on 1: 10 000 aerial photographies throughout the whole watershed (**figure 4.8b)**. Again, high order streams (i.e. 1-2-3) tend to present wider valley flats than lower orders. Valley flats are the narrowest in orders 4b and 5 where frequent ice-jams occur.

Studied sites can therefore be classified into three groups according to their morphological features: 1) wide floodplain channels 2) entrenched / narrow floodplain channels 3) entrenched / ice-scoured channels (**figure 4.2** and **4.9**). The first group is found only in the upper basin and is characterized by extensive depositional areas adjacent to the channel (**figure 4.9a, b**). Channel banks are often bordered by levee sediments indicating rapid deposition near the channel. The two other groups represent entrenched channels of the mid and lower basins. While the latter presents no particular evidences of erosion (**figure 4.9c, d**), the former depicts distinct morphological features that are associated with severe ice-scouring (**figure 4.9e, f**). In addition to their larger width and cross-sectional area (**figure 4.6a, b**), ice-scoured channels are characterized by discontinuous and partly eroded genetic floodplains. These narrow benches are covered by heavily scarred shrubs installed on freshly deposited alluvium (**figure 4.9e, f (i)**). A steep eroded talus **(ii)** (about 50 cm high) separates this flat depositional surface from a higher terrace. Mechanical erosion on this talus has excavated and scarred trees or shrub roots living on the higher terrace (**iii**). In these entrenched channels, trees installed on the higher terrace are frequently scarred (0.23 ±0.16 $yr^{-1}$, **table 4.1**). Recent alluviums are also often found at the base of scarred trees, indicating that these terraces might slowly aggrade. Finally, the previously described ice-scoured morphology is most often associated with sites that experienced frequent ice-jams. Where ice-jam events occur at least once every 5 years, (frequency ~ 0.2 $yr^{-1}$), most sites developed an ice-scoured cross-section (**figure 4.7a,b**).

## 4.5 Discussion

### 4.5.1 Are ice-jams really causing enlargement?

In the Necopastic River watershed, recurring ice-jams seem to influence the geometric and geomorphologic properties of channels, resulting in anomalously large and heavily scoured sites. However, as pointed out by Best *et al*. (2005), further discussion is needed to determine whether channel enlargement is truly caused by ice-jams or, on the contrary, if ice movements resulting in jams are just permitted in channels that are already enlarged by other environmental processes. Among the factors other than ice that could possibly influence downstream variations in channel width are longitudinal changes in slope, lithology and climate (Singh, 2003). In this study, the sampling strategy was specifically designed to minimize the influence of these variables on channel geometry. First, the Necopastic River basin can be considered hydro-climatically homogeneous due to its small size (< 250 $km^2$). Second, sampling sites are all located within a Holocene glacio-fluvial terrace complex, mainly composed of sandy-silts (**figure 4.2**). As with other small streams flowing in these geologically uniform environments, the Necopastic is just reworking "previously-sorted" deposits and consequently floodplain (modern) and terrace (inherited) sediments are indistinct granulometrically (Boucher *et al.*, 2006). Third, downstream variations in slope are not related to geometric properties of channels and the gradient of all studied sites is very low (less than 0.001 $mm^{-1}$) (**figure 4.4**). Hence, downstream channel geometry variations are more likely to be attributable to characteristics of the hydrological regime (including ice effects) than to “permanent” variables affecting geomorphological processes in the watershed.

### 4.5.2 Ice-jam frequency thresholds

In the Necopastic River, thresholds in the frequency of ice-jams have a greater influence on channel geomorphology than discharge (*Q*) or contributive area (*C*) thresholds similar to those documented in earlier works (Smith, 1979; Smith, 1980; McNamara, 2000; Best *et al.*, 2005). Discharge or contributive area thresholds imply that, once a critical *Q* or *C* value is exceeded in a watershed, streams systematically display an enlarged or scoured morphology (**figure 4.1**) regardless of the inter-site variations in ice-jam frequency. In the Necopastic watershed, mechanical breakups become possible when the drainage area exceeds 120 km$^2$ (**figure 4.2**). However, downstream of this contributive area threshold, all sites do not appear systematically scoured or enlarged. On the contrary, many mid-basin and almost-all lower basin sites appear “uninfluenced by ice” (**figure 4.6a, b**) despite the abundant evidence for ice-jamming in these environments. As demonstrated earlier, the enlarged morphology is only visible in sites where ice-jams recur more often than once every five years (**figure 4.7a, b**).

An important implication of these findings is that downstream variations in the breakup regime may hinder the precise estimation of geometric properties from hydraulic geometry curves. For example, in the Necopastic River watershed, hydraulic geometry functions are not representative of the great variability occurring at mid-basin (**figure 4.6a, b**).

Furthermore, downstream changes in geometric properties would be more accurately described from hydraulic geometry curves if ice-scoured and enlarged channels were not considered (**figure 4.6a, b**). As a consequence, our data suggest that the use of hydraulic geometry relations in jam-prone streams might only be valid in sites where ice-jams recurrence is inferior to the frequency threshold.

Finally, many factors explain why the frequency threshold is exceeded only in some mid-basin sites. First, ice-jams are well-known to occur more frequently where channel morphologies preclude ice movements, a very common situation in medium-sized flat reaches (Beltaos, 1996). In the lower basin, ice rafts possibly move further downstream due to increased channel size and discharge so that jam prone sections distance themselves from one another. In contrast, ice movements in the mid-basin are constrained in a smaller channel and rafts often accumulate as jams in the nearby sections. Second, the dendritic shape of the Necopastic River basin may enhance the flashiness of the flood wave (Gregory and Walling, 1973), therefore providing the necessary shear to fragment a mechanically intact ice cover during early spring months. Because flood routing is so efficient in our small highly responsive watershed, even events triggered in a context of low regional hydraulicity may initiate severe mechanical breakups (Boucher, 2008b).

### 4.5.3 Bank scouring processes

Downstream changes in channel geometry, valley-flat width and river morphology can be attributed to variations in ice processes in our watershed. In high-boreal regions, severe winters generate thick ice covers than often remain still during breakup in low-order streams. An important consequence is that spring flood waters frequently overtop the ice cover in the upper basin and inundate the full flood-prone area (**figure 4.10a**). The ice cover then melts *in situ* due to thermal exchanges with flood waters and the atmosphere. This, combined with flood events during the ice-free period, probably contributes to widen the flood areas in the upper basin (**figure 4.8a**). A similar process was documented for the Kuparuk basin (Best *et al.,* 2005) and is possibly representative of many small streams of the cold areas (Kellerhals and Church, 1980).

Where frequent jams occur in the Necopastic, repeated ice-scouring events cause the upper portion of the riverbank to retreat **(figure 4.11a, b**). In early spring, remnants of the initial ice cover may still be attached to the lower portion of the bank conferring additional protection (Smith, 1979). From a detailed analysis of ice-scar heights in this watershed, it was found that water level rises, in average, one meter above bankfull stage during ice-jams (Boucher, 2008a). During these events, scouring in these entrenched channels is probably very severe 1) because the energy of the system cannot dissipate laterally and 2) because the higher portion of the bank is often free of snow and unfrozen when breakup occurs (**figure 4.10b**). The resulting two-level channel is similar to the one documented by Smith (1980).

During flood recession, sediments are deposited on the lower bench forming an inclined surface of loose material (**figure 4.11c, figure 4.12**). These recently deposited sediments are very sensitive to erosion and are rapidly reworked into a lower bench by subsequent floods during the ice-free period (**Figure 4.11d**). The surface of the lower bench roughly corresponds to the bankfull stage (**figure 4.11d**). Although vegetation encroaches and stabilizes this aggradational surface, fluvial erosion steepens and eventually undercuts the lower bench. Between each ice-scouring event, benches can experience several depositional episodes during open-channel floods.

### 4.6 Conclusion

Our results demonstrate that hydraulic geometry relations lead to imprecise estimations of width (*W*) and cross-sectional area (*Aw*) in the Necopastic River, a small channel that experiences frequent ice-jams. De facto, Smith's (1979) hypothesis regarding the role of ice-jams as important and generalized erosive events in high-latitude rivers is only partly supported by our data. In our study, ice-jams have to occur at least once every five years to maintain an enlarged and ice-scoured morphology. Thus, our data suggest that some frequency of occurrence thresholds might have to be crossed for ice-jams to become geomorphologically significant.

Among the visible geomorphic impacts on the Necopastic River is a "two-level" channel occurring in frequently ice-scoured sites. Our study provided new insights on the mechanisms forming these two-level channels. It is suggested that both ice-jams and the yearly hydro-meteorological flood might be involved in shaping these landforms. First, ice-jam related flooding causes the erosion of the upper riverbank. Second, alluviums are deposited on the lower part of the riverbank during flood recession. Third, these sediments are reworked into a flat bench by hydrometeorological floods occurring during the ice-free period.

**Table 4.1** Characteristics of study sites where dendrochronological sampling was conducted

| Site | Date of site availability (yr AD) | Number of trees sampled (N) | Mean number of scars / tree (N) | Number of years with scars (N) | Frequency (N $y^{-1}$) | Status in the present study (Boucher et al, 2008b) |
|---|---|---|---|---|---|---|
| 1 | 1869 | 18 | 10,9 | 89 | 0,66 | Preserved |
| 2 | 1945 | 15 | 2,6 | 24 | 0,41 | Preserved |
| 3 | 1871 | 11 | 3,5 | 18 | 0,14 | Preserved |
| 4 | 1936 | 20 | 2,5 | 16 | 0,24 | Preserved |
| 5 | 1914 | 29 | 5,2 | 45 | 0,51 | Preserved |
| 6 | 1798 | 9 | 7,9 | 48 | 0,23 | Preserved |
| 7 | 1856 | 7 | 5,85 | 29 | 0,20 | Preserved |
| 8 | 1890 | 4 | 3 | 12 | 0,11 | Eliminated |
| 9 | 1796 | 8 | 2,5 | 16 | 0,08 | Eliminated |
| 10 | 1865 | 8 | 6,12 | 34 | 0,25 | Preserved |
| 11 | 1917 | 5 | 3,2 | 11 | 0,13 | Preserved |
| 12 | 1877 | 15 | 3,66 | 29 | 0,23 | Preserved |
| 13 | 1870 | 14 | 3,14 | 24 | 0,18 | Preserved |
| 14 | 1879 | 8 | 5,87 | 28 | 0,23 | Preserved |
| 15 | 1841 | 10 | 3 | 21 | 0,13 | Eliminated |
| 16 | ? | - | 0 | 0 | 0 | Added |
| Mean | (with site 16) | | | 4.3 ±2.6 | 0.23 ±1.6 | |
| Mean | (without site 16) | | | 4.56 ±2.4 | 0.25 ±1.6 | |

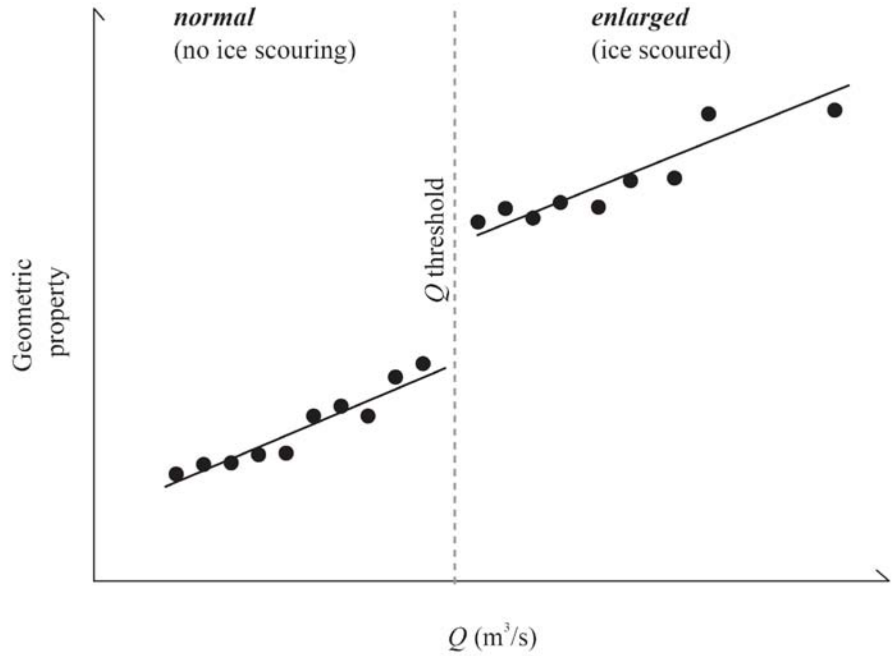


**Figure 4.1** Graphical representation of an idealized "*Q threshold*" separating between ice-scoured and normal channels.

Adapted from Smith (1980)

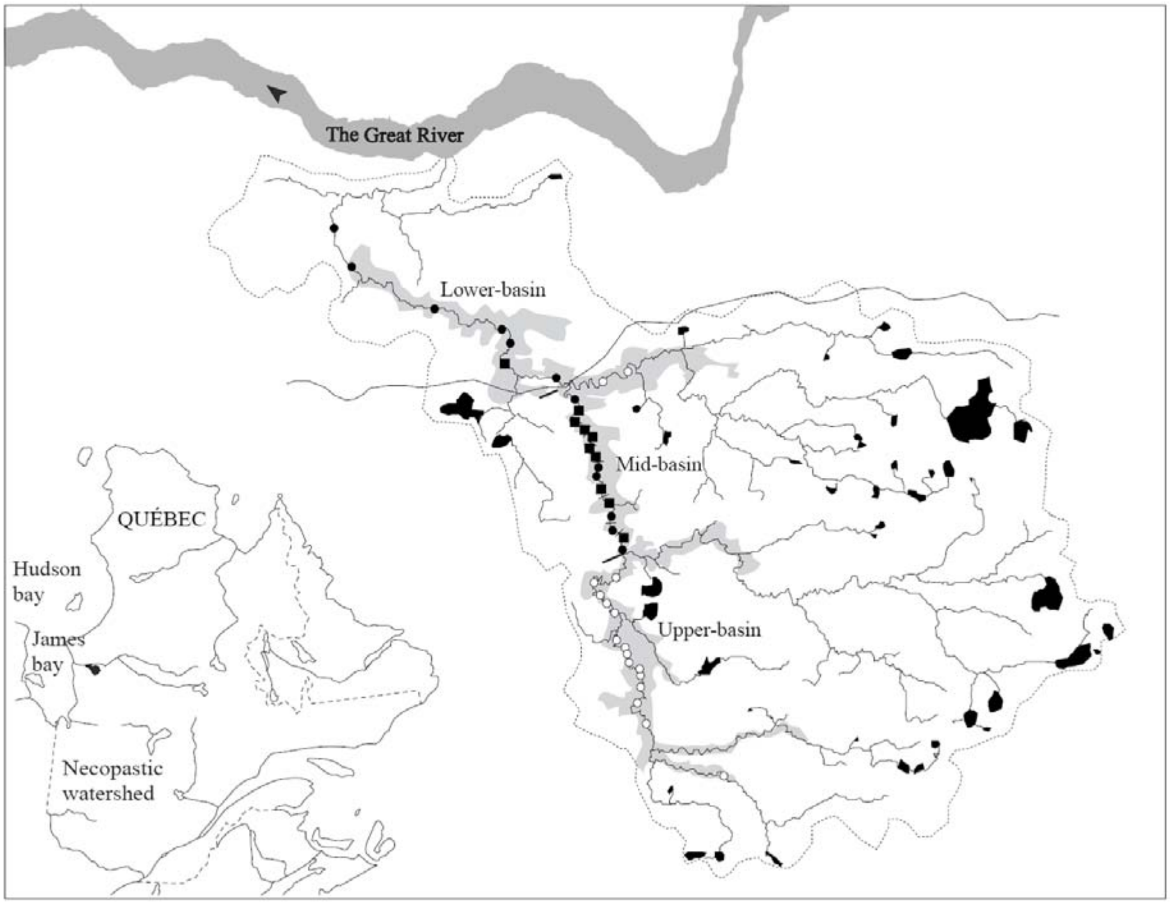


**Figure 4.2** The Necopastic watershed.

Studied sites are represented by circles and squares. White circles correspond to wide floodplain channels that present no evidence of ice jamming. Black circles and squares represent entrenched channels that experience frequent ice jams, as evidenced by the numerous scars found on shrubs and trees in these sites. Black squares refer to entrenched sites that display an ice-scoured morphology (see results for details). The shaded gray zone corresponds to the extent of lithologically homogeneous fluvio-glacial deposits (Vincent, 1985). These Holocene deposits are mainly composed of sands and silts.

**Figure 4.3** Shrubs scarred by drift ice.

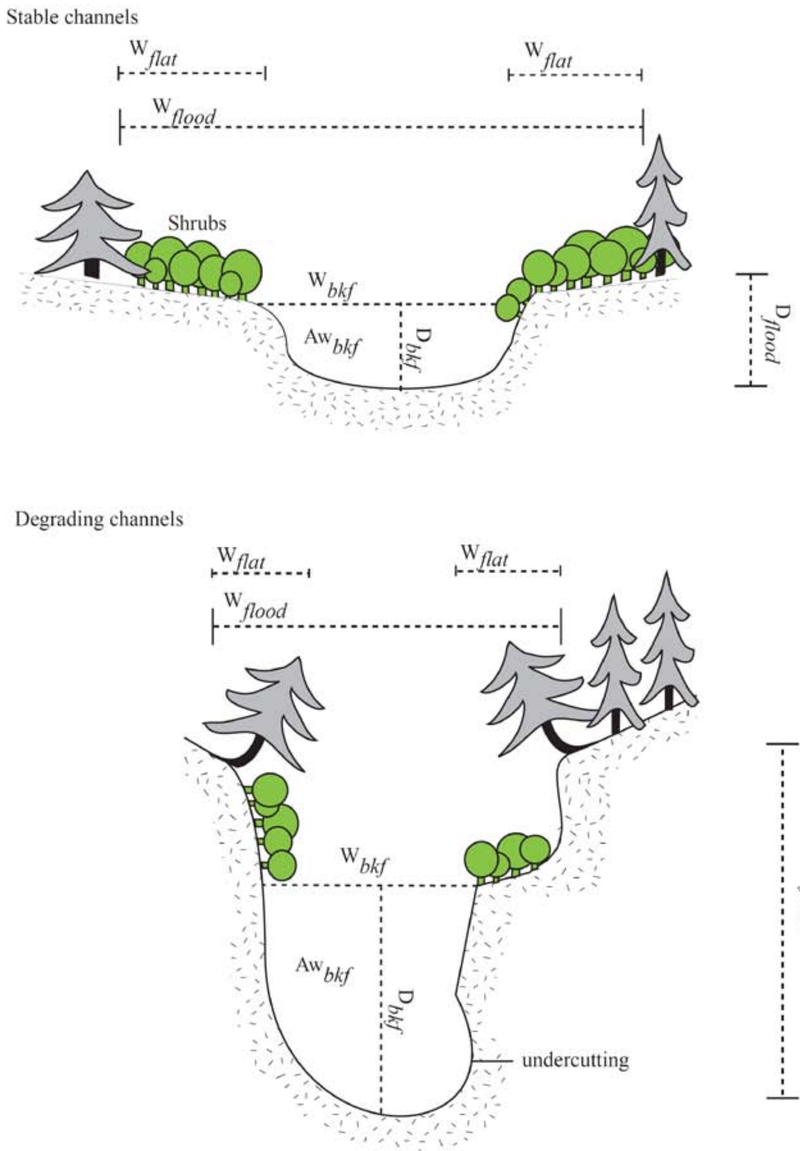


**Figure 4.4** Geometric properties and identification of the bankfull stage.

A) stable and B) entrenched channels. $W_{bkf}$, $W_{flat}$, $Aw_{bkf}$ , $D_{bkf}$ refer to bankfull width, valley flat width, bankfull cross-sectional area and bankfull depth.

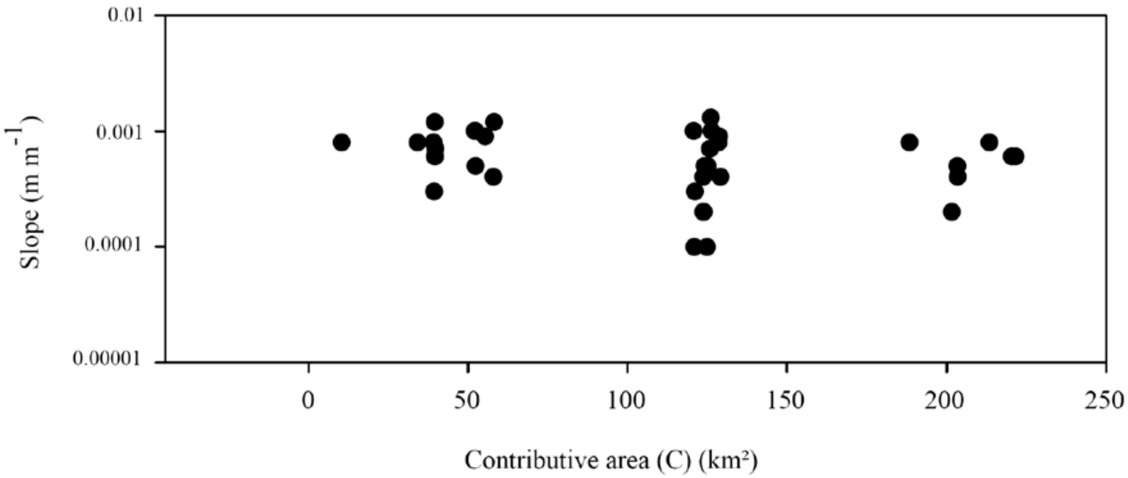


**Figure 4.5** Water slope values as a function of contributive area.

Each dot represents a study site.

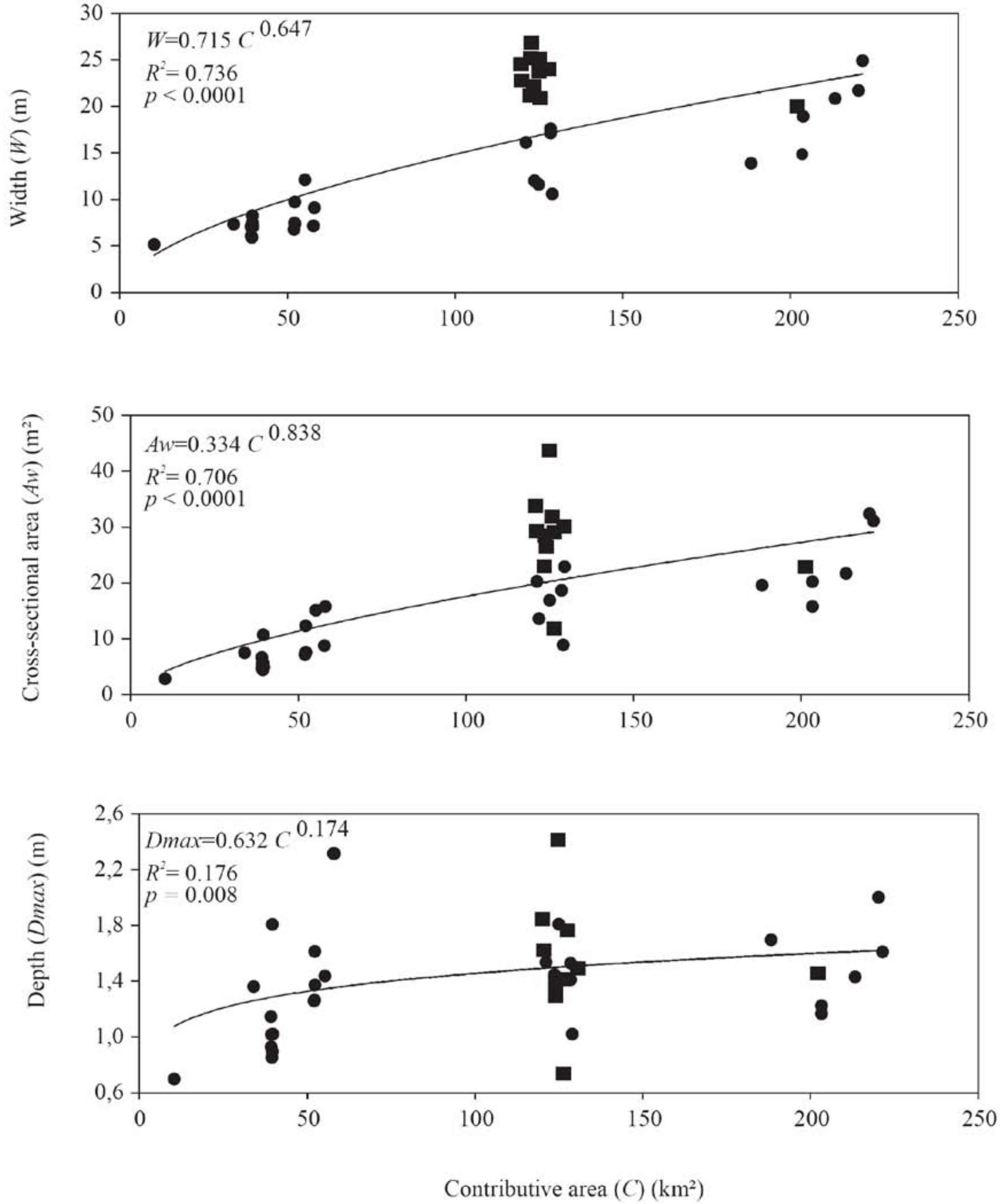


**Figure 4.6** Downstream changes in geometric properties of channels.

Each dot represents a study site. Sites presenting a typical ice-scoured morphology are illustrated as black squares.

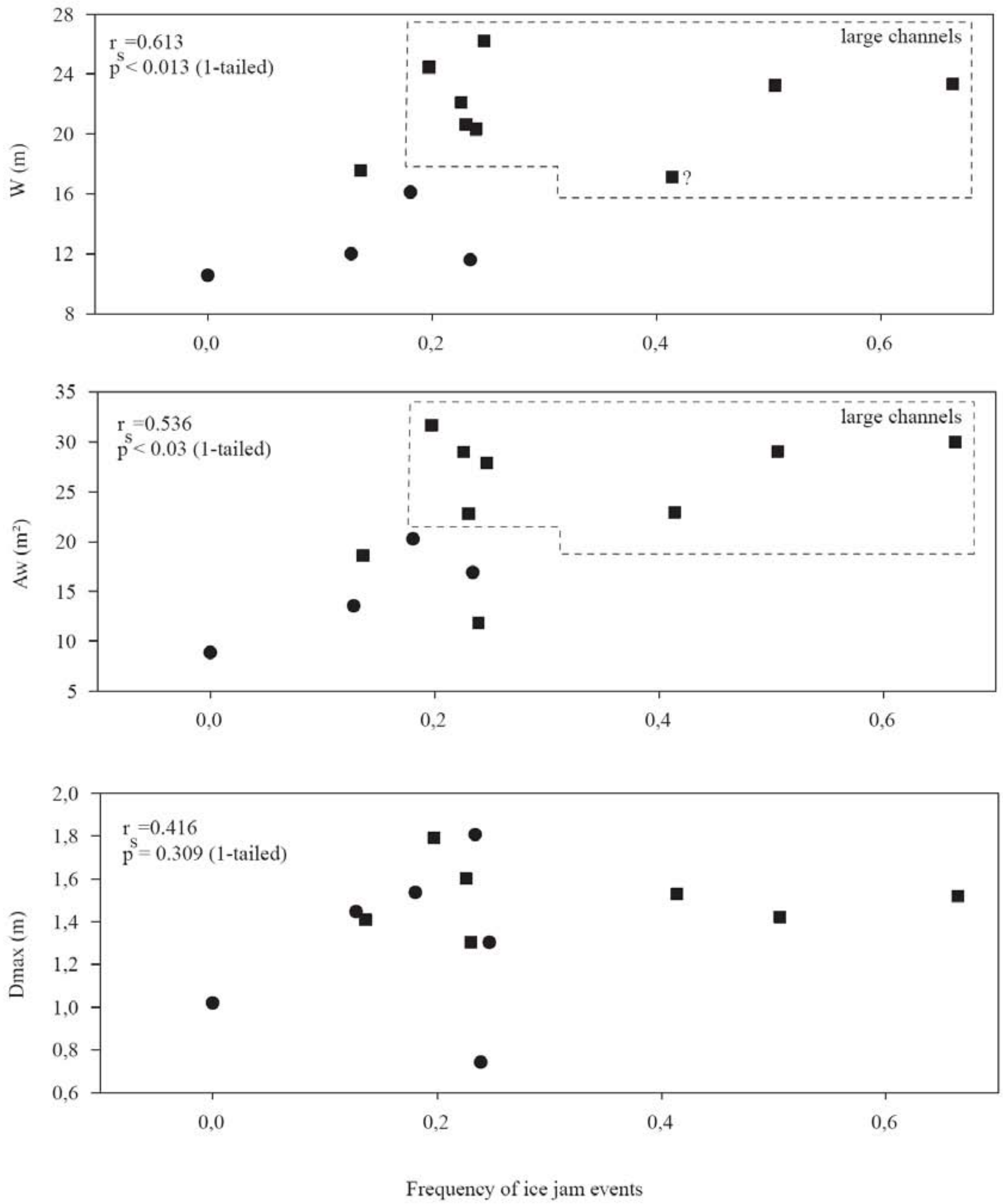


**Figure 4.7** Relationship between channel geometry and ice-jam frequencies in the mid-basin.

Only sites where the sampling was sufficient were considered (see table 1). Sites presenting a typical ice-scoured morphology are illustrated as black squares.

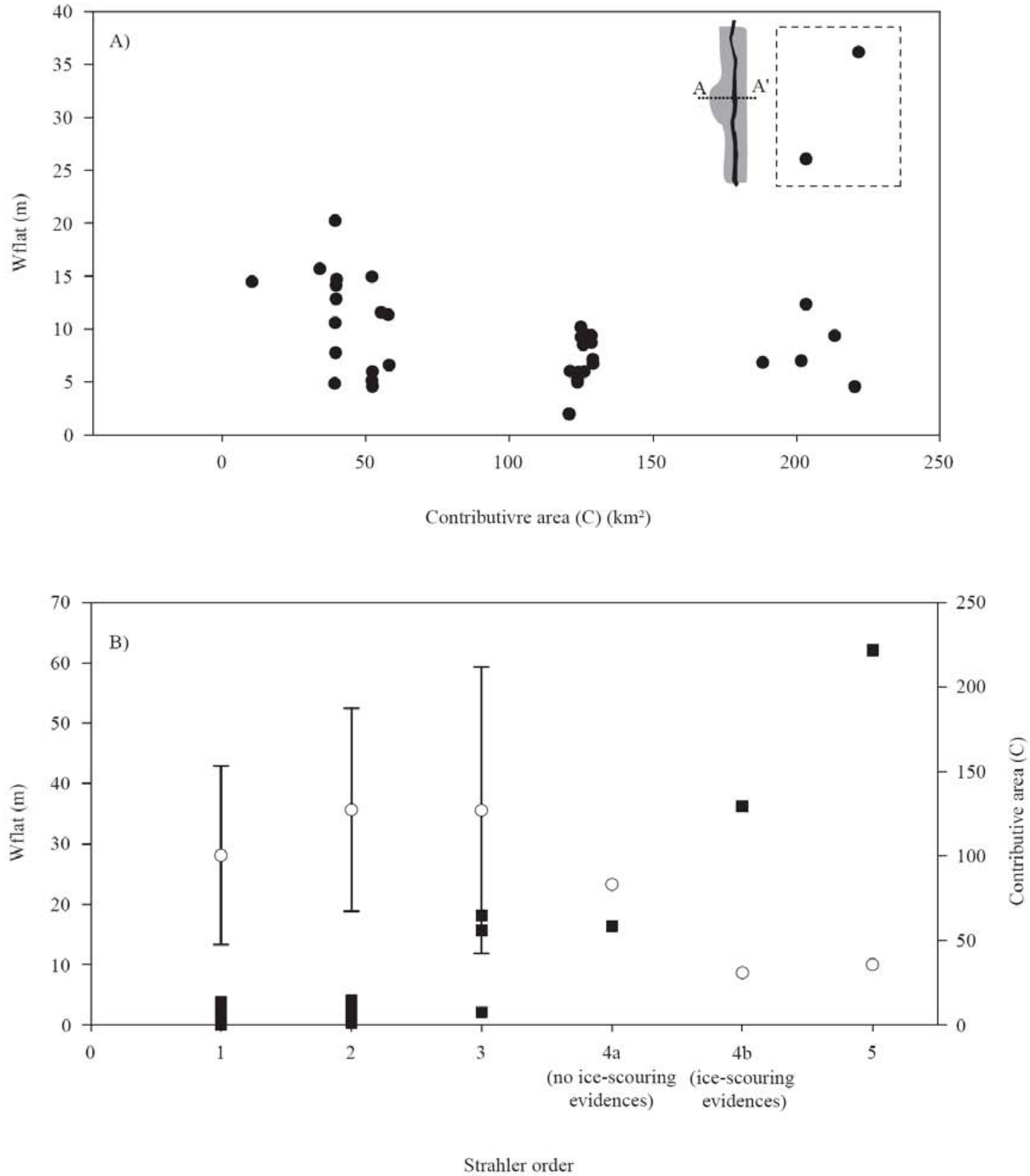


**Figure 4.8** Downstream changes in valley flat widths in the Necopastic watershed.

A) Valley flat widths measured in the studies sites. B) Mean (±SD) valley flat widths measured on 1: 10000 aerial photographies for each Strahler order. Black squares represent the contributive area of each Strahler order. Order 4 was divided into 4a and 4b because ice scouring occurs in the latter but not in the former.

**Figure 4.9** Graphical and pictorial representations of the three most common geomorphological environments encountered in the Necopastic River

A-B) wide floodplain channels B-C) entrenched / narrow floodplain channels and C-D) entrenched / ice-scoured channels.

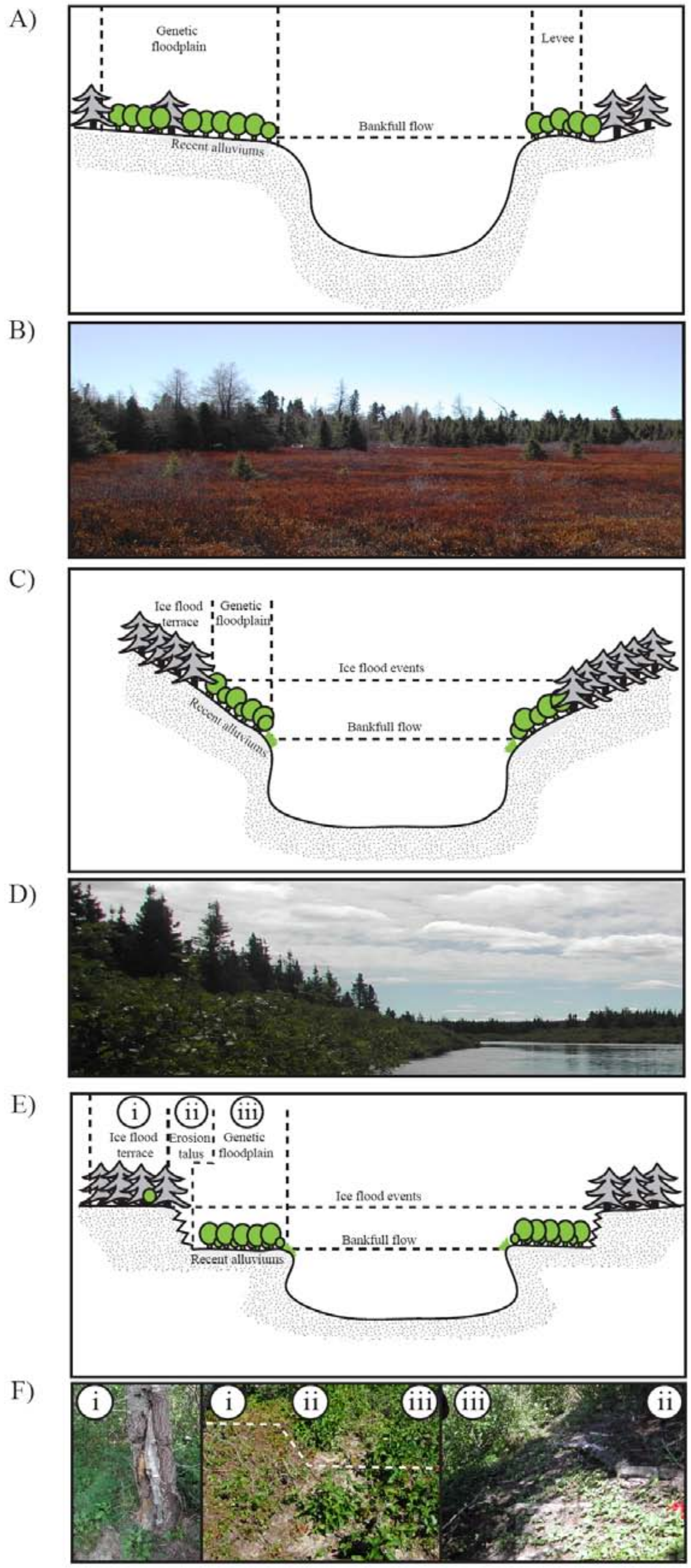

**Figure 4.10** The Necopastic just before the breakup in spring April 2006.

A) In upstream sites, flood waters are forced on top of the ice cover and inundate the full flood-prone width without eroding the banks. B) In downstream sites, the top of river banks is often free of snow due to insulation effects augmenting their sensitivity to erosion.

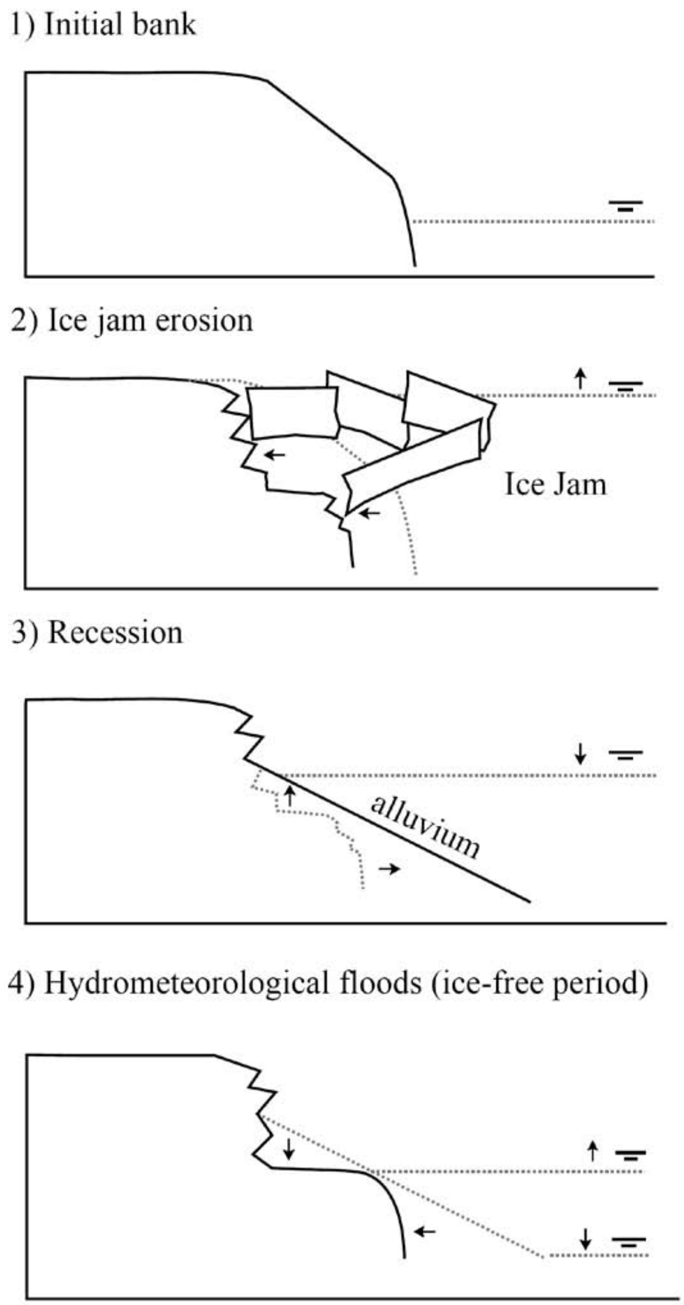


**Figure 4.11** Bank retreat mechanism in portions of the Necopastic River that are frequently affected by ice-jams

A) Initial Stage B) Ice-jam erosion C) Deposition of sediments on the lower bench during flood recession D) Reworking of fresh alluviums by hydrometeorological floods occurring during the ice-free period in these entrenched channels.

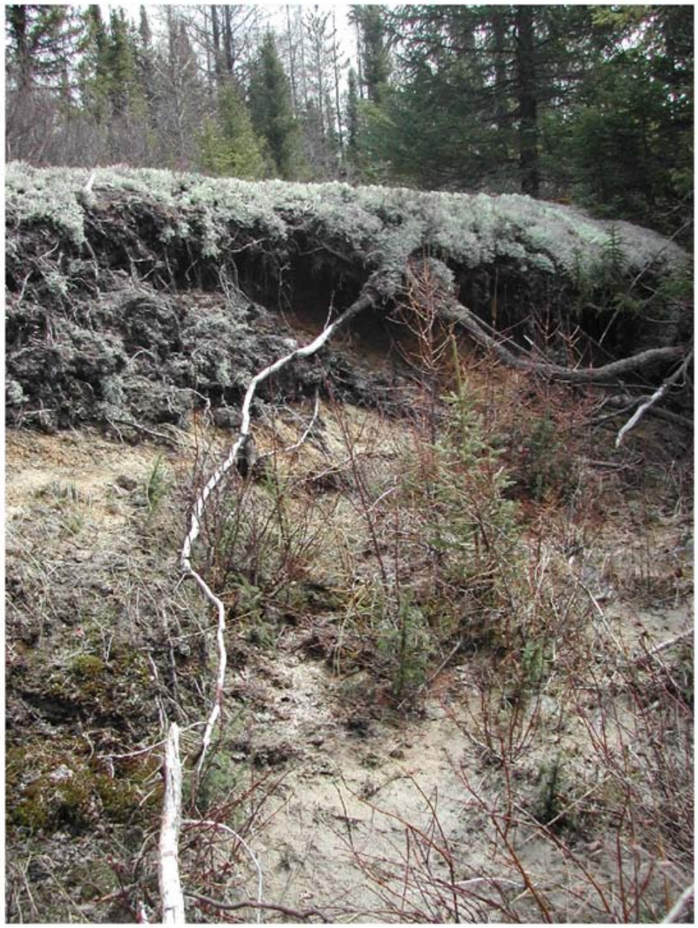

**Figure 4.12** Accumulation of loose sediments on the lower bench of the Necopastic River, may 2004.

# Chapitre 5. Conclusion générale

## 5.1 Importance de la contribution scientifique

En mettant à profit l'information historique livrée par les arbres riverains, cette thèse a contribué à préciser le contexte hydro-climatique dans lequel se déclenchent les épisodes de déglacement mécanique et à mieux définir l'impact que peuvent avoir ces événements sur la géomorphologie fluviale de la rivière Necopastic, à la Baie de James. La richesse des analyses contenues dans cette thèse vient du fait que l'historique des embâcles ne se limite pas uniquement à l'échelle stationelle, comme cela aurait été le cas, par exemple, avec des données instrumentales. Au contraire, l'utilisation de techniques dendrochronologiques a permis d'aborder la problématique du déglacement des rivières nordiques dans une perspective géographique, tout en mettant l'accent sur les variations spatiales et temporelles dans l'intensité et la fréquence des événements extrêmes à l'intérieur du bassin-versant.

L'analyse dendrochronologique du contexte hydro-climatique dans lequel se déclenchent les épisodes de déglacement mécanique ne pouvait toutefois se faire sans adapter les techniques d'échantillonnage et de construction des chronologies de cicatrices glacielles aux particularités et à la complexité du milieu fluviatile nordique (objectif spécifique 1). Le deuxième chapitre formule quatre grandes recommandations à ce sujet :

1) On doit chercher à évaluer l'intensité d'un épisode de déglacement mécanique à l'échelle d'un bassin homogène sur le plan climatique et en fonction de la proportion de sites ayant enregistré un événement. Cela permet, entre autres, de

pallier à l'importante variabilité spatiale inter-annuelle dans la localisation des embâcles et de réduire l'importance des facteurs locaux associés au déclenchement de ces événements extrêmes (e.g., obstruction localisée de l'écoulement).

2) Il faut exclure de la chronologie finale les tiges de faible diamètre et les cicatrices qu'elles recèlent. Ces tiges sont de mauvais enregistreurs, soit parce qu'elles sont trop flexibles et qu'elles plient sous la force de l'impact, ou bien parce qu'elles sont enfouies sous la neige au moment de l'embâcle. Il importe, dans le contexte d'une analyse hydro-climatique, que la sensibilité des enregistreurs ne varie pas dans le temps. Une manière empirique d'éliminer les tiges insensibles est de calculer le rayon à la première cicatrice (*RFS : Radius at the First Scar*) sur l'ensemble des tiges échantillonnées, de reporter ces mesures sur un histogramme de fréquence et enfin, d'exclure les tiges et les cicatrices formées sous la classe modale.

3) Dans les cas où il est impossible d'échantillonner l'ensemble d'une population, il importe de s'assurer qu'un nombre suffisant d'individus ait été récolté pour que les événements les plus importants dans chaque site soient découverts. Cela est important dans la mesure où l'indice d'intensité de la crue est calculé à partir de la proportion de sites touchés. Une manière de déterminer cela est d'échantillonner itérativement (avec remise) dans le pool initial d'arbres et d'évaluer la saturation de la chronologie (i.e., l'ajout d'une quantité négligeable de nouveaux événements), au fur et à mesure où l'on ajoute un nouvel individu.

L'algorithme ISR (*Iterative Sampling with Replacement*) a été conçu afin de solutionner ce problème.

4) Enfin, il faut s'assurer, en utilisant un test de comparaison de distribution (ex : Kolmogorov-Smirnov), que les variations de l'indice d'intensité des crues glacielles soient indépendantes des phases de mortalité et de régénération à l'échelle du paysage. Des variations attribuables à la dynamique des populations peuvent être perceptibles dans la chronologie, soit parce que des perturbations importantes sont survenues durant la période d'enregistrement (e.g., feux, épidémies, coupe forestière, etc.) ou bien lorsque les crues glacielles peuvent elles-mêmes avoir engendré la mortalité massive des tiges riveraines.

Ce deuxième chapitre constitue une avancée majeure dans le champ d'étude qu'est la dendrochronologie, en vertu de l'universalité des principes qui s'y retrouvent et des possibilités d'appliquer ces méthodes à l'étude des conditions de déclenchement des événements extrêmes dans d'autres environnements (e.g., crues glacielles en milieu lacustre, avalanches et éboulis rocheux).

La chronologie glacielle construite d'après les principes énumérés au deuxième chapitre a permis l'analyse des conditions hydro-climatiques contrôlent le déglacement annuel de la rivière Necopastic (objectif 2). La force de cette analyse repose sur l'extraction d'un signal hydro-climatique de bassin régionalisable par rapport au signal hautement contextuel qui aurait été obtenu si la même analyse avait été réalisée, par exemple, à partir d'une station hydrométrique. En croisant les variations de l'intensité des crues glacielles reconstituées par dendrochronologie aux variables hydro-climatiques régionales (période 1950-2003), et en incorporant ces variables dans un modèle prédictif (arbre de classification et de régression), il a été démontré que les déglacements mécaniques intenses se forment en présence d'un couvert de glace dont les propriétés ne sont pas dégradées au moment de la crue. Cette condition est rencontrée 1) lorsque la crue printanière régionale est hâtive et soudaine et 2) lorsque les précipitations nivales printanières (sous l'influence de l'indice d'Oscillation Arctique) sont suffisamment abondantes pour isoler le couvert de glace et prolonger la période de temps durant laquelle la glace préserve ses propriétés mécaniques.

Enfin, l'échantillonnage dendrochronologique a permis de camper dans un cadre fréquentiel et hydrographique l'impact que peuvent avoir ces événements extrêmes sur l'environnement physique de la rivière Necopastic (objectif 3). Bien que l'étude porte sur un seul cours d'eau, elle constitue une avancée significative en géomorphologie fluviale puisque, pour la première fois, un lien est établi entre les caractéristiques du régime d'embâcle et son inscription géomorphologique. Une des conclusions majeures de ce chapitre est que l'élargissement apparent des chenaux et l'apparition de rives sévèrement affectées par l'érosion glacielle ne se manifestent clairement, à l'intérieur du bassin-versant de la rivière Necopastic, que lorsque les embâcles surviennent au moins une fois à tous les cinq ans, en moyenne. En définitive, il est important de souligner que les implications de ce constat sont très importantes, puisqu'elles remettent en question le rôle de la glace en tant qu'agent géomorphologique, en particulier lorsque ces événements surviennent rarement. Cette étude suggère l'existence de seuils fréquentiels pour l'inscription de ces phénomènes dans le paysage fluvial. Par le fait même, ces résultats laissent sous-entendre qu'il est risqué d’assumer, sans avoir quantifié ces seuils, que tout épisode de déglacement mécanique se répercutera sur l’environnement physique du cours d’eau.

## 5.2 Perspectives

Cette thèse débouche sur de nombreuses avenues de recherche qui pourraient permettre d’améliorer la connaissance des processus régissant le déglacement des cours d’eau et d’évaluer l’impact de ces événements sur l’environnement fluvial en milieu froid. À la lumière des travaux réalisés dans cette thèse, les recherches futures devraient contribuer 1) à perfectionner les outils et les techniques de construction de chronologies glacielles en milieu fluvial, 2) à renforcer et/ou à nuancer les résultats contenus dans cette thèse en répliquant ces études dans d’autres environnements, et 3) à étendre la reconstitution hydro-climatique au-delà des archives instrumentales.

Bien que novatrices, les techniques dendrochronologiques utilisées dans cette thèse ne permettent pas d’évaluer statistiquement l’incertitude (ou l’intervalle de confiance) reliée à la mesure de l’intensité d’une crue glacielle. La technique privilégiée dans le second chapitre est le calcul du ratio (i.e., de la proportion) entre le nombre de sites ayant enregistré un événement et le nombre de sites disponibles pour l’enregistrement lors de l’année *t*. Or, le nombre de sites disponibles diminue considérablement dans les portions anciennes de la chronologie. D’un point de vue statistique, cela signifie que les chances d’enregistrer avec succès un événement s’amenuisent avec la raréfaction des sites, augmentant ainsi l’incertitude associée au calcul de la proportion. Afin de quantifier cette incertitude, il faudrait pouvoir associer un intervalle de confiance (i.e. à 95%) à la mesure de l'intensité des crues glacielles passées. Cela permettrait, entre autres, de définir la portion de la chronologie pour laquelle l'interprétation hydro-climatique est incertaine. Des travaux en cours suggèrent qu'il serait possible de traiter ce problème dans un cadre probabiliste en considérant notre échantillonnage dendrochronologique comme une épreuve Bernoulli de paramètre $p$ (où $p$ est la probabilité d'observer avec succès une crue glacielle et $q$=1-$p$ équivaut à la probabilité d'un échec de l'observation). Par la suite, on pourrait tirer les intervalles de confiance à 95% dans une loi binomiale.

Il apparaît important de répliquer notre étude sur d'autres cours d'eau de la même région. Cela permettrait, entre autres, de vérifier si les déglacements mécaniques intenses sont provoqués par les mêmes combinaisons de variables hydro-climatiques à l'échelle régionale. D'autre part, il serait intéressant de vérifier si ces relations s'appliquent aussi à des bassins de taille différente. À ce sujet, il est important de rappeler que la rivière Necopastic constitue le plus petit bassin dans lequel une activité glacielle a été enregistrée et en ce sens, il existe peu d'analogues dans la littérature scientifique. Le fait de répliquer notre étude dans d'autres bassins versants du Haut-Boréal québécois pourrait aussi permettre de valider l'existence des seuils fréquentiels associés à l'inscription géomorphologique du régime glaciel dans des systèmes de taille différente.

Enfin, bien qu'une augmentation de l'intensité des crues glacielles à partir de 1950 soit visible dans la chronologie, la signification hydro-climatique de ce changement de régime demeure non-interprétable. En somme, la chronologie laisse transparaître un phénomène hautement non-stationnaire à l'échelle du dernier siècle et, par conséquent, il serait fort imprudent d'assumer que les relations statistiques qui caractérisent le régime actuel (i.e. depuis 1950) soient aussi transférables à la première partie de la chronologie (i.e. avant 1950). Par ailleurs, le modèle prédictif (arbre de classification) construit dans le cadre de cette thèse est valable pour l'avenir uniquement si le régime actuel se maintient. Afin d'interpréter correctement la signification hydro-climatique des changements de régime (futurs et anciens), de futures études devront s'intéresser à la modélisation des événements extrêmes dans un cadre non-stationnaire.

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**ANNEXE 1** Mathematical expression of the ISR algorithm

**Step 1**) Let $T$ range from 1 to $t$ and represent the period of life (in years AD) of trees in site $x$. Let $J$ be the number of trees sampled in a site range from 1 to $j$. Summarize the dendrochronological (e.g. scars) information contained in site $x$ in a presence / absence matrix $\mathbf{B}_x$ having the dimensions $T$ by $J$ so that:

$$\mathrm{B}_x = \begin{pmatrix} PA_{1,1} & \cdots & PA_{1,j} \\ \vdots & \ddots & \vdots \\ PA_{t,1} & \cdots & PA_{t,j} \end{pmatrix} \qquad (1.1)$$

Where $PA_{TJ}$ is a binary variable taking the following values

$$PA_{TJ} = \begin{cases} 1, & \text{if tree } J \text{ presents a scar at time } T \\ 0, & \text{if tree } J \text{ does not have a scar at time } T \end{cases} \qquad (1.2)$$

To simplify the procedure, we will consider that all trees in a site have the same age (i.e. there is only one value for $t$) and were alive at the moment of the sampling.

**Step 2)** Let $\vec{k}$ be a vector with values [1,2,…$j$]. Sample with replacement $k$ trees in matrix $\mathbf{B}_x$ (starting with $k$=1) (step 2a). Sum the number of ice scars at each year using the following equation (step 2b):

$$\mathrm{E}_{T(k)} = \sum_{1}^{k} PA_{TJ} \qquad (1.3)$$

The vector $\mathrm{E}_{T(k)}$ should have a $T$ by 1 dimension and represent the at-a-site number of damaged trees from each year of $T$ when $k$ trees are sampled.

**Step 3)** Recode matrix $E_{T(k)}$ into a presence / absence vector with the following conditions:

$$E_{T(k)} = \begin{cases} 1, \text{ if } E_{T(k)} \geq 1 \\ 0, \text{ otherwise} \end{cases} \qquad (1.4)$$

where $E_{T(k)}$ is a recoded vector constructed from *k* trees and represents the presence (1) / absence (0) of an event in a site at each year of time period *T*.

**Step 4)** From the binary matrix $E_{T(k)}$, sum the absolute number of dated events ($E_{S(k)}$) during time period *T*, considering a provisory sample of *k* trees from the following equation:

$$E_{s(k)} = \sum_{1}^{t} E_{t(k)} \qquad (1.5)$$

**Step 5)** Repeat steps 2 to 4 a large number *i* of times (step 5a). An acceptable minimum is 1000 times, ie. *I*= (1…1000). Obtain and append the "iterative replications" in $\hat{E}_{s(k(I))}$ **(**step 5b) so that

$$E_{s(k(1))}, E_{s(k(2))}, ..., E_{s(k(i))} \approx \hat{E}_{s(k(I))} \qquad (1.6)$$

**Step 6)** From $\hat{\mathrm{E}}_{s(k(I))}$, calculate the mean number of events detected when k trees are drawn *I* times from $\mathbf{B}_x$ using

$$\overline{\hat{\mathrm{E}}_{s(k(I))}} = \frac{1}{i} \cdot \sum_{1}^{I} \mathrm{E}_{s(k(I))} = \frac{\mathrm{E}_{s(k(1))} + \mathrm{E}_{s(k(2))} + \ldots \mathrm{E}_{s(k(i))}}{i} \qquad (1.7)$$

**Step 7)** Repeat steps 2 through 6 to compute $\overline{\hat{\mathrm{E}}_{s(k(I))}}$ using every element in vector $\vec{k}$ (from *k*=1 to *k*=*j*) (step 7a) and append the results to $\Omega$ (step 7b) so that:

$$\Omega = \left[ \overline{\hat{\mathrm{E}}_{s(k=1)I)}}, \overline{\hat{\mathrm{E}}_{s(k=2)I)}}, \ldots, \overline{\hat{\mathrm{E}}_{s(k=j)I)}} \right] \qquad (1.8)$$

**Step 8**) From $\Omega$, compute the percentage of new events added ($\Delta\mathrm{E}\ (\%)$) at each increment in $\vec{k}$ with

$$\Delta\mathrm{E}\ (\%) = \left( \frac{\overline{\hat{\mathrm{E}}_{s((k)I)}}}{\hat{\mathrm{E}}_{s((k-1)I)} \cdot 100} \right) - 100 \qquad (1.9)$$

The limit between undersaturated and oversaturated sampling corresponds to $\Delta\mathrm{E} < 5\%$. The value of *k* at $\Delta\mathrm{E} < 5\%$ corresponds to the minimal number of trees to sample at-a-site so that every new tree added to the chronology adds in average less that 5% of new events.

**ANNEXE 2** Flowchart of the ISR algorithm