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L'IMPACT DES PROCESSUS FLUVIAUX HIVERNAUX SUR LES FRAYÈRES ET LA SURVIE INTERGRANULAIRE DU SAUMON ATLANTIQUE (*SALMO SALAR* L.)

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Résumé

Les processus d'érosion et de sédimentation des cours d'eau sont des phénomènes naturels qui façonnent les habitats aquatiques. Bien que la dynamique de ces processus géomorphologiques soit bien connue, peu d'informations sont disponibles concernant l'influence de certains aspects de ces processus sur les frayères et sur la survie interganulaire des salmonidés. Dans cette optique, le premier objectif de ce mémoire consiste à évaluer l'impact des sédiments fins sur la survie des œufs et des alevins pré-émergeant du saumon Atlantique (*Salmo salar* L.). Le deuxième objectif consiste à évaluer l'impact de l'accumulation de frasil sous le couvert de glace sur l'érosion du substrat des frayères à salmonidés.

À l'automne 1997, 53 nids artificiels contenant des œufs fécondés de saumon Atlantique ont été installés dans 6 frayères à saumons de la rivière Sainte-Marguerite située dans la région du Saguenay (Québec). Les caractéristiques géomorphologiques et granulométriques des frayères ont été déterminées à partir de coupes transversales du chenal et de mesures détaillées de la granulométrie du substrat. De plus, 15 chaînes d'érosion ont été installées dans le substrat de chaque frayères.

À l'hiver et au printemps 1998, les coupes transversales ont été relevées de nouveau afin de mesurer les variations net de l'élévation du lit fluvial et de déterminer l'épaisseur des accumulations de frasil sous le couvert de glace. Au printemps, suite à la période d'éclosion des œufs, les nids ont été retirés et la survie des œufs et des alevins vésiculés a été déterminée et comparée à la quantité de sédiments fins infiltrés dans les nids et au pourcentage de sable déposé à leur surface. Au début de l'été 1998, les chaînes d'érosion ont été récupérées afin de mesurer l'affouillement maximal du lit fluvial au cours du développement intergranulaire des œufs et des alevins.

Les résultats démontrent que les sédiments fins (<1mm de diamètre) infiltrés dans les nids artificiels ont un effet négatif significatif sur la survie intergranulaire des saumons. En ce qui concerne la survie jusqu'aux stades pré-oeillé (STPE) et oeillé (STE), les résultats démontrent qu'il existe une corrélation négative plus forte (STPE $r=-0.67$ $p<0.05$; STE $r=-0.66$ $p<0.05$) entre la survie intergranulaire et la quantité de particules très fines infiltrée dans les nids, soit les limons et les argiles (particules de diamètre <0.063mm), que les particules de plus grosses tailles. Pour ce

qui est de la survie jusqu'à l'éclosion, les résultats indiquent l'existence d'une corrélation plus élevée ($r=-0.76$, $p<0.05$) avec la quantité totale des sédiments inférieurs à 1mm infiltrés dans les nids. Les analyses ont aussi démontré une corrélation positive faible mais significative ($r=0.47$, $p<0.05$) entre le taux d'ensablement superficiel du substrat et la survie intergranulaire jusqu'à l'éclosion.

L'étude statistique des données fournies par les chaînes d'érosion a démontré que la profondeur maximale de l'érosion du substrat des frayères est significativement accrue (ANOVA, $F= 177.64$, $p<0.001$) en présence de bancs d'accumulation de frasil. L'analyse des données topographiques démontre que l'accumulation de frasil sous le couvert de glace réduit le chenal d'écoulement de la rivière. Cette réduction pourrait contraindre l'écoulement du cours d'eau et augmenter les forces de cisaillement appliquées sur le lit fluvial. Cette hypothèse expliquerait l'augmentation de la profondeur d'affouillement des frayères, en présence de frasil, observé dans la présente étude. Ce phénomène pourrait avoir des conséquences majeures sur la stabilité des nids et la survie intergranulaire de la progéniture des salmonidés frayant en milieu lotique.

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Introduction générale

Les processus d'érosion et de sédimentation sont des phénomènes naturels qui font partis de l'évolution normale de tout cours d'eau alluvial. Ces processus façonnent les habitats aquatiques et ont un impact considérable sur les caractéristiques géomorphologiques des frayères à salmonidés. Ainsi, bien que les œufs de saumon Atlantique (*Salmo salar*) soient enfouis dans le substrat à une profondeur variant de 15 à 30 cm (DeVries 1997), ceux-ci ne sont pas entièrement à l'abri des phénomènes d'ensablement et d'affouillement du lit fluvial.

Par exemple, il est bien connu qu'une sédimentation excessive peut colmater les interstices du substrat et réduire considérablement la survie à l'émergence des alevins (Chapman 1988). Cependant, malgré l'abondance de travaux traitant de l'effet nocif des sédiments fins sur l'émergence, peu d'études en milieu naturel ont documenté leurs impacts sur les stades de développement précédant l'émergence. Le premier objectif de ce mémoire consiste à déterminer l'impact des sédiments fins dans le substrat des frayères naturelles sur la survie des œufs et des alevins pré-émergeants de saumon.

De plus, des études ont démontré que l'affouillement du lit fluvial peut nuire à la survie intergranulaire des salmonidés en érodant les nids (Montgomery et al. 1996) ou en exposant des couches plus profondes du substrat à l'infiltration de sédiments fins (Lisle 1989). Cependant, bien que l'affouillement des frayères lors des crues soit un phénomène bien connu (DeVries 1997), aucune recherche n'a encore documenté l'impact du frasil sur l'érosion du substrat des frayères à salmonidés. Le frasil est constitué de cristaux de glace qui peuvent s'accumuler sous le couvert de glace solide et diminuer la section d'écoulement des cours d'eau (Lawson et al. 1989). En contraignant la section d'écoulement, le frasil peut augmenter les contraintes de cisaillements appliquées sur le lit et ainsi favoriser l'affouillement du substrat (Prowse et Gridley 1993). Dans cette optique, le deuxième objectif de ce projet consiste à évaluer l'impact potentiel du frasil sur l'affouillement du substrat des frayères à salmonidés.

Le mémoire est divisé en quatre chapitres. Le premier chapitre présente une revue de certaines notions de bases concernant les caractéristiques des frayères à saumons ainsi que les processus de sédimentation et d'érosion qui s'y produisent. On y retrouve aussi une description détaillée des objectifs et des hypothèses de la recherche. Le deuxième chapitre décrit de façon succincte les travaux de recherche et les principaux résultats de l'étude. Ceux-ci sont exposés de façon plus complète dans les troisième et quatrième chapitres, composés de deux articles rédigés en anglais. Le premier traite de l'impact des sédiments infiltrés dans les nids de saumon sur la survie des œufs et des alevins pré-émergeant. Le deuxième présente les résultats concernant l'impact du frasil sur l'érosion du substrat des frayères à salmonidés. Bien que le deuxième article ait été rédigé par M. Normand Bergeron, la revue de littérature, le travail de terrain ainsi que l'analyse et l'interprétation des résultats ont été effectués par Héryk Julien. Ces deux articles seront soumis pour publication dans des revues avec comité de lecture.

Chapitre 1
Le saumon et son habitat de reproduction

1.1 La reproduction du saumon

Le saumon Atlantique (*Salmo salar*) est un poisson anadrome, c'est-à-dire qu'il effectue la majeure partie de sa croissance en mer et migre en rivière pour se reproduire. Au Canada, le saumon Atlantique se reproduit généralement au cours des mois d'octobre et de novembre (Scott et Crossman 1974). Quand vient le moment de frayer, la femelle sélectionne un site de nidification caractérisé par un substrat graveleux dans une zone d'accélération de l'écoulement de faible profondeur (Belding 1934). Les nids sont fréquemment positionnés à l'aval des fosses, sur le côté ascendant des seuils ou des bancs de gravier, là où l'écoulement intergranulaire est accentué (Fleming 1996). La femelle creuse une dépression de 15 à 30cm (DeVries 1997) à l'aide de sa nageoire caudale et y dépose une partie de ses œufs qui sont immédiatement fertilisés par un ou plusieurs mâles (Fleming 1996). Suite à la fertilisation, la femelle enfouit ses œufs en excavant le substrat situé en amont du nid (Figure 1.1). Lors de l'excavation et du remblayage, la femelle soulève les particules du lit dans la colonne d'eau, ce qui a pour effet d'évacuer les sédiments fins qui sont emportés par l'écoulement. Ce tri granulométrique augmente la perméabilité des nids et facilite l'écoulement intergranulaire nécessaire à l'oxygénation adéquate de la progéniture (Chapman 1988). L'oxygénation des œufs et des alevins est aussi accentuée par la forme des nids qui favorise les échanges d'eau entre le cours d'eau et le substrat fluvial (Cooper 1965).

Au Canada, l'éclosion des œufs a lieu en moyenne en avril mais elle est plus tardive dès que l'on se déplace vers le nord (Scott et Crossman 1974). Suite à l'éclosion, les alevins vésiculés demeurent enfouis dans le gravier, subsistant à même leur vitellus. L'émergence des alevins a lieu en mai ou juin, lorsque débute l'alimentation orale.

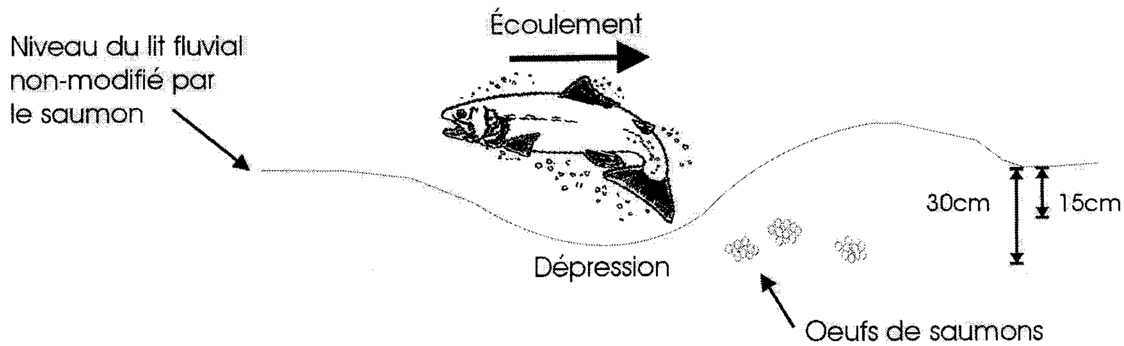

Figure 1.1 Vue en coupe de la morphologie d'un nid de saumon.

1.2 La sédimentation et la survie intergranulaire des saumons

Suite à la ponte et au remblayage des œufs, les nids de saumon sont exposés à une sédimentation naturelle qui se poursuit tout au long du développement intergranulaire des œufs et des alevins. Il est depuis longtemps présumé que la présence de sédiments fins dans les frayères peut limiter la survie intergranulaire des salmonidés (Chapman 1988). En colmatant le substrat, les particules fines réduisent l'écoulement intergranulaire responsable de l'oxygénation des salmonidés en incubation (Cooper 1965). Des études ont démontré qu'une déficience en oxygène pour les alevins peut se manifester, entre autre, par un retard de croissance, une résorption moindre du sac vitellin, des malformations, ainsi qu'une mortalité accrue (Garside 1959; Silver et al. 1963). D'après Cooper (1965), le moment le plus critique de la survie intergranulaire se situe à l'éclosion, lorsque la demande en oxygène est maximale. Cependant, même lorsque la concentration en oxygène est supérieure au seuil critique, les sédiments fins peuvent réduire de façon significative l'évacuation de déchets métaboliques et ainsi favoriser une accumulation létale de dioxyde de carbone et de déchets azotés (Wood et Armitage 1997). Il est aussi bien connu que le colmatage du substrat peut emprisonner les alevins, ce qui a pour effet de réduire considérablement la survie à l'émergence (Chapman 1988). Des études ont démontré que les alevins se développant dans un substrat plus fin sont de plus petite taille (Phillips et al. 1975) et émergent prématurément afin de fuir les conditions défavorables associées à une fine granulométrie (Tappel et Bjornn 1983).

Malgré l'important volume d'études traitant des effets néfastes des sédiments fins sur le succès à l'émergence des salmonidés, peu de travaux effectués en milieu naturel ont démontré l'impact des sédiments fins sur la survie aux stades de développement qui précèdent l'émergence. White (1942) a observé une mortalité élevée dans des nids naturels de saumon contenant une grande quantité de limon et de sable. Cooper (1965) a publié des résultats de travaux en laboratoire indiquant une mortalité embryonnaire accrue en présence de sédiments fins. Reiser et White (1988) ont conclu, suite à des expériences en laboratoire avec des œufs de saumon chinook, que la quantité totale des sédiments de plus petites tailles (particules de diamètre <0.84mm) sont les plus néfastes pour la survie jusqu'à l'éclosion. Cependant, les travaux en milieu naturel de Sowden et Power (1985) n'ont pu valider cette relation.

1.3 L'affouillement du lit fluvial et des frayères

L'érosion du lit fluvial peut nuire considérablement à la survie intergranulaire des salmonidés en délogeant les œufs et les alevins (Montgomery et al. 1996) ou en exposant des couches plus profondes du substrat à l'infiltration des sédiments fins (Lisle 1989). En milieu nordique, la glace modifie l'écoulement fluvial ainsi que les processus d'érosion et de sédimentation qui s'y produisent. Cependant, peu d'études ont traité de l'impact de la glace fluviale sur l'affouillement des frayères à salmonidés. Parmi les différentes formes de glace fluviale, le frasil est souvent considéré comme l'une des plus néfaste pour la vie aquatique (Prowse et Gridley 1993). Le frasil est constitué de cristaux de glace qui sont produits dans les écoulements turbulents des rapides et des chutes où l'absence de couvert de glace permet un contact direct entre l'eau et l'air froid ambiant. Ainsi, lorsque la température de l'air est suffisamment basse, la température de l'eau est refroidie de quelques centièmes de degrés en-dessous du point de congélation. Les gouttelettes d'eau en état de surfusion forment alors des particules de frasil particulièrement collantes qui adhèrent aux matériaux submergés et à d'autres particules de frasil. Les particules et amas de frasil sont transportés par l'écoulement et peuvent s'accumuler là où les vitesses de courant sont faibles, soit le long des berges irrégulières, dans les fosses et en amont des bancs d'accumulation (Figure 1.2a) (Prowse et Gridley 1993). Cunjak et Caissie (1994) ont observé un banc d'accumulation de frasil atteignant le fond d'une fosse de 8.7m de profondeur et remplissant jusqu'à 75% de son volume. Par conséquent, les accumulations de frasil sous le couvert de glace peuvent réduire considérablement l'aire de la coupe transversale des cours d'eau, contraindre l'écoulement et ainsi favoriser l'érosion du lit fluvial (Figure 1.2b) (Prowse et Gridley 1993). En accentuant la profondeur d'affouillement du lit fluvial, le frasil pourrait avoir des conséquences écologiques majeurs sur la stabilité des nids et sur la survie intergranulaire des œufs et des alevins de salmonidés. Cependant, aucune recherche n'a encore démontré l'impact potentiel de l'accumulation de frasil sur l'érosion des frayères à salmonidés.

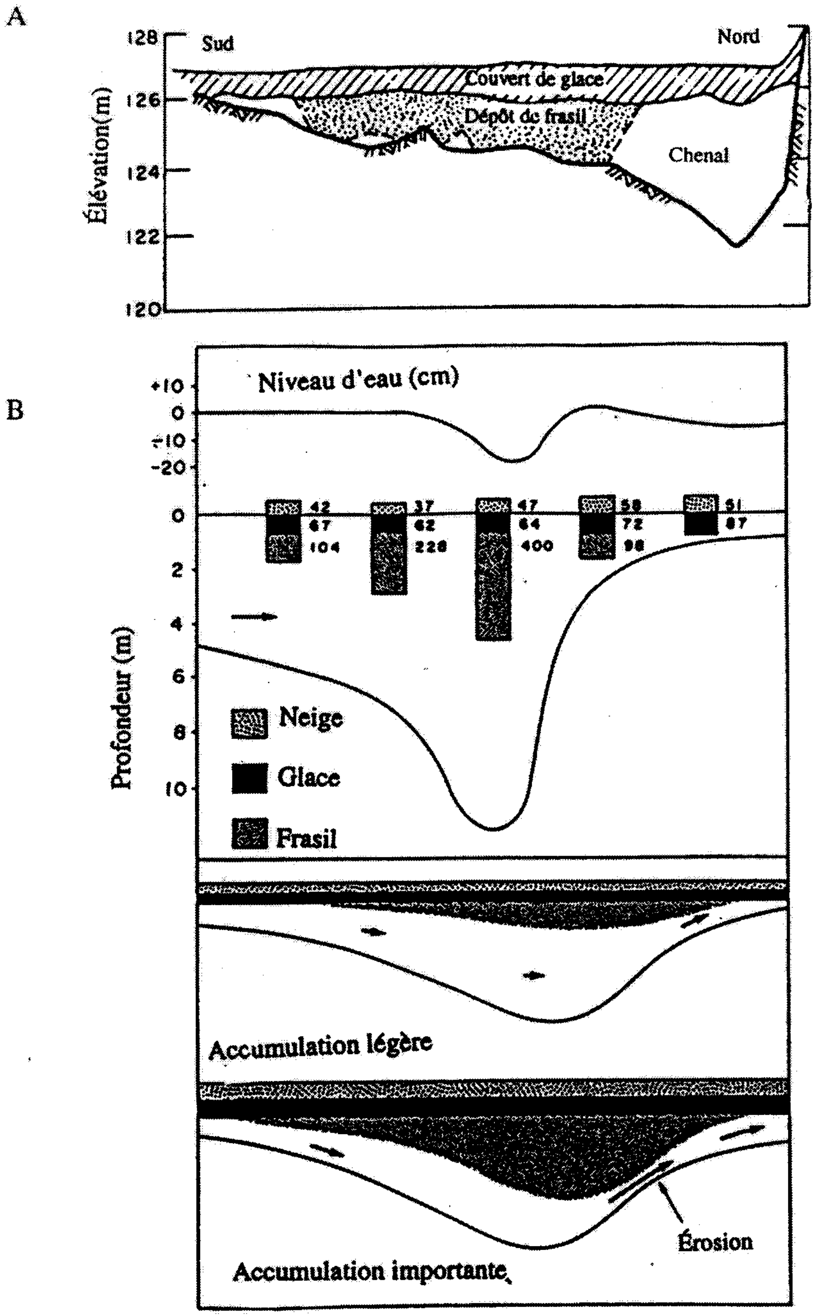

Figure 1.2 Exemples d'accumulation de frasil dans un cours d'eau. (A) Coupe transversale de la rivière Tanana en Alaska (Lawson, Chaco et Brockett 1989). (B) Coupe longitudinale d'une fosse illustrant l'impact du frasil sur l'érosion du substrat (Cunjak et Caissie 1993; Prowse et Gridley 1993).

1.4 Objectifs

Ce projet de maîtrise a pour objectif général d'étudier l'impact des processus de sédimentation et d'érosion sur les frayères et la survie intergranulaire des salmonidés. Le premier objectif spécifique consiste à déterminer l'impact de l'infiltration de sédiments fins dans le substrat des frayères sur la survie des œufs et des alevins pré-émergeants de saumon Atlantique. Le deuxième objectif spécifique consiste à évaluer l'impact potentiel du frasil sur l'affouillement du substrat des frayères à salmonidés.

1.5 Hypothèses de travail

Il a été suggéré dans la littérature que les particules fines colmatent le substrat et réduisent l'écoulement intergranulaire nécessaire pour l'oxygénation adéquate des œufs et des alevins enfouis dans les frayères. Nous posons donc l'hypothèse que les sédiments fins infiltrés dans les nids de saumon Atlantique au cours du développement intergranulaire diminuent de façon significative la survie des œufs et des alevins pré-émergeants.

Une revue de la littérature concernant l'impact de la glace fluviale sur la géomorphologie fluviale démontre que le frasil peut favoriser l'érosion du substrat des cours d'eau. Dans cette optique, nous posons comme deuxième hypothèse que le frasil accentue la profondeur d'affouillement du substrat des frayères à salmonidés.

Chapitre 2
Résumé des travaux de recherche et des résultats

2.1 Méthodologie

Les travaux ont été effectués sur la rivière Sainte-Marguerite, un tributaire de la rivière Saguenay au Québec. La branche Nord-Est de la rivière montre des chutes et des rapides qui produisent de très grande quantité de frasil au cours de l'hiver. Ce phénomène est pratiquement absent de la branche principale de la rivière. Afin d'atteindre le premier objectif du projet, nous avons installé des nids artificiels de saumons sur les branches Principale et Nord-Est et procédé à une caractérisation géomorphologique de frayères naturelles (Tableau 3.1 et Figure 3.1). Les noms de sites utilisés dans cette étude sont basés sur la terminologie utilisée par la ZEC Sainte-Marguerite, le club de pêche de l'Alcan et le Centre Interuniversitaire de Recherche sur le Saumon Atlantique (CIRSA).

Nids artificiels

À l'automne 1997, 53 nids artificiels contenant des œufs fécondés de saumons Atlantique (*Salmo salar*) ont été installés dans 6 frayères de la rivière Sainte-Marguerite (Tableau 3.1). Les nids artificiels de forme cylindrique ont été fabriqués de plastique de plomberie ABS et de filet Nitex 1mm (Figure 3.2). Au printemps 1998, lors de la période d'éclosion, les nids ont été retirés du substrat et la survie des œufs et alevins déterminée et comparée à la quantité de particules fines infiltrées dans les nids et au taux d'ensablement superficiel du substrat.

Caractérisation géomorphologique des frayères

Après la période de reproduction de l'automne 1997, nous avons caractérisé 10 frayères à saumons (Tableau 4.1) à l'aide d'échantillonnage granulométrique et de coupes topographiques transversales produites avec un théodolite digital (station totale). À chaque site, trois échantillons volumétriques du substrat ont été prélevés à l'intérieur de la zone frayée à l'aide d'une pelle et d'un déflecteur hydraulique (Figure. 2.1) (Honeywill et Driscoll 1996). Le déflecteur permet de diminuer les vitesses d'écoulement dans la zone d'échantillonnage et de récupérer dans un filet les sédiments fins remis en suspension lors de l'excavation. Les échantillons d'environ 100kg chacun ont été tamisés et la proportion de chaque classe granulométrique déterminée (Tableau 4.1). Grâce à des repères fixes, les coupes transversales ont été mesurées de nouveau à l'hiver et au printemps

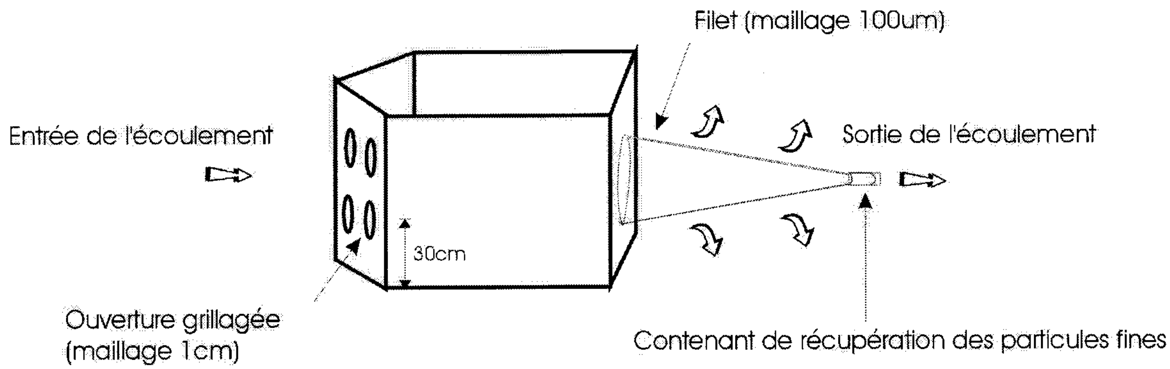

Figure 2.1 Schéma d'un déflecteur hydraulique pour l'échantillonnage granulométrique du substrat fluvial. La structure en bois permet de réduire les vitesses d'écoulement dans la zone d'échantillonnage. Les sédiments fins remis en suspension lors de l'excavation sont captés dans un filet à la sortie de l'eau.

afin d'évaluer les variations d'élévation du lit fluvial ainsi que les épaisseurs d'accumulation de glace et de frasil. De plus, l'installation automnale de 15 chaînes d'érosion (Nawa et Frissell 1993) par site dans la zone frayée, nous a permis de mesurer l'affouillement maximal du lit fluvial au cours du développement intergranulaire des œufs et des alevins. La figure 2.2 décrit de façon succincte le fonctionnement des chaînes d'érosion.

2.2 Résultats et discussion

L'infiltration des sédiments fins et la survie intergranulaire

Le tableau en annexe à ce mémoire présente la compilation des données brutes recueillies suite à la récupération des nids artificiels. L'analyse de ces données (Tableau 3.4) démontre que les sédiments fins (<1mm de diamètre) infiltrés dans les nids artificiels (Tableau 3.2) ont un effet négatif significatif sur la survie intergranulaire des saumons (Tableau 3.3). En ce qui concerne la survie jusqu'aux stades pré-oeillé (STPE) et oeillé (STE), les résultats démontrent qu'il existe une corrélation plus forte (STPE $r=-0.67$ $p<0.05$; STE $r=-0.66$ $p<0.05$) entre la survie intergranulaire et la quantité de particules les plus fines infiltrées dans les nids, soit les limons et les argiles (particules de diamètre <0.063mm). Pour ce qui est de la survie jusqu'à l'éclosion (STH), les résultats indiquent l'existence d'une corrélation plus élevée ($r=-0.76$, $p<0.05$) avec la quantité totale des sédiments inférieure à 1mm infiltrés dans les nids. Les analyses ont aussi démontré une faible corrélation positive ($r=0.47$, $p<0.05$) entre le taux d'ensablement superficiel du substrat et la survie intergranulaire jusqu'à l'éclosion.

Le frasil et l'érosion des frayères

L'analyse statistique des données fournies par les chaînes d'érosion (Figure 4.3) démontre que la profondeur de l'affouillement du substrat des frayères est significativement plus grande ($F=177.64$, $p<0.001$) en présence de bancs d'accumulation de frasil. Par exemple, au site de Trinité, 40% des chaînes ont été érodées de plus de 10cm et 13% ont été érodées de plus de 15cm (maximum 16.8cm) comparativement aux sites sans frasil où l'érosion n'a jamais dépassée 10cm.

L'analyse des coupes transversales a démontré que l'accumulation de bancs de frasil, à deux des sites à l'étude, a considérablement réduit l'aire de la coupe transversale du cours d'eau à ces sites (Figure 4.2). Nous posons comme hypothèse qu'en réduisant le chenal le frasil concentre l'écoulement, ce qui peut entraîner un accroissement de la vitesse de courant et de la force de cisaillement appliquée sur le lit fluvial. Par conséquent, l'accumulation de frasil peut favoriser

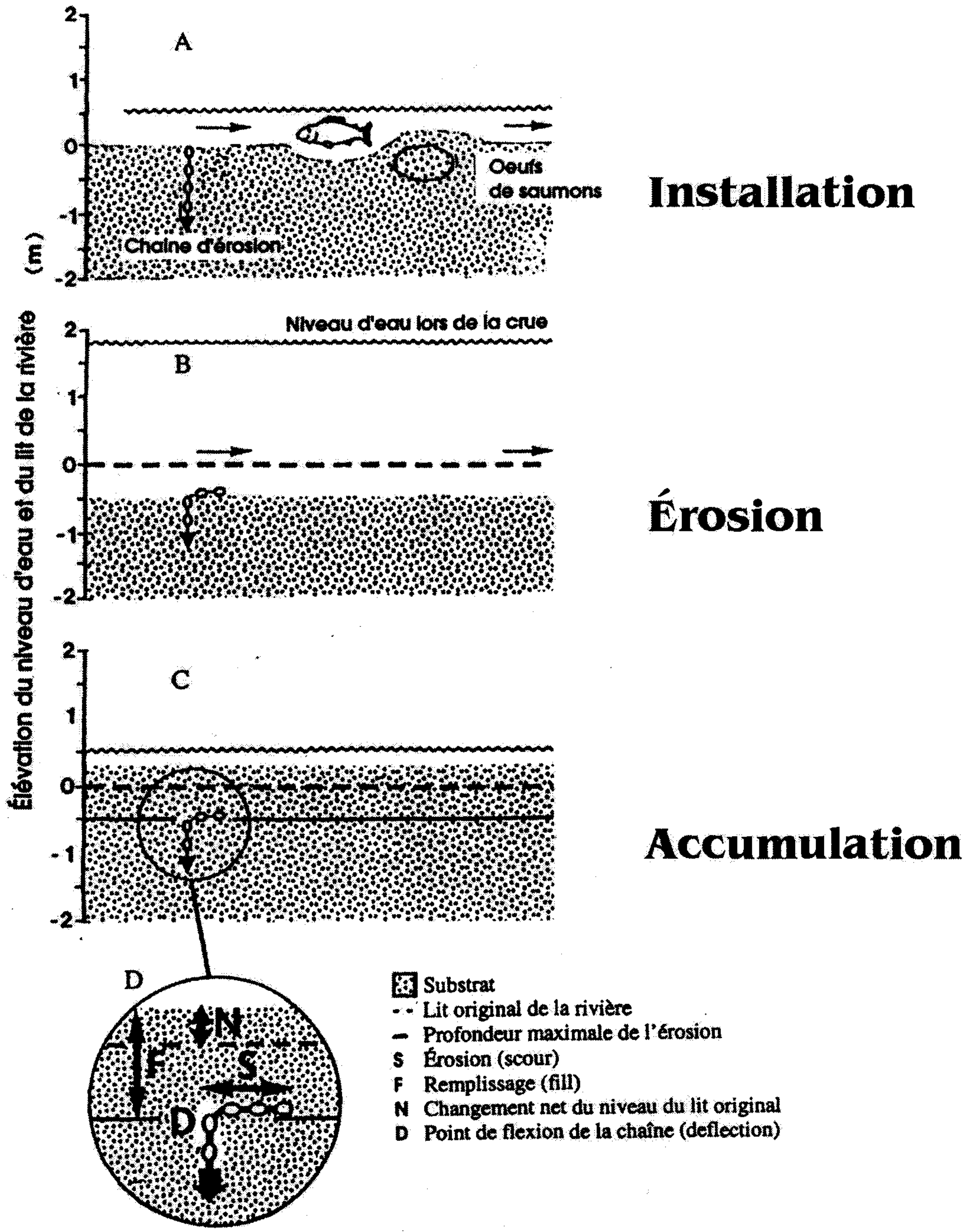

Figure 2.2 Illustration de la mesure de l'érosion et de l'accumulation du substrat d'une frayère à l'aide d'une chaîne d'érosion (modifiée à partir de Nawa et Frissell 1993). (A) Vue de côté avant la crue. (B) Érosion maximale du lit suite à une crue. L'érosion s'effectue jusqu'à une profondeur de 50 cm. Les œufs sont lessivés. La chaîne d'érosion se couche dans le sens du courant. (C) La chaîne d'érosion conserve sont point de flexion lors du remplissage. (D) Illustration de l'érosion et du remplissage et de sa mesure avec une chaîne d'érosion.

une augmentation de la profondeur d'affouillement des frayères. La figure 4.2 illustre une érosion locale du lit fluvial jusqu'à un demi mètre de profondeur dans la partie droite de la zone frayée. Même si le canal d'érosion a évité la zone d'incubation au cours de l'hiver 1997-98, une étude préliminaire effectuée à l'hiver 1996-97 nous a permis d'observer que le chenal ne se positionne pas au même endroit d'une année à l'autre. Ainsi, au cours de l'hiver 1996-97, le chenal d'écoulement se trouvait au centre de la frayère, érodant complètement 5 des 6 nids artificiels installés lors de travaux préliminaires à ceux de ce mémoire.

Il est bien connu qu'un léger approfondissement de l'affouillement du substrat peut nuire considérablement à la survie intergranulaire des salmonidés en érodant les nids (Montgomery et al. 1996) ou en facilitant la pénétration des sédiments fins dans des couches plus profondes du substrat (Lisle 1989). Nos résultats démontrent que pour les sites étudiés, l'affouillement est significativement accru en présence d'accumulation de frasil. En comparant nos résultats avec le tableau récapitulatif des profondeurs d'enfouissement des œufs de salmonidés en milieu lotique de DeVries (1997), nous constatons que les nids de plusieurs espèces de salmonidés frayant en milieu fluvial pourraient être potentiellement menacées dans un environnement d'accumulation de frasil.

2.3 Conclusion

Les processus naturels d'érosion et de sédimentation des cours d'eau ont un impact majeur sur les caractéristiques géomorphologiques des frayères ainsi que sur la survie intergranulaire des œufs et des alevins de salmonidés. Suite à leur enfouissement dans le lit des cours d'eau, les œufs de salmonidés sont exposés à des processus de sédimentation et d'infiltration de particules fines. Notre étude a démontré que les sédiments fins infiltrés dans les nids de saumon Atlantique ont un impact négatif significatif sur la survie précédant l'émergence des alevins. Par contre, nos analyses ont démontré qu'une augmentation de la quantité de sable à la surface des nids ne diminue pas la survie intergranulaire. En somme, les résultats suggèrent que la qualité du substrat d'incubation dépend de la quantité et de la taille des sédiments infiltrés ainsi que de la période au cours de laquelle la sédimentation se produit. Les résultats soulignent l'importance de mesurer l'infiltration de sédiments fins dans les nids au cours du développement intergranulaire afin d'évaluer la qualité du substrat de frai. L'analyse de la stabilité des frayères à démontré que l'accumulation de bancs de frasil sous le couvert de glace des cours d'eau peut accentuer de façon significative la profondeur d'affouillement du substrat et de ce fait même menacer l'intégrité des nids exposés et potentiellement réduire la survie intergranulaire des salmonidés.

Chapitre 3

Fine sediment infiltration into spawning gravel and Atlantic salmon (*Salmo salar* L.) intragravel survival

Fine sediment infiltration into spawning gravel and

Atlantic salmon (*Salmo salar* L.) intragravel survival

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3.1 Abstract

While the negative impact of fine sediments on successful salmonid emergence has been well documented in the past, few information is available concerning the effect of fine sediments on intragravel survival during pre-emergence life stages. This study shows the impact of fine sediments on Atlantic salmon (*Salmo salar* L.) eggs and pre-emerging fry survival. In the autumn of 1997, 53 artificial nests containing fertilised salmon eggs where installed in the substrate of six spawning sites of the Saint-Marguerite River (Saguenay, Québec). In the following spring, during the hatching period, the artificial nests were recovered and intragravel egg and sac fry survival determined. Results were compared to the quantity of fine sediments infiltrated in the nests and to the percentage of sand deposited at the bed surface. A statistical analysis showed that most pre-emergence mortality occurred before the eyeing stage, thus during the autumn and winter incubation period. A significant negative correlation between salmon intragravel survival and the percent weight of infiltrated sediments was observed. Survival to the eyed stage of development is more strongly correlated ($r = -0.66$, $p<0.05$) to very fine sediments such as silts and clays (particle diameter <0.063mm) than to coarser sediments. In contrast, survival to the hatched stage is more strongly correlated ($r=-0.76$, $p<0.05$) to the sum of all infiltrated sediments finer than 1mm in diameter. A low but significant negative correlation ($r=-0.41$, $p<0.01$) was observed between the percentage of sand deposited at the bed surface and the quantities of fine sediment infiltrated within the nests. In addition, a low positive correlation ($r=0.47$, $p<0.05$) was observed between overall survival to hatching and the percentage of sand deposited at the bed surface.

Key words: spawning habitat, fine sediment, infiltration, sac fry, egg, salmon redd, *Salmo salar*.

3.2 Résumé

Il a été démontré par le passé que la présence de particules fines dans les nids de saumon a un impact néfaste sur le succès de l'émergence des alevins de salmonidés. Toutefois, peu de travaux sont disponibles concernant l'effet des particules fines sur la survie intergranulaire des œufs et des alevins pré-émergeant. Les données présentées ici démontrent l'influence des sédiments fins sur la survie des œufs et des alevins pré-émergeant de saumon Atlantique (*Salmo salar* L.). À l'automne 1997, 53 nids artificiels contenant des œufs fertilisés de saumon ont été installés dans le substrat de six frayères de la rivière Sainte-Marguerite (Saguenay, Québec). Au printemps 1998, lors de la période d'éclosion, les nids ont été retirés. La survie des œufs et des alevins vésiculés a été déterminée et comparée à la quantité de particules fines infiltrées dans les nids ainsi qu'au pourcentage de sable déposé à leur surface. L'analyse statistique des taux de survie a dévoilé qu'une plus grande partie de la mortalité précédant l'émergence se produit avant l'atteinte du stade oeillé, donc au cours de l'automne et de l'hiver. Les résultats ont démontré qu'il existe un lien significatif entre la survie intergranulaire précédant l'émergence et la quantité de particules fines infiltrée dans les nids. La corrélation négative la plus forte entre la survie jusqu'au stade oeillé et la quantité de sédiments infiltrés est observée avec les particules de diamètre inférieur à 0.063mm, soit les limons et les argiles ($r=-0.66$, $p<0.05$). Les résultats indiquent aussi l'existence d'une corrélation négative ($r=-0.76$, $p<0.05$) entre la survie à l'éclosion et la quantité de sédiments de taille inférieure à 1mm infiltrés dans les nids. Une relation négative faible mais significative ($r=-0.41$, $p<0.01$) a été observée entre le pourcentage de sable déposé à la surface du lit fluvial et la quantité de sédiments fins infiltrés à l'intérieur des nids. De plus, les résultats ont démontré une faible relation positive ($r=0.47$, $p<0.05$) entre la survie jusqu'à l'éclosion et le pourcentage de sable déposé à la surface du lit.

3.3 Introduction

Erosion and sedimentation processes are an integral part of the natural dynamics of alluvial stream channels. When neither of these processes is dominant, a stream is said to be in equilibrium and there is a balance between the capacity of the flow to transport sediment and the volume of sediment available for transport. However, besides seasonal variations this natural equilibrium is frequently disrupted by human activities such as agriculture, mining, forestry, road construction or flow regulation (Wood and Armitage 1997). These activities may either reduce the sediment transport capacity of a stream or lead to the injection of large quantities of sediments in the fluvial system, thereby resulting in fine sediment deposition at the bed surface and infiltration within the channel substrate.

Several laboratory and field studies have shown that the presence of fine sediments within the spawning substrate of salmonids is a key factor limiting successful fry emergence (Shelton 1955; Dill and Northcote 1970; Hausle and Coble 1976; Peterson 1978; Peterson and Metcalfe 1981; Witzel and MacCrimmon 1981; Tappel and Bjornn 1983; Chapman 1988; Lisle 1989; Lisle and Lewis 1992). It is generally considered that the effect of fine sediments on salmonid eggs and fry is twofold. First, prior to emergence, fine sediments may affect survival by filling gravel pore spaces, which reduces the intragravel flow necessary for the oxygenation of incubating eggs and removal of metabolic wastes. Second, fine sediments may reduce the emergence success of fry by trapping them within the substrate. However, while the effect of fine sediments on survival-to-emergence has received considerable attention, very few studies have specifically addressed that effect on life stages prior to emergence. Since White (1942) observed a large number of dead salmon eggs in redds containing high amounts of silt and sand, Cooper (1965), Sowden and Power (1985) and Reiser and White (1988) have attempted to study the effect of fine sediments on pre-emergent mortality. While Cooper (1965) reported laboratory results showing high egg mortality in the presence of fine sediments, Sowden and Power (1985) found no significant relationship between the survival of pre-emergent salmonids and the percentage of fine sediments within natural redds. In contrats, laboratory studies conducted by Reiser and White (1988) on Chinook salmon eggs have shown that sediments finer than 0.84 mm are the most detrimental to incubating eggs. In order to elucidate the impact of fine sediments on life stages prior to fry emergence, we conducted a field experiment examining the relationship between survival of Atlantic salmon (*Salmo salar*) eggs and fry contained in artificial nests and the characteristics of fine sediments infiltrated within the nests.

3.4 Material and methods

3.4.1 Study sites

The study was conducted on the Sainte-Marguerite River, a north shore tributary of the Saguenay River, Québec, Canada. At the end of October 1997, immediately after the reproduction period of the Atlantic salmon, the Principale and Nord-Est branches of the Sainte-Marguerite River were surveyed in order to locate six stream reaches actively used by salmons for spawning and representative of various geomorphologic conditions (width, bed material size). For each reach, the zone used by salmons for spawning was delimited from the location of natural redds. Three bulk samples of the bed material were extracted from each spawning zone in order to determine the grain size characteristics of the spawning substrate. Table 3.1 presents the general physical characteristics of the selected study sites.

3.4.2 Artificial nests installation and retrieval

At each spawning site, 6 to 10 artificial nests containing a known numbers of fertilised Atlantic salmon eggs (green eggs) were buried in the substrate after the natural spawning period and retrieved immediately after the estimated hatching period. At a given site, the artificial nests were distributed evenly across the active spawning zone (Figure 3.1). The artificial nests had a cylindrical form (16 x 13 cm) and were made of ABS plastic tubing and 1mm Nitex netting (Figure 3.2). A floatable, 1 m-long, fluorescent green silicone tubing was glued to each nest in order to facilitate their localisation and recovery. Each nest contained 60 green eggs and was filled with on-site gravel ranging from 0.4 to 8 cm in diameter in order to eliminate initial fine sediment content. Eggs and milt were collected from reconditioned Atlantic salmon adults native of the Sainte-Marguerite River. The eggs were fertilised and water-hardened at the Tadoussac hatchery located approximately 25 km from river, and then transported to the field in cooled water filled jars. The eggs were kept at the same temperature as the stream water to avoid thermal shocking during artificial nest installation. In order to evaluate egg fertility and viability ratios, five hundred green eggs were kept as a control sample at the hatchery. While inserting the eggs in a nest, care was taken to distribute them evenly to prevent eventual fungal contamination from adjacent dead eggs. Once filled, the nest was closed with a plastic cap, thereby ensuring that neither eggs nor fry could enter or leave the nest.

Each artificial nest was installed using a procedure that aimed to mimic the construction and structure of a natural salmon redd. First, a depression about 30 cm deep and 75 cm wide was dug in the substrate by manually excavating the particles and pushing them downstream. The nest was then installed horizontally at the bottom of the hole with the long axis oriented perpendicularly to the flow. The centre of the nest was positioned approximately 20 to 25 cm below the surface, which is within the range of typical burial depths of Atlantic salmon eggs (DeVries, 1997). Finally, the nest was completely buried in the substrate by delicately lifting upstream particles over the nest in a manner that enabled fine particles to be swept downstream by the flow. Once installed, nests and cross sections were positioned with an electronic total station in order to facilitate their localization for the winter survey and their recovery in the following spring. In January 1998, each site was surveyed in order to assess eventual dewatering or freezing of the nests during winter low flows.

The artificial nests were retrieved from the substrate between May 16th and 21st 1998, during the hatching period. The hatching period was estimated from an hourly temperature data recorder buried within the substrate of the Glass Pool study site, and by extrapolating the degree-day hatching threshold published by MAPAQ (1996). The 12th of May was the estimated date at which 50% of the eggs would have hatched. It was considered that on May 16th, a large proportion of the surviving eggs should have hatched while most of the dead eggs would have not had the time to decompose, thereby allowing the evaluation of mortality at different pre-emergent life stages. Before extracting the nests from the substrate, a visual estimation of the percentage of sand at the surface of the bed (PSAND) was made to the nearest 5% over a $1 m^2$ quadrant above each nest. Bed particles were then gently removed until the top portion of the artificial nest was reached. The nest was then delicately pulled from the substrate and immediately put in a water filled plastic bag in order to minimise the lost of fine sediments which had infiltrated the nest.

Every nest was carefully examined in order to determine the number of eggs and fry falling into each of the following seven categories: dead pre-eyed egg (DPEE), living pre-eyed egg (LPEE), dead eyed egg (DEE), living eyed egg (LEE), dead sac fry (DSF), living sac fry (LSF) and absent or partly decomposed egg (X). The terminology used in this article for identifying salmonid intragravel life stages is based on Legendre and Bergeron (1987). Absent or partly decomposed eggs were assumed to have died during the pre-eyeing incubation period. Furthermore, since the degree-day hatching threshold at 10°C (510 deg-day) is twice that of the eyeing stage (245 deg-day) (MAPAQ 1996), we considered that living non-eyed eggs retrieved at this date would have not survived to the pre-eyeing incubation period. For each nest, three different survival ratios were calculated using the following equations:

Survival-to-pre-eyed stage of development (STPE):

$$STPE = 100 \times (DEE + LEE + DSF + LSF) / 60$$

Survival-to-eyed stage of development (STE):

$$STE = 100 \times (LEE + DSF + LSF) / 60$$

Survival-to-hatched stage of development (STH):

$$STH = 100 \times (LSF + (LEE \times Egg\_Alev)) / 60$$

where Egg_Alev is the estimated ratio of live eyed eggs (LEE) which would eventually have successfully hatched and survived (LSF). The use of this equation supposes that all LEE retrieved at this period would have reached the hatched stage either dead or alive. Egg_Alev was calculated from the following equation developed for each nest:

$$Egg\_Alev = LSF / (LSF + DSF)$$

The sediments contained in each artificial nest were oven-dried and weighted to obtain the total dry-weight of sediments. The size fraction smaller than 1mm was sieved and analysed separately in order to determine the amount and size distribution of particles that infiltrated through the 1mm netting of the artificial nests. The proportion of infiltrated sediments in each nest was then determined for cumulative sample weights less than 1mm, 0.5mm, 0.25mm, 0.125mm and 0.063mm. A non-parametric Kruskal-Wallis test was used to test for the heterogeneity of fine sediment infiltration and salmonid intragravel survival among sites. The effect of fine sediment infiltration on pre-emerging salmon survival was analysed by performing correlation analysis between the infiltrated sediment data and the survival ratios measured for each nest. Correlation analysis was also performed between the percentage of sand measured at the bed surface of each nest (PSAND) and the total percent weight of infiltrated sand and salmon survival ratios.

3.5 Results

3.5.1 Winter conditions

The observations made during the winter of 1998 indicated that none of the artificial nests were subjected to dewatering or freezing. However, a substantial accumulation of frazil ice was observed over the artificial nests of the Trinité study site. Although frazil ice extended throughout the water column and covered the entire spawning area, a thin water layer, approximately 1-5 cm deep, was observed over the bed surface, thereby preventing dewatering of the nests or freezing of the incubating eggs.

3.5.2 Artificial nests recovery and salmon intragravel survival

Artificial nest recovery

The overall recovery success of the artificial nests was 87% (Table 3.2). One nest was eroded and lost at the Xavier study site, whereas six nests were either partially or completely eroded at the Ilet study site. For the remaining four artificial nests of the Ilet study site, difficult field conditions due to high spring flows caused fine sediments to be washed away from the nests during their retrieval from the substrate. These nests were thus analysed for egg and fry survival, but not for particle size distribution.

Intragravel survival

At the time of nests retrieval, 55% of the planted eggs were hatched (13% dead and 42% live), while 12% were at the eyed stage (3% dead and 9% live) and 24 % were at the pre-eyed stage (21% dead and 3% live). The remaining 9% were either eggs lost or decomposed beyond recognition of their developmental stage. Table 3.3 presents the mean survival ratios STPE, STE and STH calculated for each site and for the total number of nests retrieved. The survival ratios obtained for each nest were also used to calculate the temporal distribution of mortality among the various developmental stages. An analysis of variance ($F = 14.83$, $p < 0.001$) and a Tukey HSD test ($p < 0.001$) indicated that the mortalities observed in the artificial nests are significantly different among all developmental stages. The results revealed that of the overall 52% mortality that occurred during the pre-emergence life stages, a significantly greater number of salmons died at the pre-eyed stage (34%) while mortality was much lower at the eyed stage (3%) and intermediate at the hatched stage (15%). The observed high mortality prior to hatching (37%) was not due to poor egg quality since the control sample of green eggs kept at the Tadoussac hatchery had an overall mortality of only 7.6% (N=500) up to the eyed stage of development.

3.5.3 Relation between salmon survival and fine sediments

Site comparison of fine sediment infiltration and salmonid survival

Table 3.2 presents the mean percent weight of particles infiltrated in the artificial nests of each site. Comparison of fine sediment infiltration among sites using a Kruskal-Wallis test showed that the sites are significantly heterogeneous ($p<0.05$). The same analysis applied to the survival ratios presented in table 3.3 revealed that survival up to all three developmental stages are also significantly ($p<0.05$) heterogeneous among sites. These results indicate that the selected spawning sites are representative of various fine sediment infiltration conditions and spawning habitat quality.

Infiltrated fine particles

Table 3.4 presents a correlation matrix between the three survival ratios and the five classes of infiltrated fine particles analysed in this study. The table shows that all observed relations are negatively correlated therefore intragravel survival decreases when the percentage of fine sediments infiltrated within the nests increases. However, some differences in the strength of these relations are observed. In the case of STPE and STE, correlations with the percent weight of cumulative size classes of infiltrated sediments finer than 1mm is not significant once the Bonferroni correction is applied. However, correlations are significant with the percent weight of all cumulative particle classes finer 0.5mm. In addition, the table also reveals that the strength of the relation increases as the size of infiltrated sediments decreases, the highest correlation being obtained with particles finer than 0.063mm ($r=-0.66$, $p<0.05$). In contrast with the results obtained for STPE and STE, STH is more strongly correlated with the percent weight of cumulative size class of particles finer then 1mm ($r=-0.76$, $p<0.05$) than with finer particles.

Particles deposited at the bed surface

In the present study, the observed percentage of sand deposited at the bed surface ranged from 0 to 30%. In contrast to expected results, the observed relation between PSAND and the quantity of particles infiltrated within the artificial nests revealed a low negative correlation ($r=-0.41$, $p<0.01$). These results indicate that quantities of infiltrated fine sediments decreases when PSAND increases. This may explain why the observed intragravel survival does not decrease when PSAND increases. In fact, a correlation analysis between PSAND and intragravel survival showed a weak but significant positive correlation ($r=0.47$, $p<0.05$) with STH once the Bonferroni correction (α_b=0.05/number of correlations=0.05/3) is applied. However no significant correlation was found with STPE and STE.

3.6 Discussion

3.6.1 Intragravel survival

A literature review of Atlantic salmon pre-emergence survival revealed that reported survivals up to distinct developmental stages are quite variable among studies and in comparison with the results obtained in the present study. In contrast with the low pre-eyed survival 66% (SD=21) observed in our study, Mackenzie and Moring (1988) found an average survival to the pre-eyed stage of 95% (SD=2.9). Furthermore, Mackenzie and Moring (1988) and Jordan and Beland (1981) obtained survivals to the eyed stage of 89% (SD=4.2) and 93% respectively, which is higher than our 63% (SD=22) survival rate. In comparison with the 48% (SD=29) survival to the hatched stage of our study, mean survival ranges from 13 to 88% in reviewed literature (Lacroix 1985; Mackenzie and Moring 1988; Pauwels and Haines, 1994). For example, Pauwels and Haines (1994) reported that survival to the hatched stage ranged from 7 to 61% in their study, while Mackenzie and Moring (1988) obtained a survival up to the hatched stage of 74%.

These discrepancies in mean survival to various life stages may be attributed to two main factors. First, the observed variability may be due to the experimental protocol. Rubin (1995) pointed out that the characteristics of artificial nests *in vivo* or *in vitro* may not be exactly identical to those of natural redds. He also suggested that early embryonic survival may be overestimated when using redd excavation techniques of survival estimations by neglecting to include, in survival calculations, naturally occurring egg disappearance by gravel movement, predation and decomposition. A second factor that may explain the survival variability reported in published data is the local spawning site environment. The results obtained in the present study have shown that intragravel survival and fine sediment infiltration are significantly heterogeneous among spawning sites. Consequently, observed differences in intragravel survival among studies may be attributed to environmental factors such as fine sediment transport, deposition and infiltration rates which may vary from one river to another and also among spawning sites in the same river.

3.6.2 Fine sediment infiltration and intragravel survival

Most of the mortality observed in the present study occurred before the eggs reached their eyed stage of development. Extrapolation of the degree-day hatching threshold data provided by the MAPAQ (1996) indicates that approximately 50% of the eggs should have reached the eyed stage before February 12th 1998 This suggest that most of the mortality occurred before mid-winter. This result, combined to the observed significant correlation between survival to the pre-eyed stage and fine sediment infiltration, suggest that fine sediment infiltration must have occurred before mid-winter. Although the temporal variation of fine sediment infiltration during the incubation period of salmonids is still unknown, we suggest that the onset of winter may have caused a marked decrease of the transport capacity of the river, which resulted in fine sediment deposition and infiltration within the spawning gravel. This reduction of transport capacity could have followed from the decrease of discharge generally observed when precipitation switches from rain to snow and from the additional resistance to flow associated to the formation of the ice cover (Prowse et Gridley, 1993).

Reiser and White (1988) suggested that although oxygen demand is low in early embryonic development, sediment accumulations during initial egg development may result in higher mortalities than accumulations that occur after the circulatory system becomes functional which is about the time of the eyed stage of development. Our correlation analysis between pre-eyed and eyed survival and the quantity of infiltrated fine sediments also revealed that the strength of this negative relation increases with finer particle sizes. It is believed that finer infiltrated sediments such as silts and clays, which have a lower permeability than coarser sediments (Freeze and Cherry 1979), may have a greater impact on intragravel inflow of oxygen rich water to incubating embryos. It is also hypothesised that small amounts of infiltrated silts and clay may adhere to the incubating embryos and thus reduce diffusion of gases through their enveloping chorion and thus limit intragravel survival.

Present results have also shown that mortality is very low during the eyed stage of development and that a significant 15% drop in survival occurred when the eggs reach the hatched stage. These results suggest that the hatching period may be an important threshold for intragravel survival, especially since oxygen demand is maximum at that stage (Davis 1976). Mackenzie and Moring reported a mean egg and fry survival of 74% up to the hatching period, which however dropped to 13% four weeks later, but prior to emergence. This could imply that the mortality measured in the present study might have been more important if the nests would have been retrieved later in their pre-emergence development. Despite early nest retrieval, correlation analysis revealed that infiltrated sediments finer then 1mm significantly influenced survival to the hatched stage. Reiser and White (1988) reached similar conclusions in laboratory tests with Chinook salmon eggs and found that the sum of sediments finer that 0.84mm are the most detrimental to overall survival to the hatched stage. By filling interstitial pore spaces, fine sediments may limit movement of hatching embryos and reduce intragravel flow of oxygen rich water essential for intragravel survival (Chapman 1988).

3.6.3 Superficial sand content and intragravel survival

The present study revealed a significant negative relation between the percentage of sand at the bed surface and the amount of infiltrated sediments within the bed. This result may be explained by the formation of a sand seal in the upper layer of the fluvial gravel. Beschta and Jackson (1979) found that coarser infiltrating sediments (0.5 mm diameter) formed a seal in the upper layers of the fluvial substrate by bridging the voids of adjacent gravels. The formation of a similar sand seal may have protected intragravel pore spaces and salmon egg pockets by preventing further downward migration of deposited sand into the redd structure. This could explain the significant positive relation observed between the percent of sand at the bed surface and the overall survival up to the hatched stage. However, while the presence of a sand seal may have a potential positive effect on incubating eggs, it may also entomb emerging fry and thus significantly lower overall survival to emergence.

3.7 Conclusion

Once buried, incubating embryos and fry are subjected to sedimentation and infiltration of fine particles that may clog interstitial pore spaces. In this paper, we have shown that an important limiting factor for Atlantic salmon pre-emergence survival is the infiltration of fine sediments in the redds. A significant relationship was found between quantities of infiltrated fine sediments in the artificial nests and intragravel pre-emergence survival. The results suggest that the suitability of incubating gravel depends on how much, what size, and when sediments are transported and infiltrated. This result supports the suggestion of Lisle and Lewis (1992) that the key to embryo survival is not the condition of spawning gravel before or immediately after spawning but during the several weeks and months of incubation. Finally, a significant positive relation was observed between percent of sand at the bed surface and overall survival to the hatched stage. It is hypothesised that the presence of a sand seal may have impeded further migration of deposited sand into lower layers of gravel and protected incubating eggs from further fine sediment infiltration into the nest.

3.8 Acknowledgements

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Table 3.1 Characteristics of selected spawning sites on the Sainte-Marguerite River, Saguenay (Québec).

		Channel	Bed material size			Number of redds	
	Sites	Width (m)	D16 (mm)	D50 (mm)	D84 (mm)	Natural	Artificial
Principale branch	Cascades	7	3.1	29.2	63.8	6	8
	Glass pool	42	3.2	36.7	78.2	> 15	9
	Épinette	53	1.2	33.9	116.9	> 15	10
Nord-Est branch	Xavier	8	7.2	64.0	133.3	1	6
	Ilet	27	*	*	*	> 10	10
	Trinité	58	9.2	50.4	87.8	> 15	10

* Data not available due to high flow conditions

Table 3.2 Mean percent weight of cumulative particle sizes infiltrated in the artificial nests of each site.

Sites	Ni	Nr	< 1mm	< 0.5mm	< 0.25mm	< 0.125mm	< 0.063mm
Cascades	8	8	3.34 (1.37)	1.76 (0.90)	0.46 (0.28)	0.12 (0.07)	0.03 (0.02)
Glass pool	9	9	3.95 (3.95)	3.14 (3.78)	1.5 (2.72)	0.33 (0.71)	0.06 (0.12)
Épinette	10	10	10.31 (6.64)	7.18 (5.38)	2.34 (1.93)	0.28 (0.29)	0.05 (0.06)
Xavier	6	5	29.24 (12.92)	9.71 (5.17)	1.94 (1.23)	0.33 (0.23)	0.05 (0.03)
Ilet	10	4	*	*	*	*	*
Trinité	10	10	27.25 (10.75)	15.53 (6.89)	6.4 (3.70)	1.69 (1.04)	0.41 (0.20)

* Fine sediments lost due to very high spring flow conditions.
Ni = number of nests installed; Nr = number of nests retreived
Standard deviations in brackets.

Table 3.3 Mean percent survival-to-pre-eyed, survival-to-eyed and survival-to-hatched developmental stages at study sites.

Sites	Pre-eyed (STPE)	Eyed (STE)	Hatched (STH)
Cascades	72 (8)	68 (11)	63 (14)
Glass pool	66 (16)	64 (17)	59 (19)
Épinette	85 (9)	85 (10)	71 (15)
Xavier	55 (9)	53 (14)	30 (22)
Ilet	68 (5)	60 (6)	49 (17)
Trinité	49 (26)	45 (26)	11 (15)
Total mean*	66 (21)	63 (22)	48 (29)

* Calculated from the total number of nests retreived (N=46).
Standard deviations in brackets.

Table 3.4 Correlation matrix between salmon intragravel survival ratios at various development stages and proportion of infiltrated fine particles in the 42 recovered artificial nests.

Particle diameter (mm)	Pre-eyed (STPE) (r)	Eyed (STE) (r)	Hatched (STH) (r)
< 1	-0.41 (0.0063)	-0.39 (0.0098)	-0.76* (0.0000)
< 0.5	-0.50* (0.0007)	-0.48* (0.0014)	-0.72* (0.0000)
< 0.25	-0.58* (0.0001)	-0.56* (0.0001)	-0.65* (0.0000)
< 0.125	-0.66* (0.0000)	-0.65* (0.0000)	-0.67* (0.0000)
< 0.063	-0.67* (0.0000)	-0.66* (0.0000)	-0.69* (0.0000)

Significance level (p) in brackets.
* Marked correlation coefficients are significant at $p<0.05$ using the Bonferroni correction procedure (α =0.05/(number of correlations) =0.05/15).

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Figure 3.1 Plan view of Glass Pool study site with position of transects, and salmon natural redds and artificial nests.

Figure 3.2 Sketch (top view) of an artificial salmon nest made of 1mm Nitex netting and ABS plastic tubing.

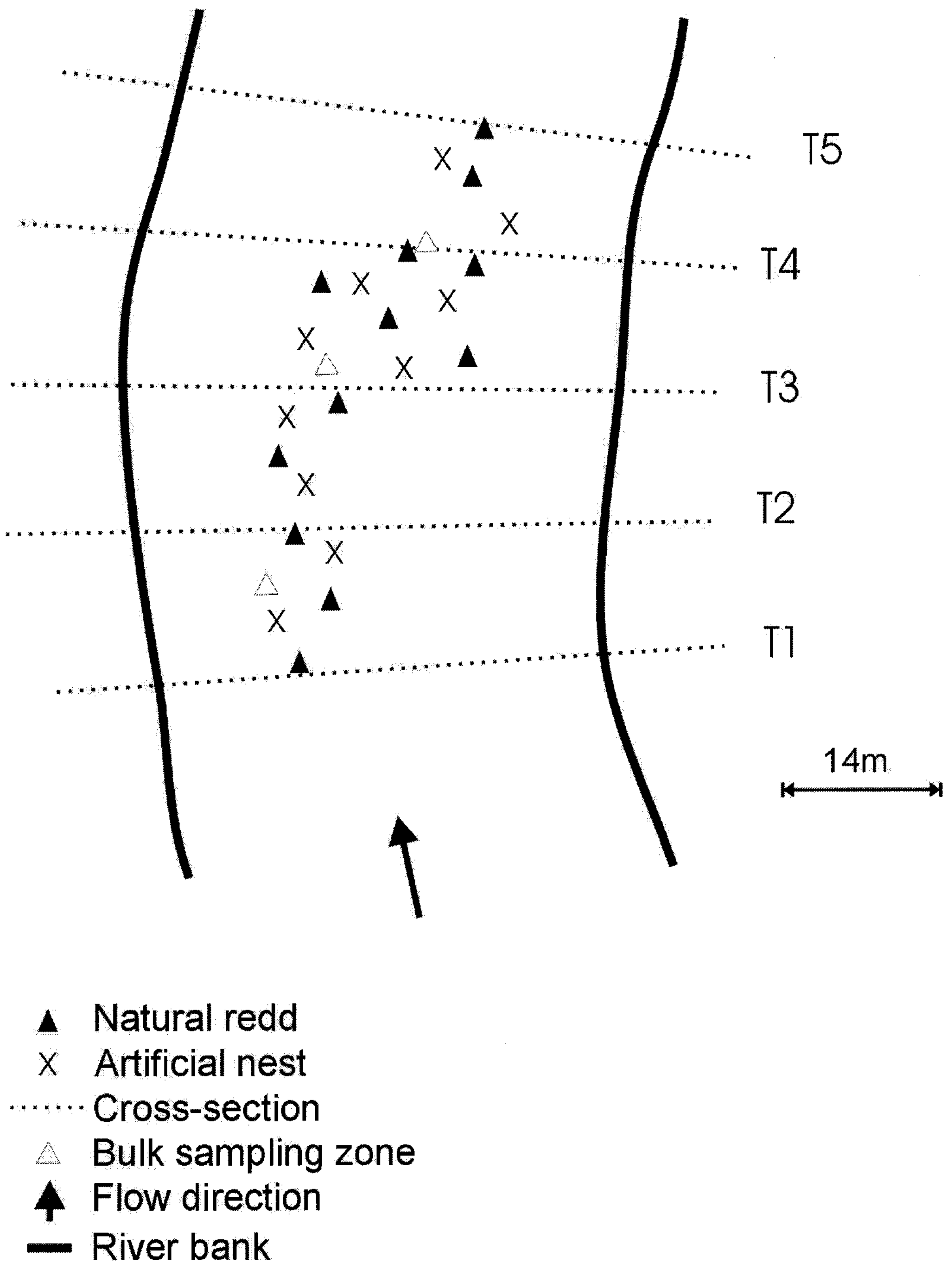
T5
T4
T3
T2
T1
14m
Natural redd
Artificial nest
Cross-section
Bulk sampling zone
Flow direction
River bank

Figure 3.1

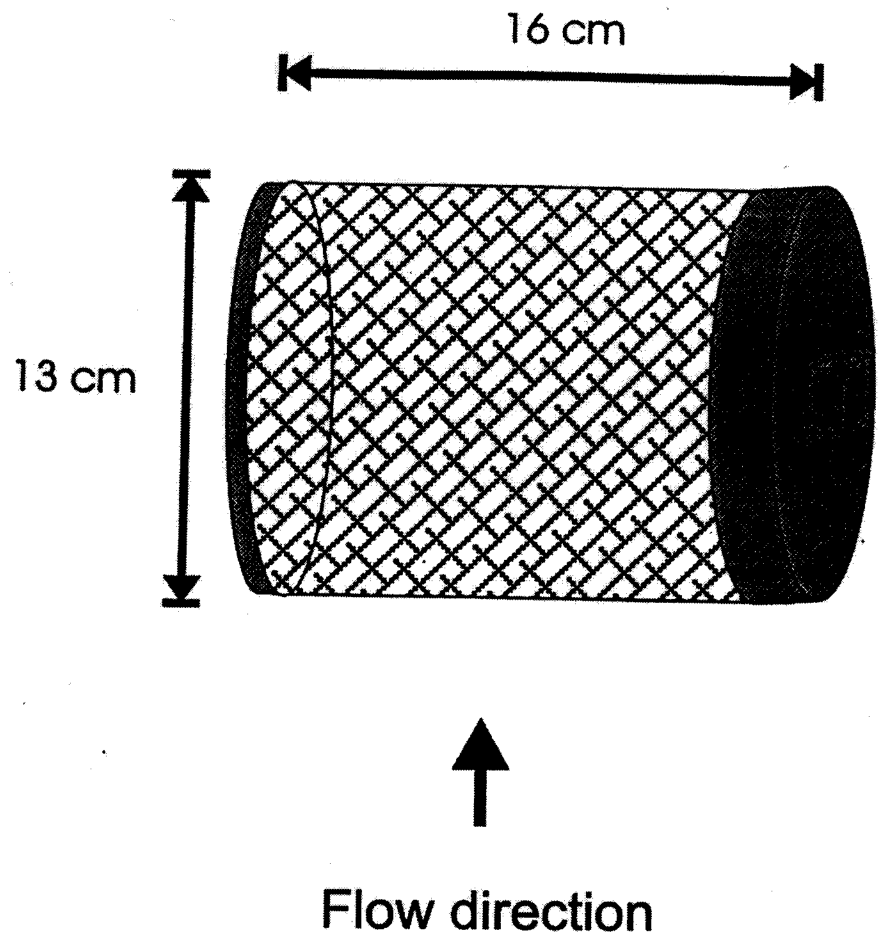

Figure 3.2

Chapitre 4

Scouring of riverine salmonid spawning gravel in a frazil ice environment

Scouring of riverine salmonid spawning gravel in a frazil ice environment

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4.1 Abstract

This paper reports the results of a study that was planned to investigate the potential effect of frazil ice on the stability of salmonid spawning gravel. The study was conducted on the Sainte-Marguerite River, a north shore tributary of the Saguenay River, Québec, Canada. In October 1997, scour chains were installed and cross-sections were surveyed at six stream reaches actively used by Atlantic salmon (*Salmo salar*) for spawning. A winter survey of the sites indicated the presence of large frazil ice accumulations at two of the six sites. In June 1998, scour depth information were recorded from the scour chains and comparisons were made among sites. Statistical analysis of the scour depth data showed that sites where large accumulations of frazil ice occurred over the winter period were scoured significantly deeper than sites where no frazil ice accumulated. Greater scouring in frazil ice environments is probably due to partial blockage of the cross-section by frazil ice, leading to flow concentration and scouring of the bed. However, additional scouring of the bed could have also been produced during the ice break-up period when the mobilisation of large volumes of frazil ice may have directly eroded the bed surface. These results suggest that frazil ice represents a potential hazard for incubating salmonid embryos and fry.

Keywords: frazil ice, spawning gravel, scour depth, salmonid.

4.2 Résumé

Cet article présente les résultats de travaux de terrain dont le but était d'étudier l'effet de la glace de frasil sur la stabilité du substrat des frayères à salmonidés. L'étude a été réalisée sur la rivière Sainte-Marguerite, un tributaire de la rive nord de la rivière Saguenay, Québec, Canada. Au mois d'octobre 1997, des coupes transversales ont été mesurées et des chaînes d'érosions installées dans le substrat de six frayères à saumon atlantique (*Salmo salar*). Des données récoltées au cours de l'hiver ont permis d'observer la présence d'importantes accumulations de glace de frasil à deux des six sites à l'étude. Au mois de juin 1998, les données d'érosion du substrat ont été mesurées à partir des chaînes d'érosion et comparées entre les sites. L'analyse statistique de ces données d'érosion a démontré que la profondeur d'érosion maximum du substrat est significativement plus grande pour les sites avec frasil que pour les sites sans frasil. Ce résultat est probablement lié au blocage partiel du chenal par le frasil qui a eu pour effet de concentrer l'écoulement et de causer l'érosion du lit. Cependant, il est possible qu'une érosion additionnelle se soit produite lors de la débâcle, alors que la mobilisation de la grande masse de frasil a probablement causée une érosion directe du substrat. Ces résultats suggèrent que la glace de frasil entraîne une plus grande instabilité du substrat de fraie des salmonidés et constitue, par le fait même, un risque pour la survie des œufs et des alevins.

4.3 Introduction

Many salmonid fishes, such as salmon, trout and char, bury their eggs in the substrate of gravel bed streams where they develop, hatch and eventually emerge as free swimming fry. Depending on the species and on the size of the female fish, typical egg burial depth ranges from 3 to 50 cm and the duration of intragravel development varies from 2 to 8 months (Crisp and Carling, 1989; DeVries, 1997). During this relatively long period of development, the spawning gravel is subjected to a variety of fluvial processes, which may contribute to reduce survival-to-emergence. For example, it has long been recognised in the literature that sediment transport events often scour the bed sufficiently to cause direct mortalities by entraining and killing incubating embryos and fry (McNeil, 1964; Duncan and Ward, 1985; Holtby and Healy, 1986; Carling, 1987; Lisle, 1989; Kondolf *et al.*, 1991; Montgomery *et al.*, 1996; Schuett-Hames *et al.*, 1996; Harvey and Lisle, 1999). It has also been suggested that partial scouring of the substrate above the egg pocket may be detrimental to fish survival by exposing deeper levels of the fluvial bed to the infiltration of fine sediments which may in turn affect survival by reducing the intragravel flow necessary to the oxygenation of developing eggs and fry (Lisle, 1989).

Streambed scouring is generally produced by high discharge events generating large flow shear stress values capable of moving the bed material. In such situations, it has been shown that a functional relationship exists between scour depth and water discharge (Leopold *et al.*, 1966; Carling, 1987; Hassan, 1990). However, in cold environments, streambed scouring is not only related to water discharge alone but also to various river ice processes. Most of the available information concerning the scouring effect of river ice relates to processes associated with the formation and break-up of ice-jams (e.g. Mercer and Cooper, 1977; Wuebben, 1988; Beltaos 1993; Scrimgeour *et al.*, 1994). However, streambed scouring has also been observed in association with extensive accumulation of frazil ice (Zhenwen, 1988; Prowse, 1994). Frazil ice is composed of fine ice crystals which form in the turbulent supercooled water of stream riffles, rapids and falls. In such areas, water supercooling is attained because of the absence of a static ice-cover, which enhances heat loss from the river to the cold atmosphere (Michel, 1971; Osterkamp, 1978; Beltaos, 1993). Frazil ice crystals are initially small but they tend to agglomerate and form flocs that are transported near the water surface or the underside of the ice because of their buoyancy (Shen and Wang, 1995). Frazil is transported downstream until it reaches stream areas where water velocity is sufficiently low to allow deposition. Frazil ice deposits are found beneath the ice covers of slow flowing pools (Michel and Drouin, 1981; Cunjak and Caissie, 1994; Cunjak *et al.*, 1998) and along irregularities of the bed, banks, and ice cover base (Lawson *et al.*, 1986). Because these deposits may extend over the entire flow depth and occupy a large proportion of the cross-section, they sometimes force the water to flow within only the deepest and highest velocity portions of the river channel (Prowse, 1994; Yamazaki *et al.*, 1996). This situation may produce high bed shear stress and sediment transport (Lawson *et al.*, 1986) thereby causing local scouring of the bed.

Although streambed scouring due to frazil ice may represent a potential hazard for incubating eggs and fry, the implication of this process on the stability of salmonid spawning gravel has never been addressed in the past. In this paper, we compare scour depth data obtained from Atlantic salmon (*Salmo salar*) spawning sites in the presence and absence of frazil ice accumulation in order to assess the potential effect of frazil ice on the stability of salmonid spawning gravel.

4.4 Material and methods

4.4.1 Study sites

The study was conducted on the Sainte-Marguerite River, a north shore tributary of the Saguenay River, Québec, Canada. The Sainte-Marguerite River basin is divided in two main drainage units: the Principale and Nord-Est branches. The two basins are of comparable size (Principale: 100km^2, Nord-Est: 114km^2) and both support an indigenous population of Atlantic salmon (*Salmo salar*). In contrast with the Principale branch, the Nord-Est branch is characterised by the recurrent production and accumulation of large volumes of frazil ice during the winter period. Most of the frazil ice is produced in the downstream portion of the stream, approximately between kilometres 5 and 10 above the confluence of the Nord-Est with the Principale branch. In this portion of the river, several large rapids and one major river falls remain partially free of ice-cover for most part of the winter, thereby exposing large surface areas of water to the very cold winter temperature of the air. This situation results in supercooling of water and production of large amounts of frazil ice throughout the winter season. Downstream from the frazil ice production zone, slower flow velocities associated to the gentler stream gradient favours the accumulation of frazil ice in pools, along the stream margins, and upstream from major flow obstacle such as islands, bars and shallow riffles

At the end of October 1997, immediately after the reproduction period of Atlantic salmon, the Principale and Nord-Est branches of the Sainte-Marguerite River were surveyed in order to locate six stream reaches actively used by salmons for spawning. Three reaches were selected on the

Principale branch and three on the Nord-Est branch. On the Nord-Est branch, one site was selected upstream and the two other downstream from the frazil ice production zone.

4.4.2 Cross-sections surveys and scour chain measurements

At each site, the zone used by salmons for spawning was delimited from the position of salmon redds. Between the upstream and downstream limit of this zone, five cross-sections were established and surveyed in November 1997 (Figure 4.1). Fifteen scour indicators were installed throughout the spawning zone of each site in order to obtain scour depth measurements. Five scour indicators were placed along each of the three central cross-sections of a spawning zone (Figure 4.1). The scour indicators consisted of 60 cm-long steel chains inserted vertically within the substrate. In January 1998, the three central cross-sections of each site were surveyed by drilling holes through the ice cover in order to obtain measurements of bed surface elevation, ice cover thickness, frazil ice accumulation and water depth. At least five holes were drilled at each of the three central cross-sections surveyed at each site. In June 1998, the scour chains were removed from the substrate and the maximum scour depth recorded following the method described by Nawa and Frissell (1993) and Laronne *et al.* (1994). At the same time, three 100kg bulk samples of the bed material were extracted from each spawning zone in order to determine the grain size characteristics of the spawning substrate, except for site Red Bank where bed material could not be sampled because of high flow conditions. Table 1 presents the general physical characteristics of the studied sites.

4.5 Results and discussion

4.5.1 Cross-sections data

The results of the winter survey indicated that sites La Cache, Glass Pool, Épinette and Ulysse remained free from frazil ice deposits during the winter period. However, as expected from previous winter surveys on the Sainte-Marguerite River, substantial accumulation of partly consolidated frazil ice were found at sites Red Bank and Trinitié of the Nord-Est branch. At these sites, frazil ice deposits respectively occupied 63% and 72% of the surface area of the ice-covered stream. The deposits generally extended throughout the water column but a thin layer of water less than 5 cm deep was often measured immediately above the bed surface. Figure 4.2 shows an example of a typical accumulation frazil ice at a cross-section. The data used for this example were measured at cross-section T4 of site Trinité. On this figure, the solid line shows the bed cross-section as measured in November 1997, the open squares correspond to the local bed elevation measured in January 1998, and the solid circles show the position of the scour chains. It can be seen from this figure that most of the left and central part of the cross-section was occupied by frazil ice, and that a small channel, approximately 15 m wide and 50 cm deep, was scoured near the right bank of the channel, probably as a result of flow concentration and increased flow shear stress caused by the partial blockage of the cross-section by frazil ice. This configuration is very similar to the sub-ice channels and longitudinal frazil bars described by Lawson *et al.* (1986) in the Tanana River, Alaska.

4.5.2 Scour depth data

In June 1998, all scour chains were successfully recovered from the substrate of the surveyed sites. However, at site Red Bank, two scour chains seemed to have been slightly pulled out of the substrate. Thus, the scour depth information provided by these two chains was excluded from the analyses. Figure 4.3 summarises the results of the scour depth data determined from the scour chains. This figure shows that between November 1997 and June 1998, mean scour depth values were less than 5 cm at sites La Cache, Glass Pool, Épinette and Ulysse. These small scour depth values are due to the unusually low spring flow conditions, which prevailed in 1998. However, Figure 4.3 also indicates that scouring was much more important at sites Red Bank and Trinité where mean scour depth values of 10.6 cm and 15.3 cm were respectively measured. The results of an ANOVA indicated that the mean scour depth value of at least one site was significantly different from the others ($F = 37.68$, $p<0.001$). A planned comparison of mean scour depth values among sites with and without frazil ice accumulations demonstrated that there was a highly significant difference between the scour depth values of the two groups of sites ($F=177.64$, $p<0.001$). Therefore, statistical analysis of the scour depth data measured in this study show that spawning sites where large accumulations of frazil occurred over the winter period were more deeply scoured than sites where no frazil ice accumulated.

On the basis of the observations and measurements made for this study, greater scouring of spawning gravel in frazil ice environments is probably due to partial blockage of the cross-section by frazil ice leading to flow concentration and scouring of the bed. In such cases, scouring would tend to be linear and parallel to flow direction. Additional scouring of the bed can also be produced during the ice break-up period, when the mobilisation of large volumes of frazil ice may directly erode the bed surface. Such process would then more likely result in a planar erosion of the streambed surface.

4.5.3 Implication for salmonid egg and fry survival

According to the 15 to 30 cm egg burial depth criteria proposed by DeVries (1997) for Atlantic salmon, the stream bed scouring values measured within the spawning zones of our study were not large enough to have caused any mortalities to the incubating eggs by directly scouring the redds. However, deeper scouring of the bed at frazil ice sites might have been detrimental to the development of the eggs and fry by exposing deeper level of the substrate to the infiltration of fine sediments.

Because the newly scoured channel observed at site Trinité was located just outside from the spawning zone (corresponding to the position of the scour chains on Figure 4.2), it did not affect the Atlantic salmon redds that year. However, field observations made the previous winter at the same location indicated that a similar channel was scoured in the central part of the zone used by salmon for spawning, where it probably eroded several salmon redds. These observations corroborate those of Lawson *et al.* (1986) indicating that the exact location and dimension of sub-ice channels and frazil deposits may vary from year to year. Thus, despite the fact that frazil ice accumulations usually form at the same stream reaches year after year, their exact morphology, position and scouring effects appear to be highly variable, thereby conferring a very unpredictable character to the stability of salmonids redds in frazil ice environments.

Despite the evidences presented in the present study, it is difficult to assess the overall significance of the effect of frazil ice on incubating eggs and fry because no other comparable work has been done in the past. It is therefore suggested that more studies of this type should be conducted in a variety of fluvial environments and for various salmonid species.

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Table 4.1 Characteristics of selected spawning sites on the Sainte-Marguerite River, Saguenay, Québec 1997.

	Sites	Channel Width (m)	Bed material size D16 (mm)	D50 (mm)	D84 (mm)
Principale branch	La Cache	18	2.3	25.7	72.5
	Glass pool	42	3.2	36.7	78.2
	Épinette	53	1.2	33.9	116.9
Nord-Est branch	Ulysse	37	6.2	40.5	105.3
	Trinité*	58	9.2	50.4	87.8
	Red-Bank*	52	--	--	--

* Sites with frasil ice accumulations

-- Data not available

List of figures

Figure 4.1 Plan view of Glass Pool study site with position of transects and scour chains.

Figure 4.2 Frazil ice accumulation and scouring of the fluvial bed at cross-section T4 in January 1998 at Trinité site.

Figure 4.3 Summary of scour depth data obtained from scour chain measurements. Based on 15 measurements at each site, except for site Red Bank where only 13 measurements were obtained.

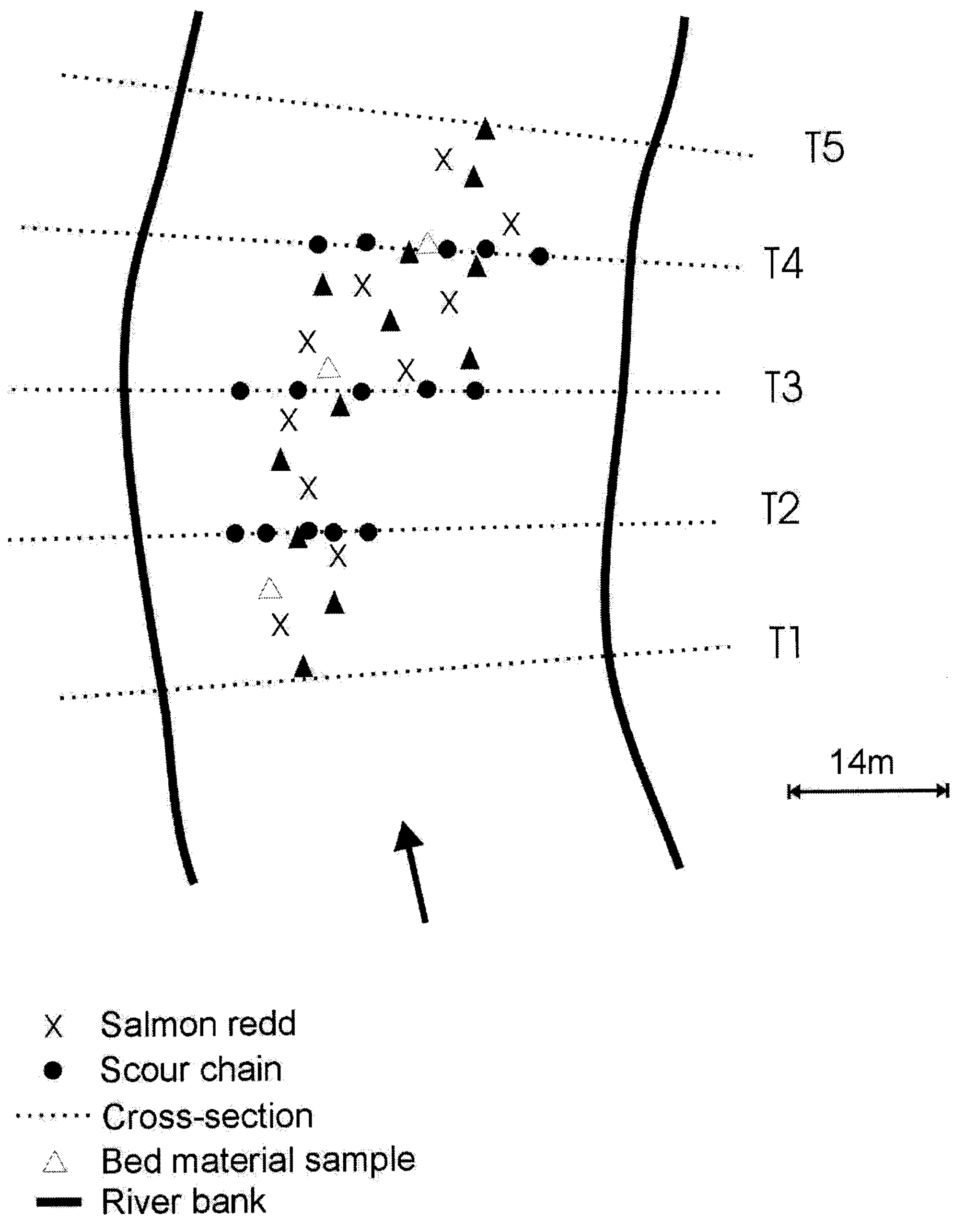
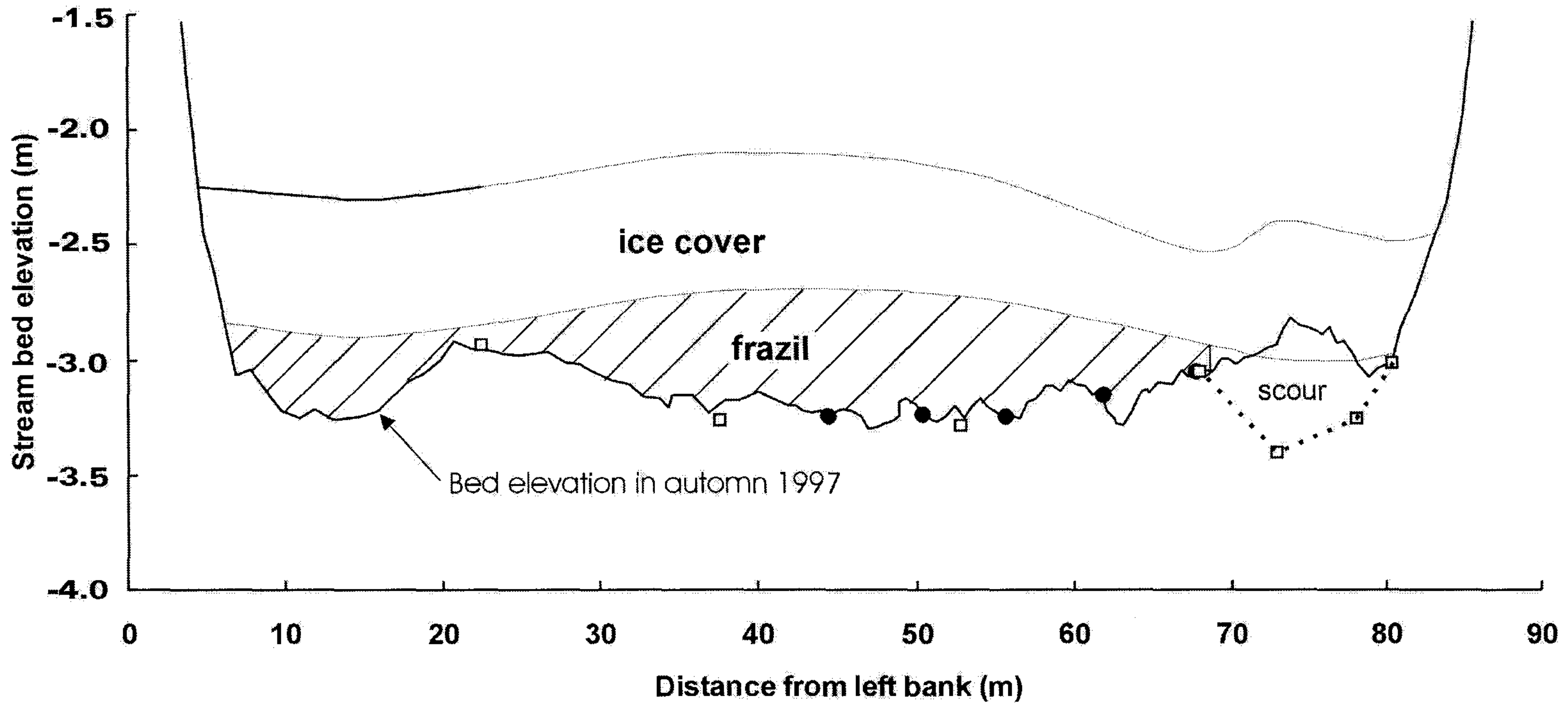

T5
T4
T3
T2
T1
14m
X Salmon redd
Scour chain
Cross-section
Bed material sample
River bank

Figure 4.1

Figure 4.2



● : Position of scour chains

□ : Position of winter bed elevation mesurements

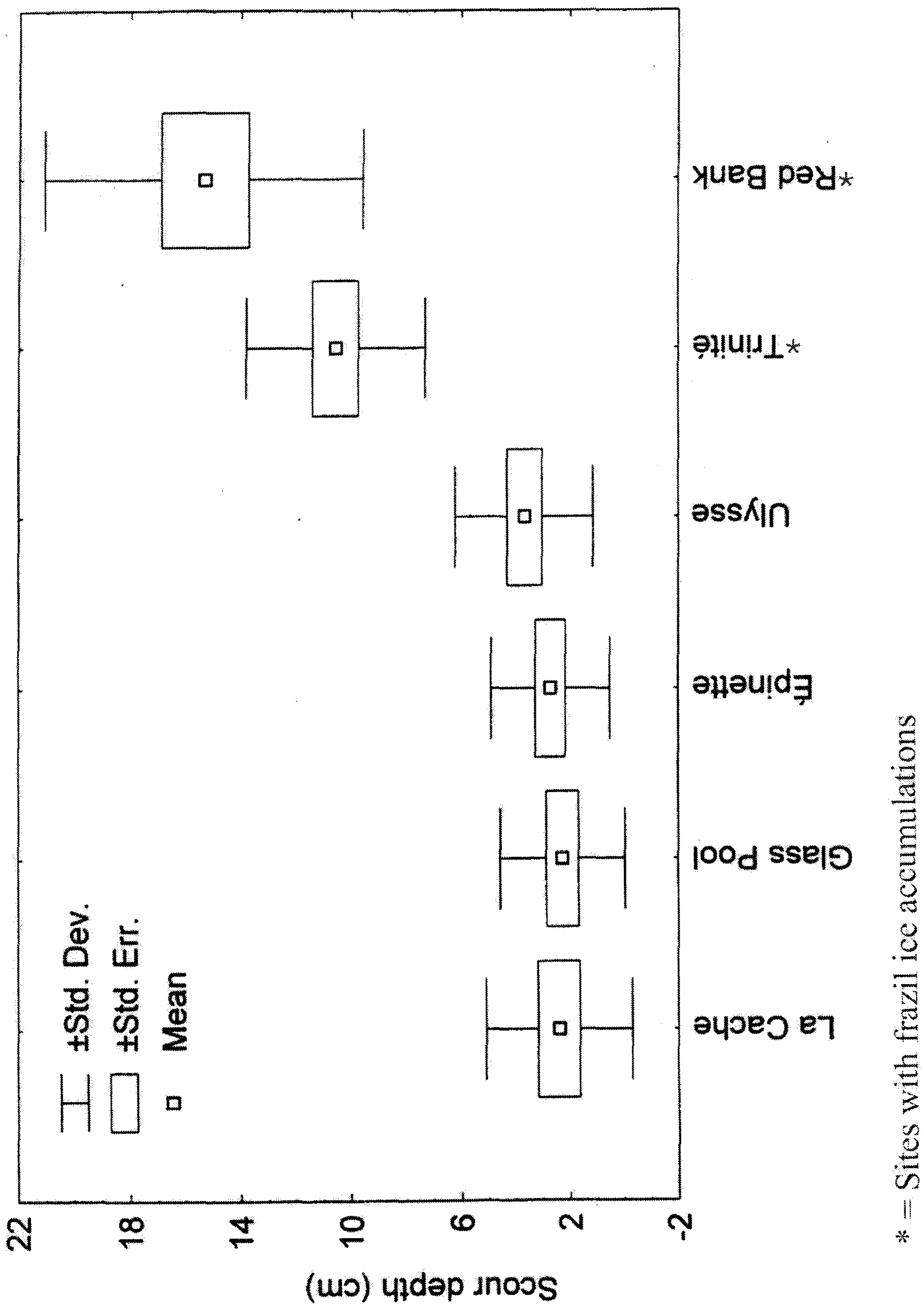

±Std. Dev.
±Std. Err.
Mean
Scour depth (cm)
22
18
14
10
6
2
-2
La Cache
Glass Pool
Epinette
Ulysse
*Trinité
*Red Bank
* = Sites with frazil ice accumulations

Figure 4.3

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Annexe: Compilation des données suite à la récupération des nids artificiels de saumon Atlantique au printemps 1998.

		Quantité de sédiments fins infiltrés à l'intérieur des nids inférieure à différente taille granulométrique					Nombre de saumons à chaque stade de développement								Pourcentage de sable à la surface du lit fluvial
SITES	NIDS	1mm %	0.5mm %	0.25mm %	0.125mm %	0.063mm %	DPEE	LPEE	DEE	LEE	DSA	LSA	X	TOTAL	PSAND %
Glass pool	1	2.737	1.120	0.308	0.058	0.008	1	1	0	3	3	51	1	60	5
	2	13.316	12.384	8.669	2.214	0.387	25	0	3	8	2	14	8	60	5
	3	2.350	1.872	0.826	0.187	0.043	12	0	0	4	1	39	4	60	5
	4	1.793	0.976	0.303	0.047	0.008	9	0	3	4	5	34	5	60	5
	5	5.844	4.427	0.979	0.116	0.021	6	2	0	2	2	37	11	60	15
	6	3.573	2.710	1.067	0.173	0.029	9	0	0	9	0	32	10	60	5
	8	0.076	0.037	0.016	0.003	0.001	9	0	3	3	0	34	11	60	15
	9	0.988	0.686	0.249	0.052	0.008	15	1	0	5	2	29	8	60	30
	10	4.884	4.009	1.110	0.081	0.021	31	1	0	5	7	12	4	60	5
Épinette	1	8.877	3.936	1.037	0.104	0.022	1	0	0	2	15	40	2	60	15
	2	3.699	2.564	1.053	0.111	0.029	4	3	0	2	4	47	0	60	15
	3	5.122	2.407	0.584	0.052	0.012	4	2	0	2	3	45	4	60	20
	4	12.618	8.602	2.658	0.327	0.053	15	8	2	11	4	19	1	60	20
	5	3.947	2.295	0.689	0.078	0.019	2	1	0	2	0	53	2	60	15
	6	24.860	17.371	4.160	0.490	0.076	2	0	0	21	10	22	5	60	15
	7	17.448	15.454	6.713	1.010	0.210	5	0	0	43	7	10	5	70	2.5
	8	11.229	8.314	3.128	0.283	0.038	6	0	0	5	3	45	1	60	15
	9	7.232	5.242	1.311	0.126	0.024	1	2	0	1	3	46	7	60	10
	10	8.089	5.649	2.051	0.252	0.052	6	1	0	4	9	39	1	60	2.5
Trinité	1	33.947	15.052	4.562	1.114	0.295	20	4	7	9	25	1	4	70	0
	2	35.752	21.820	7.341	1.601	0.422	48	1	1	9	10	0	1	70	0
	3	13.261	9.140	4.267	1.331	0.375	21	2	4	8	5	26	4	70	0
	4	31.574	9.812	2.685	0.472	0.097	13	4	0	5	35	6	7	70	0
	5	16.654	12.213	6.431	2.157	0.598	52	5	1	8	0	0	4	70	0
	6	32.921	14.823	5.107	1.280	0.282	6	2	1	5	50	5	1	70	0
	7	36.116	19.370	6.486	1.385	0.397	12	4	0	1	35	11	7	70	0
	8	6.858	4.234	1.967	0.699	0.215	18	5	8	22	9	8	0	70	0
	9	30.453	25.517	11.494	3.042	0.645	47	9	3	7	2	0	2	70	0
	10	34.973	23.284	13.688	3.814	0.729	48	3	3	7	5	2	2	70	0

Annexe (suite)

		Quantité de sédiments fins infiltrés à l'intérieur des nids inférieure à différente taille granulométrique					Nombre de saumons à chaque stade de développement								Pourcentage de sable à la surface du lit fluvial
SITES	NIDS	1mm %	0.5mm %	0.25mm %	0.125mm %	0.063mm %	DPEE	LPEE	DEE	LEE	DSA	LSA	X	TOTAL	PSAND %
Cascades	1	2.954	1.105	0.211	0.050	0.012	1	1	0	3	0	50	5	60	20
	2	5.960	3.645	1.027	0.247	0.069	4	2	0	15	9	17	13	60	5
	3	3.364	1.794	0.493	0.132	0.043	8	0	1	0	3	40	8	60	15
	4	3.938	2.154	0.579	0.124	0.034	7	0	15	8	1	21	8	60	20
	5	3.966	1.791	0.355	0.085	0.026	5	1	0	0	2	43	9	60	5
	6	2.421	1.067	0.255	0.064	0.017	8	1	0	0	1	37	13	60	10
	7	2.826	1.738	0.579	0.175	0.049	9	1	4	2	3	33	8	60	5
	8	1.286	0.761	0.177	0.055	0.015	2	2	0	1	0	36	19	60	5
Xavier	3	7.817	2.695	0.409	0.055	0.008	14	3	0	0	2	33	8	60	5
	4	40.068	14.362	3.377	0.596	0.064	16	2	1	0	30	7	4	60	5
	5	32.595	7.139	1.210	0.164	0.020	35	0	0	0	20	33	12	100	5
	6	38.064	15.138	2.979	0.541	0.075	18	1	0	0	9	28	4	60	10
	7	27.683	9.538	1.707	0.277	0.056	18	3	7	0	15	2	15	60	20
Ilet	1	--	--	--	--	--	8	0	4	1	1	37	9	60	0
	2	--	--	--	--	--	5	0	3	1	1	36	14	60	0
	4	--	--	--	--	--	6	3	6	1	15	15	14	60	0
	7	--	--	--	--	--	5	2	8	0	7	28	10	60	0

DPEE: Oeufs morts avant l'atteinte du stade oeillé (Dead pre-eyed eggs)
LPEE: Oeufs vivants récupérés au stade pré-oeillé (Live pre-eyed eggs).
DEE: Oeufs morts au stade oeillé (Dead eyed eggs)
LEE: Oeufs vivants récupérés au stade oeillé (Live eyed eggs).
DSA: Alevins vésiculés morts (Dead sac fry)
LSA: Alevins vésiculés vivants (Live sac fry)
X: Œufs non récupérés due à la décomposition (Decomposed eggs)
PSAND: Pourcentage de sable à la surface du lit fluvial (Percent sand at the bed surface)
--: Sédiments non-récupérés suite une haute crue printanière (Sediments lost due to high spring flow conditions)