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Atlas des courants du Saint-Laurent : Lac Saint-François

Morin, J., P. Fortin, P. Boudreau., Y. Secretan et M. Leclerc. 2001

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Préface

Le lac Saint-François comme la plupart des hydrosystèmes des régions développées du globe a subi des transformations physiques importantes depuis l'arrivée de l'âge industriel. La production d'hydroélectricité, la navigation, les nombreux ouvrages de génie, l'aménagement des rives, la gestion des débits et niveaux d'eau et les changements physico-chimiques sont les principaux facteurs qui y ont contribué. Ce document témoigne de plusieurs de ces changements sur la dynamique des courants.

Ce document s'adresse à l'ensemble des intervenants qui agissent ou s'intéressent au fleuve Saint-Laurent, plus particulièrement au lac Saint-François. Conçu dans un esprit multidisciplinaire, il représente une synthèse de l'information physique sur le système, qu'elle ait été obtenue par des mesures sur le terrain, ou par modélisation numérique. Le lecteur intéressé à en connaître plus sur les résultats ou l'approche utilisée est invité à consulter la bibliographie à la fin de ce document. De plus, afin d'alléger la consultation, les auteurs ont choisi de ne pas mentionner les références au fur et à mesure de la progression du propos comme c'est souvent le cas pour les rapports scientifiques.

En plus de rendre accessible la connaissance des courants du lac Saint-François et les données de base sous-jacentes, ce document désire promouvoir les nombreuses applications possibles de ces informations en vue de la protection et de la restauration, quand cela s'avère possible, de l'écosystème Saint-Laurent. Il est notamment possible de répondre aux besoins d'urgences maritimes, d'améliorer les plans de gestion des débits et niveaux d'eau, de soutenir les efforts d'aménagement faunique, voire même d'optimiser les utilisations industrielles actuelles du fleuve en tenant compte du volet environnemental.

Ce document ainsi que le modèle numérique qui le sous-tend est le fruit d'un partenariat entre le Ministère de l'Environnement du Canada – Service météorologique du Canada (EC-SMC) et l'Institut national de la recherche scientifique - Eau (INRS-Eau). Développé « par tronçon », le modèle du fleuve Saint-Laurent est subdivisé en tenant compte des frontières naturelles de l'hydrosystème. Celui du lac Saint-François constitue donc le premier volume d'une série d'atlas qui couvriront éventuellement toute la partie fluviale du Saint-Laurent. Il n'est évidemment pas possible de rendre compte de l'ensemble de la complexité du lac Saint-François dans un seul

document. C'est pourquoi nous avons procédé par *événements de référence* considérés comme représentatifs, en première approximation, des principaux états du système en période libre de glace.

Cet atlas présente un bilan de l'état, encore en évolution, de la modélisation abiotique du lac Saint-François, initiative qui ouvre la voie vers la modélisation des habitats, de la propagation et la dispersion des panaches d'effluents, ainsi que vers la gestion optimale et écologique des niveaux et des débits. Dans le cadre du PASL-SLV2000-Phase III, d'autres travaux de modélisation du Saint-Laurent, notamment autour de l'archipel de Montréal, entre Montréal et Sorel ainsi qu'au lac Saint-Pierre, sont présentement en cours.

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Introduction

Le lac fluvial

Le lac Saint-François (Figure 1) est un élargissement majeur du fleuve Saint-Laurent : le premier élargissement naturel en aval des Grands-Lacs. On le qualifie de « *lac fluvial* » car il présente les caractéristiques d'un lac par sa superficie et d'un fleuve par l'importance du débit qui y transite et la nature gravitationnelle de ses écoulements. Sa superficie est de 254,2 km^2, son volume total est de 1.45 km^3 pour une profondeur maximale de 26.0 m. La profondeur moyenne est de 5.7 m et le débit moyen interannuel est d'environ 7 500 m^3/s. Un tel débit en milieu peu profond engendre des courants gravitationnels forts, qui expliquent la quasi-absence de stratification thermique.

Le contexte économique et politique

Le lac Saint-François est partagé par trois frontières politiques qui délimitent le Québec, l'Ontario et l'état de New York. De plus, la réserve amérindienne d'Akwésasné est située sur le point de jonction de ces trois frontières. La région amont du lac est industrialisée et les fonderies, les alumineries et les papetières y profitent de la présence de l'énergie hydroélectrique. Le barrage hydroélectrique Moses-Saunders délimite l'amont du lac Saint-François tandis que celui de Beauharnois en constitue l'extrémité aval. La navigation commerciale de fort tonnage y transite par la voie maritime du Saint-Laurent laquelle comprend des écluses à l'amont et à l'aval. La navigation de plaisance y est également importante.

Les habitats

Le fleuve et ses berges sont diversifiés en termes d'habitats. Ces habitats sont le milieu de vie et de reproduction de plusieurs centaines d'espèces floristiques et fauniques dont plusieurs sont menacées. Les habitats les plus en danger sont situés dans les milieux humides de l'ancienne plaine inondable puisque les fluctuations de niveau d'eau ont subi une régularisation très significative. Les facteurs abiotiques définissent une grande partie de l'habitat ; ce sont par exemple les courants, les niveaux d'eau, les vagues, la température ainsi que la qualité de l'eau. Le travail de modélisation que cet ouvrage présente permettra de connaître par le biais de simulations, la distribution de plusieurs de ces facteurs, et donc de décrire, de comprendre et éventuellement, d'améliorer les habitats les plus propices aux espèces menacées.

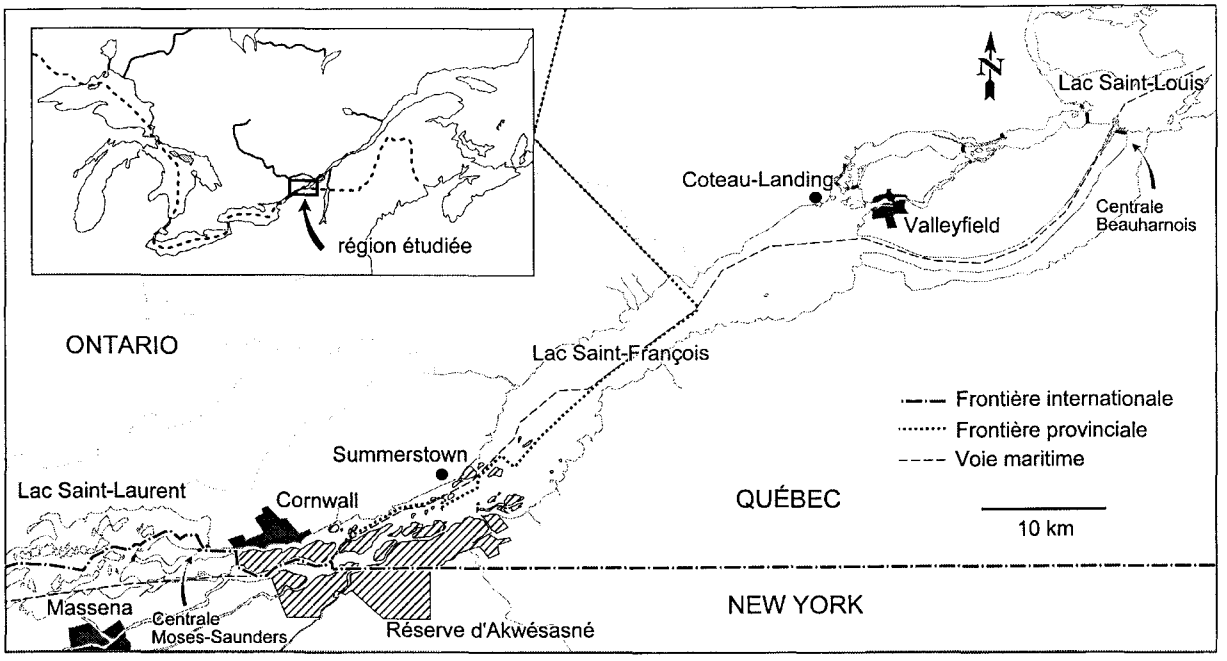

Figure 1: Carte géopolitique du lac Saint-François

La connaissance des courants : une nécessité

La connaissance des courants est essentielle afin de simuler le transport des contaminants dans les panaches des rejets industriels et municipaux ; il en est de même pour la propagation des hydrocarbures, en cas de déversement accidentel, ainsi que pour la dynamique sédimentaire, parfois nuisible à la navigation. De plus, cette connaissance peut être intéressante pour la navigation tant de plaisance que commerciale. Enfin, elle contribue à mieux comprendre les échanges internes et la dynamique d'un hydrosystème complexe.

La modélisation hydrodynamique

Les renseignements sur les courants peuvent être obtenus soit par mesures directes dans le milieu, soit par modélisation numérique. La mesure directe a l'inconvénient d'être coûteuse et fastidieuse ; c'est une valeur ponctuelle et valide seulement pour l'événement hydrodynamique mesuré, ce qui restreint sa portée synoptique. La modélisation permet, une fois validée, de simuler des vitesses associées à une large gamme de débits et ce, sur l'ensemble du tronçon. L'impact de changements morphologiques ou d'aménagements peut également être prédit.

La modélisation hydrodynamique permet de simuler des événements récurrents survenant régulièrement, ou encore, des événements rarissimes de fort ou de faible débit. On peut

également simuler des événements qui ne se sont jamais produits tels que des crues maximales probables (CMP), et d'en évaluer les impacts potentiels. Le calcul de l'écoulement incorpore de grandes quantités de données de terrain et il s'effectue en spécifiant certaines conditions d'interaction avec l'amont et l'aval (conditions aux limites). Les données de terrain comprennent principalement la topométrie et les caractéristiques de résistance du milieu à l'écoulement (ex : substrat, plantes aquatiques), tandis que les conditions aux limites sont les niveaux et débits imposés aux frontières du tronçon simulé.

L'atlas des courants

Le présent document montre la distribution des courants dans différentes conditions contrastées ainsi que la complexité de l'hydrologie du lac Saint-François et d'une partie de son écosystème. Puisque les variations de débit et de résistance des plantes aquatiques à l'écoulement sont importantes au cours de l'année, toutes ces conditions ne peuvent pas être présentées dans cet atlas. Pour représenter cette variabilité, une approche par événements de référence a été choisie. Cette méthode permet de montrer la diversité de l'écoulement par un nombre limité de simulations. Les conditions d'hiver demeurent encore exclues de l'exercice faute des modules de calcul requis pour le faire.

La méthode de modélisation retenue ici est exigeante quant à l'élaboration du modèle de terrain, à la connaissance de l'hydrologie et à la validation des résultats obtenus. Il nous est apparu utile de présenter sommairement la méthodologie utilisée pour en arriver à cette représentation de la réalité physique et abiotique du lac Saint-François: l'hydrologie, le modèle de terrain, le modèle mathématique, l'élaboration de la grille de calcul, le choix des événements de référence et la validation des résultats sont décrits de façon simple mais précise.

Hydrologie du système : les débits

La connaissance de l'hydrologie est essentielle afin de bien comprendre le comportement de ce milieu dans toutes les gammes de débits possibles. Les débits à l'entrée du lac, à l'embouchure des tributaires ainsi que la répartition des débits aux différents exutoires du lac Saint-François ont donc été analysés. Les niveaux du lac Saint-François sont contrôlés à son embouchure. Toutefois, l'effet des plantes aquatiques et de la glace est important sur les variations de niveau à l'amont de cette frontière; nous reviendrons un peu plus loin sur la question des niveaux d'eau. L'analyse des niveaux et des débits sert à établir les conditions qui doivent être imposées aux limites du modèle et permet partiellement d'en contrôler le bon fonctionnement, notamment durant la phase de validation.

Les eaux qui alimentent le lac Saint-François à sa limite amont près de Cornwall proviennent essentiellement du lac Ontario. Le niveau du lac Ontario et le débit qui en sort sont contrôlés par le barrage hydroélectrique de Moses-Saunders. La gestion de ces débits et niveaux est sous la responsabilité de la Commission mixte internationale (CMI). Divers critères entrent en ligne de compte dans la gestion du débit sortant du lac Ontario : ils représentent les intérêts principaux que sont le contrôle des inondations, la navigation commerciale et la production hydroélectrique.

Les variations saisonnières

Les Grands Lacs agissent comme un puissant régulateur sur le débit du Saint-Laurent, étant donné leur immense superficie et leur capacité d'emmagasinement considérable. Durant une année moyenne, le débit du fleuve est à son minimum en janvier et à son maximum en juillet. Le débit annuel moyen est de 7500 m^3/s, tandis que les débits maximum et minimum mensuels moyens sont respectivement d'environ 7900 m^3/s au mois de juillet, et de 6500 m^3/s au mois de janvier. La Figure 2 montre que le débit est relativement constant entre la mi-avril et le mois de novembre, qu'il diminue rapidement entre décembre et le début de janvier, atteignant un plancher durant ce mois, puis qu'il augmente graduellement jusqu'à la mi-avril. La fin du mois de décembre est caractérisée par une diminution brusque du débit, une réduction artificielle imposée aux ouvrages de Moses-Saunders afin de favoriser la formation d'un couvert de glace stable en amont des barrages, suivie rapidement d'un rétablissement à la normale. Le lac Saint-François n'ajoute pas d'effet régulateur au débit du fleuve Saint-Laurent, son niveau étant très étroitement

contrôlé à Beauharnois afin de reconduire exactement le débit reçu de Moses-Saunders vers l'aval.

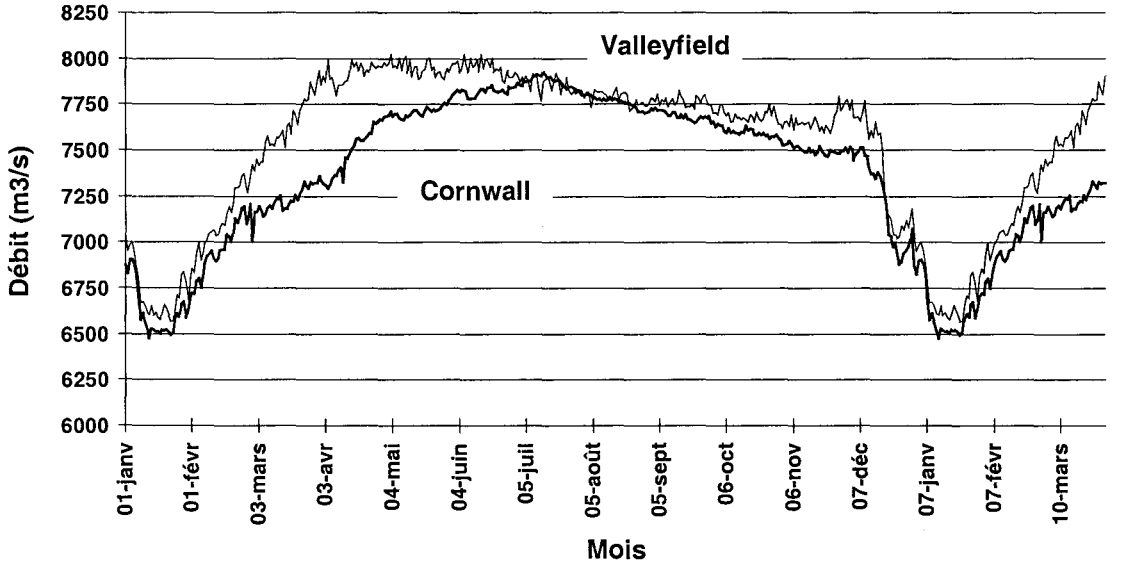

Figure 2 : Distribution des débits du fleuve Saint-Laurent au lac Saint-François ; moyenne journalière interannuelle entre 1963 et 1992.

Les variations à long terme du débit

Les variations à long terme du débit du fleuve Saint-Laurent montrent de grandes fluctuations qui sont directement reliées aux variations dans les précipitations sur le bassin versant. Les fluctuations semblent former des cycles variant de 10 à 30 ans qui sont souvent qualifiés de périodes de faible et forte hydraulicité. La Figure 3 montre l'évolution des moyennes mensuelles du débit du fleuve à l'amont du lac Saint-François et la succession de périodes de forte et de faible hydraulicité depuis 1860. Les débits mensuels extrêmes qui ont été enregistrés sont de 4500 m³/s en janvier 1935 et de 10 012 m³/s en mai 1993.

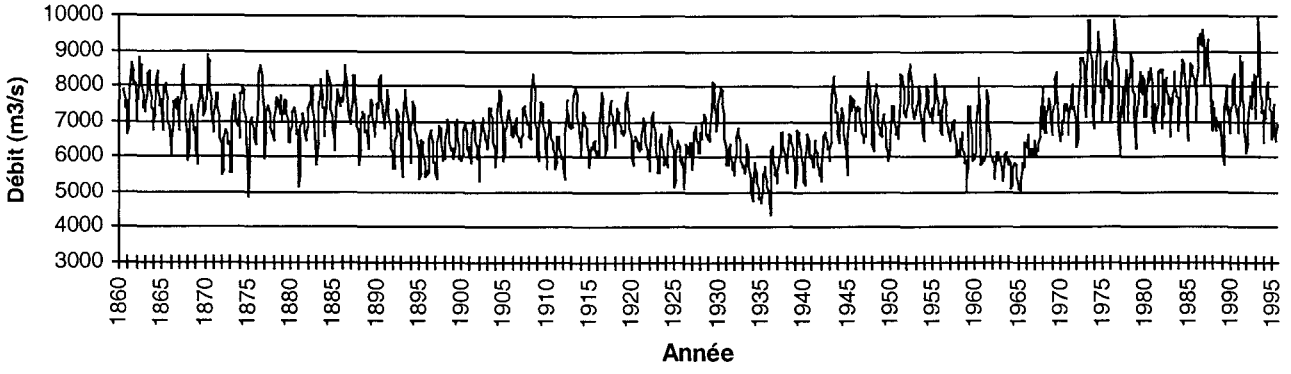

Figure 3 : Évolution à long terme des débits du lac Saint-François

Le débit à l'exutoire

L'exutoire du lac Saint-François se compose de deux sorties : le canal de Beauharnois et les ouvrages de contrôle de Coteau. Le canal de Beauharnois, un ouvrage de dérivation vers le barrage hydroélectrique du même nom, détourne la plus grande partie du débit du Saint-Laurent, soit 87%, tandis que seulement 13% emprunte le chenal naturel ; les débits respectifs résultant de cette gestion sont d'environ 6500 m^3/s et de 1000 m^3/s. De façon générale, le régime du canal de Beauharnois est relativement stable et déterminé par la capacité installée de la centrale hydroélectrique qu'il alimente directement. Le chenal naturel sert donc de trop-plein pour les débits en provenance des Grands Lacs car, comme nous l'avons mentionné, le faible marnage imposé au lac Saint-François n'induit aucune régulation de son débit à l'exutoire.

Le débit passant par le canal de Beauharnois est utilisé pour la génération d'hydroélectricité. Cette production s'effectue habituellement à la capacité installée de l'ouvrage, sauf en certaines périodes où il est nécessaire de tenir compte de la contrainte de formation du couvert de glace. La courbe des débits journaliers moyens interannuels sur 30 ans (Figure 4) montre un débit moyen variant entre 5600 m^3/s en hiver, durant la période de formation de la glace, et 6800 m^3/s en automne. Le débit est stable entre le début de mai jusqu'au début de décembre, à 6700 m^3/s (Figure 4). On l'abaisse brusquement à la mi-décembre, afin de favoriser la formation du couvert de glace. Le débit augmente progressivement jusqu'au début de mars, puis diminue jusqu'au début d'avril.

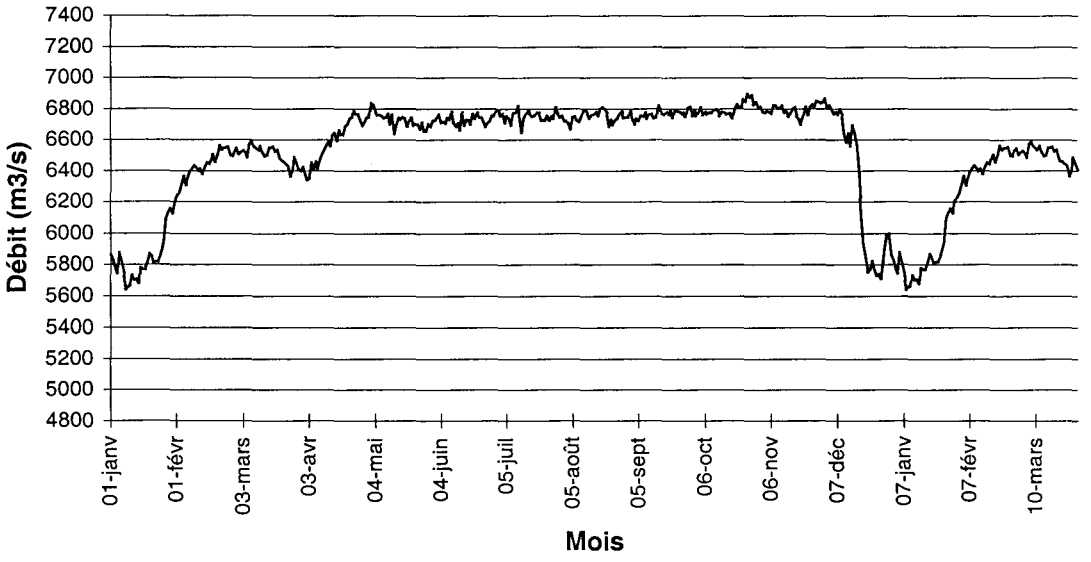

Figure 4 : Distribution des débits à la sortie du canal de Beauharnois; moyenne journalière interannuelle entre 1963 et 1992.

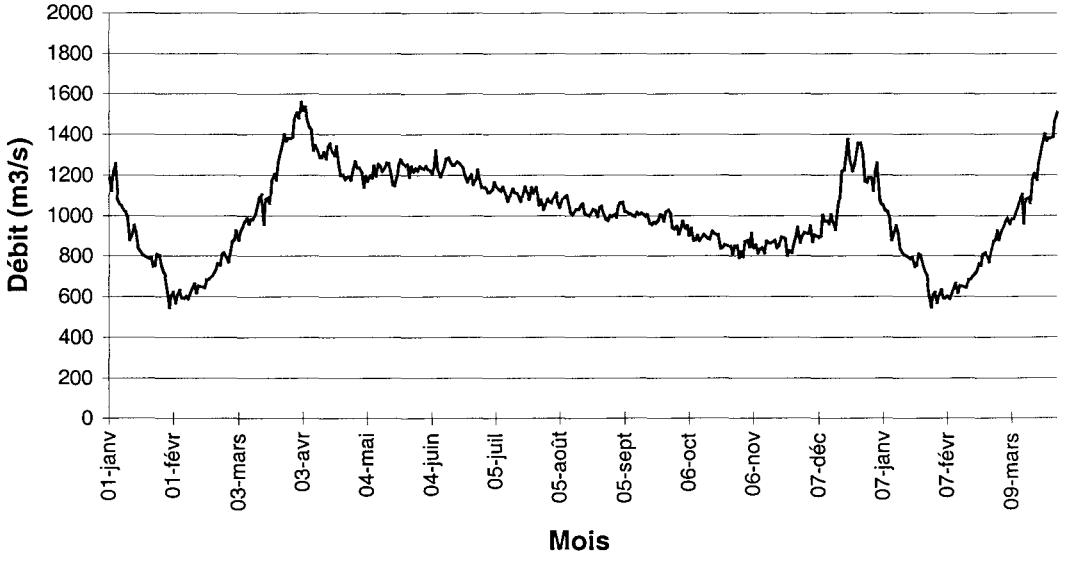

Figure 5 : Distribution des débits hivernaux du lac Saint-François aux ouvrages de Coteau; moyenne journalière interannuelle entre 1963 et 1992.

La courbe des débits passant aux ouvrages de Coteau (Figure 5) laisse voir un débit maximum de près de 1600 m^3/s au début de mai, valeur qui diminue progressivement jusqu'au début de décembre. Cet abaissement graduel est suivi d'un second sommet au début de l'hiver, puis d'un minimum en février. Le débit qui est déversé à Coteau constitue l'excédent qui n'est pas turbiné à Beauharnois. Durant la période « à l'eau libre » (sans glace), le débit diminue graduellement,

condition nécessaire pour maintenir un débit régulier à Beauharnois. Pendant la période de formation de la glace, le débit est diminué dans le canal de Beauharnois et augmenté aux ouvrages de Coteau; c'est l'inverse lorsque le couvert de glace est stable. Vers le début d'avril, à la fonte des glaces, le débit est diminué temporairement dans le canal afin de réduire les vitesses de courant, et ainsi faciliter la manœuvre des navires à travers les glaces flottantes.

Tributaires

Les débits sortant du lac Saint-François sont plus forts que les débits qui y entrent en provenance des Grands Lacs au barrage de Moses-Saunders, la différence atteignant un maximum moyen d'environ 700 m^3/s au printemps et 300 m^3/s en automne. Cet écart est bien sûr dû aux apports des tributaires entrant dans le fleuve Saint-Laurent entre Cornwall et Valleyfield.

Mis à part l'apport des Grands Lacs, la contribution des tributaires les plus importants du lac Saint-François s'effectue du côté sud, à la tête du lac, à partir des territoires américain et québécois (Figure 6). D'ouest en est, ce sont les rivières Grasse, Raquette, Saint-Régis et aux Saumons qui ont respectivement des débits annuels moyens de 32 m^3/s, 67 m^3/s, 31 m^3/s et 19 m^3/s à leur embouchure. Les rivières Beaudette, Raisin et à la Guerre ont des débits moyens de moins de 5 m^3/s. De façon générale, le débit de ces tributaires est plus fort au printemps avec une autre pointe de moindre importance à la fin novembre. Les conditions d'étiage se manifestent aux mois de juillet et d'août. La rivière Raquette, le plus important tributaire, a un débit journalier maximum (moyenne interannuelle) de 120 m^3/s au printemps et un minimum de 40 m^3/s en été. Les rivières Raisin, Beaudette et à la Guerre drainent des zones essentiellement agricoles tandis, que les rivières Grasse, Raquette, Saint-Régis et aux Saumons prennent leur source dans les zones forestières des monts Adirondacks et drainent également des zones agricoles plus au nord.

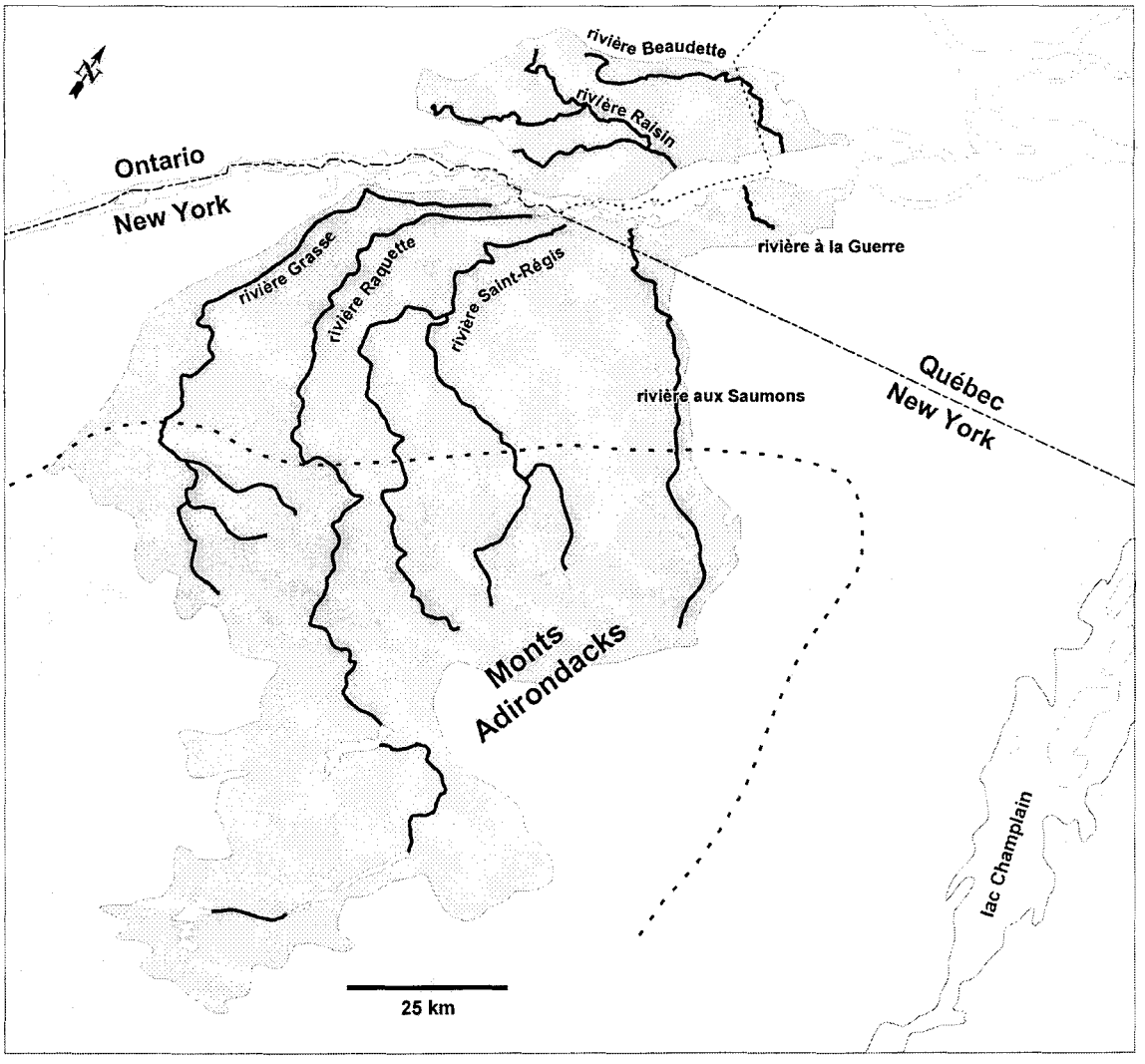

Figure 6 : Bassins de drainage des tributaires secondaires du lac Saint-François

Hydrologie du système : les niveaux d'eau

De façon générale dans le fleuve Saint-Laurent, les niveaux varient directement en fonction du débit qui y transite. Comme nous l'avons évoqué précédemment, le lac Saint-François fait exception puisque les niveaux sont étroitement stabilisés à l'aval par les ouvrages de Coteau et par le barrage de Beauharnois. En effet, le débit sortant du lac Saint-François est ajusté rigoureusement au débit entrant, permettant ainsi une stabilisation du niveau. La gestion des niveaux est sous la responsabilité d'Hydro-Québec. Le but d'une telle gestion est de maximiser le tirant d'eau (tonnage) des navires dans la voie maritime du Saint-Laurent tout en minimisant les risques d'inondation.

Le niveau d'eau à Coteau-Landing

La gestion du niveau à Coteau-Landing a varié énormément depuis la construction du canal de Beauharnois en 1932. Brièvement, les niveaux fluctuaient en fonction du débit avec un niveau moyen maintenu de plus en plus haut jusqu'en 1960. Depuis la construction de la voie maritime du Saint-Laurent (vers 1960), la variation des niveaux a été stabilisée à moins de 30 cm d'écart, soit entre 46.33 m et 46.63 m. Actuellement, les navires transitant par la voie maritime peuvent compter sur un tirant d'eau minimum de 8.0 m. Puisqu'un tel tirant d'eau exige un niveau stable et élevé, les niveaux actuels sont maintenus à près de 46.58 m à Coteau durant la période sans glace. En hiver, le niveau est augmenté d'environ 0.08 m.

La pente du plan d'eau

La pente du plan d'eau est représentée par l'écart du niveau d'eau entre l'amont et l'aval sur la longueur du lac. Elle varie en fonction du débit, de la résistance à l'écoulement exercée par la glace en surface et par les plantes aquatiques au fond et dans la colonne d'eau. Les quatre stations de mesures limnimétriques disponibles, Beauharnois (centrale), Coteau-Landing, Summerstown et Cornwall, ont été utilisées pour les fins de ce type d'analyse.

Les variations annuelles moyennes de niveau au lac Saint-François sont d'environ 10 cm à Coteau-Landing et de 20 cm à Cornwall. De façon générale, les pentes dans le lac sont plus fortes en présence de glace en hiver, plus faibles au printemps et en automne, et sont moyennes en présence de plantes aquatiques durant l'été. La Figure 7 montre en détails la variation de la pente au cours de l'année. Entre Summerstown et Coteau-Landing, l'influence des plantes aquatiques et

de la glace sur la pente sont du même ordre de grandeur. Les effets de la glace en hiver et des plantes aquatiques en été y sont marqués; la pente est forte à la fin du mois d'août, et est sensiblement plus forte en présence de glace durant le mois de mars.

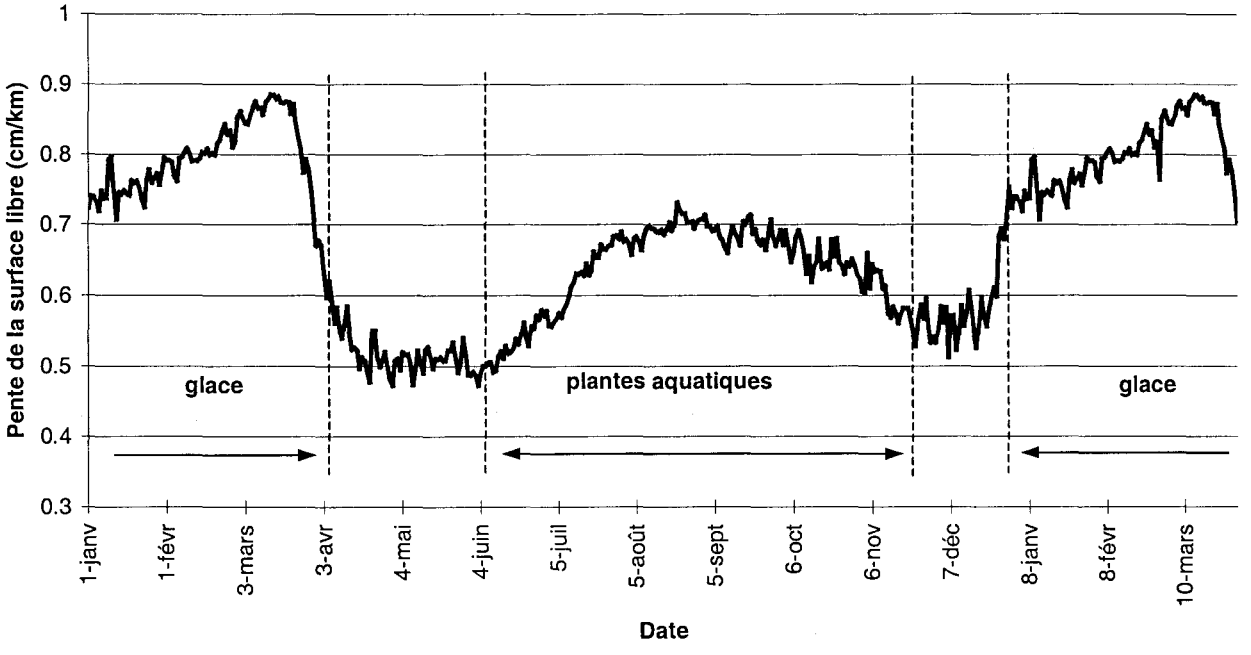

Figure 7 : Variation de la pente du plan d'eau entre Summerstown et Coteau-Landing durant l'année, moyenne journalière interannuelle entre 1963 et 1992.

Modèle numérique de terrain

Le modèle numérique de terrain comprend les données géoréférencées provenant des nombreuses mesures du milieu étudié ; il s'agit principalement de la description numérique de la topométrie du fond du fleuve, de la nature du substrat et des plantes aquatiques. Toutes ces informations sont variables dans l'espace et doivent donc être connues sur l'ensemble du tronçon pour obtenir des simulations hydrodynamiques représentatives de la réalité des courants. En plus de procurer des simulations fiables, un modèle de terrain de qualité permet aux experts de mieux comprendre les modes de fonctionnement du milieu naturel.

Topographie

La topographie est la description de l'élévation du terrain, il s'agit de la variable la plus importante dans le calcul de l'hydrodynamique du fleuve Saint-Laurent. Elle sert à décrire la morphologie du cours d'eau pour le modèle hydrodynamique. En général pour la modélisation hydrodynamique, les informations sur la topographie du fond du cours d'eau et sur l'élévation des plaines inondables sont intégrées dans le modèle de terrain. Étant donnée la stabilisation des niveaux au lac Saint-François, seule la description du lit du fleuve demeure pertinente aujourd'hui.

Les données

Ces données proviennent d'une caractérisation du terrain par le Service hydrographique du Canada (SHC) effectuée entre 1986 et 1988. Les sondages du SHC sont rassemblés sur 14 cartes appelées « minutes hydrographiques » dont l'échelle varie de 1:5 000 à 1:10 000. La majorité des sondages étaient disponibles en format numérique mais quelque 70 000 points additionnels ont dû être numérisés. Un total de 292 270 points de sondage à une précision verticale de ±10 cm ont été assemblés dans le modèle de topométrie. Un sous-ensemble de la base de données de topographie décrivant bien la complexité du fond est présenté à la planche 2.

Classification morphologique

Selon la morphologie des fonds, le lac Saint-François peut être subdivisé en trois parties distinctes : *fluviale, chenalisée et lacustre*. La partie fluviale s'étend entre le barrage de Moses-Saunders et Summerstown; cette zone est caractérisée par un petit nombre de chenaux larges et

profonds, entrecoupés par des îles de grande taille (Planche 2). La partie chenalisée, au centre du lac, est caractérisée par des zones peu profondes (0 à 10 m) traversées par un réseau complexe de chenaux anastomosés sous-fluviaux relativement profonds (jusqu'à 26 m). Les zones peu profondes comprennent des îles et des hauts-fonds de moins de 1.5 m de profondeur. La partie lacustre occupe l'est du lac Saint-François, elle comporte un fond régulier de moins de 10 m de profondeur, coupé par un chenal central profond de plus de 21 m.

Substrat

La distribution spatiale du substrat doit être connue sur tout le tronçon puisque ce facteur, en plus de contribuer à la résistance à l'écoulement, influence divers aspects du vivant. Le frottement par le substrat est introduit localement dans le calcul de l'hydrodynamique à l'aide d'un coefficient (le « n » de Manning) qui varie, ici, en fonction de la granulométrie (Planche 3). Pour connaître la distribution spatiale des sédiments, la caractérisation directe sur le terrain est la seule méthode fiable disponible. La réponse en termes de résistance à l'écoulement peut nécessiter des ajustements additionnels lors de la calibration des simulations.

Les données

La carte du substrat utilisée au lac Saint-François a été constituée à l'aide de données provenant de diverses sources. Environ 16000 observations qualitatives ont été colligées par le SHC et intégrées aux minutes hydrographiques. Ces observations, bien que très grossières et d'un intérêt variable, ont été ajoutées aux 234 sondages granulométriques disponibles dans la littérature scientifique. Chacun de ces derniers procurait le % de gravier, de sable, de silt et d'argile. Par ailleurs, environ 300 observations qualitatives ont été effectuées lors de nos propres campagnes de caractérisation. Ces observations ont été effectuées à l'aide d'une caméra sous-marine et/ou d'une benne à sédiments. Toutes ces données ont été assemblées sur une carte au 1:15 000 et superposées sur la topographie du lac. Puisque localement la distribution du substrat est fortement corrélée avec la profondeur, l'interpolation des points de sondage de substrat s'est faite en partie à l'aide des courbes de niveau. Un modèle d'interprétation basé sur la stratigraphie des dépôts quaternaires a également été mis à contribution.

Le terrain

La granulométrie varie en fonction de l'énergie du milieu telle que conditionnée par les courants

et les vagues, mais également en fonction des sources de sédiments et de la composition du sous-sol. Au lac Saint-François, la distribution du substrat est fortement influencée par la présence des dépôts quaternaires et des roches sous-jacentes. Le lac est limité à l'amont et à l'aval par des affleurements rocheux résistants, à l'origine des zones de rapides qui étaient présentes autrefois à l'état naturel. De l'amont à l'aval, la granulométrie du chenal central obéit à la diminution graduelle des vitesses. Le substrat est très grossier autour de l'île de Cornwall, passe ensuite à du gravier, puis du sable graveleux, du sable et finalement du silt. Les sédiments sont très fins dans la partie lacustre où les vitesses de courant sont relativement faibles. Des sédiments fins (boue) sont également présents dans les bassins fermés que l'on retrouve dans la partie chenalisée au centre du lac. Par les fortes expositions au vent (fetchs) qui la caractérisent, toute la rive sud offre une très forte emprise au vent dominant d'ouest et l'effet des vagues sur le substrat y est donc important et déterminant. Ainsi, on y retrouve des plages de sable dans des baies fermées par des pointes composées de matériaux grossiers et résistants à l'érosion (till). On peut également noter la présence de forts pourcentages de sable à l'embouchure de tous les tributaires ce qui s'explique par les apports sédimentaires des rivières alluvionnaires en période de crue.

Plantes aquatiques

Les plantes aquatiques jouent un rôle déterminant sur l'écoulement dans le lac Saint-François, particulièrement durant l'été et l'automne et ce, tant sur le niveau d'eau que sur la distribution spatiale des courants et des masses d'eau. Les éléments ayant le plus d'influence sont les plantes submergées de grande taille (macrophytes submergés). Leur effet sur l'écoulement est introduit dans le calcul hydrodynamique d'une façon similaire au substrat (Planche 4), par un coefficient de frottement local de type «*n* de Manning ». La valeur locale de ce coefficient est fonction du type, de la taille, et de la concentration relative des espèces ainsi que de la phase de croissance annuelle.

Les données

Les données sur la distribution spatiale des macrophytes submergés ont été acquises lors d'une campagne de terrain réalisée à la fin de l'été 1995 (24 septembre au 3 octobre). Une technique de cartographie impliquant un échosondeur, une caméra vidéo sous-marine et un système de positionnement dGPS (GPS différentiel) a été utilisée pour réaliser 35 transects répartis sur

l'ensemble du lac Saint-François. Les lectures d'échosondages ainsi que leur calibration avec la caméra vidéo ont permis de distinguer 12 assemblages d'espèces de macrophytes avec diverses variations quantitatives sur les hauteurs et les densités Ces dernières variables sont celles utilisées pour le calcul du coefficient de frottement local de chaque *faciès* macrophytique.

Le terrain

Ces travaux de terrain ont contribué à comprendre la distribution générale des macrophytes dans le lac Saint-François. Les facteurs influençant cette distribution sont principalement des facteurs abiotiques tels que les vagues, les courants, la pénétration de la lumière et le type de substrat. La planche 3 montre la distribution spatiale des assemblages de plantes au lac Saint-François. On peut y noter plusieurs particularités résumant l'adaptation des espèces face aux facteurs abiotiques dominant leurs habitats.

Le *potamot pectiné* est présent principalement en bordure des chenaux principaux et des hauts fonds où l'on trouve de forts courants. Cette plante est particulièrement bien adaptée aux courants, ayant des tissus longs et flexibles. La *vallisnérie* se retrouve en colonie pure dans les zones où l'action des vagues est relativement forte, principalement dans la partie est du lac. L'association de la *vallisnérie* et du *potamot de Richardson* est présente lorsque l'énergie des vagues est moins importante. Le *cératophylle* est abondant dans les zones protégées des courants et des vagues. Le *myriophylle* avec des formes de croissance en canopé est abondant dans la partie chenalisée, dans les zones où les sédiments fins riches en nutriments ont tendance à se déposer. L'algue *Nitella* est présente dans les zones les plus profondes à la limite de la pénétration de la lumière. Les zones où l'on ne retrouve aucune plante s'expliquent soit parce qu'elles sont trop profondes, sont soumises à de trop forts courants ou de trop fortes vagues, ou encore parce qu'elles sont composées de matériaux résistants à la pénétration des racines. En effet, les racines ne peuvent pénétrer la roche mère ni l'argile cohésive présente dans les dépôts quaternaires.

Modèle hydrodynamique

La modélisation hydrodynamique est effectuée à l'aide du modèle HYDROSIM, développé à l'INRS-Eau. Ce simulateur est couplé à MODELEUR, un outil de type SIG (Système d'information géographique) dédié à l'hydraulique fluviale qui permet de pré-traiter et post-traiter les données en plus de piloter les simulations. L'approche utilisée est basée sur une modélisation numérique bidimensionnelle (2D) des équations d'ondes longues aussi appelées « équations des eaux peu profondes », qui sont résolues par la méthode des éléments finis. Ce modèle utilise la forme conservative des équations de conservation de la masse et de la quantité de mouvement des équations de Saint-Venant et prend en compte localement les paramètres de frottement dus aux substrats, aux plantes aquatiques et à la glace. Il procure en sortie les composantes (x, y) de la vitesse moyenne (intégrée dans la verticale) sur tous les nœuds de calcul. Tout le domaine de simulation est ainsi décrit soit directement aux nœuds de calcul, ou encore par interpolation entre ces nœuds. Le modèle prend en compte le recouvrement et le découvrement des berges en fonction du débit et du niveau d'eau. Le modèle mathématique est représenté par le système d'équations de la figure 8. Le simulateur peut être opéré en régime transitoire mais les conditions d'écoulement quasi-permanentes dans le lac Saint-François permettent une résolution stationnaire (régime permanent).

Grille éléments finis

Le tronçon simulé est subdivisé en de nombreux éléments triangulaires qui forment le « maillage » ou la « grille d'éléments finis ». La forme et la taille de ces éléments peuvent être adaptées pour représenter la forme et la complexité du terrain, du substrat, des plantes aquatiques ou de toute autre variable. Plus le terrain est complexe, plus le maillage est raffiné, et plus le nombre d'éléments est important. Cependant, un maillage avec un trop grand nombre d'éléments peut se traduire en des temps de calcul excessifs. Un des objectifs du modélisateur est d'optimiser le maillage en tenant compte des besoins de précision et du temps de calcul sur les ordinateurs disponibles.

Équation de conservation de la masse

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = 0$$

Équation de conservation de la quantité de mouvement

$$\frac{\partial}{\partial x}\left(\frac{q_x q_x}{H}\right) + \frac{\partial}{\partial y}\left(\frac{q_x q_y}{H}\right) + c^2 \frac{\partial h}{\partial x} - \frac{1}{\rho}\left(\frac{\partial}{\partial x}(H\tau_{xx}) + \frac{\partial}{\partial y}(H\tau_{xy}) - \tau_x^b - \tau_x^s\right) - f_c q_y = 0$$

$$\frac{\partial}{\partial x}\left(\frac{q_y q_x}{H}\right) + \frac{\partial}{\partial y}\left(\frac{q_y q_y}{H}\right) + c^2 \frac{\partial h}{\partial y} - \frac{1}{\rho}\left(\frac{\partial}{\partial x}(H\tau_{yx}) + \frac{\partial}{\partial y}(H\tau_{yy}) - \tau_y^b - \tau_y^s\right) + f_c q_x = 0$$

$x(x,y)$ = Coordonnées (x vers l'est et y vers le nord)
q_x , q_y = débit spécifique selon x et y (m²/s)
h = hauteur d'eau (niveau)
H = profondeur de la colonne d'eau (=h-z_f) (m)
c = célérité des vagues ($c = \sqrt{gH}$) (m/s)
r = masse spécifique de l'eau (10^3 kg/m)
$u(u,v)$ = composant de la vitesse (m/s) où;
$u = q_x/H$ (m/s)
$v = q_y/H$ (m/s)

f_c = force de Coriolis ($f_c = 2\omega\sin\phi$) (s^{-1})
τ_{ij} = contraintes de Reynolds (kg/s²m)
τ_x^b, τ_y^b = friction au fond en x et en y (kg/s²m)
τ_x^s, τ_y^s = friction en surface en x et en y (kg/s²m)

Figure 8 : Équations des ondes longues (forme conservative) en régime permanent résolues par HYDROSIM (Modèle de Saint-Venant)

La discrétisation

Les données du modèle de terrain sont rendues accessibles au modèle de calcul hydrodynamique par la méthode des éléments finis. Les éléments utilisés sont des triangles à six noeuds (interpolation P1-isoP2) qui sont tous impliqués dans le calcul des vitesses moyennes (Planche 1). Ces nœuds portent les informations sur le frottement et la topographie. La topographie et le niveau d'eau sont portés par les 3 nœuds sommets, mais une interpolation linéaire permet de connaître ces variables sur tout l'élément.

Le maillage du lac Saint-François

Le maillage du lac Saint-François utilisé pour cet atlas est composé de 27 618 éléments et de 57 468 nœuds. La taille des éléments varie de 10 m à 400 m de côté (Planche 1). Une attention particulière a été apportée à la construction du maillage. La forme du terrain dans la partie fluviale et chenalisée est très accidentée ; les éléments dans ces deux parties sont de petite taille et épousent très bien le contour des chenaux. Cette précision permet d'obtenir des vitesses simulées réalistes même dans les petits chenaux.

Le maillage a été construit à l'aide du MODELEUR ; cet outil est au cœur de la gestion des données du modèle de terrain, de la préparation des données à la simulation et de la visualisation des résultats. Le MODELEUR a été conçu pour construire de façon semi-automatique les éléments du maillage. L'utilisateur a la possibilité de choisir la dimension des mailles et la limite du maillage. Une fois la grille de calcul construite, les données de terrain sont interpolées sur les nœuds de calcul (projetées). Cette même grille, ou un autre maillage de représentation, peuvent être utilisés pour consulter graphiquement les résultats sous forme d'isosurfaces, d'isolignes ou de vecteurs. Dans le cas du présent atlas, le même maillage a été utilisé pour la représentation graphique et les calculs hydrodynamiques.

Concept d'événements de référence

En période à l'eau libre (sans glace), la variation temporelle des courants au lac Saint-François est principalement fonction des débits du fleuve et des tributaires, ainsi que de la présence de plantes. Toute variation de l'influence de chacune de ces variables crée autant d'ensembles de conditions différentes qui peuvent être simulées. Toutefois, puisque toutes ces conditions représentent une masse d'information importante et souvent très redondante, des événements dits « de référence » ont été choisis pour montrer la diversité des courants dans le cadre de cet atlas. Ces événements de référence ont été sélectionnés pour représenter des conditions moyennes et fixer les bornes extrêmes ; la plupart des autres conditions possibles sont donc comprises quelque part parmi ces événements. Parmi les événements de référence, on compte aussi ceux utilisés pour vérifier les résultats du simulateur et qui ont fait l'objet de mesures. Le vent et la glace peuvent avoir une influence significative sur l'écoulement ; toutefois, seulement les variations dans les conditions de débits et de plantes aquatiques sont prises en considération dans le cadre de cet atlas.

Le choix des événements de référence

Les chroniques historiques de débit montrent que la gamme des débits mensuels au lac Saint-François varie entre des extrêmes qui vont de 4500 m^3/s à 10 000 m^3/s avec une moyenne d'environ 7500 m^3/s. La diversité des courants est montrée à l'aide des événements extrêmes ainsi qu'avec la moyenne des événements possibles par tranche de 2500 m^3/s, soit de 5000, 7500 et 10 000 m^3/s (Tableau 1). Ces événements sont simulés en absence de plantes et de glace et au

maximum de croissance des plantes. La période d'absence des plantes et de la glace correspond au printemps, entre la fonte des glaces jusqu'au début juin, ou encore à l'automne, entre la fin de novembre et la prise des glaces (période printemps-automne). La période de croissance des macrophytes aquatiques débute au mois de juin et se poursuit jusqu'à la mi-octobre (période été).

Tableau 1 : Événements de référence représentés dans cet atlas

Événement	Débit du fleuve	Débit des tributaires	Résistance des plantes	Période représentée
Planche 5	5000 m³/s	150 m^3/s	Maximum	fin de l'été (août-oct.)
Planche 6	5000 m³/s	750 m^3/s	Absence	printemps et fin de l'automne
Planche 7	7500 m³/s	150 m^3/s	Maximum	fin de l'été (août-oct.)
Planche 8	7500 m³/s	750 m^3/s	Absence	printemps et fin de l'automne
Planche 9	10 000 m³/s	150 m^3/s	Maximum	fin de l'été (août-oct.)
Planche 10	10 000 m³/s	750 m^3/s	Absence	printemps et fin de l'automne

Les tributaires ont une influence réduite sur le patron d'écoulement puisque leur débit moyen reste généralement faible en comparaison avec le débit du fleuve ; les débits moyens des tributaires ont été utilisés pour définir les événements de référence. Le débit total des tributaires utilisé est de 150 m³/s pour les simulations de l'été et de 750 m³/s pour les simulations du printemps et de l'automne.

Validation

Afin d'établir le degré de confiance qui peut être accordé aux résultats de simulations, il est nécessaire de les valider. La validation du modèle hydrodynamique du lac Saint-François a été effectuée en deux étapes, d'abord avec les niveaux d'eau historiques mesurés aux trois stations du lac et avec deux séries de mesures de courant prises en deux périodes distinctes. Dans tous les cas, la vérification du débit simulé aux frontières du modèle et de sa conservation globale dans l'ensemble du domaine de simulation est une condition essentielle à la validation d'une simulation.

La validation des niveaux

La validation par les niveaux d'eau est relativement grossière et permet d'évaluer rapidement la qualité d'une simulation. Étant donné l'importance des plantes aquatiques dans les processus d'écoulement du système, la validation se devait de recouper toute la gamme de résistances

reliées à ce facteur. C'est pourquoi des observations du niveau d'eau réalisées avec des niveaux de croissance des plantes aquatiques de 0% (25-28 avril 1996), 50% (4-7 juillet 1996) et 80% (25-29 juillet 1994) ont été retenues pour vérifier le modèle. Pour chacun de ces événements, le débit du fleuve était respectivement de 6887 m^3/s, 7685 m^3/s et 8410m^3/s , tandis que les débits totaux des tributaires étaient respectivement de 620 m^3/s, 73 m^3/s et 200 m^3/s. Le tableau 2 permet de comparer les niveaux mesurés lors de différents événements avec les niveaux simulés par le modèle hydrodynamique ; la correspondance est excellente.

Tableau 2 : Résultats de la validation des niveaux d'eau (RIGL55)

	Cornwall		Summerstown		Coteau-Landing	
	Mesuré	simulé	Mesuré	simulé	mesuré	simulé
0% de croissance 25-28 avril 1996	46.80 m	46.796 m	46.61 m	46.613 m	46.47 m	46.472 m
50% de croissance 4-7 juillet 1994	46.99 m	46.995 m	46.72 m	46.719 m	46.45 m	46.452 m
80% de croissance 25-29 juillet 1996	46.94 m	46.939 m	47.70 m	46.701 m	45.45 m	46.449 m

La validation des vitesses

La validation du modèle par les mesures des vitesses est plus exigeante que celle réalisée pour les niveaux d'eau. D'abord à cause de la variabilité locale du phénomène qui requiert un effort de caractérisation très étendu sur le terrain, et ensuite à cause des problèmes d'hétérogénéité des ensembles de données que l'on veut comparer. Ce type de validation permet de s'assurer que la résistance à l'écoulement telle que paramétrisée dans le modèle à l'aide des coefficients de Manning reproduit efficacement non seulement l'inclinaison du plan d'eau dans son ensemble mais aussi la distribution des masses d'eau tributaires des courants

La méthode de caractérisation retenue est basée sur l'utilisation d'un courantomètre profileur à effet Doppler (ADCP) sur des transects localisés en des sites jugés représentatifs des grands patrons hydrodynamiques du domaine dans son ensemble ou des conditions particulières typiques comme les transitions abruptes de profondeurs, les contours des îles ou des baies et l'effet des plantes aquatiques. Deux événements de débit distincts ont été utilisés pour la validation : le premier a une faible densité de plantes (4-7 juillet 1996) et le second représente la période près de la croissance maximale (25-29 juillet 1994). La base de données se compose d'environ 15 000 points de mesure de vitesses répartis sur le lac Saint-François, appartenant à 22

sections mesurées en 1994 et à 14 en 1996.

La validation des résultats des simulations exige que les ensembles de données puissent être comparables en nature, c'est-à-dire, homogènes. Les données simulées représentent la vitesse moyenne sur la colonne d'eau tandis que les mesures représentent la vitesse instantanée au point d'échantillonnage. Le courantomètre à effet Doppler mesure la vitesse à tous les 25 cm d'intervalle dans la verticale sur toute la colonne d'eau. Toutefois, cet instrument ne peut mesurer la vitesse près de la surface ni près du fond ; de plus, il ne peut mesurer la portion de la colonne d'eau densément occupée par les plantes. Par ailleurs, l'instrument permet d'obtenir la vitesse instantanée du courant dans les trois directions; par le fait même, les effets aléatoires de la turbulence (tous les mouvements périodiques de fréquence supérieure à quelques secondes comme les tourbillons de Von Karman) ne sont pas filtrés et les mesures peuvent dévier significativement de la direction moyenne. De son côté, le modèle génère la composante moyenne des vitesses donc une valeur exempte de fluctuations turbulentes, et sur une certaine superficie qui est fonction de la taille de la maille de calcul locale. Bref, il est nécessaire de traiter les données mesurées de telle sorte qu'elles puissent être comparées de façon homogène avec les résultats des simulations.

Pour ce faire, les mesures sont intégrées dans la verticale et dans l'espace. La taille de la maille de calcul fixe la dimension de l'intégration spatiale. Par exemple, dans la partie aval du lac où les mailles sont d'environ 100 m de diamètre, les données mesurées sont intégrées sur une distance d'environ 100 m.

Deux événements ont, rappelons-le, été utilisés pour la validation du modèle à l'aide des mesures de courants. Ce sont ceux qui ont également servi à la validation des niveaux d'eau avec des coefficients de croissance des macrophytes de 50% et de 80% (4-7 juillet 1996 et 25-29 juillet 1994). Les champs de vitesse correspondants se distinguent à maints égards, notamment dans les régions peu profondes où les plantes sont présentes.

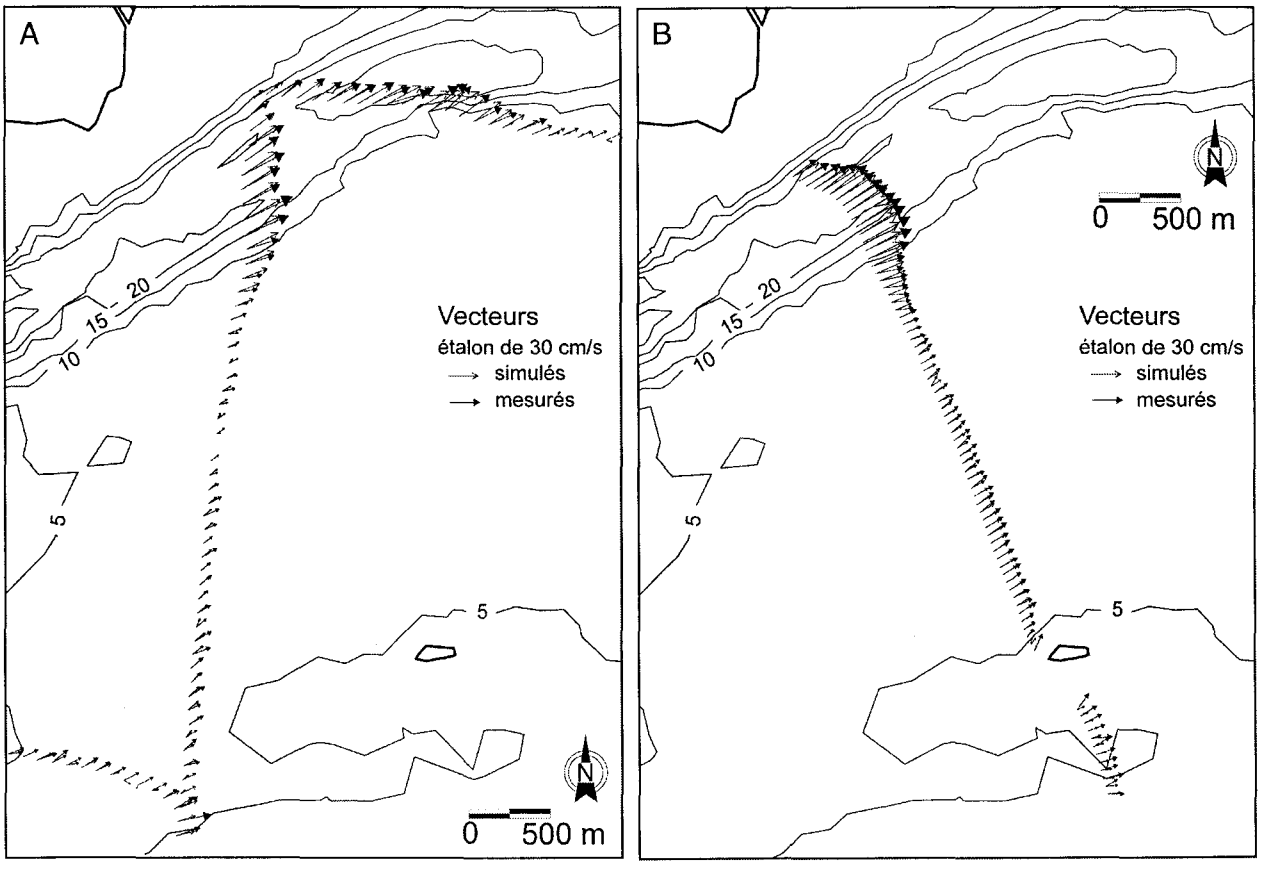

Figure 9 : Exemples de validation des vitesses à l'aide de deux événements différents. A : événement du 4-7 juillet 1996 avec 8410 m^3/s et 50% de croissance des plantes. B : événement du 25-29 juillet 1994 avec 7685 m^3/s et 80% de croissance des plantes.

La figure 9A permet de comparer quelques résultats de la simulation à 50% de macrophytes avec les mesures, tandis que la figure 9B présente une comparaison équivalente pendant la phase de croissance à 80%. Graphiquement, la comparaison utilise des vecteurs dont la longueur est proportionnelle au courant et la direction consistante avec l'orientation du courant. On peut constater la bonne qualité des simulations notamment dans les transitions rapides de profondeurs observables en périphérie de la voie navigable.

Présentation des résultats

La plupart des résultats illustrés ci-après sous forme de planches découlent de l'exercice de modélisation de terrain, ou encore des simulations hydrodynamiques. La signification exacte des variables traitées a été introduite dans la première partie du document sauf la fonction courant qui nécessite d'être définie. Nous y reviendrons un peu plus bas. La vitesse du courant représentée sur les planches est obtenue en divisant localement le débit spécifique des simulations - la variable primitive du simulateur - par la profondeur. Le module du débit spécifique est obtenu à partir des composantes vectorielles selon x et y de cette variable. La direction du courant n'est donc pas représentée.

Il a été décidé de ne pas commenter en détails ni de discuter les résultats présentés et de laisser, comme c'est la plupart du temps le cas avec les atlas, les images parler d'elles-mêmes. Seul un bref commentaire est fourni avec la légende afin de rappeler quelques éléments de compréhension indispensables.

La fonction courant est un des multiples résultats (planches 13 et 14) qui peuvent être obtenus par un simple post-traitement des variables de base de la modélisation de terrain et/ou hydrodynamique, comme par exemple, la diffusivité due à la turbulence, le régime d'écoulement représenté par le nombre de Froude, la vitesse de cisaillement, pour ne nommer que celles-là. Seule la fonction courant a été illustrée ici car cette variable permet de se faire une idée très rapide de la provenance et de la destination moyennes des masses d'eau dans le système. Le lecteur devra se souvenir que la principale simplification tient à l'absence de la diffusion turbulente comme facteur participant à la propagation des masses d'eau. Il faut donc interpréter ce résultat à titre indicatif seulement.

Mathématiquement, la fonction courant est obtenue par l'intégration numérique du débit spécifique sur l'ensemble du domaine de simulation. Le débit spécifique est le produit local de la vitesse moyenne du courant (module) par la profondeur. Ses unités sont des m^2/s. Pour obtenir un débit en m^3/s transitant par une section donnée, il faut intégrer transversalement au courant sur la largeur considérée. C'est un peu ce que fait la fonction courant mais en utilisant une approche spatialisée sur l'ensemble du domaine. Pour l'interpréter, on n'a qu'à considérer les isosurfaces comme des couloirs où transite un certain débit égal à l'incrément de l'intervalle de classes.

Ainsi, en partant d'une berge, les couloirs de débit s'additionnent les uns aux autres jusqu'à la berge opposée où l'on retrouve alors le débit total du fleuve.

Résultats (planches)

Planche 1 : Grille de calcul de type éléments finis

Cette planche représente l'ensemble du maillage d'éléments finis utilisé pour les fins du calcul hydrodynamique ainsi que trois agrandissements correspondant aux parties fluviale, chenalisée et lacustre. La dimension des éléments utilisés est dictée par la nécessité d'un temps de calcul informatique raisonnable ainsi que par une représentation acceptable des facteurs de résistance à l'écoulement et de la topographie. Les parties fluviale et chenalisée comportent des éléments plus petits en raison d'une topographie beaucoup plus complexe à ces endroits que dans la partie lacustre. Les éléments du maillage peuvent être raffinés pour des applications particulières.

Planche 2 : Topographie

Cette planche montre la topographie de l'ensemble du lac Saint-François. Pour les fins de l'atlas, la topographie est délimitée par les berges correspondant au niveau du lac tel que stabilisé artificiellement. Autrement dit, elle n'inclut pas les anciennes plaines de débordement. Les agrandissements dans les parties fluviale, chenalisée et lacustre montrent bien les différents types de physiographie rencontrés dans le lac. La topographie est particulièrement complexe (anastomosée) dans la partie médiane du lac.

Planche 3 : Substrat et plantes aquatiques

Cette planche illustre la distribution du substrat et des plantes. Les macrophytes sont absents de la partie fluviale (amont) sauf à proximité des berges. La partie chenalisée (centre) est nettement plus colonisée par les macrophytes en particulier par le myriophylle (*Myriophyllum spicatum).* La partie lacustre (aval) est également couverte de plantes aquatiques ; l'espèce la plus abondante est la vallisnérie (*Vallisneria americana*).

La taille caractéristique des sédiments est généralement faible. Seules la blocaille (till délavé) située principalement à l'amont et la roche mère à l'aval sont des substrats de dimension plus

importante. De façon générale, la dimension du substrat diminue de l'amont vers l'aval, en relation directe avec la diminution des vitesses de courant.

Planche 4 : Frottement des plantes aquatiques et du substrat

Cette planche montre les coefficients de frottement (sous la forme d'un « n » de Manning) liés au substrat et aux plantes aquatiques. Ces coefficients sont ceux utilisés par le modèle hydrodynamique. Les valeurs du coefficient de Manning liées au substrat sont généralement entre 0.016 et 0.027. Les valeurs sont un peu plus élevées dans la partie amont (fluviale) puisque le substrat y est plus grossier. Des valeurs de coefficient élevées ont également été utilisées sur le seuil près des ouvrages de Coteau.

Les valeurs liées aux plantes aquatiques varient énormément et atteignent des valeurs extrêmement élevées (0.180) quand on les compare à celles du substrat. Ces fortes valeurs se retrouvent à des endroits où la densité de plante est telle que l'écoulement est pratiquement nul.

Planche 5 : Vitesses de courant (module) simulées pour un débit de 5000 m^3/s, plantes au maximum de croissance

L'agrandissement dans la partie fluviale (partie B) possède sa propre légende car les vitesses y sont beaucoup plus élevées que dans le reste du lac. La légende principale est valable pour la vue générale du lac (figure A) ainsi que pour les agrandissements des zones chenalisée et lacustre (figures C et D). La direction des courants n'est pas représentée ici.

Les vitesses les plus grandes se retrouvent dans la partie fluviale à l'amont du lac et diminuent graduellement en allant vers l'aval, soit au fur et à mesure que s'élargit la section d'écoulement. A la sortie du lac, un accroissement des vitesses est observé dans le canal de Beauharnois. La présence de plantes aquatiques au stade maximum de leur croissance accentue le contraste entre les vitesses rapides des chenaux et les vitesses plus lentes associées aux parties moins profondes du lac.

Planche 6 : Vitesses de courant simulées pour un débit de 5000 m^3/s, plantes au minimum de croissance

Comme pour la précédente planche, l'agrandissement dans la partie fluviale (partie B) possède sa propre légende car les vitesses y sont beaucoup plus élevées que dans le reste du lac. La légende

principale est valable pour la vue globale du lac (partie A) ainsi que pour les agrandissements des zones chenalisée et lacustre (parties C et D).

Les vitesses les plus grandes se retrouvent dans la partie fluviale à l'amont du lac et diminuent graduellement en allant vers l'aval. A la sortie du lac, un accroissement des vitesses est observé dans le Canal de Beauharnois. Généralement, les vitesses les plus rapides se retrouvent dans les chenaux tandis que les vitesses les plus lentes sont associées aux parties moins profondes du lac. Les contrastes de vitesses entre les différentes parties de la section d'écoulement sont moins accentués que dans la planche précédente, laquelle montrait le maximum de la résistance des plantes et une structuration plus prononcée des courants.

Planche 7 : Vitesses de courant (module) simulées pour un débit de 7500 m^3/s, plantes au maximum de croissance

L'agrandissement dans la partie fluviale (partie B) possède sa propre légende car les vitesses y sont beaucoup plus élevées que dans le reste du lac. La légende principale est valable pour la vue globale du lac (partie A) ainsi que pour les agrandissements des zones chenalisée et lacustre (parties C et D).

Les vitesses les plus grandes se retrouvent dans la partie fluviale à l'amont du lac et diminuent graduellement en allant vers l'aval. A la sortie du lac, un accroissement des vitesses est observé dans le Canal de Beauharnois. La présence de plantes aquatiques au stade maximum de leur croissance accentue le contraste entre les vitesses rapides des chenaux et les vitesses plus lentes associées aux parties moins profondes du lac.

Planche 8 : Vitesses de courant (module) simulées pour un débit de 7500 m^3/s, plantes au minimum de croissance

L'agrandissement dans la partie fluviale (partie B) possède sa propre légende car les vitesses y sont beaucoup plus élevées que dans le reste du lac. La légende générale est valable pour la vue globale du lac (partie A) ainsi que pour les agrandissements des zones chenalisée et lacustre (parties C et D).

Les vitesses les plus grandes se retrouvent dans la partie fluviale à l'amont du lac et diminuent graduellement en allant vers l'aval. A la sortie du lac, un accroissement des vitesses est observé

dans le Canal de Beauharnois. Généralement, les vitesses les plus rapides se retrouvent dans les chenaux tandis que les vitesses les plus lentes sont associées aux parties moins profondes du lac. Les contrastes de vitesses entre les différentes parties de la section d'écoulement sont moins accentués que dans la planche précédente laquelle montrait le maximum de la résistance des plantes et une structuration plus prononcée des courants.

Planche 9 : Vitesses de courant (module) simulées pour un débit de 10 000 m^3/s, plantes au maximum de croissance

L'agrandissement dans la partie fluviale (partie B) possède sa propre légende car les vitesses y sont beaucoup plus élevées que dans le reste du lac. La légende principale est valable pour la vue globale du lac (partie A) ainsi que pour les agrandissements des zones chenalisée et lacustre (parties C et D).

Les vitesses les plus grandes se retrouvent dans la partie fluviale à l'amont du lac et diminuent graduellement en allant vers l'aval. A la sortie du lac, un accroissement des vitesses est observé dans le Canal de Beauharnois ainsi qu'en approchant de Coteau I et Coteau III. La présence de plantes aquatiques au stade maximum de leur croissance accentue le contraste entre les vitesses rapides des chenaux et les vitesses plus lentes associées aux parties moins profondes du lac.

Planche 10 : Vitesses de courant (module) simulées pour un débit de 10 000 m^3/s, plantes au minimum de croissance

L'agrandissement dans la partie fluviale (partie B) possède sa propre légende car les vitesses y sont beaucoup plus élevées que dans le reste du lac. La légende principale est valable pour la vue globale du lac (partie A) ainsi que pour les agrandissements des zones chenalisée et lacustre (parties C et D).

Les vitesses les plus grandes (3.5 à 4.1 m/s) se retrouvent dans la partie fluviale à l'amont du lac et diminuent graduellement en allant vers l'aval. A la sortie du lac, un accroissement des vitesses est observé dans le Canal de Beauharnois ainsi qu'en approchant de Coteau I et Coteau III. Généralement, les vitesses les plus rapides se retrouvent dans les chenaux tandis que les vitesses les plus lentes sont associées aux parties moins profondes du lac. Les contrastes de vitesses entre les différentes parties de la section d'écoulement sont moins accentués que dans la planche

précédente laquelle montrait le maximum de la résistance des plantes et une structuration plus prononcée des courants.

Planche 11 : Niveaux d'eau simulés pour un débit de 7500 m^3/s, plantes au maximum de croissance

La planche 11 illustre le niveau d'eau obtenu pour un débit de 7500 m^3/s avec les plantes aquatiques au maximum de leur croissance. Les pertes de charge associées à la résistance des plantes et du substrat sont beaucoup plus importantes à l'amont du lac et s'amenuisent au fur et à mesure que l'on se dirige vers l'aval du lac. Les pertes de charge sont plus importantes dans les parties chenalisée et lacustre en présence de plantes aquatiques qu'en leur absence. Cela est causé par la résistance supplémentaire induite par les plantes.

Les niveaux présentés ici sont réduits au RIGL55 (repère international des Grands Lacs), dont la base est à quelques centimètres du niveau moyen des mers. Le niveau présenté ici est le niveau de la surface du lac. Pour connaître la profondeur, il suffit de soustraire la topographie du niveau d'eau.

Planche 12 : Niveaux d'eau simulés pour un débit de 7500 m^3/s, plantes au minimum de croissance

La planche 12 illustre le niveau d'eau obtenu pour un débit de 7500 m^3/s avec les plantes aquatiques au minimum de croissance. Les pertes de charge sont beaucoup plus importantes à l'amont du lac et s'amenuisent au fur et à mesure que l'on se dirige vers l'aval du lac.

Les niveaux présentés ici sont réduits au RIGL55 (repère international des Grands Lacs), dont la base est à quelques centimètres du niveau moyen des mers. Le niveau présenté ici est le niveau de la surface du lac. Pour connaître la profondeur, il suffit de soustraire la topographie du niveau d'eau.

Planche 13 : Fonction courant pour un débit de 7500 m^3/s, plantes au maximum de croissance

La planche 13 montre la répartition spatiale moyenne des masses d'eau à l'aide de la fonction courant en supposant qu'il n'y a aucun mélange. Cette hypothèse limite l'interprétation à une simple valeur descriptive de la provenance et de la destination moyenne des masses d'eau. Les

classes de débit permettent d'identifier la proportion du débit occupé par les tributaires ainsi que les eaux passant de part et d'autre de l'île de Cornwall. Il ne s'agit pas ici de la position réelle des masses d'eau puisqu'on ne tient pas compte des mélanges latéraux.

Planche 14 : Fonction courant pour un débit de 7500 m^3/s, plantes au minimum de croissance

La planche 14 montre la répartition spatiale moyenne des masses d'eau à l'aide de la fonction courant en supposant qu'il n'y a aucun mélange. Cette hypothèse limite l'interprétation à une simple valeur descriptive de la provenance et de la destination moyenne des masses d'eau. Les classes de débit permettent d'identifier les masses d'eau correspondant aux différents tributaires ainsi que les eaux passant de part et d'autre de l'île de Cornwall. Il ne s'agit pas ici de la position réelle des masses d'eau puisqu'on ne tient pas compte des mélanges latéraux.

Pour en savoir plus :

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Service météorologique du Canada
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Tél : (514) 283-1629
Fax : (514) 296-1867

Documents pertinents sur la physique du lac Saint-François :

MORIN, J., Y. SECRETAN et M. LECLERC 2000. Hydrodynamic modeling of pristine Lake Saint-François, St. Lawrence river. *Journal of Great Lakes Research* 26 : 384-401.

MORIN, J., M. LECLERC, Y. SECRETAN et P. BOUDREAU 2000. Integrated two-dimensional macrophytes-hydrodynamic modeling. *Journal of Hydraulic Research* 38 : 163-172.

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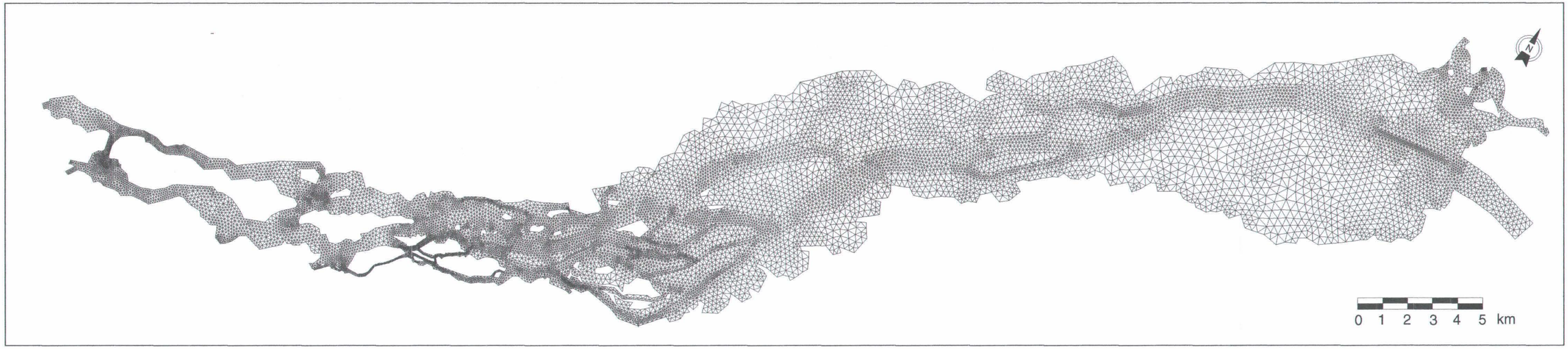
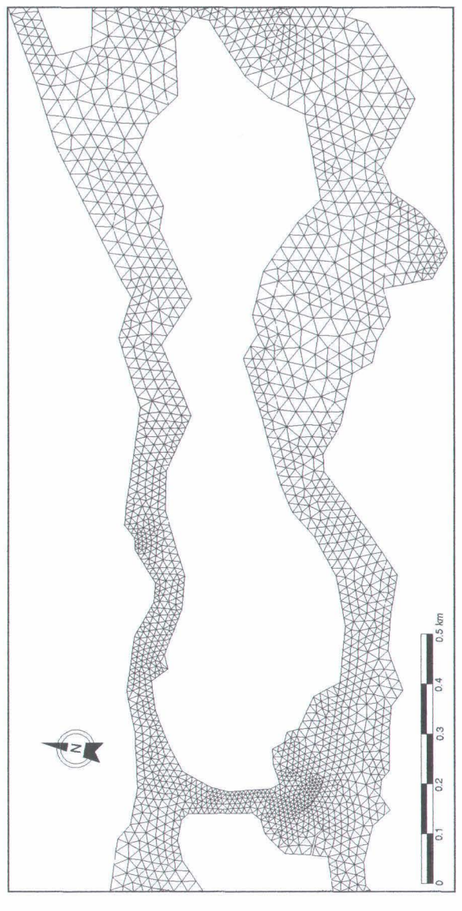
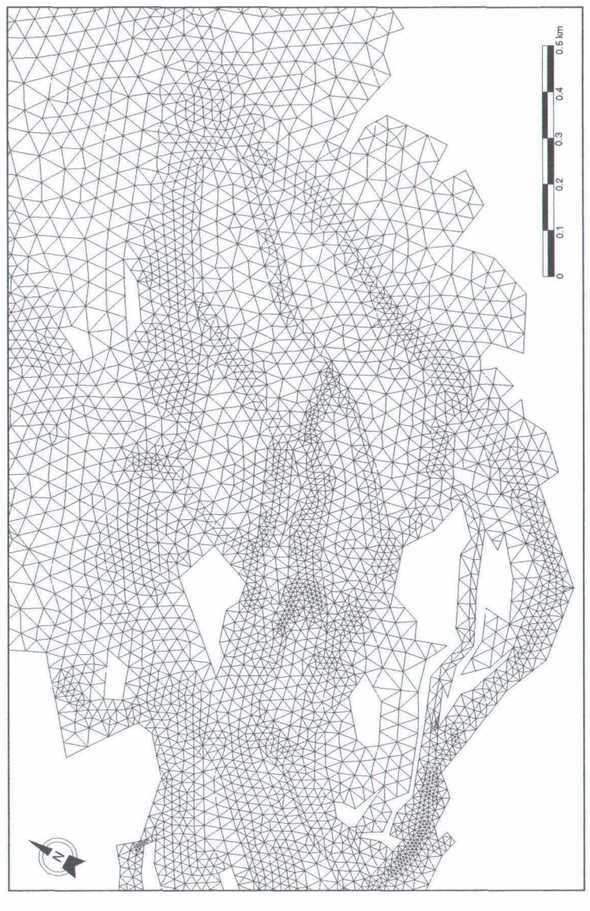
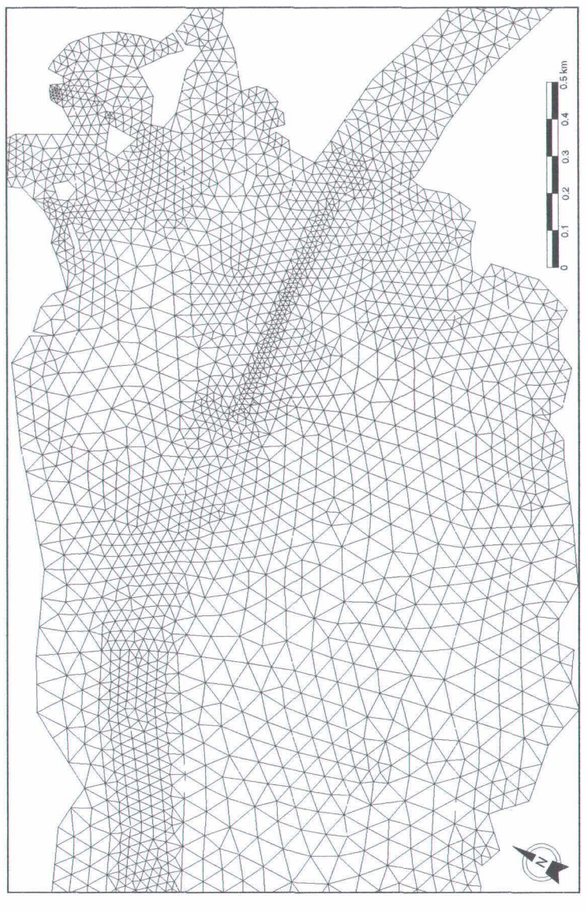
LORRAIN, S., V. JARRY et K. GUERTIN 1993. Répartition spatiale et évolution temporelle des biphényles polychlorés et du mercure dans les sédiments du lac Saint-François; 1979-1989. Environnement Canada, Centre Saint-Laurent. 64 p.

SLOTERDIJK, H. 1985. Substances toxiques dans les sédiments du lac Saint-François, Direction générale des eaux intérieurs, Environnement Canada, Région du Québec. 75 p.



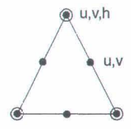






Maillage éléments finis

57 468 noeuds
27 618 éléments
129 842 degrés de liberté



Triangle à 6 noeuds à interpolation linéaire (T6L)

Dimension maximum: 400 m
Dimension minimum: 10 m

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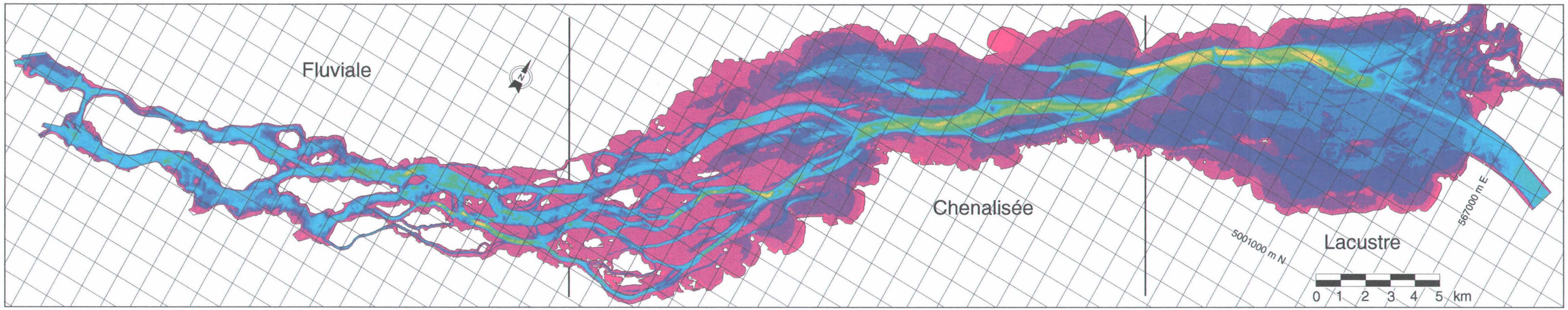
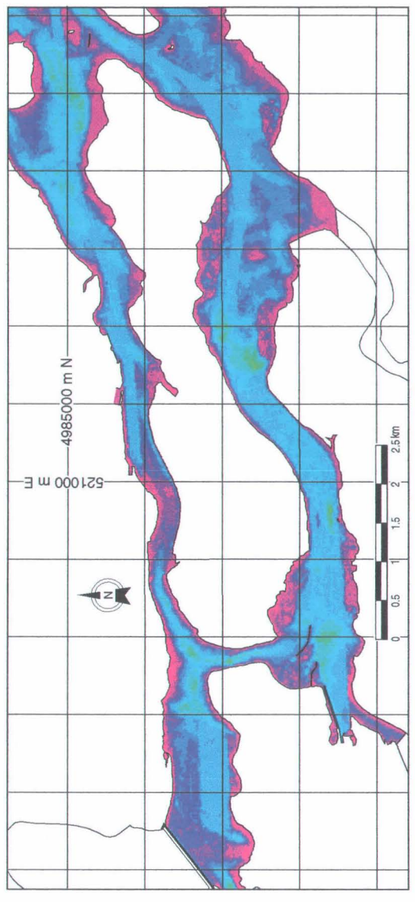
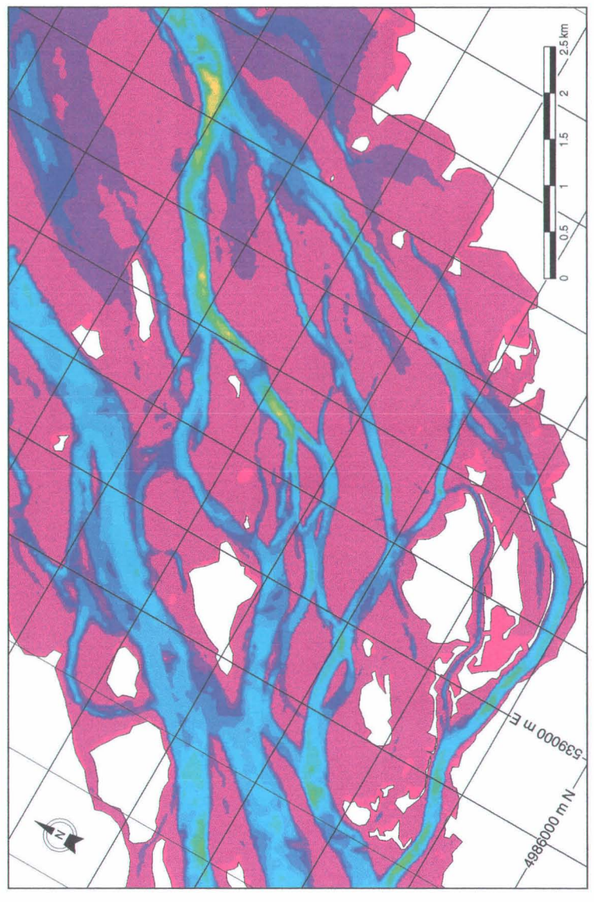
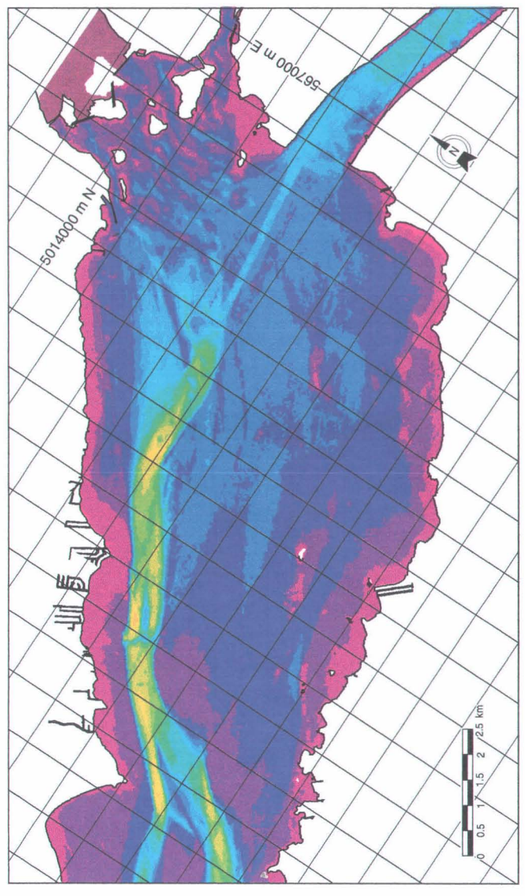
Planche 1









Topométrie

292 270 points de sondage du Service Hydrographique du Canada (1989) à une précision verticale de 0,15 m

Grille 1000 m, UTM 18, NAD 27

Topométrie (m, RIGL 55)

48.0
46.0
44.0
42.0
40.0
38.0
36.0
34.0
32.0
30.0
28.0
26.0
24.0
22.0
20.0
18.0

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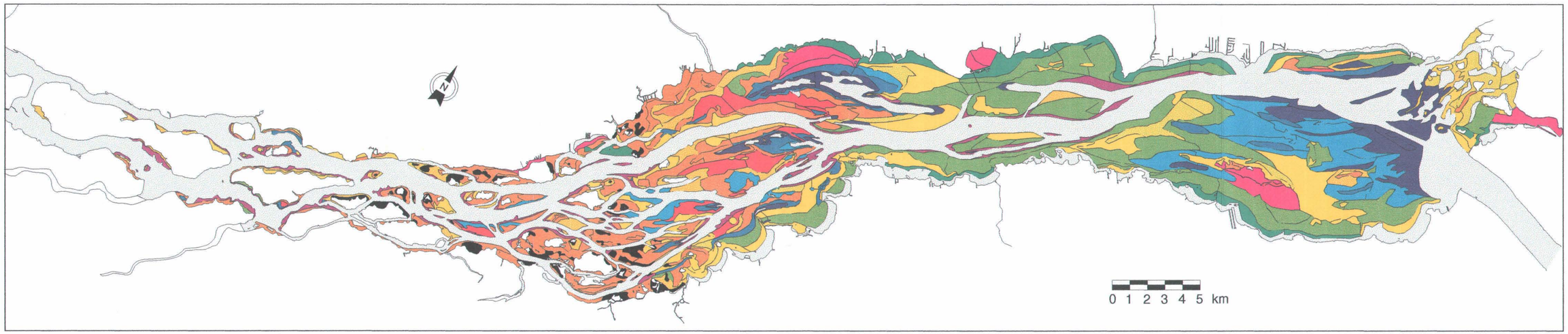
Planche 2



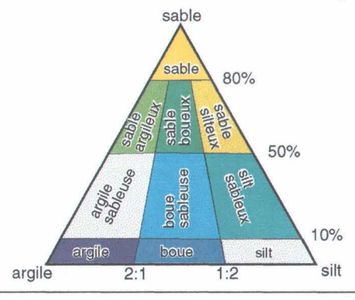
Macrophytes aquatiques du lac Saint-François

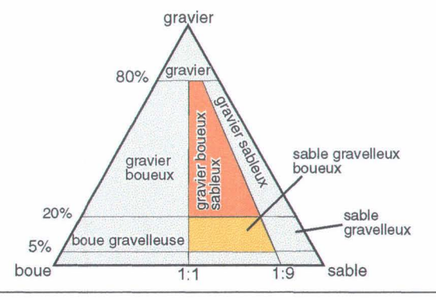
Macrophytes submergés

- *Nitella* sp.
- *Elodea canadensis/ Ceratophyllum demersum*
- *Vallisneria americana/Nitella* sp.
- *Vallisneria americana/Alisma gramineus*
- *Vallisneria americana/Potamogeton richarsonii*
- *Myriophyllum spicatum/Vallisneria americana/ Potamogeton richardsonii*
- *Vallisneria americana*
- *Myriophyllum spicatum/Vallisneria americana*
- *Myriophyllum spicatum*
- *Myriophyllum spicatum* (formes en canopé)
- *Potamogeton pectinatus*
- *Heteranthera dubia/ Ceratophyllum demersum/ Potamogeton pectinatus/Potamogeton richarsonii/ Myriophyllum spicatum/Elodea canadensis*

Macrophytes émergents

Substrat du lac Saint-François





- blocaille (till)
- roche mère

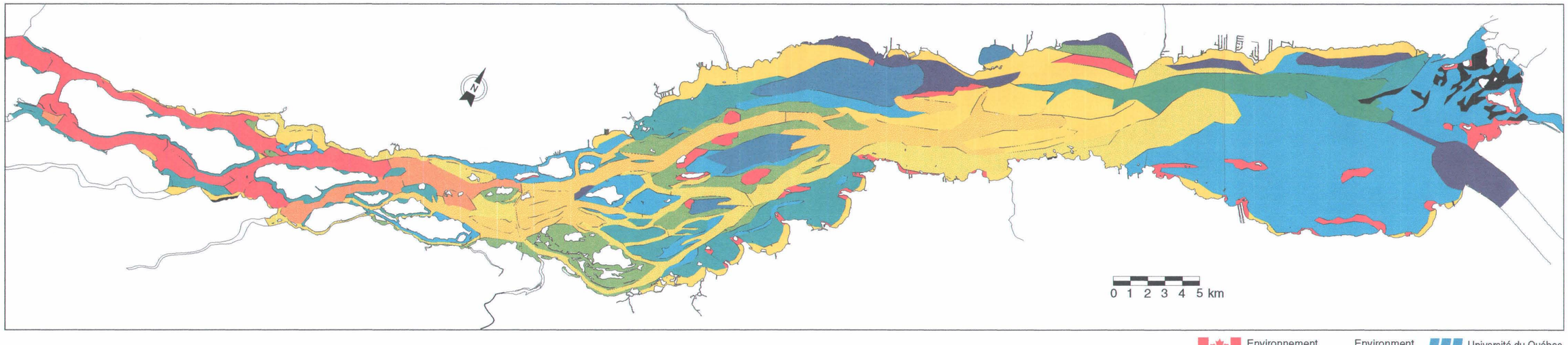


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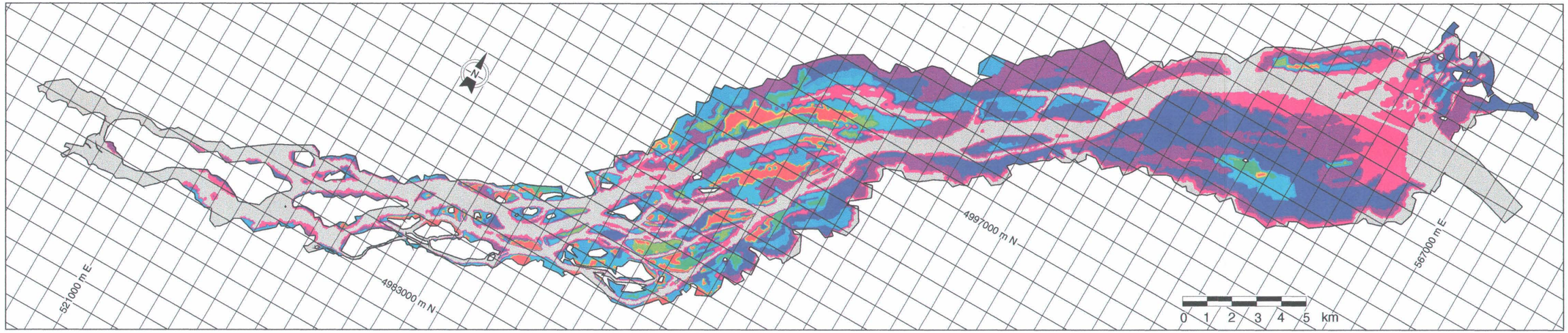
Planche 3



Coefficient de Manning

0.180
0.162
0.144
0.126
0.108
0.090
0.072
0.054
0.036
0.018
0.010
absence de plante

Coefficient de frottement des plantes aquatiques (Manning)

Maximum de croissance

Coefficient de Manning

0.051
0.048
0.044
0.041
0.037
0.034
0.030
0.027
0.023
0.020
0.016

Coefficient de frottement des substrats (Manning)

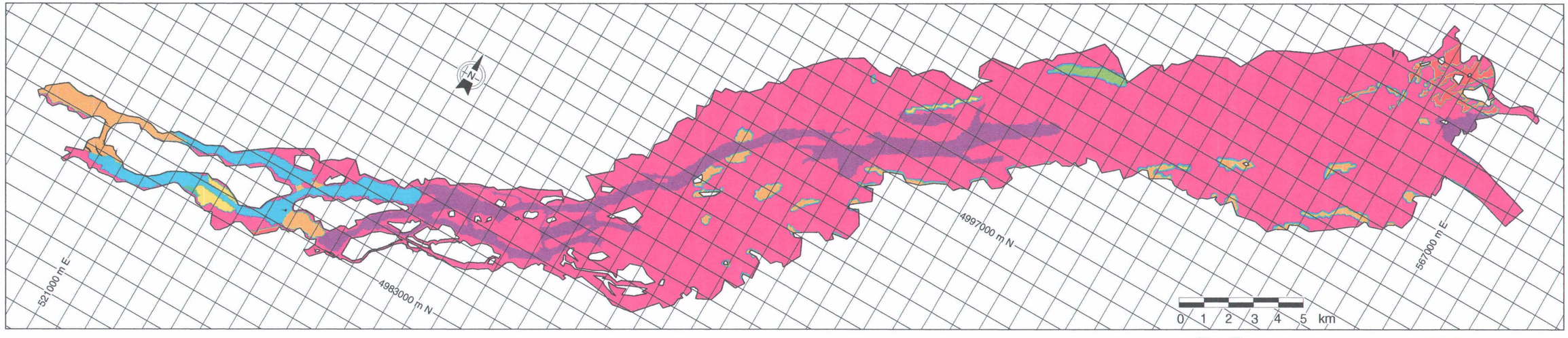


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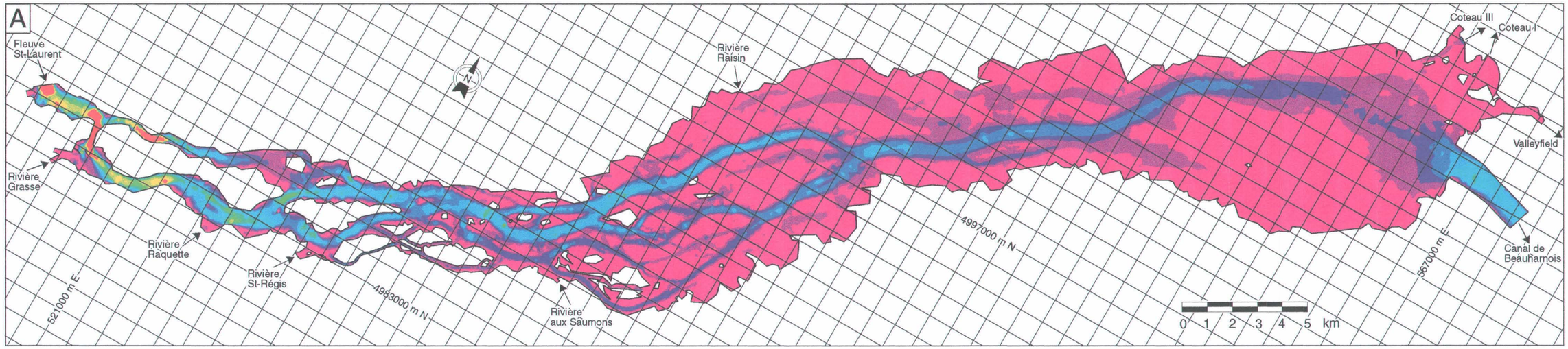
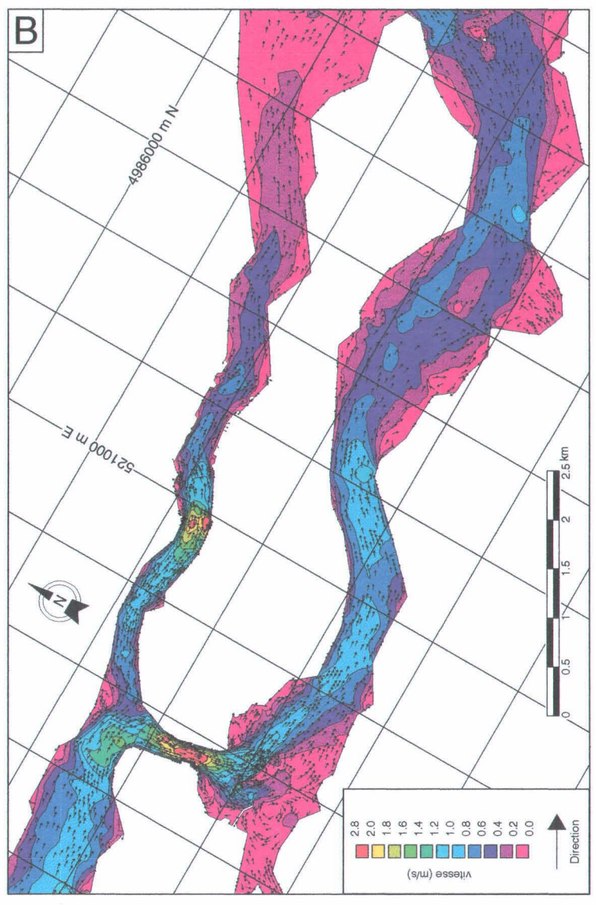
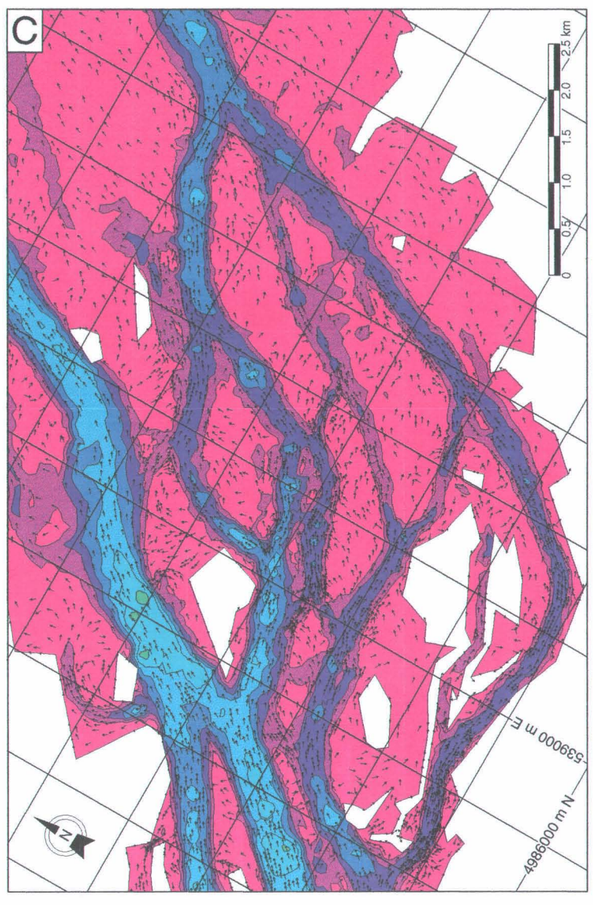
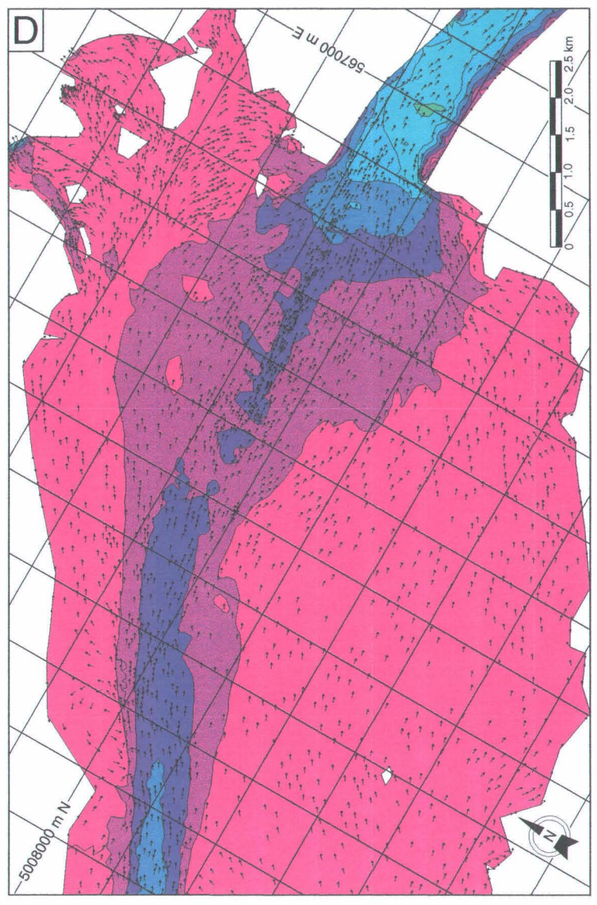
Planche 4









Simulations hydrodynamiques

ÉTÉ 5 000 m^3/s

Plantes aquatiques: Croissance maximum
Grille 1000 m, UTM 18, NAD 27

Entrée:	
Fleuve	5 000 m^3/s
Tributaires:	
Riv. Grasse	20 m^3/s
Riv. Raquette	70 m^3/s
Riv. St-Régis	30 m^3/s
Riv. aux Saumons	10 m^3/s
Riv. Raisin	5 m^3/s
Sorties:	
Coteau III	200 m^3/s
Coteau I	90 m^3/s
Valleyfield	5 m^3/s
Beauharnois	4 840 m^3/s

Direction des vitesses

Vitesse (m/s)

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 2.8

Note: La légende ci-haut est valide pour les figures A, C et D.

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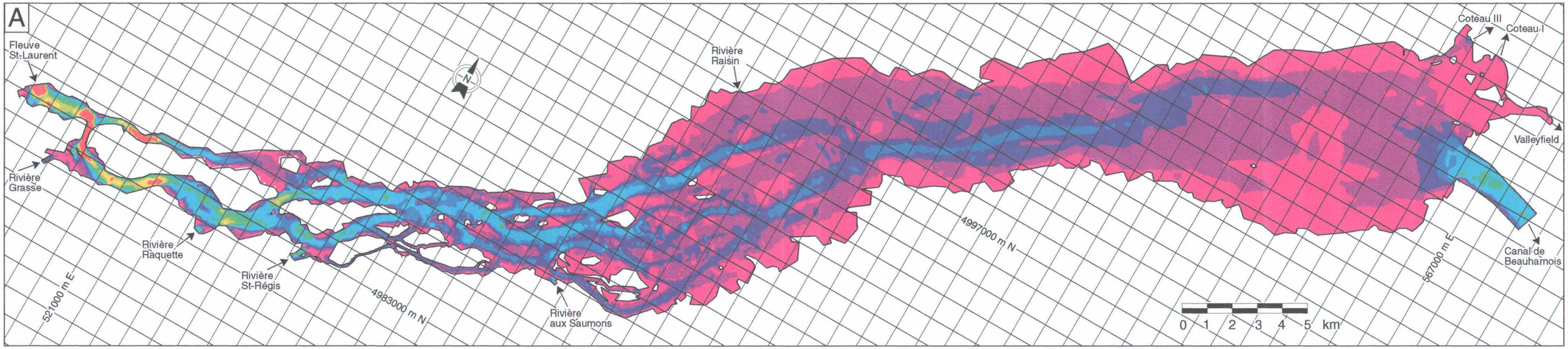
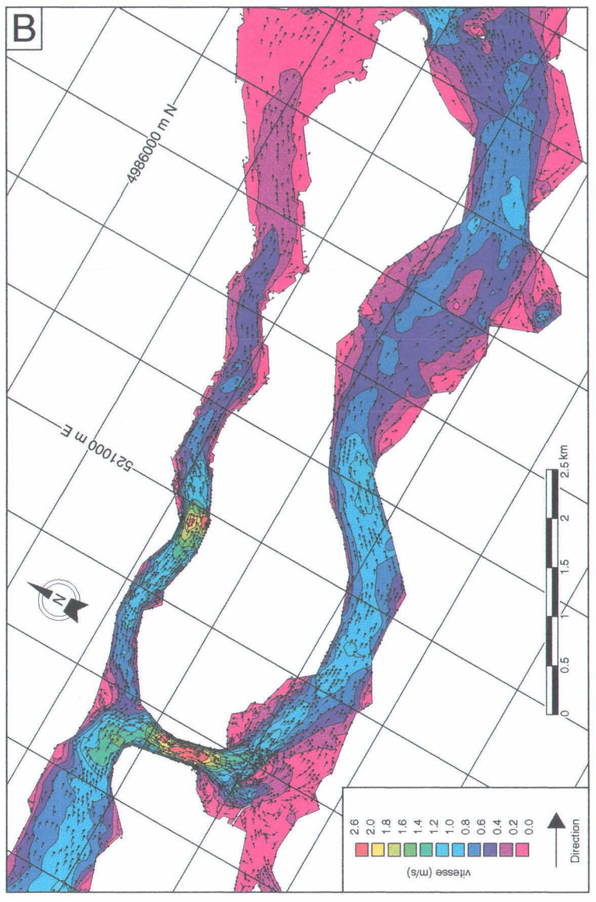
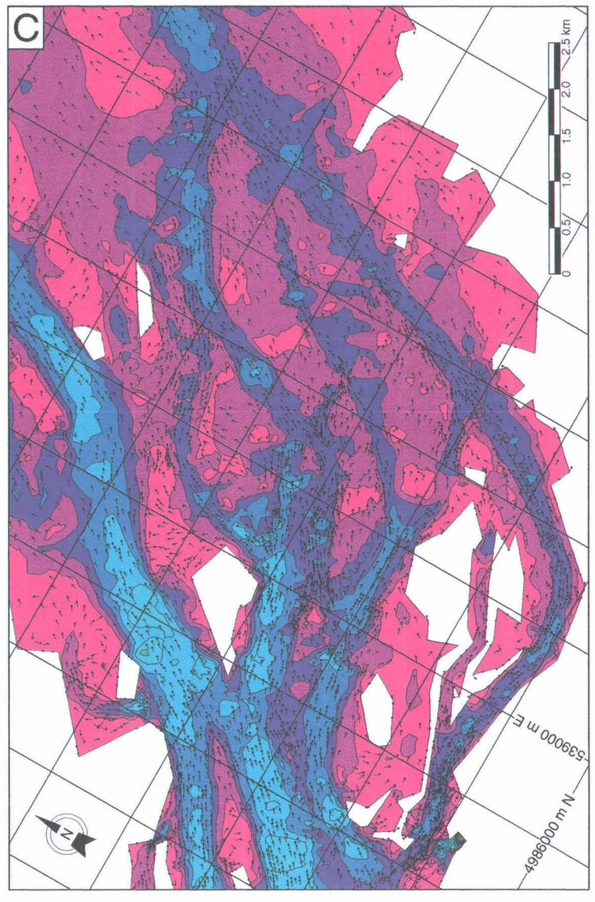
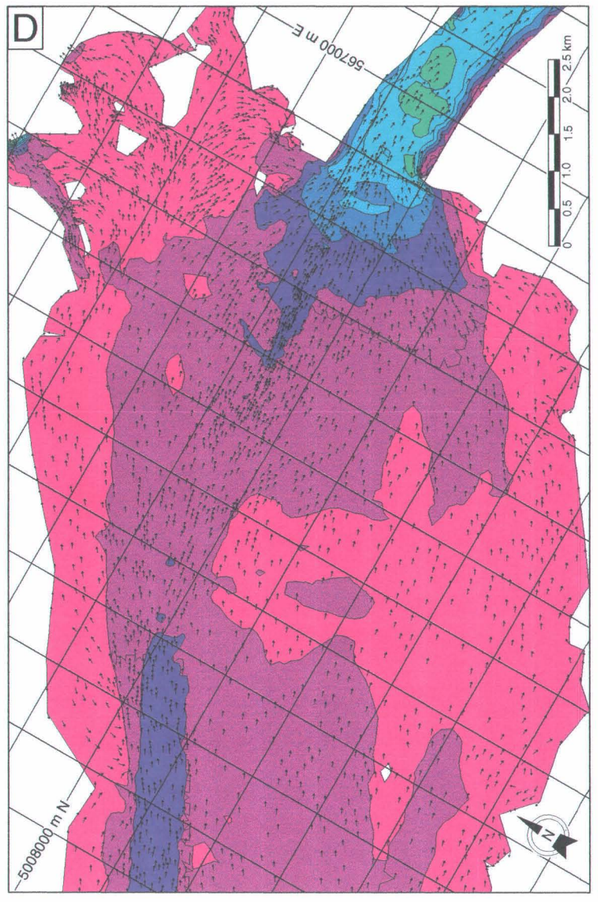
Planche 5









Simulations hydrodynamiques

PRINTEMPS-AUTOMNE 5 000 m³/s

Absence de plantes aquatiques
Grid 1000 m, UTM 18, NAD 27

Entrée:

Fleuve	5 000 m³/s

Tributaires:

Riv. Grasse	150 m³/s
Riv. Raquette	280 m³/s
Riv. St-Régis	195 m³/s
Riv. aux Saumons	90 m³/s
Riv. Raisin	35 m³/s

Sorties:

Coteau III	300 m³/s
Coteau I	140 m³/s
Valleyfield	5 m³/s
Beauharnois	5 305 m³/s

Direction des vitesses

Vitesse (m/s)

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 2.6

Note: La légende ci-haut est valide pour les figures A, C et D.

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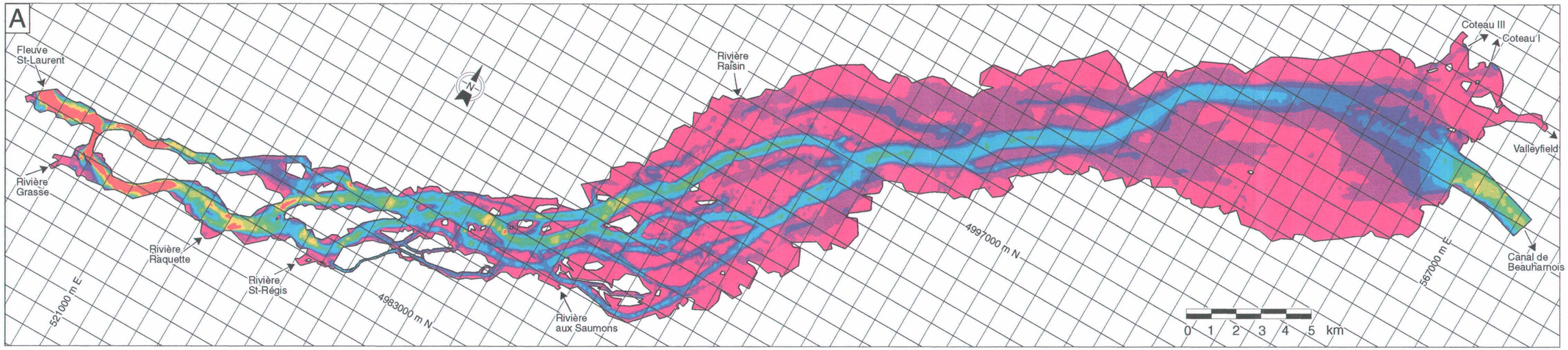

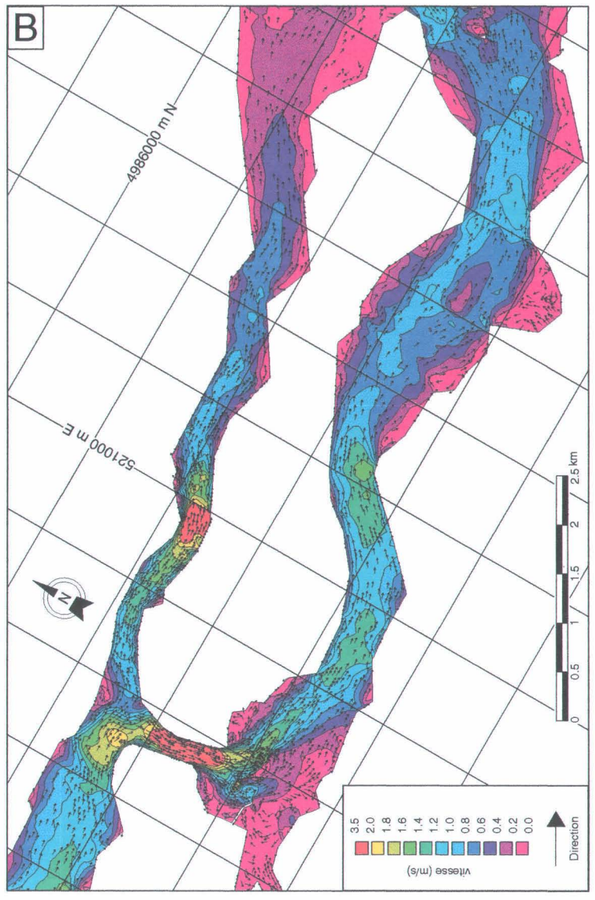

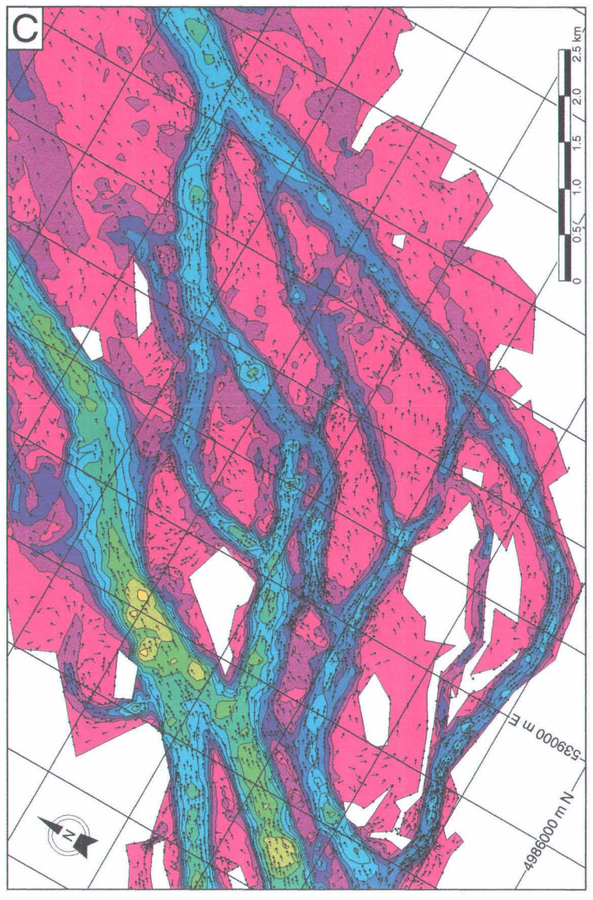

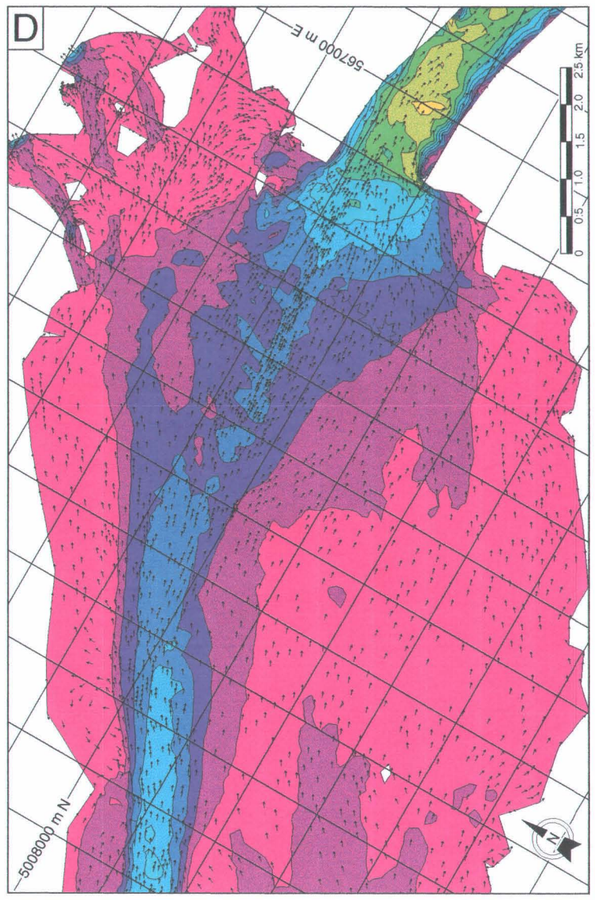

Simulations hydrodynamiques

ÉTÉ 7 500 m³/s

Plantes aquatiques: Croissance maximum
Grille 1000 m, UTM 18, NAD 27

Entrée:	
Fleuve	7 500 m³/s
Tributaires:	
Riv. Grasse	20 m³/s
Riv. Raquette	70 m³/s
Riv. St-Régis	30 m³/s
Riv. aux Saumons	10 m³/s
Riv. Raisin	5 m³/s
Sorties:	
Coteau III	200 m³/s
Coteau I	350 m³/s
Valleyfield	5 m³/s
Beauharnois	7 080 m³/s

Direction des vitesses

Vitesse (m/s)

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 3.5

Note: La légende ci-haut est valide pour les figures A, C et D.

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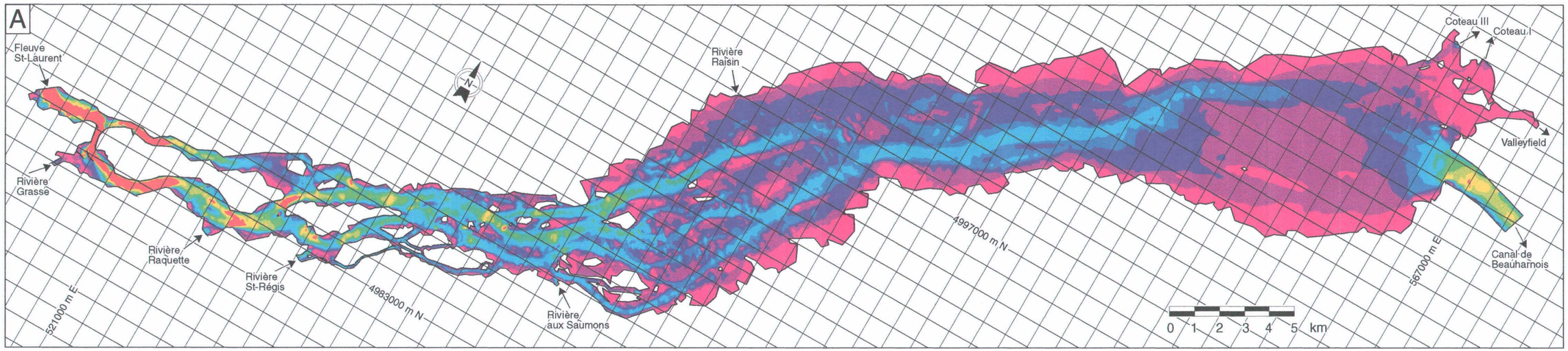

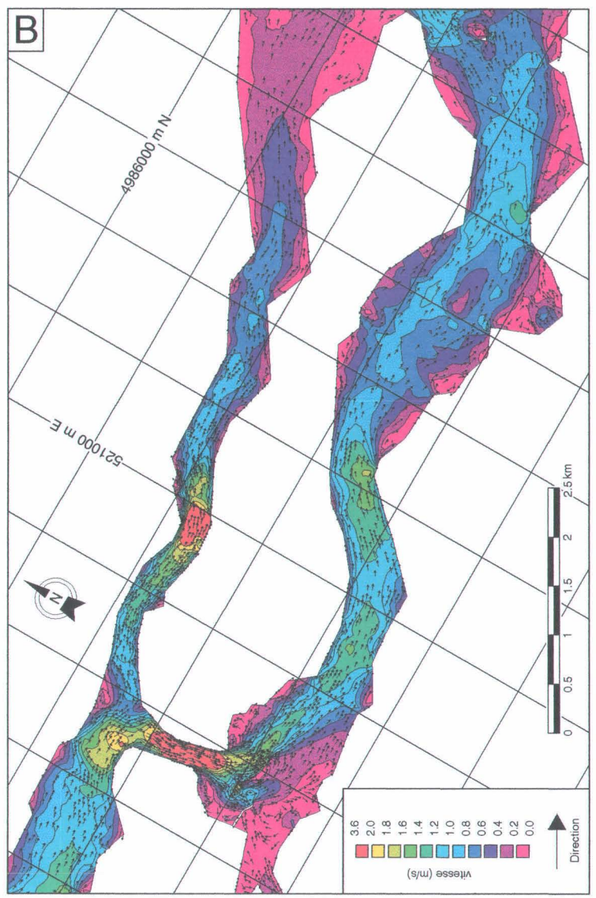

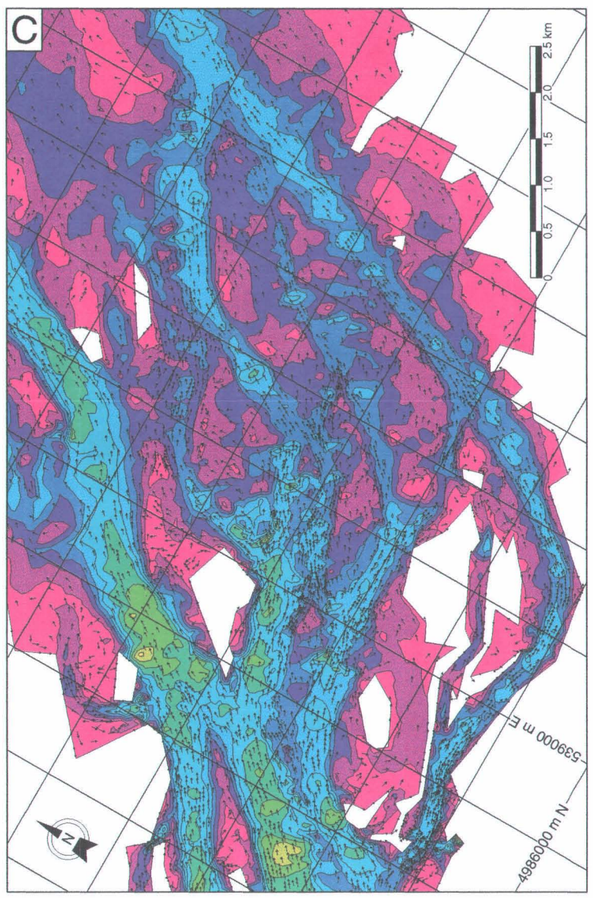

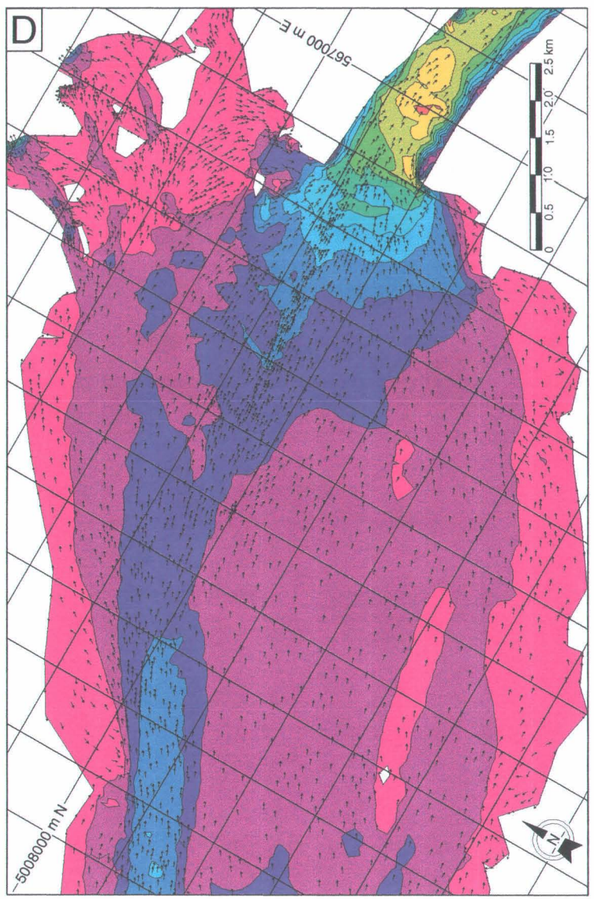

Simulations hydrodynamiques

PRINTEMPS-AUTOMNE 7 500 m^3/s

Absence de plantes aquatiques
Grille 1000 m, UTM 18, NAD 27

Entrée:	
Fleuve	7 500 m^3/s
Tributaires:	
Riv. Grasse	150 m^3/s
Riv. Raquette	280 m^3/s
Riv. St-Régis	195 m^3/s
Riv. aux Saumons	90 m^3/s
Riv. Raisin	35 m^3/s
Sorties:	
Coteau III	300 m^3/s
Coteau I	250 m^3/s
Valleyfield	5 m^3/s
Beauharnois	7 695 m^3/s

Direction des vitesses

Vitesse (m/s)

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 3.6

Note: La légende ci-haut est valide pour les figures A, C et D.

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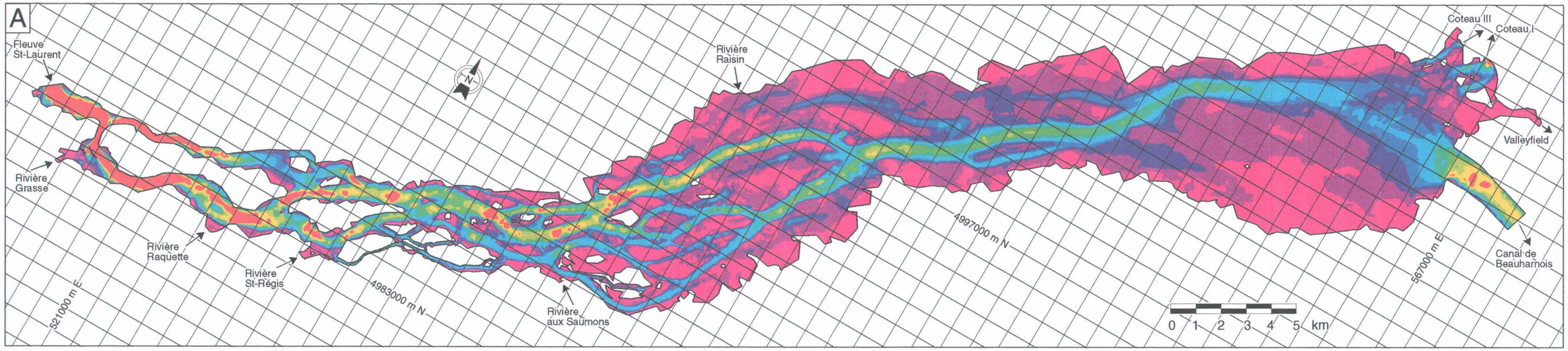

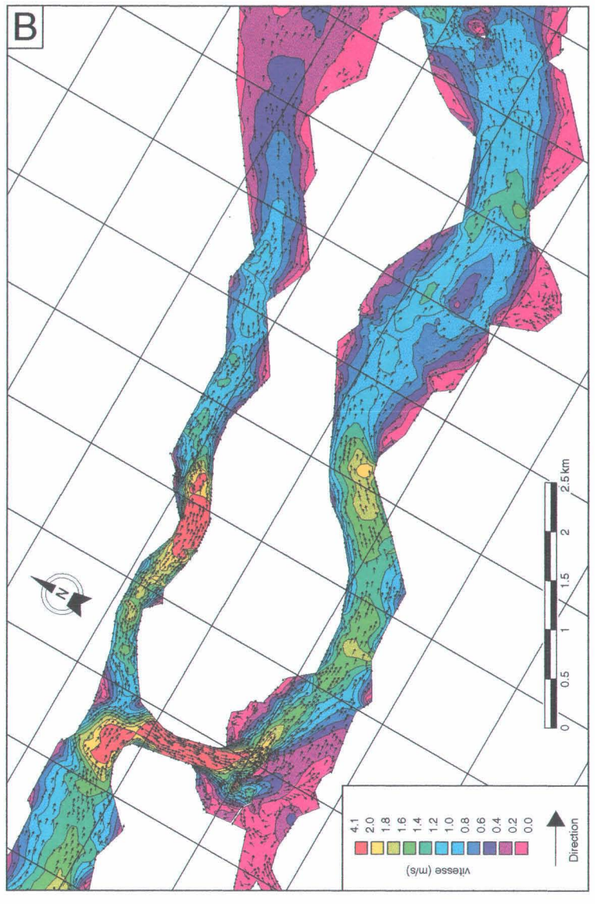

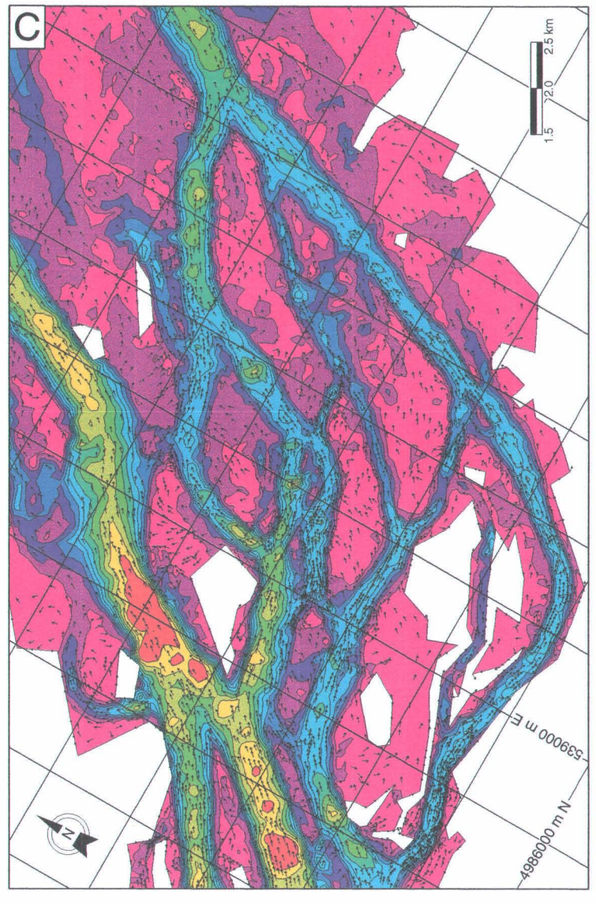

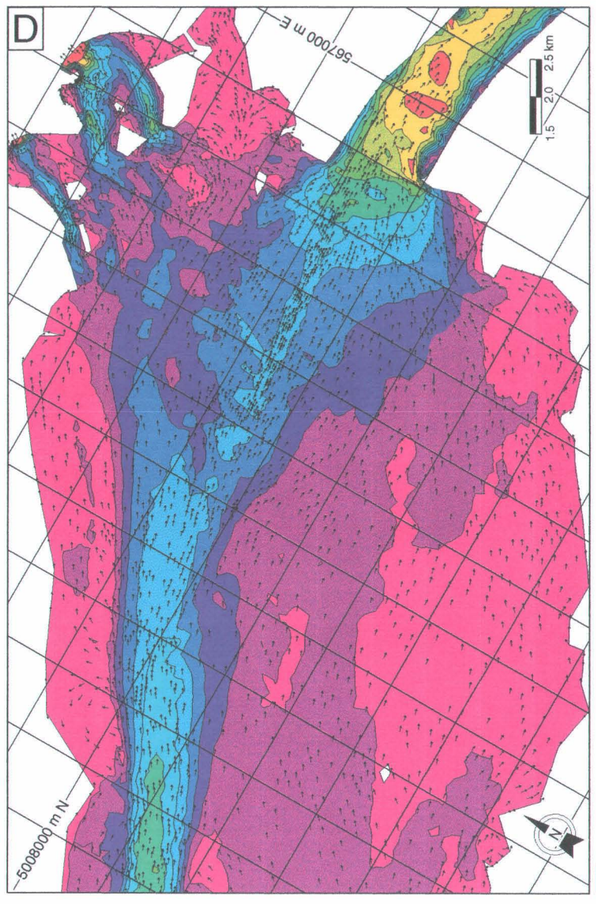

Simulations hydrodynamiques

ÉTÉ 10 000 m³/s

Plantes aquatiques: Croissance maximum
Grille 1000 m, UTM 18, NAD 27

Entrée:

Fleuve	10 000 m³/s

Tributaires:

Riv. Grasse	20 m³/s
Riv. Raquette	70 m³/s
Riv. St-Régis	30 m³/s
Riv. aux Saumons	10 m³/s
Riv. Raisin	5 m³/s

Sorties:

Coteau III	555 m³/s
Coteau I	1445 m³/s
Valleyfield	5 m³/s
Beauharnois	8 130 m³/s

Direction des vitesses

Vitesse (m/s)

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 4.1

Note: La légende ci-haut est valide pour les figures A, C et D.

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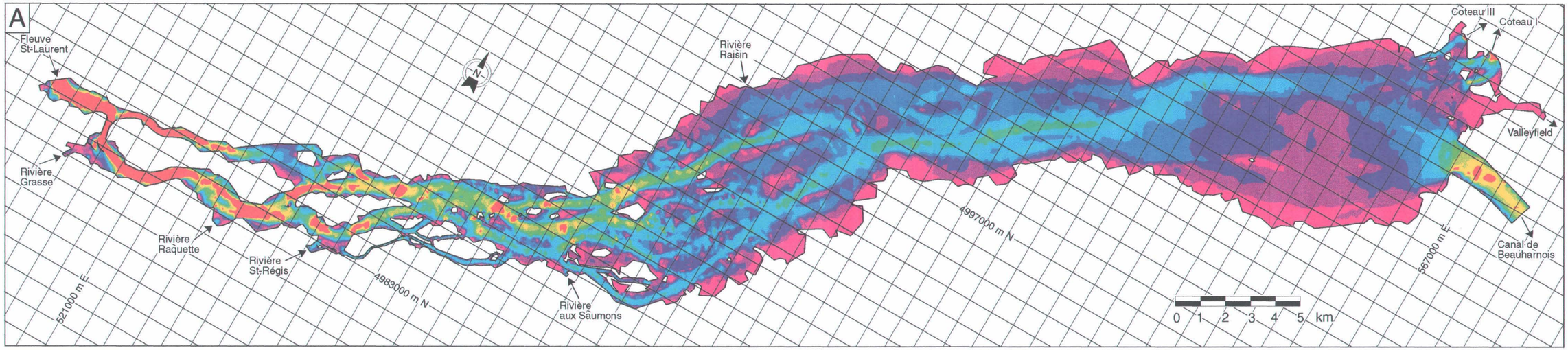

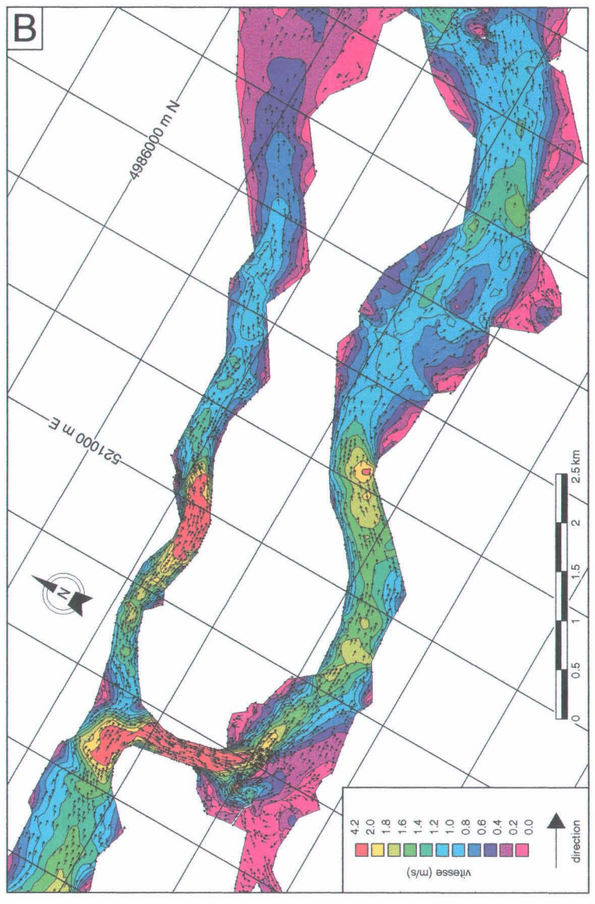

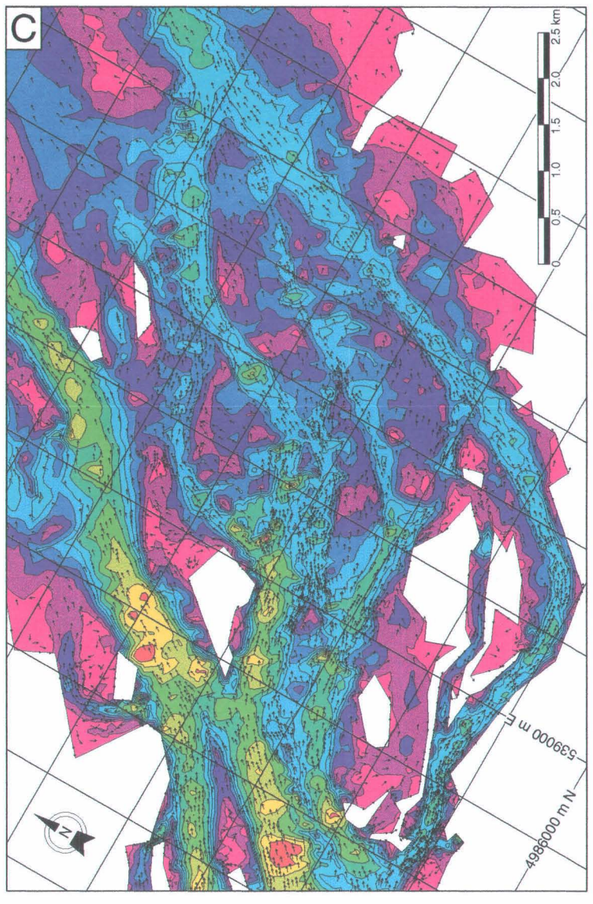

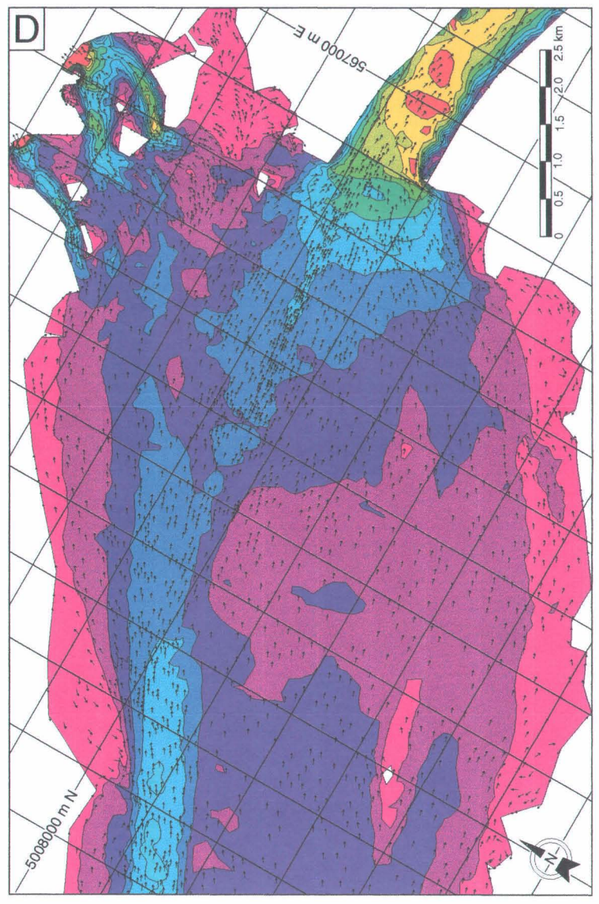

Simulations hydrodynamiques

PRINTEMPS-AUTOMNE 10 000 m^3/s

Absence de plantes aquatiques
Grille 1000 m, UTM 18, NAD 27

Entrée:	
Fleuve	10 000 m^3/s
Tributaires:	
Riv. Grasse	150 m^3/s
Riv. Raquette	280 m^3/s
Riv. St-Régis	195 m^3/s
Riv. aux Saumons	90 m^3/s
Riv. Raisin	35 m^3/s
Sorties:	
Coteau III	880 m^3/s
Coteau I	1 720 m^3/s
Valleyfield	5 m^3/s
Beauharnois	8 145 m^3/s

Direction des vitesses

Vitesse (m/s)

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 4.2

Note: La légende ci-haut est valide pour les figures A, C et D.

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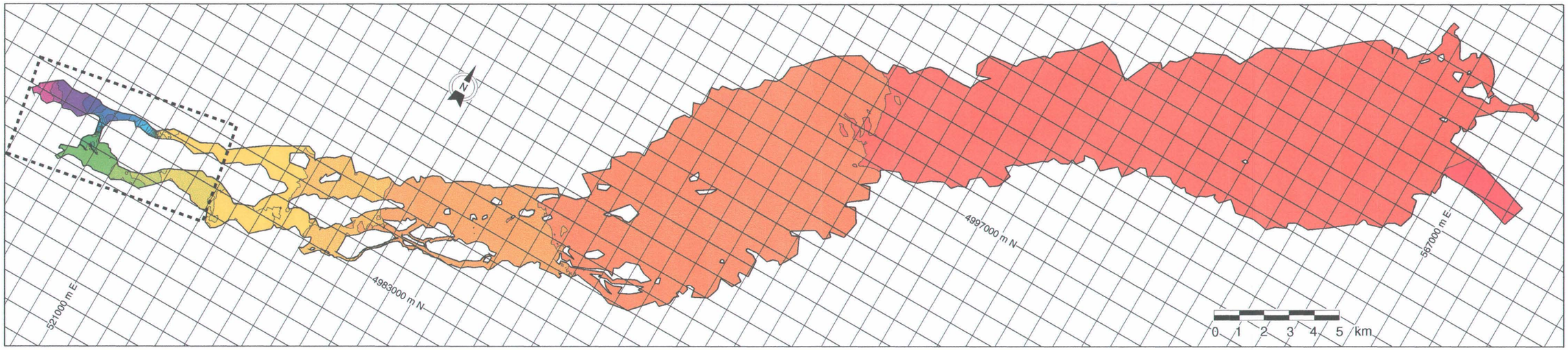
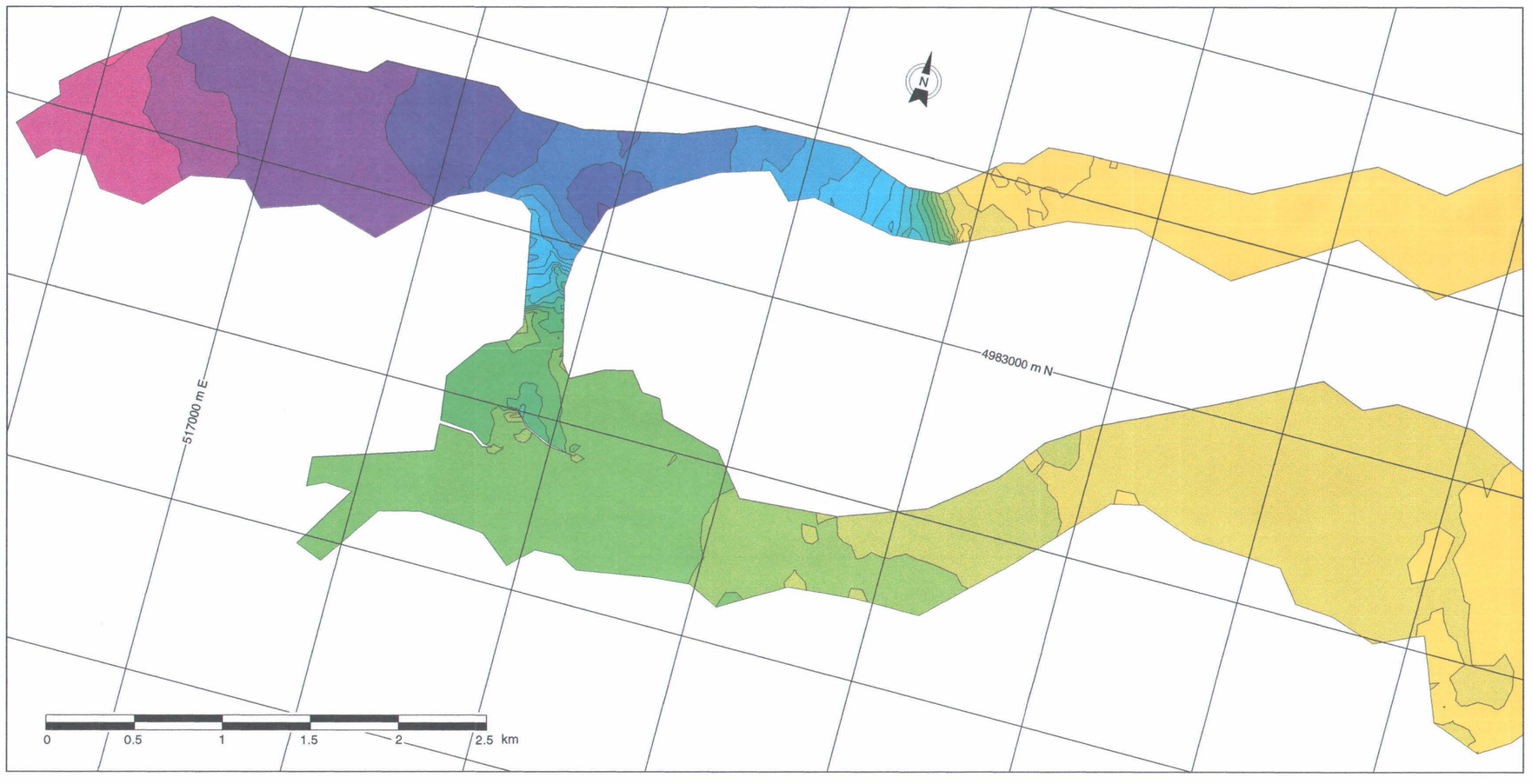
Planche 10





Niveaux simulés

ÉTÉ 7 500 m^3/s

Plantes aquatiques: Croissance maximum
Grille 1000 m, UTM 18, NAD 27

Niveaux d'eau (m, RIGL 55)
Isosurfaces de 0,1 m

49.1
49.0
48.9
48.8
48.7
48.6
48.5
48.4
48.3
48.2
48.1
48.0
47.9
47.8
47.7
47.6
47.5
47.4
47.3
47.2
47.1
47.0
46.9
46.8
46.7
46.6
46.5
46.4
46.3

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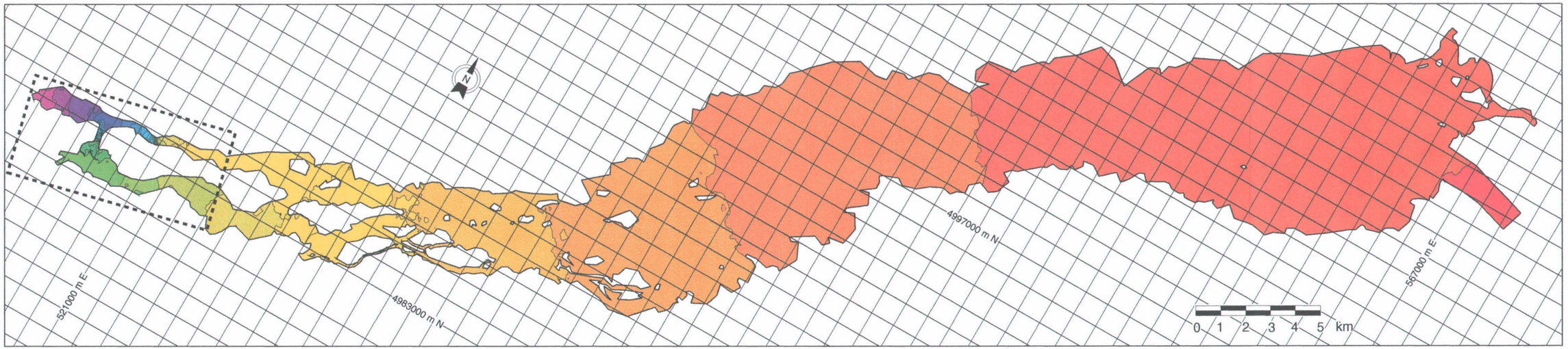
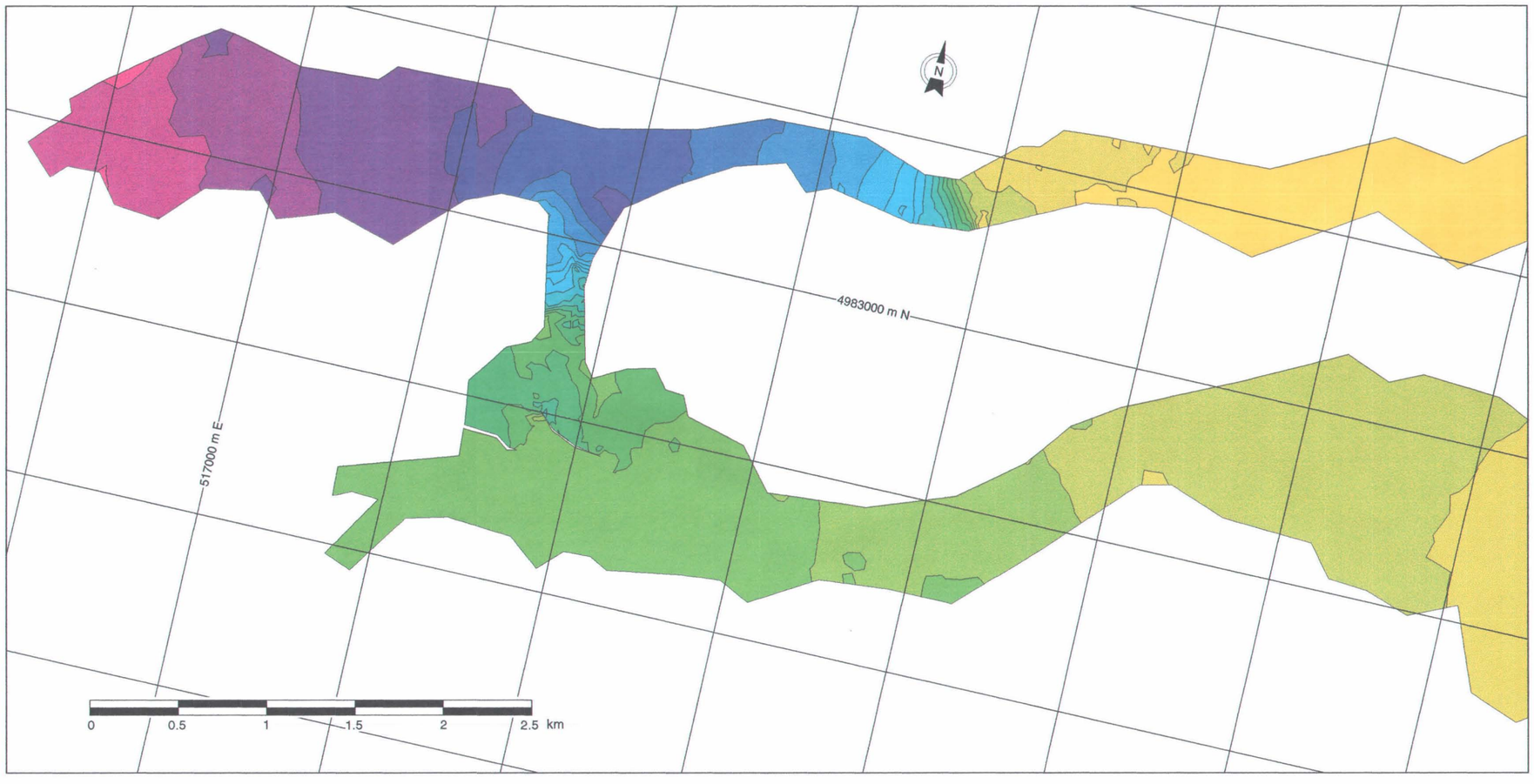
Planche 11





Niveaux simulés

PRINTEMPS-AUTOMNE 7 500 m^3/s

Absence de plantes aquatiques
Grille 1000 m, UTM 18, NAD 27

Niveaux d'eau (m, RIGL 55)
Isosurfaces de 0,1 m

49.1
49.0
48.9
48.8
48.7
48.6
48.5
48.4
48.3
48.2
48.1
48.0
47.9
47.8
47.7
47.6
47.5
47.4
47.3
47.2
47.1
47.0
46.9
46.8
46.7
46.6
46.5
46.4
46.3

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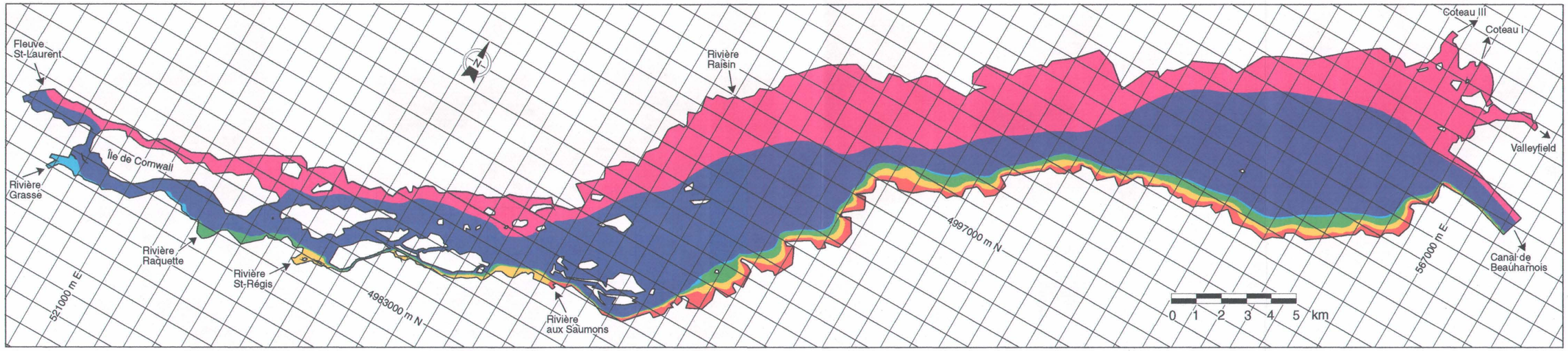
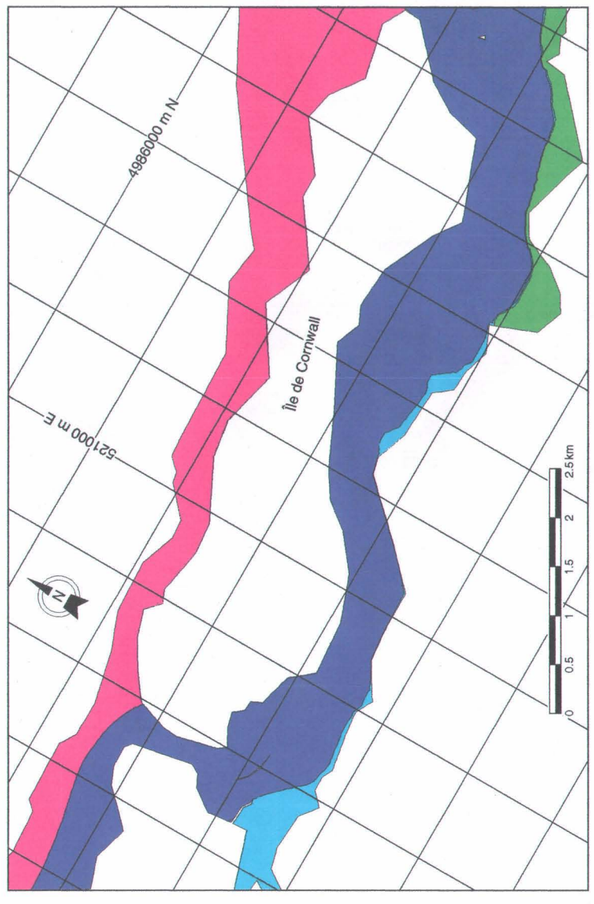
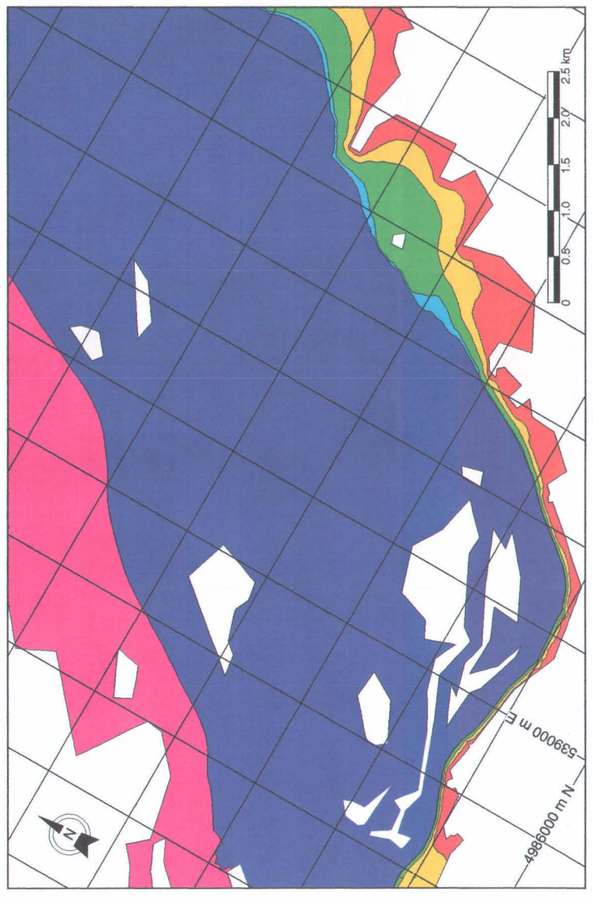
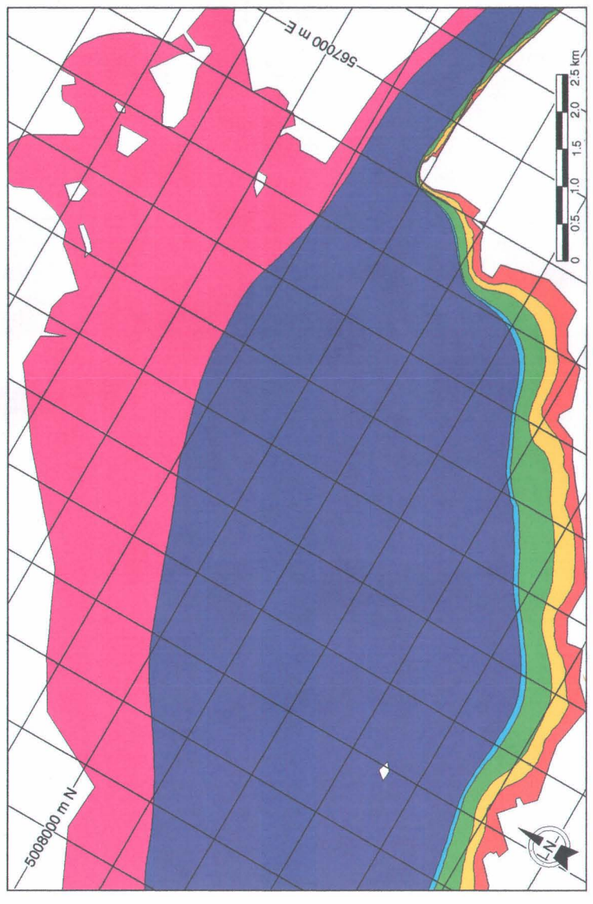
Planche 12









Fonction courant
(masses d'eau, sans mélange)

ÉTÉ 7 500 m^3/s

Plantes aquatiques: Croissance maximum
Grille 1000 m, UTM 18, NAD 27

ISODÉBIT

Rivière aux Saumons	10 m^3/s
Rivière St-Régis	30 m^3/s
Rivière Raquette	70 m^3/s
Rivière Grasse	20 m^3/s
Île de Cornwall (SUD)	5 300 m^3/s
Île de Cornwall (NORD)	2 200 m^3/s

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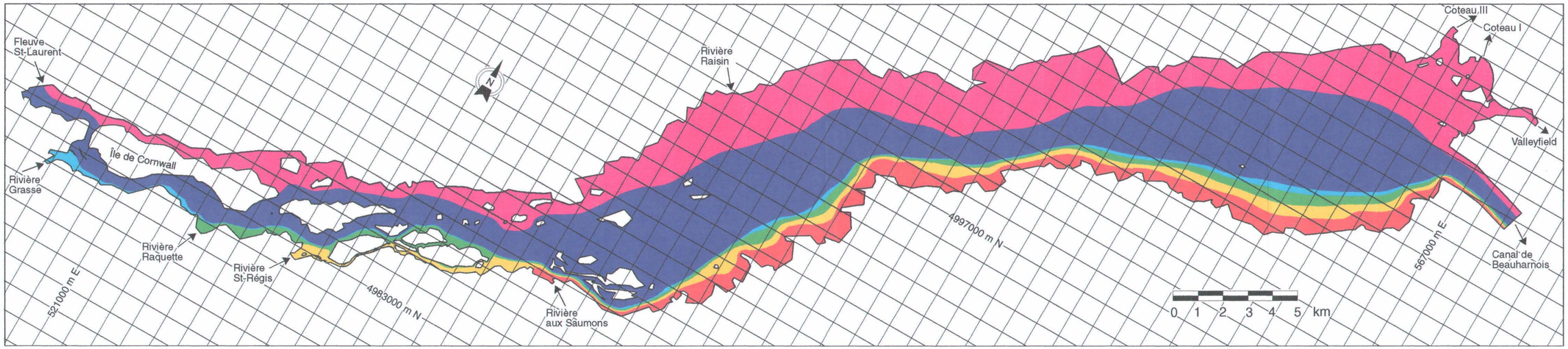

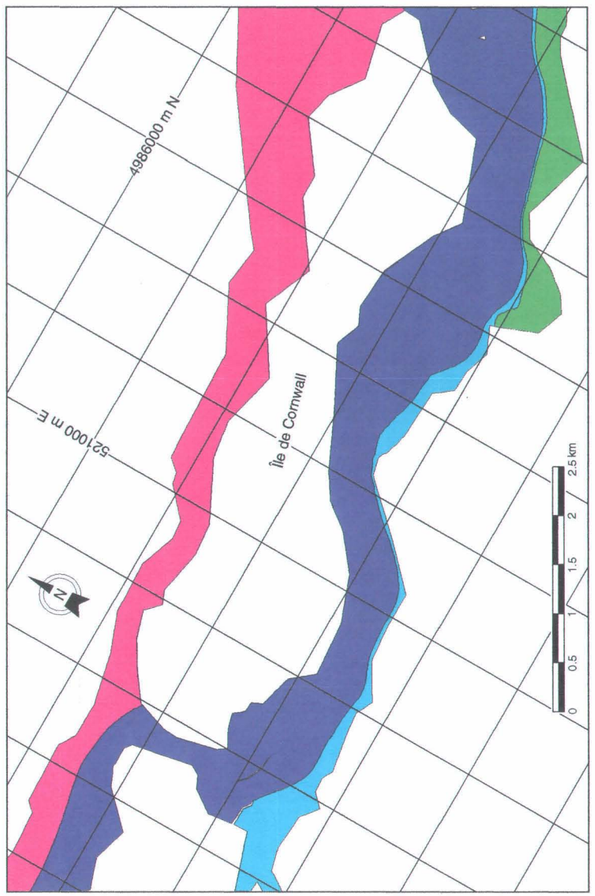

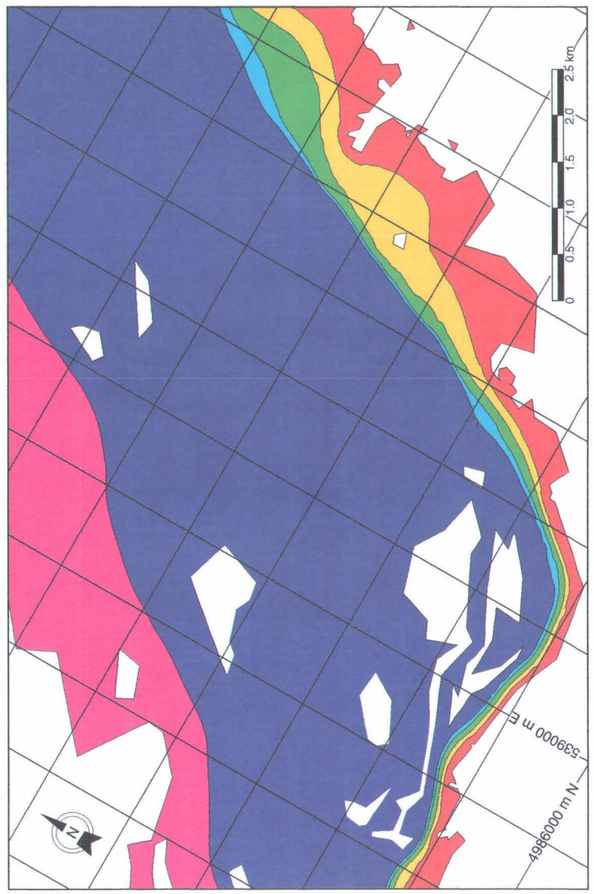

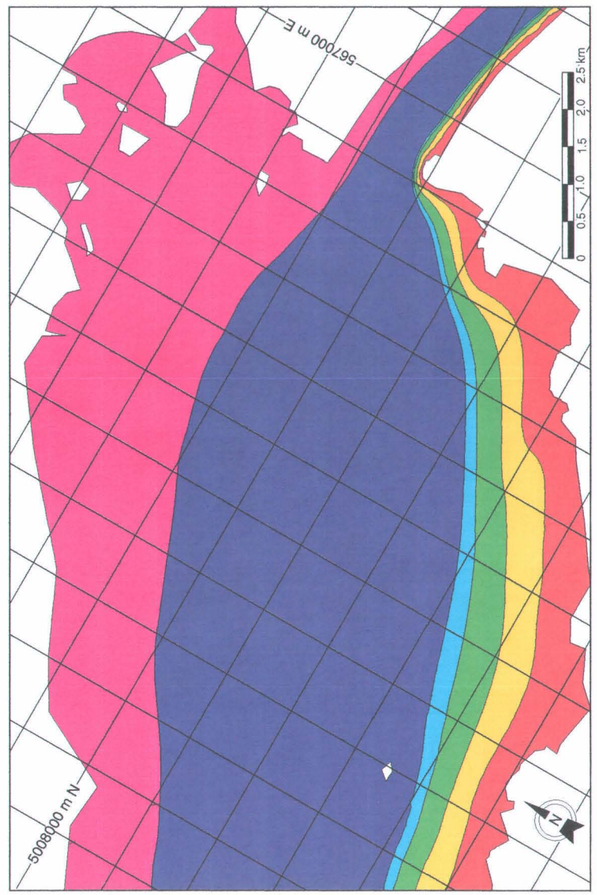

Fonction courant

(masses d'eau, sans mélange)

PRINTEMPS-AUTOMNE 7 500 m^3/s

Absence de plantes aquatiques
Grille 1000 m, UTM 18, NAD 27

ISODÉBIT

Rivière aux Saumons	90 m^3/s
Rivière St-Régis	195 m^3/s
Rivière Raquette	280 m^3/s
Rivière Grasse	150 m^3/s
Île de Cornwall (SUD)	5 300 m^3/s
Île de Cornwall (NORD)	2 200 m^3/s

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Integrated two-dimensional macrophytes-hydrodynamic modeling
Modélisation bidimensionelle intégrée des macrophytes et de l'hydrodynamique

J. MORIN, M. LECLERC, Y. SECRETAN and P. BOUDREAU, *Institut national de la recherche scientifique, INRS-Eau, 2800 Einstein, Sainte-Foy, Qc, Canada, G1V 4C7.* E-mail : *Jean.Morin@ec.gc.ca*

ABSTRACT

Lake Saint-François is the first fluvial lake downstream of the Great Lakes. Aquatic macrophytes are abundant because of water level stabilization and increased nutrient loads. The influence of plants on flow modification is very important and must be considered in order to simulate hydrodynamic conditions. The spatial distribution of plant species is linked to their instream flow preferences. Several abiotic variables are of importance: light penetration, wave energy, current velocity, nutrients in substrate and physical characteristics of the substrate are controlling the species and their biomass.

Field characterization of macrophytes was performed using echosounder transects in association with a submersible video camera. This technique allowed the calibration of each echofacies for species identification and their relative proportion, height and density. The main eleven assemblages appear to be strongly correlated with abiotic conditions. A basic interpretation key was set up in order to describe plant distribution over the entire lake. Species, relative proportion, density and plant height were interpolated between transects. This information is used to adjust the Manning's friction coefficient for each assemblage. Simulations of the flow fields with plants and in absence of plants show a contrasted pattern. During the summer (with plants), the flow is mainly concentrated in deep channels where velocities are clearly increased by approximately 20% compared to spring-fall simulation (without plants).

RÉSUMÉ

Le lac Saint-François est le premier lac fluvial en aval des Grands Lacs. Les macrophytes aquatiques y sont abondants étant donné la stabilisation des niveaux et les apports croissants en nutriments. L'influence des plantes aquatiques sur l'écoulement est très important et doit être pris en compte afin de simuler l'hydrodynamique en période estivale. La distribution spatiale des espèces de plantes est liée aux facteurs abiotiques décrivant leur habitat. Plusieurs variables abiotiques doivent être considérées : la pénétration de la lumière, l'énergie des vagues, la vitesse des courants, les nutriments dans le substrat et les caractéristiques physiques du substrat contrôlent la distribution des espèce et leur biomasse.

La caractérisation des macrophytes sur le terrain a été effectuée à l'aide de transects d'échosondeur combinés à l'utilisation d'une caméra vidéo submersible. Cette technique a permis de calibrer les échofaciès en terme d'espèces, de proportion, de hauteur et de densité. Les 11 assemblages principaux apparaissent être fortement liés aux facteurs abiotiques. Une clef d'interprétation a été bâtie afin de décrire la distribution des plantes à l'échelle du lac. Les espèces, leur proportion relative, leur densité et la hauteur des plantes ont ainsi été interpolées entre les transects. Cette information est utilisée pour calculer le coefficient de frottement de Manning pour chacun des assemblages. Les simulations des champs de vitesse avec les plantes et en absence de plantes sont contrastées. Pendant l'été (avec plantes), l'écoulement est principalement concentré dans les chenaux profonds, où les vitesses sont plus élevées d'environ 20% par rapport aux simulations du printemps-automne (sans plantes).

Introduction

Context

Lake Saint-François is a complex fluvio-lacustrine system that has been submitted to important modifications associated with industrialization. Politically, this part of the St. Lawrence River plays the role of a border: it is shared by two Canadian provinces, Ontario and Québec and by New York State (Figure 1). Lake Saint-François is the first fluvial lake of the St. Lawrence River, downstream of the Great Lakes. It is an important enlargement of the river. The lake has a maximum width that reaches almost 8 km on its larger part and nearly 50 km in length, covering a total area of 254 km^2 (Allan 1986; Lorrain *et al.* 1993, Morin and Leclerc 1998). The mean flow discharge of the river at Cornwall is 7500 m^3/s, creating strong currents responsible for the lack of stratification in the lake.

Morphologically, Lake Saint-François can be subdivided in three main parts (Figure 2): a multi-channel riverine reach with large islands forming an archipelago at its upstream part; a middle part which presents the aspect of a sub-fluvial braided reach, with deep channels and shallow water flat zones; and a lacustrine section on the downstream side where the mean depth is approximately 10 m, with a 21 m deep navigation seaway. This complex morphology strongly determines the flow distribution over the lake. Water levels are heavily regulated for navigation purposes, and by hydropower stations located upstream and downstream of the lake. The historic unregulated regime used to allow a 60 cm annual variation of the level at the lake outlet. Regulation has reduced this variation to less than 12 cm on an annual basis which favors luxuriant submerged plant growth.

The lake is covered with ice during winter, a factor which contributes to particular flow patterns during this season. Figure 3 illustrates the seasonal surface slope of the river in relation to the presence of ice during winter. The river increases its water level difference between upstream and downstream to compensate for the ice resistance and to allow an efficient flow transit through the system. Similarly, during summer, aquatic plants grow on area where physical conditions are acceptable or suitable for them. This results in a transient reinforcement of the flow patterns already present in the lake due to its morphology. Figure 3 also depicts this influence. For hydrodynamic modeling purposes, taking into account the aquatic plant resistance to flow is an absolute necessity in order to provide reliable results for application related to river enhancements and to water quality management.

This research focuses on the modeling strategy adopted to represent the distribution of aquatic plants and the effect of plants

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within a finite element hydrodynamic model, taking into account that the relation between plants and flow behaves non-linearly. In fact, plant distribution is dependent on the flow field to grow and, at the same time, plants slow down the currents due to their resistance, contributing to the establishment of their own suitable microhabitat. This work is the first step towards integrated microhabitat modeling of aquatic plants.

This article presents successively the theoretical background behind plant suitable microhabitat modeling and its basic application in the cartography of aquatic plant, hydrodynamic modeling and its formal aspects related to flow resistance, validation considerations, and finally, some hydrodynamic results.

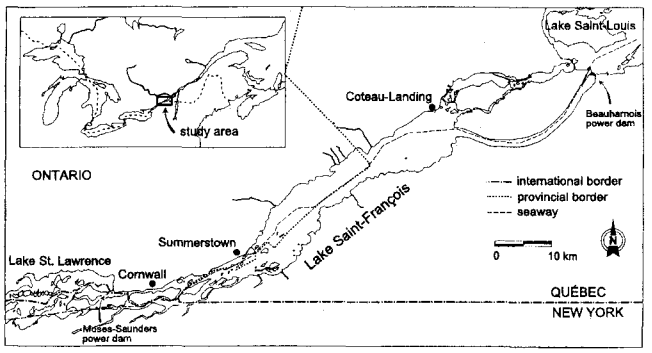

Fig. 1. Location of Lake Saint-François, St. Lawrence River.

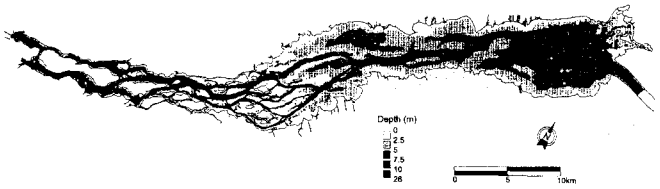

Fig. 2. Topography of the Lake Saint-François.

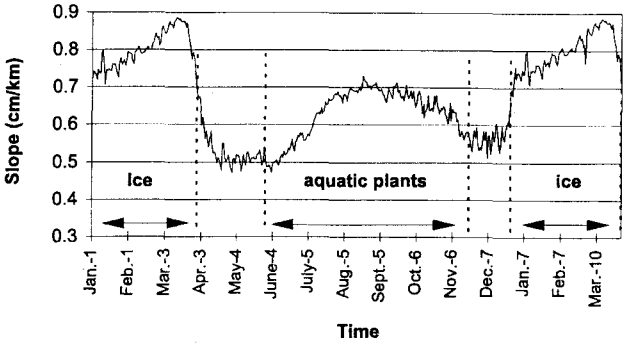

Fig. 3. Seasonal evolution of the surface slope in relation to ice and plant resistance in Lake Saint-François (daily interannual average 1963-1990). Modified from Morin and Leclerc 1998.

Towards simulation of the suitable microhabitat of aquatic plants

Plant ecology and abiotic factors

One can distinguish two main groups among aquatic plants: those floating freely with currents, and those rooted in the substrate. The second group have a significant influence on the currents by resisting to the flow. This second group splits again into three classes (Sculthorpe 1967; Wetzel 1975): plants with floating leaves (0.5 m < depth < 3 m), plants emerging above the water surface (depth < 1.5 m) and submerged plants growing to almost any depth where light penetrates. For hydrodynamic modeling purposes, only the last two really play a significant role on the main water body. From an ecological point of view, the emergent plants constitute the ecotope between terrestrial ecosystem (eventually wetlands) and the hydrosystem.

The submerged plants were classified by using a distinction based on the growth form (Figure 4): *canopy-producer, erect-form, rosette-form, bent-down form* and *bottom-dwellers.* The canopy-producers concentrate their photosynthetic biomass near the water surface and their stems can reach 4.5 m. Erect-forms have long stems which can reach 4 m but are not forming canopy. Rosette-forms have their photosynthetic biomass located close to the bottom, their maximum length is 1.5 m but they do not reach the surface. The bent-down form is typical of an environment dominated by currents, their height is less than 1 m but they could reach 3 m in length. Finally, bottom-dwellers are less than 0.5 m in height and can form dense mats.

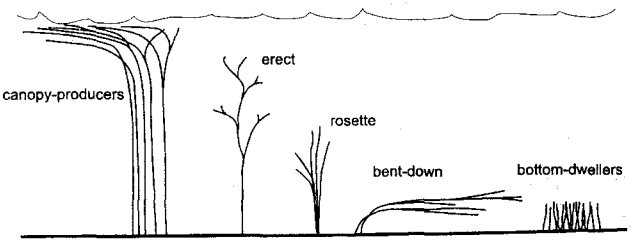

Fig. 4. Schematic representation of aquatic plants growth forms.

Classification by growth forms is more helpful to modelers than any other because it is more closely related to abiotic conditions (Chambers and Kalff 1987). For example, canopy-producers are growing in nutrient rich substrate while bottom-dwellers are favored by low-nutrient substrate. The growth form could be considered as an adaptation to the abiotic conditions since rosette-forms are resistant to wave action and the bent-down forms are adapted to fast currents. Chambers and Kalff (1987) and Chambers (1987) mention that some species sharing the same growth form have also comparable abiotic preferences for light (depth) and nutrients (substrate). Inversely, similar abiotic conditions would generate similar growth forms; a principle that allows to consider habitat modeling from abiotic conditions as independent variables.

Spatial distribution of macrophytes is related to their instream flow needs (or preferences) and consequently, to abiotic conditions in the water body. Figure 5 depicts the complex network of relationships that govern the interactions between submerged plants and their habitat in the aquatic environment (after Morin 1995). The main variables which contribute to habitat selection by plants are the substrate (in relation to nutrients availability), light penetration (turbidity and depth), wind stresses and waves (or, more simply the wind fetch), flow velocity, substrate (in relation to rooting) and seasonal water level variations, riverbed slope, etc...

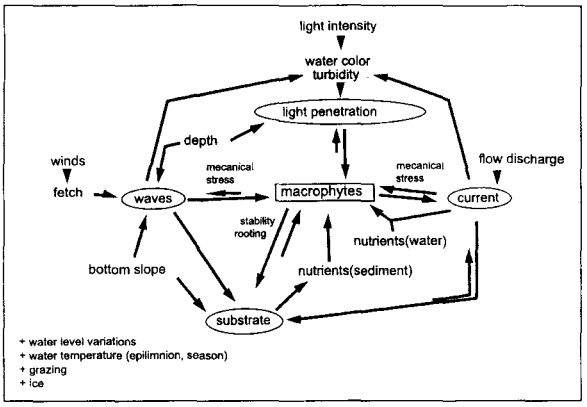

Fig. 5. Conceptual representation of relationship between aquatic plans and their microhabitat.

Role of abiotic factors

According to Duarte and Kalff (1986), *riverbed slopes* can affect plants microhabitat selection by indirectly influencing the thickness of sediment, the grain size and the stability of deposits. Wave dissipation is also related to this factor (Duarte and Kalff 1988). In general, macrophytes seem to prefer slopes less than 15%. An adequate Numerical Field Model (NFM) can easily provide the spatial distribution of this information in the flow domain. The NFM is a georeferenced database that contains all the information used for analysis and modeling such as topometry, fetch, wave and current simulations, field data, plants distribution, substratum distribution and all other data that can be developed such as water depth, riverbed slopes etc.

Waves play a significant role in habitat suitability for plants. In fact, they apply mechanical stresses on them, but they also contribute to seeds propagation (Keddy 1982). Waves affect directly the sedimentary dynamics within shallow water zones. When not controlled by current velocities, grain size and substrate composition are strongly correlated to wave energy dissipation on the riverbed (Häkanson 1977; Keddy 1982, Petticrew and Kalff 1991). Plants can also contribute to wave damping (Kobayashi *et al.,* 1993; Camfield 1977). In the absence of a wave model, the wind fetch can be used. Again this data can be generated by spatial analysis within terrain morphology analytical tools.

Light penetration is related to turbidity and depth. It determines the maximum depth in a particular water body at which plants can grow (Dale 1986; Spence 1982; Wetzel 1975). The capacity to assimilate light energy varies from a plant category to another, a characteristic that determines their distribution (Chambers and Kalff 1985). Depth is provided directly by coupled topometry - hydrodynamic model. Turbidity may be interpreted as a global property of water bodies within a river (accounting for tributary plumes), or simulated with a sedimentation model able to calculate the concentration of suspended load. Relation between suspended load and light penetration can easily be calibrated with Secchi depth measurements.

Current velocity or turbulence can inhibit macrophytes growth by breaking leaves, uprooting, or by making rooting difficult. Presence of currents reduces plant biomass and diversity without regards to substrate composition (Chambers *et al.,* 1991). Virtually, no plant can grow in water bodies with velocities higher than 1 m/s. However, macrophytes can modify the flow distribution by offering resistance to flow (Petticrew and Kalff 1992). This resistance depends on the total surface of leaves, stem rigidity and thickness. However, in the Lake Saint-François context, because of the small range of velocity and depth variations the resistance can be considered function of the total surface of leaves. Hydrodynamic models can predict precisely the current velocity as long as the resistance is well accounted for in the model parameterization .

Nutrients can also be a dominant factor for plant species distribution (Anderson and Kalff 1986). Sediment is the main source of nutrients to plants, over direct assimilation in the water column (Barko and Smart 1980; Carignan and Kalff 1980). As for currents, macrophytes contribute to sedimentation processes by reducing velocities and facilitating deposition of fine material which usually carry adsorbed nutrient, and their own organic matter after senescence. This effect results in increased habitat value for plants (Chambers and Prepas 1994; Petticrew and Kalff 1991). The nutrients content in substrate is related to wave action and to current velocity (Chambers and Prepas 1990) implying that nutrients are associated to fine particles, and that this type of material settles in protected areas (Wilson and Keddy 1985).

Substrate composition, as previously stated, plays significant physical and chemical roles for plant habitat selection. Penetration and anchoring of roots necessitate a light and stable substrate. Thus, zones subject to erosion do not present favorable conditions as plant microhabitat (Madsen and Adams 1989). Finally, *water level variation* has an important influence on macrophytes by exposing their structures to air or to freezing.

Macrophytes in Lake Saint-François

In Lake Saint-François, macrophytes biomass have benefited from increased sources of nutrients related to human activity, and from water level regulation for navigation (Morin and Leclerc 1998). The creation of very favorable abiotic conditions for plant growth was due to 1) constant depths by stabilization of water levels, 2) alteration of current velocity by dredging, 3) reduction of ice scouring, 4) the anthropogenic increase of nutrients. The actual equilibrium in submerged plants composition includes mainly species listed in Table 1.

Table 1. List of most abundant species of submerged macrophytes in Lake Saint-François and their growth form.

Growth form	Species
canopy-producer and erect	*Myriophyllum spicatum*
erect	*Elodea canadensis*
erect	*Ceratophyllum demersum*
erect	*Potamogeton richardsonii*
erect	*Heteranthera dubia*
bend-down and erect	*Potamageton pectinatus*
rosette	*Alisma gramineus*
rosette	*Vallisneria americana*
bottom-dweller	*Nitella sp*

Field characterization of macrophytes

The influence of macrophytes on flow varies for each species, depending mainly on their total surface area. Therefore, a precise knowledge of their spatial distribution is a necessary condition for accurate flow simulation. The approach proposed herein for macrophytes mapping is an adaptation of one proposed in Fortin *et al.* (1993) and Boudreau *et al.* (1994). On October 1995, the maximum growth phase of plants for that year, several echosounder profiles were obtained on transects (Figure 6) during a five days field campaign to provide the basic information for setting up the macrophytes map. Regular controls of plants species and composition with a submersible camera were made during echosounder recording, especially at echofacies changes. Positioning was done by a dGPS (differential Global Positioning System) providing a reliable spatial referencing output with about 1 m precision. Plant taxonomy has been verified by Norman Dignard (Min. Énergie et Ressources, Québec) over samples collected in the field.

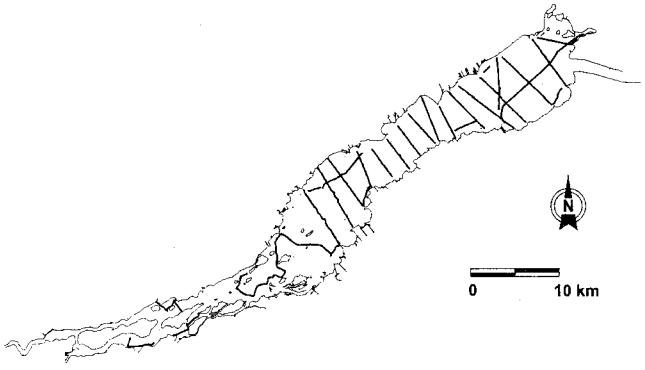

Fig. 6. Echosounding transects on Lake Saint-François (October 1995).

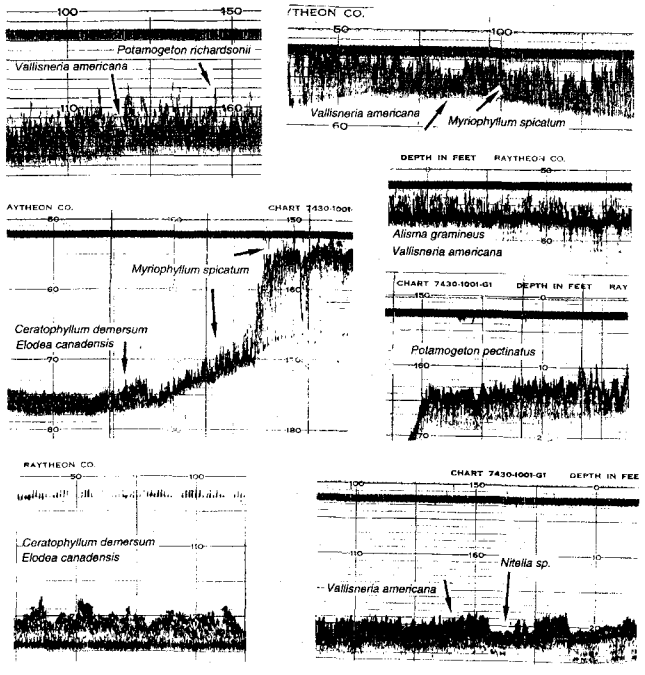

Fig. 7. Typical echofacies of plants assemblages from Lake Saint-François.

An interpretation key of the specific response of echosoundings to particular patterns of plant association and growth forms was built by adapting Fortin's approach and it was calibrated with camera observations. Species composition, rough species proportion, plant height and relative evaluation of density were extracted from each assemblages. A total of eleven plant assemblages, when refined with relative proportions, density or plant height compose a grand total of 83 distinct echofacies. Some examples of echofacies and corresponding interpretation are depicted in figure 7.

Macrophytes mapping: an "educated" interpolation task

Light is the most important factor for the occurrence of aquatic plants (Wetzel 1975). Light intensity is function of turbidity and depth. Close to a sampled area, as turbidity remains constant, one can argue that light intensity is only a function of depth. Similar logic can be applied to other abiotic variables. Therefore, the use of a precise topographic map was essential in order to allow for a precise interpolation between transects ; a topographic map with 1 m depth isocontour intervals at a scale of 1:15 000 was used. This map was drawn directly with a Delauney's triangulation procedure from an extensive topometric data base.

Between the transects, plant distribution was estimated by using an interpolation procedure accounting for the visual interpretation of relevant abiotic variables available in the NFM database. Rules governing the habitat selection by plants according to their growth form were also exploited. Provenance of these rules came first from the literature. But, it was mostly associated with a quick "learning curve" that took place while analyzing echofacies - vs - abiotic variables. A relatively small amount of the total echofacies data set was necessary to calibrate this conceptual interpretation and interpolation key. Depth, riverbed slopes, rough estimation of flow field and shelter effects, substrate composition, wind fetch and a rough estimation of nutrients distribution which participate in the application of the key are the components of the NFM.

Just to give a brief idea of the spatial distribution of plants, assemblages with *Vallisneria americana* as dominant species are found in areas with waves being the dominant abiotic factor, *Myriophyllum spicatum* assemblages are mainly related to nutrients rich substrates, *Potamogeton pectinatus* is found in areas dominated by currents and *Nitella sp.* is present where other plants have difficulties to grow, mainly in deeper parts.

Modeling plant influence on hydrodynamics

Two-dimensional (2-D) hydrodynamic model

Briefly, the hydrodynamic model provides dynamic drying-wetting capabilities, an essential feature to deal with natural watercourse processes where the lateral flow boundaries move continuously with flow discharge or tides (Leclerc *et al.*, 1990a, b). As in every 2-D horizontal model, velocities are vertically integrated (mean value). The model uses a "non-

conservative" mathematical formulation (velocities and water levels as primitive state variables) based on St-Venant, or shallow water equations. It also uses a finite spatial and numerical discretization scheme to reproduce adequately the topometric data from the NFM. The hydrodynamic calculation grid is a triangulation containing 27000 elements. The size of these elements varies from 10 m in small channels to 200 m in the eastern portion of the lake where topography is relatively flat over an extended area. The 2-D model used in this research covers the entire range of forces and accelerations occurring in the natural flow equilibrium, e.g. local and convective accelerations, gravity (surface slope), riverbed, plant and ice resistance, wind stresses, turbulent shear stress and compression, and Coriolis force.

Coupling the hydrodynamic model with plants resistance

Resistance to flow by plants was the object of several studies (Haslam 1978; Manz and Westhoff 1988; Marshall and Westlake 1990, among others). A logarithmic velocity profile, which usually characterizes turbulent shear layers in open flow must be applied carefully in flows dominated by vegetation. Within the hydrodynamic model (Boudreau *et al.*, 1994), resistance of riverbed, ice and plants are being represented by a Manning's type formula.

$$\tau_i = \frac{\rho g n^2 |V| u_i}{H^{1/3}} \tag{1}$$

Where τ_i represent the i^{th} (according to x, y coordinates, $i = 1,2$) component of resistance, ρ the water density, g the gravity, n the Manning roughness coefficient, V the velocity module (vertically integrated), u_i the i^{th} component of the velocity vector, and H the local depth.

This classical formula, relates quadratically the resistance to the velocity and from the roughness coefficient, which is similar to "drag" type formulas. The influence of bottom and plant resistance is represented by

$$\tau = \sqrt{\tau_x^2 + \tau_y^2} \tag{2}$$

where $\tau_x = \tau_{xm} + \tau_{xb}$ and $\tau_y = \tau_{ym} + \tau_{yb}$

Where τ_b and τ_m are respectively bottom and macrophytes resistance modules.

As for the n for substrate (n_b), this parameter is related to local mean rugosity or grain size. Concerning the parameterization of the plants (Manning's n_m) in the formula, it is necessary to take into account the main characteristics of plants which contribute to the resistance. Typical rough growth form, seasonal growth phase, local density and relative area coverage in plant associations were the variables considered by Boudreau *et al.* (1994). Because there is a directly proportional relation between the total surface area of a plant and its resistance to flow (Petticrew and Kalff 1992), there is also a direct relation between plant resistance to flow and its height. In the actual work, identified species and measured plant heights are used in the Manning's coefficient calculation.

$$n_{m_i}^2 = \frac{h_i}{h_{imax}} C_i(t) P_i(r) D_{tot}(x, y) n_{m_i max}^2$$
$$0 \le P_i(r) \le 1 \tag{3}$$
with $$0 \le D_{tot}(x, y) \le 1$$
$$0 \le C_i t \le 1$$

Where n_{mi} represents the i^{th} species contribution to resistance, the maximum value provided by the species in the highest density, for its maximum height observed and during the maximum growth season, $C_i(t)$ is a growth phase factor varying between 0 and 1 (see below), h_i the local plant height at the maximum growth phase, h_{imax} the maximum *maximorum* height observed for a species, $P_i(r)$ the ratio of a species within an assemblage, and $D_{tot}(x,y)$ a density factor related to the relative area coverage of the assemblage.

$D_{tot}(x,y)$ allows to modulate the spatial influence of plants according to their distribution; $P_i(r)$ permits to take into account the percentage of the i^{th} species in the assemblage; and finally, the ratio h_i / h_{imax} allows a modulation of the friction coefficient with plant height. A combination of C_i, P_i and $D_i = 1$ and a height h_i corresponding to the maximum growth phase generates the maximum influence of the species considered.

Consistent with (1), (2) and (3), n_{mi} for several plants (total count number = M) species within an association cumulates quadratically to express to total influence of the considered association n_m.

$$n_m^2 = \sum_{i=1}^{M} n_{m_i}^2 \tag{4}$$

Topometry of the riverbed

Topometry of Lake Saint-François was characterized by the Canadian Hydrographic Service for navigation purposes. 292 000 measurement points were available in a digitized "field sheet" form, thus providing a convenient and precise estimation of riverbed morphology. This information was mobilized by a Delaunay's triangulation procedure as a representation and interpolation tool, and used for setting up the hydrodynamic FEM (Finite Element Mesh).

For Lake Saint-François, a FEM was set up resulting into 97 618 triangular T6 elements (six interpolation nodes providing a quadratic approximation of variables) and thus, 57 468 nodes. Such a grid generates more than 130 000 unknown variables (degree of freedom) which are solved by the algebraic resolution of flow equations. Nevertheless, this amount of data is much less than the original topographic data set.

Parameterization of plant resistance

One needs a reliable map of plants including their growth form and density and an estimation of n_{imax} in order to implement the

proposed roughness algebraic closure. Our approach consists in five main steps:

1. First estimation of plant distribution using a transect-based echosounding field characterization of plants;
2. Simultaneous measuring of flow velocities for calibration and validation of the hydrodynamic model;
3. Bio-interpretation of transects data with respect to macrophytes preferences - vs - abiotic factors, educated interpolation between transects in order to set a map of plant growth forms;
4. Calibration of roughness coefficient by using flow distribution measurements;
5. Validation of hydrodynamic model.

Field current measurements for calibration and validation

For calibrating and validating plants roughness parameters, velocity measurements were collected along the transects by using an ADCP (Acoustical Doppler Current Profiler). 15 000 measurement points, each offering the vertical velocity profile at every 25 cm, resulted from this effort. For providing spatially homogeneous velocity data with regards to hydrodynamic model, a vertical integration of these profiles was required. Again, the large size of this data set required the development of the proper tools to manipulate readily the information. The graphical package that resulted is called DOPPVISI. Distribution of velocities can be visualized either in plan or in vertical sections.

Dealing with roughness

Classification of the flow domain with respect to plants distribution and roughness allows the closure of the hydrodynamic model on the resistance parameterization. The values of Manning's coefficients used herein are inspired from Boudreau *et al.* (1994). Calculation of the Manning's coefficient was performed using the described parameterization method on every node of the simulation grid. Validation of these coefficients is an iterative process that is based on the physics of flow resistance. It is known that the friction is proportional to the total surface area of plants, which varies with species. The literature data on specific surface of plants species (Duarte and Kalff 1990) were used to fix the maximum Manning's coefficient for each species $n_{m_i max}$. These values were integrated in the equation [3] and modulated for validation with three different periods of plant growth.

Validation of Manning's friction coefficients for plants

Validation of Manning's coefficients was performed using three different events by comparing simulated water levels and velocities with measured data. These three events used for validation are characterized by:

- 0% of plant growth on 25–28th April 1996, with 6 887 m^3/s for the St. Lawrence and 620 m^3/s from tributaries;
- 50% of plant growth on 26–29th July 1994 with 8 410 m^3/s for the St. Lawrence and 200 m^3/s from tributaries;
- 80% of plant growth on 4–7th July 1996 with 7 685 m^3/s for the St. Lawrence and 73 m^3/s from tributaries.

Water levels were measured in three locations on the lake by Environment Canada and Hydro-Québec. Velocities data were measured for two different events: 22 transects in 1994 and 14 transects in 1996. The field work lasted for less than 4 days each and the flow variation during these periods were of less than 5% of the averaged flow for both periods. Thus the measurements can be considered for validation for the respective simulations. These ADCP measurements were averaged vertically (entire water column), and spatially averaged on a distance varying from 50 m to 100 m. The size of the spatial averaging is a function of the mesh size of the hydrodynamic grid in the transect locations. This type of averaging was chosen in order to properly compare measured data with data produced by the hydrodynamic model, which are vertically, temporally (steady state) and quadratically interpolated over the element. A total of 785 averaged measurements in 1994 and 439 in 1996 were used to compare velocities on the flow field.

Parameterization of roughness from the bottom (n_b) was the only friction parameter to set for simulation without plants. For the simulation with vegetation, the friction coefficient of the plants (n_m) and bottom coefficient (n_b) were used. Calibration and validation allowed to establish the distributed value of plants roughness coefficient according to our parameterization scheme (Figure 8). Table 2 shows the maximum value of Manning's coefficient for each species and growth form at their maximum density, and for their maximum height ($n_{m,\max}$).

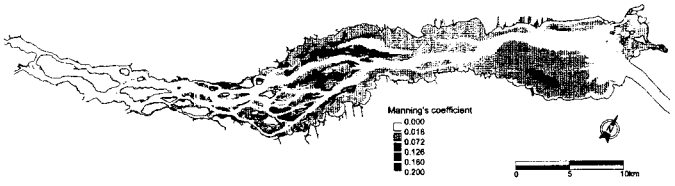

Fig. 8. Map of maximum plants resistance as indicated by the global roughness coefficient: n_m.

Table 2. Classification of plants roughness coefficients scheme used in Lake Saint-François.

Species (growth form)	Manning's coefficient (n_{max})	Maximum height (m)
EMERGING	0,200	Surface
Myriophyllum spicatum (canopy)	0,180	surface (4,5)
Myriophyllum spicatum (erect)	0,135	3,0
Ceratophyllum demersum	0,090	1,5
Elodea canadensis	0,072	1,0
Heteranthera dubia	0,675	1,7
Potamogeton richardsonii	0,063	1,6
Vallisneria americana	0,054	1,2
Potamogeton pectinatus	0,027	0,8
Nitella sp.	0,018	0,5
Alisma gramineus	0,018	0,4

Annual growth parameterization

Annual plant growth modulation ($C(t)$) must be taken into account for simulations that represent flow conditions between minimum and maximum plant growth. The difficulty is to set properly the growth parameter corresponding to the observed growth conditions. The solution proposed herein uses the Manning's friction coefficient evolution throughout the year. Figure 9 represents the daily average interannual values of plant's friction coefficient between 1963 and 1995. The typical curve of plants friction evolution was calculated by using the Manning's equation on daily average data over 30 years, with the following formulation :

$$\bar{n} = \frac{1}{Q}\overline{AR}^{2/3}S^{1/2} \tag{5}$$

where $\bar{n}$ is the global equivalent Manning's coefficient of Lake Saint-François; Q is the flow discharge (m^3/s); A = *volume/length* is the average wetted area of the section considered (m^2); R = *volume/surface area* is the hydraulic radius or depth (m); $S = (h_0 - h_1)/length$ is the slope of the free surface ; h is the water level (m).

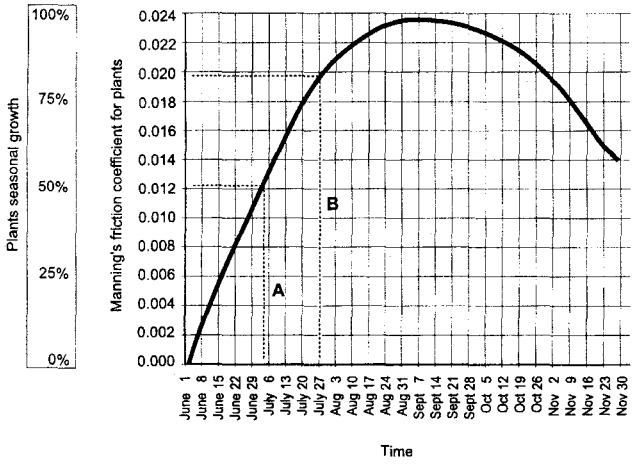

Fig. 9. Evolution of plants related Manning's friction coefficient. Interannual daily average from 1963 and 1995. A : validation simulation with 50% of plants growth. B : validation simulation with 80% of plants growth.

In order to deal only with plant related friction, global Manning's coefficient is subtracted from substratum related Manning's coefficient, within the quadratic space (equation [2]):

$$n_{plants}^2 = n_{total}^2 - n_{bottom}^2 \tag{6}$$

where n_{plants} is the Manning's coefficient due to aquatic plants resistance to flow; n_{bottom} is the Manning's coefficient due to substrate resistance to flow (May); n_{total} is the total Manning's coefficient that comprises the effect of plants and of substrate (August and September).

Substrate related friction coefficient can be inferred from data of the spring period while ice and plant related frictions are non existent. This period has the lowest friction during the year. In Lake Saint-François, it corresponds to late spring, generally during the month of May. Figure 9 shows the evolution of plant related friction coefficient during the growth season, where growth state used for validation simulations are shown : conditions are of 50% and 80% of the maximum friction observed and corresponds to the 4–7 July 1996 and 26–29 July 1994 respectively. Because there is a linear relationship between biomass and flow restriction, these conditions represent 50% and 80% of the maximum growth. Since timing of plant growth varies from a year to an other, a better precision can be reached by using the daily data of Manning's coefficient for the year concerned.

Velocities and water levels validation

Validation of simulated conditions were first performed with water levels data for 0%, 50% and 80% of plant growth and in a second step, with velocities from ADCP data for 50% and 80% of plants growth. Comparison of water levels data from simulations shows that they match very well with the data measured at gage stations (Table 3).

Table 3. Comparison of water levels between measured and simulated conditions.

	Cornwall		Summerstown		Coteau-Landing	
	measured	simulated	measured	simulated	measured	simulated
0% of plant	46.80 m	46.796 m	46.61 m	46.613 m	46.47 m	46.472 m
50% of plant growth	46.99 m	46.995 m	46.72 m	46.719 m	46.45 m	46.452 m
80% of plant growth	46.94 m	46.939 m	47.70 m	46.701 m	45.45 m	46.449 m

Validation with velocity measurements are also quite satisfactory. In the context of this paper it is not possible to show all transects of ADCP measurements; two representative transects of measured velocities with simulated results are presented. One of these transects compares the simulation of 50% of plants growth, with measured data (Figure 10a) while the other compares the simulation with 80% of plant growth (Figure 10b).

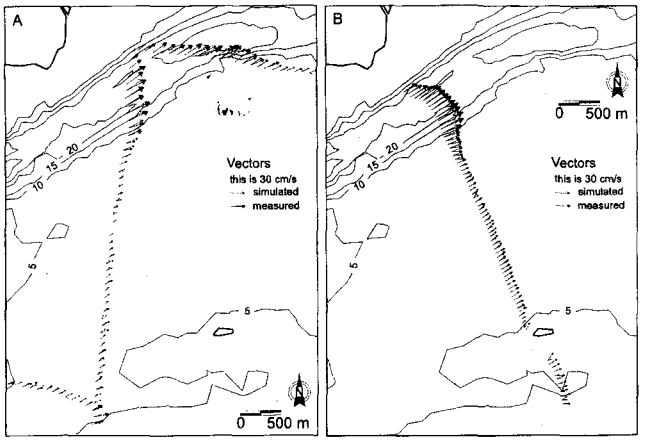

Fig. 10. Examples of validation with velocities for two different macrophytes growth states, measured data can be compared with the simulated velocities: A: 50% of plants growth and B: 80% of plants growth.

Part from the general concordance between simulated and measured velocities and directions, several interesting aspects can be observed. Velocities are significantly smaller in the shallow portion in the simulation of 80% compared to the 50% of plant growth, mainly because of the increased friction by plants that are abundant at these depths. As expected, measured velocities are slightly faster than the simulated ones. This is caused by the ADCP's technical characteristics, were about 1 m in the upper part as well as in the bottom portion of the water column can not be measured. Also, the ADCP cannot measure through aquatic plants. The result is that the measured velocities are overestimated in comparison with the hydrodynamic simulator that averages velocities over the entire water column. Correction methods for better comparisons are planed for the near future. Moreover, from the general pattern of simulated velocities, one can appreciate that because of the large number of elements, the intensity contrast is relatively well captured between shallow and deeper waters.

Results

In order to demonstrate the contrasting flow patterns of the lake in presence of vegetation - vs - plant-free flowing conditions, figures 11 and 12 depict velocity results of two hydrodynamic model simulations obtained with similar conditions, except for plant presence, of the model. Flow discharge through the model was imposed as the average value of 7 500 m^3/s, only the plant friction is set differently to a minimum growth (0%) and to a maximum growth 100% (maximum). In these figures, only a part of the flow field located within the middle part of the lake is shown. This detailed view shows very distinctly the local differences between the two simulations.

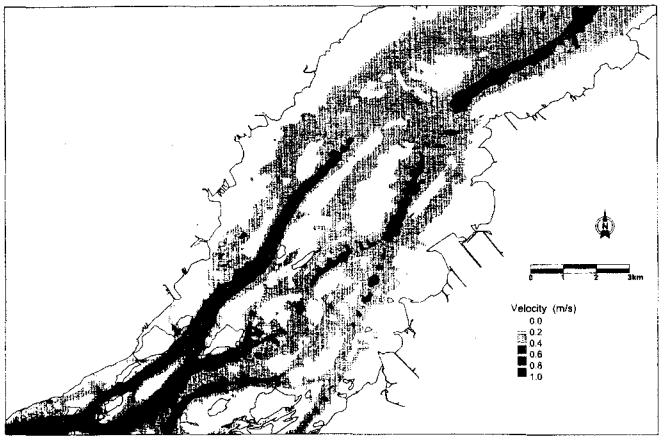

Fig. 11. Simulation of flow velocity with spring-fall model: 0% of plants growth (7 500 m^3/s).

The maximum values of simulated velocities are within the plant-free deepest zones of the lake in the summer. The influence of plants on flow is dramatically demonstrated by these simulations. Already well-structured by a contrasting topography, current patterns in Lake Saint-François are amplified or inhibited by the distribution of plants.

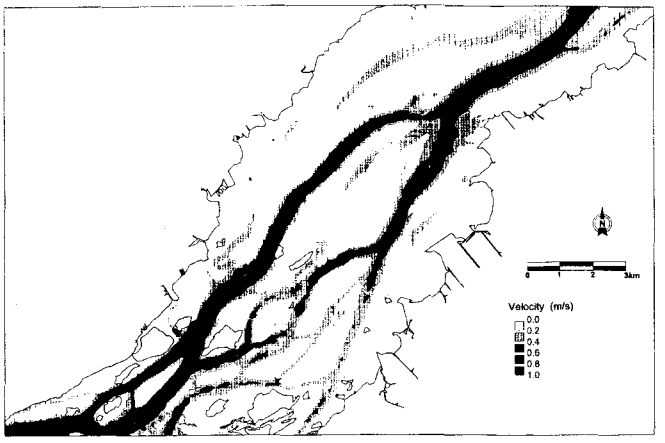

Fig. 12. Simulation of flow velocity with summer model: maximum plants growth (7 500 m^3/s).

Discussion

Numerical modeling of complex flow fields like Lake Saint-François is a difficult task which involves interdisciplinary knowledge including, hydraulics, botany, geomatics, computer engineering, field work and numerical modeling.

On plant friction parameterization

For the actual situation the growth curve is global and represents the integration of all species. In the future, because different species start their growth season and reach their senescence at different times, the curve will be defined for every species. Preliminary analysis of growth timing suggests that the water temperature is the key factor for relative growth of submerged macrophytes. Also, a portion of the total roughness during the winter is caused by the plant residues and roots, however this type of friction has never been assessed. More precise data on plant total surface area as a function of growth period will drastically refine the precision of friction coefficient with the hydrodynamic modeling. In order to validate these improved friction coefficients, it has to be followed by an appropriate correction for ADCP data in shallow waters with abundant aquatic plants.

On the future of submerged plant modeling

The next step will be to undertake the macrophytes microhabitat modeling for predicting plant distribution and biomass without the necessity of extensive field data collection programs. Rules derived by previous researchers and expertise obtained from echosounding interpretation will be exploited to produce a predictive mathematical model of plant distribution. Basic abiotic data will be provided through the NFM database and simulation of wave energy, light penetration, and nutrient distribution. Validation of plant distribution model will be performed using existing databases with some field validation.

Conclusion

This work is a first step towards a predictive model of aquatic macrophytes habitat. Biomass, growth forms and possibly plant species appear predictable by this approach. Macrophytes of Lake Saint-François have been mapped using echosounder transects in association with a submersible video camera. Plant distribution between transects was interpreted using a basic habitat model in the form of an interpretation key using distributed abiotic variables as provided by a Numerical Field Model. Several measurements were extracted from echosounding data : plant species composition, proportion, density and height. These heuristics were used in the estimation of the Manning's roughness coefficient. A technique for plant growth parameterization was developed and used successfully for the validation of a plant related friction coefficient.

Hydrodynamic simulations performed with this form of the friction coefficient show that macrophytes tend to concentrate the flow in the main channels. In the future, we believe that plant microhabitat predictions integrating currents, wind waves, light availability and nutrient simulations will allow a significant description of plant distribution and biomass, and consequently, improve the precision and the reliability of field modeling.

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Pristine Lake Saint-François, St. Lawrence River: Hydrodynamic Simulation and Cumulative Impact

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ABSTRACT. *Lake Saint-François is a fluvial lake of the St. Lawrence system which is used for hydropower production and commercial navigation. For 150 years, it was dredged and dammed regularly without any impact analysis being made. The cumulative impact of dredging and damming on large rivers such as the St. Lawrence is an issue with only qualitative answers. Bidimensional hydrodynamics was used to simulate ancient flow conditions and to produce quantitative descriptors. Two Numerical Field Models (NFM) were prepared, one representing present state geometry, which contains 300,000 sounding points, and the other representing pristine state, based on 1900 and 1870 measurements and containing 70,000 soundings. These two NFMs were compared, showing important changes in the morphology of the lake. The NFMs were then used for bidimensional hydrodynamic simulations of both actual and pristine states for 3 different discharges: 5,000 m^3/s, 7,500 m^3/s, and 10,000 m^3/s. Results highlight the cumulative physical transformation of the system. Hydrodynamic simulations and velocity differences show an increase of velocities over shoals for discharge under 8,800 m^3/s, and a decrease of velocities in deeper water for the same range of discharge. Dredging and straightening around Cornwall Island resulted in changes from 64% to 71% of the total river flow passing through the south channel while the flow in the north channel decreased from 36% to 29%. These hydrodynamic transformations had a definitive impact on sedimentation and most probably on aquatic plant distribution.*

INDEX WORDS: *Lake Saint-François, St. Lawrence River, hydrodynamic modeling, dredging damming.*

INTRODUCTION

Evaluation of cumulative impacts of dredging and damming on large rivers like the St. Lawrence is a problem with rare quantitative descriptors. The St. Lawrence River reach of Lake Saint-François was dredged and dammed regularly over an extended period of about 150 years without any impact analysis being made. It appears that the only reliable way to understand, assess, and quantify these impacts is to compare the river in its pristine state with the river in its present conditions. This simple statement underlies a major problem: the absence or scarcity of any pristine state description.

Bidimensional hydrodynamic modeling has become an important but still underexploited tool for environmental assessment. It is commonly used to calibrate and assess the impact of civil works or intervention like damming or dredging. As long as it is possible to simulate future conditions, it is theoretically possible to simulate past conditions. Thus, it is possible to perform a backward impact analysis, taking into account all the physical modifications imposed on the system.

Study Area

Lake Saint-François is a fluvial lake of the St. Lawrence system and is the first natural enlargement of the river downstream of Lake Ontario (Fig. 1). It is used as a political border between Québec, Ontario, and New York State. Lake Saint-François is about 50 km long and reaches 8 km at its widest section. The lake surface area is 254.2 km^2, its average depth is 5.7 m for a total volume of 1.45 km^3. The average flow discharge is about 7,500 m^3/s, creating strong currents which are responsible for the quasi absence of thermal stratification in the lake.

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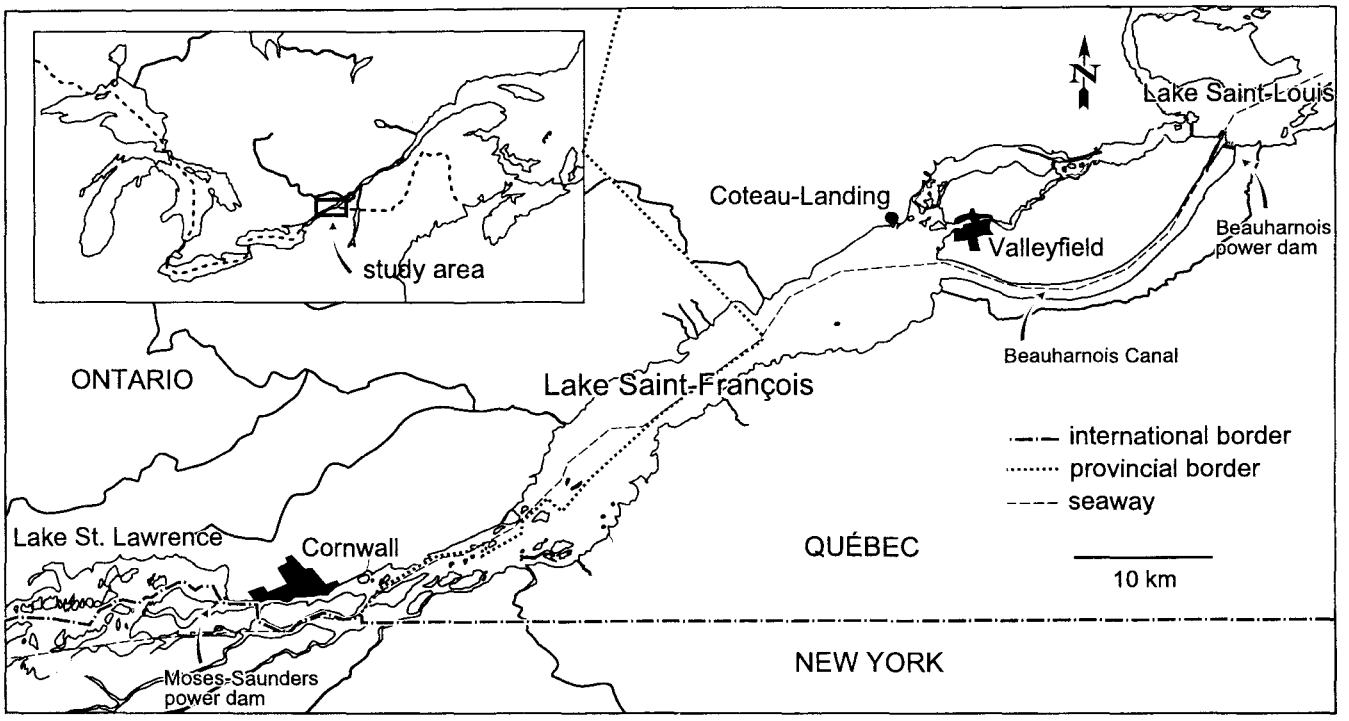


FIG. 1. Geographic location of the study area.

Important Contrast on the River

At present, the water level of Lake Saint-François is highly stabilized downstream by the Beauharnois and Coteau dams and the flow is regulated upstream by the Moses-Saunders dam (Yee *et al.* 1990, Morin *et al.* 1994). Moreover, dredging has deeply modified the lake bottom, and the flow was diverted into the Beauharnois canal. Regulation of the flow and of the water level has a long history that began in 1849 with the damming of a branch of the lake outlets (Morin and Leclerc 1998). In its pristine conditions, the water level of Lake Saint-François was fluctuating with the unregulated flow coming from Lake Ontario, creating long-term fluctuations of the water level. The outflow was passing through two outlets that are now used only for overflow evacuation.

Impact on Habitat

The direct impacts of dredging, damming, and water level control, as well as flow regulation, on the physics of the lake are not known quantitatively. However, several aspects of the impact on wildlife are found in the literature. Impact of these changes on the aquatic fauna is obvious on some species of fish who have lost access to their migratory routes with the erection of dams (Environment Canada 1994, SLRT 1992). Lack of flooding over wetlands has reduced access to spawning areas for several fish species. Traditionally, long-term fluctuations of the river hydrology allowed cyclic flooding of important surfaces of wetlands; these wetlands are now endangered by the water level stabilization (IJC 1993, Environment Canada 1994, Jean and Bouchard 1991). Impact on the submerged flora is not yet well understood, but it is known that plant biomass has more than doubled since 1919 (Morin and Leclerc 1998). Impacts on sedimentation and erosion are present but valuable studies on this topic are scarce (Carignan *et al.* 1993, Lorrain *et al.* 1993).

General Approach

Bidimensional hydrodynamic simulations of the present state are compared with simulations of the pristine conditions. In these simulations, velocities are calculated for the entire domain. It is then possible to compare velocities from present and ancient state simulations, and thus highlight the differences. Given that the long-term fluctuations of flow dis-

charge are important, conditions for representative discharges are compared.

The objectives of the paper are:

1. to build and describe a topographic model of the ancient Lake Saint-François, before 1849;
2. to simulate hydrodynamic conditions prevailing in the pristine state;
3. and to compare the hydrodynamic conditions of the pristine state with the present conditions.

This study shows some aspects of the essential contribution that applied hydrodynamic modeling can bring for assessing the impact of past interventions. An analysis of the topographic evolution of a small portion of the St. Lawrence River was performed by Lapointe (1994), but the actual work appears to be the first attempt to simulate ancient flow conditions of a large river reach.

PRISTINE FLOW CONDITIONS OF LAKE SAINT-FRANÇOIS

Pristine hydrology of Lake Saint-François is considerably different than the present situation. Several interventions have modified its cyclical behavior and also the lake geometry. The flow pattern is certainly different and it probably had a significant impact on the ecosystem. Simulations of the pristine state require an accurate Numerical Field Model (NFM) and reliable boundary conditions. Ancient conditions prevailing in Lake Saint-François were the object of an exhaustive study by Morin and Leclerc (1998), who examined the evolution of civil works and hydrology since the pristine state.

Evolution of Civil Works

Interventions in the area are related to rapid zones upstream and downstream of Lake Saint-François. These were a problem for navigation but a source of energy for hydropower productions. The first series of navigation canals, 9 feet deep (2.7 m), were dug around 1845 at the entrance (Old Cornwall Canal) and outlet of the lake (Old Beauharnois Canal). In 1849, because of strong currents at the entrance of the Old Beauharnois Canal, a dam was built on the southern branch of the St. Lawrence River at Valleyfield. Under natural conditions, about ⅙ of the total outflow was transiting through that channel and this was reduced to about 300 m^3/s. The old canals were replaced or deepened to 14 feet (4.3 m) around 1900 and were used until 1958 (Cornwall and Soulanges Canals). The present Beauharnois Canal was finished in 1932, and allowed diversion of a part of the St. Lawrence flow to the Beauharnois power dam. The discharge in this canal was 2,350 m^3/s in 1932, 4,500 m^3/s in 1952, and 6,500 m^3/s in 1960. Currently, most of the flow is transiting through it. In 1933, the Coteau I dam was built to increase flow diversion through the Beauharnois canal, and Coteau II, III, and IV dams were completed in 1942. Important surfaces were dredged within the lake for the construction of the St. Lawrence Seaway in 1958. During the same period, the Moses-Saunders dam was erected at the entrance of Lake Saint-François.

Pristine Hydrology

Flow has been regulated since 1958. Regulation tends to transfer part of the flow from spring to the end of the summer but does not affect the long term fluctuations of the hydraulicity (fluctuation of the water resource provided by the river basin). Long-term fluctuations of about 10 to 30 years are present in the discharge series. These fluctuations are related to pluviometric variations over the Great Lakes drainage basin. They are intrinsic to the system and are an essential part of the ecosystem dynamics. The lowest monthly average discharge recorded is about 4,500 m^3/s while the highest flow is 10,012 m^3/s (Morin and Leclerc 1998).

Under natural conditions, water levels were fluctuating mainly with the Lake Ontario outflow, local tributaries having only a limited influence. The ancient stage-discharge relationship of Lake Saint-François was reconstructed from water level and flow discharge data that predate 1932. From that relationship, the impact of the 1849 damming was removed by estimation of the ancient threshold capacity. Figure 2 presents the stage-discharge relationships that were valid before 1849, and between 1849 and 1932 at the Lake Saint-François outlets. After 1932, the influence of the newly created Beauharnois Canal slightly disturbed the natural fluctuation of water levels. Stabilization of water levels started in 1942 but became drastic only in 1958 (Morin and Leclerc 1998). Water levels are now stabilized at Coteau-Landing; the level varies less than 15 cm annually.

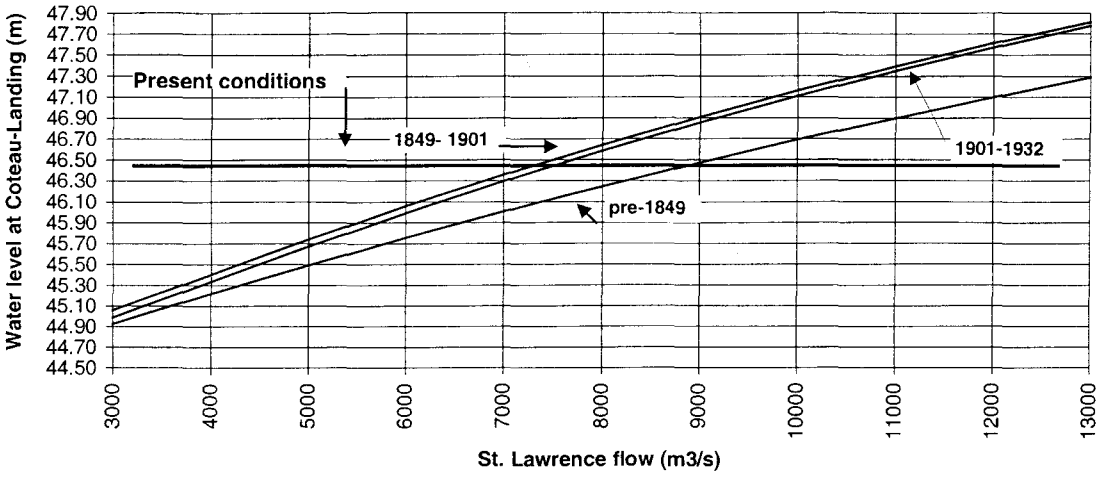


FIG. 2. Stage discharge relationships at the Lake Saint-François outlets.

METHODOLOGY

Simulation and analysis of a river reach that no longer exists is a task that requires multidisciplinary knowledge input like history, hydraulics, geomorphology, geomatics, biology, and computer science. The general approach consists in subtracting the pristine state simulation results from present conditions, in order to get the net cumulative transformation. This is conceptually simple but its application is labor intensive, mostly with the elaboration of the NFM. As schematically detailed in Figure 3, the methodology used is based on hydrodynamic simulations of pristine state conditions. Simulated events were chosen from the large spectrum of hydrological conditions that are typical of the pristine state and the geometry of the NFM corresponds to the pristine conditions of the mid-1800s. Cumulative impacts were interpreted from the differences between pristine and present time simulations. Simulations of present state velocities were already produced prior to this study (Morin *et al.* 1998).

Data manipulation was performed using the MODELEUR (Secretan and Leclerc 1998). This tool is a powerful software similar to a GIS but built specifically for fluvial applications, with excellent modeling capabilities. Raw numerical data are included as summits of finite element triangles forming a Triangular Irregular Network (TIN) so that values can be interpolated over the entire domain. Because of its calculation capacities, any mathematical operation can simply be applied to the entire domain.

PRISTINE STATE NUMERICAL FIELD MODEL

Pristine description of the topography is based on data from old bathymetric maps gathered at the National Archives of Canada and at the Canadian Hydrographic Service (CHS).

Topographic Data

The main sources of information are the 1900 to 1907 maps of the CHS, field sheets number 252, 255, 256, 257, and 495. These field sheets cover the entire lake at a scale of 1:12,000 for soundings every 50 to 100 m. A 1873 map from the U.S. Corps of Engineers, *Chart #1 St. Lawrence River* of the upper part of the Lake Saint-François, at a scale of 1:30,000 was used to add data on areas modified prior to 1900. Another map of 1887, *Plan of the town of Salaberry of Valleyfield* at a scale of 1:7,200, was used for the same purpose for the Valleyfield area. As data were available only on paper format, a total of 66,778 sounding points representing the topography of the entire Lake Saint-François had to be digitized. Data positioning was done using UTM coordinates in the NAD 27 referential. Control points on the map were localized. They are mainly geographical accidents that are resistant to erosion, and main roads that were drawn on old maps. Digitalization was performed on an ALTEK AC30 digitizing table of 1x1.5 m with ATLAS*DRAW^{tm} software. Depth was introduced as an attribute of the point. An in-house program permitted building a XYZ file containing the posi-

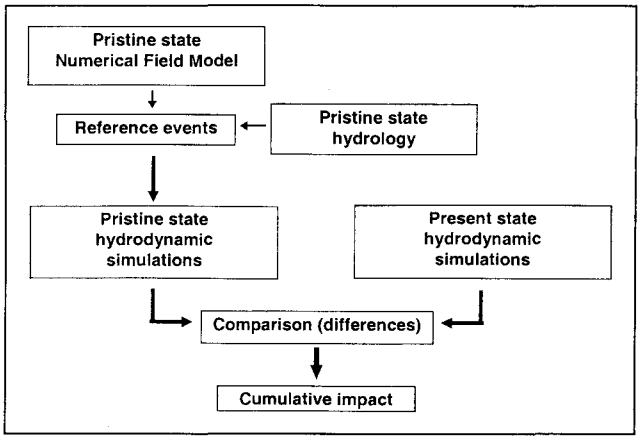


FIG. 3. Flow chart of the methodology.

tion in easting, northing, and the measured depth of each sounding.

Transformation of depth measurements into topographic data was done using CHS chart datum. Chart datum is the local elevation from the mean sea level to which the soundings refer. A Triangular Irregular Network (TIN) containing all datum positions was prepared with MODELEUR. All sounding points were projected on this grid with a linear interpolation within triangles in order to produce the elevation model.

Coast lines of the lake shore and islands were digitized. Because these lines represent the junction of water level with the topography, they can be used as topographic information. A few significant points were kept from these lines. An in-house algorithm was used to select points that were meaningful in curve description and with a maximum distance of 20 m. The elevation of coastline points was fixed at 0.3 m over the chart datum for the entire lake. About 10,000 points were then added to the NFM.

Validation of digitized data was performed using MODELEUR's interpolation tools. All digitized points were integrated in a TIN with the Delauney's triangulation algorithm. Visual examination of 1-m-deep isosurfaces allowed isolating and eliminating aberrant entries, which appeared as peaks or holes within the surrounding elevation model.

Errors and Precision

Possible errors within elevation data of ancient maps are mainly related to positioning (x,y) or to depth measurement. Since soundings were measured with weighted line, errors can then be associated with the softness of bottom, to the effect of currents on the line or to bad reading caused by the movement of waves. Sounding data are reported on the map with a precision of 1 foot (0.3 m). Generally, the precision of field notation corresponds to the precision of the sounding method. Positioning errors were obvious when pristine and actual NFM were compared. These errors are related to the positioning methods used in the early 1900s, generally done using a triangulation method based on fixed points on the shore: their precision varies with distance and angle.

Correction of Position: Aerotriangulation

Systematic positioning errors were corrected in order to superpose as accurately as possible the two NFMs; a technique known as aerotriangulation was used. This technique consists of correcting linearly the deformation between points that should be superimposed. Corresponding points were gathered in both pristine and present NFMs. These points are the position of erosion resistant part of the coast line, islands, river mouths, bridge pillars, etc. A total of 117 comparative points were collected.

These points were then assembled in one TIN of pristine state with the actual x and y coordinates as two attributes (nodal values) to each triangle summits for the 117 comparative points. With MODELEUR, the x nodal values were projected on the pristine state NFM that contains 66,778 nodes. The same procedure was done with the y nodal values. The projected results of 66,778 new x and y were then reassembled as the new and corrected coordinates of the pristine state NFM. This corrected NFM was used for the entire project and is presented in the results.

Presentation of Topographic Models

Pristine and actual state NFMs are best presented by complete images of both elevation models along with an image of the spatial distribution of their depth differences. Differences between the two NFMs were calculated using MODELEUR. The elevations of the Delauney's triangulation of the present NFM were projected on the nodes of the pristine TIN. These new nodal values were then subtracted from the pristine elevation nodes, resulting in nodal differences. Nodal differences were then mapped to enlighten their spatial distribution.

This map includes random differences related to all kinds of error caused by the precision of depth measurements, of the planar positioning method

and of the interpolation between soundings. In order to remove random and systematic noises observed in the lake in the areas of the lake that are relatively stable, differences of less than ±1.5 m are considered as non-significant. A detailed analysis of this spatial distribution compared with both NFM elevation maps allowed segregation of significant differences. Differences based only on one node or on interpolation aberration were also removed from the map of differences.

Substratum

Spatial distribution of substrate must be known over the entire domain because the friction influence can be significant on the flow distribution. The distribution of pristine state sediments is believed to be largely similar to the present state situation. This statement is based on the fact that there is little amount of sediment coming from upstream of the lake, and that the tributaries have relatively small sediment input (Lorrain *et al.* 1993). However, significant differences are present where vast surfaces of dredging have modified the lake bottom and also where erosion has withdrawn and moved sand downstream. A precise sediment map prepared for the present state simulation of hydrodynamics was used to interpret the pristine state substrate (Morin *et al.* 1998a). This map was modified for alterations caused by dredging and dredged material deposit as well as for the impact of erosion. Friction is introduced in the hydrodynamic calculation with the Manning's coefficient. This coefficient is a function of the average size of sediment particles, represented by this following equation based on a linear regression analysis:
where,

$$\frac{1}{n} = 34.9(-\log \bar{d}')^{0.31} + 0.0017 \qquad (1)$$

$\bar{d}'$ = average size of sediment particles (m).

This curve is modified from Boudreau *et al.* (1994), which was overestimating the friction coefficient for particles smaller than gravel. The average size of sediment particles was calculated for each combination of materials as :

$$\bar{d}' = \sum_{i=1}^{p} w_i d_i \qquad (2)$$

where,

d_i = median value of the i^{th} substrate class

w_i = weight used according to the number of substrate classes

p = number of classes identified at each observation point

REFERENCE EVENTS

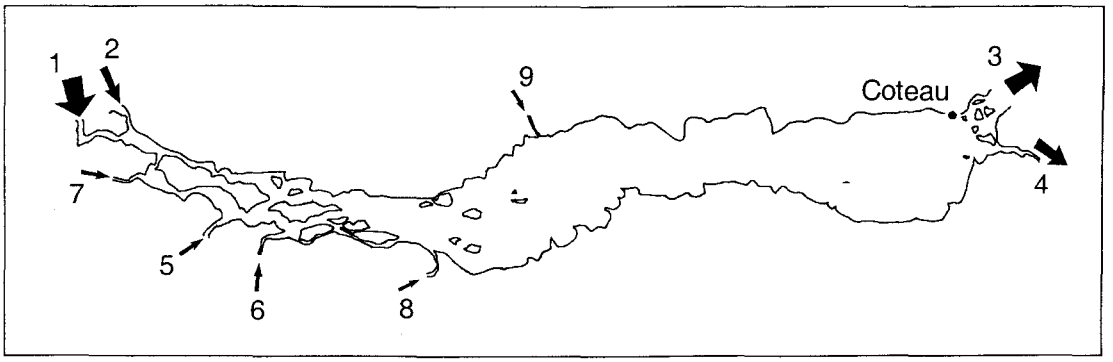
A large spectrum of conditions occurs in the hydrodynamics of Lake Saint-François (see Morin *et al.* 1998a). These conditions are mainly a function of the outflow of Lake Ontario because tributaries have a limited impact on the total flow. All possible hydrological conditions can neither be simulated nor analyzed within the scope of this paper; an approach of reference events are used (Boudreau *et al.* 1994). The reduced number of reference events allows capture of the river complexity with a manageable amount of information, avoiding the need to simulate numerous conditions that are partly redundant.

Measurements of historical flow discharge show that the spectrum of monthly average flow entering Lake Saint-François varies between extremes of 4,500 and 10,000 m^3/s with an overall average of about 7,500 m^3/s. The pristine hydrodynamics of Lake Saint-François is simulated with three reference events: low, average and high flow of 5,000, 7,500, and 10,000 m^3/s, respectively (Fig. 4). These events were simulated in absence of aquatic plants because there is a lack of knowledge about the amount and distribution of plants during the summer in the pristine state. Therefore, simulated events represent hydrodynamic conditions of spring and fall, i.e. in absence of ice and plants.

PRISTINE STATE SIMULATIONS OF HYDRODYNAMICS

Finite Element Grid

The hydrodynamic model uses a discretization approach based on the finite elements method. The triangular element used is composed of six nodes with bilinear approximation. Elements form a grid (triangular irregular network TIN) that is semi-automatically generated by the MODELEUR. This grid carries all the information related to topography and substratum. The same grid was used for both simulation of the pristine state and the present conditions. The Lake Saint-Francois calculation grid was imposing by its size, comprising as many as 27,669 elements and 57,531 calculation nodes. The size of elements varies from 10 m in small



	Simulations		
	5000 m^3/s	7500 m^3/s	10 000 m^3/s
1 St. Lawrence upstream	4 770 m^3/s	7 150 m^3/s	9 530 m^3/s
2 St. Lawrence upstream	230 m^3/s	350 m^3/s	470 m^3/s
3 St. Lawrence downstream	4 340 m^3/s	6 340 m^3/s	8 330 m^3/s
4 St. Lawrence downstream	795 m^3/s	1 295 m^3/s	1 805 m^3/s
Water level at **Coteau** (RIGL 55)	45.50 m	46.13 m	46.70 m
5 Raquette river	70 m^3/s	70 m^3/s	70 m^3/s
6 Saint-Régis river	30 m^3/s	30 m^3/s	30 m^3/s
7 Grass river	20 m^3/s	20 m^3/s	20 m^3/s
8 Salmon river	10 m^3/s	10 m^3/s	10 m^3/s
9 Raisin river	5 m^3/s	5 m^3/s	5 m^3/s

FIG. 4. Boundary conditions of simulations of 5,000, 7,500, and 10,000 m^3/s.

channels to 400 m in the eastern part of the lake where the bottom is fairly flat.

Hydrodynamic Model

The hydrodynamic modeling was performed using the HYDROSIM model developed at INRS-Eau. The approach used is based on the two-dimensional finite element discretization of the St. Venant equations (flux formulation), which are solved using an iterative transient solution method Euler-GMRES (Heniche *et al.* 1999). It solves simultaneously the mass and momentum conservation principles, and takes into account the local friction coefficient for parameterization. The turbulence closure scheme uses the mixing length theory (0-equation model) which involves the horizontal velocity gradients. Vertically integrated, the model produces reliable predictions of mean velocity of the water column, water level, and specific discharge for a wide range of hydrological conditions. The model solves the wetted surface since it incorporates a drying-wetting functionality that allows dynamical estimates of the flow boundary. The theoretical model is represented by the equation system of Figure 5.

As one seeks the steady-state conditions, the solution is considered independent of the initial conditions. As for the boundary conditions scheme, one usually solves the problem using specified discharge at the upstream boundary, water level at the main outlet and specified discharges at the tributary and secondary outlets. Moreover, tangent velocities are being imposed as null. For closed lateral boundary, the drying-wetting functionality is equivalent to imposing a zero normal flux and a slip flow condition.

Boundary Conditions

The boundary conditions are the parameters that drive the simulations. As presented earlier in the reference events, boundary conditions were prepared for three simulations of 5,000, 7,500, and 10,000 m^3/s. Water levels and discharge distribution at the lake outlets were set following rebuilt stage-discharge relationships occurring during pristine state (Morin and Leclerc 1998). About ⅓ of the total discharge transits through the southern

Mass conservation equation

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = 0$$

Momentum conservation equation

$$\frac{\partial}{\partial x}\left(\frac{q_x q_x}{H}\right) + \frac{\partial}{\partial y}\left(\frac{q_x q_y}{H}\right) + c^2 \frac{\partial h}{\partial x} - \frac{1}{\rho}\left(\frac{\partial}{\partial x}(H\tau_{xx}) + \frac{\partial}{\partial y}(H\tau_{xy}) - \tau_x^b - \tau_x^s\right) - f_c q_y = 0$$

$$\frac{\partial}{\partial x}\left(\frac{q_y q_x}{H}\right) + \frac{\partial}{\partial y}\left(\frac{q_y q_y}{H}\right) + c^2 \frac{\partial h}{\partial y} - \frac{1}{\rho}\left(\frac{\partial}{\partial x}(H\tau_{yx}) + \frac{\partial}{\partial y}(H\tau_{yy}) - \tau_y^b - \tau_y^s\right) + f_c q_x = 0$$

$x(x,y)$ = Cartesian components (x=east and y=north)
q_x , q_y = specific discharge, regard to x and y (m^2/s)
h = water surface level (m)
H = water depth ($=h-z_f$) (m)
c = celerity of waves ($c = \sqrt{gH}$) (m/s)
r = density of water (10^3 kg/m^3)
$u(u,v)$ = velocity components (m/s) where;
$u = q_x/H$ (m/s)
$v = q_y/H$ (m/s)

f_c = Coriolis factor ($f_c=2\omega\sin\phi$) (s^{-1})
τ_{ij} = Reynolds stresses (kg/s^2m)
τ_x^b, τ_y^b = bottom friction in x and y (N/m^2)
τ_x^s, τ_y^s = surface friction in x and y (N/m^2)

FIG. 5. Equations of the hydrodynamic model HYDROSIM.

branch, while the main portion uses the northern channel at Coteau. Upstream of Lake Saint-François, the discharge distribution between the northern and southern branches was evaluated from the relative size of the sections. Tributaries have a reduced influence on the flow pattern because their average flow is low compared to the St. Lawrence River. The mean annual flow discharge of the tributaries, i.e., a total of 135 m^3/s, was used for the three simulations.

Differences and Cumulative Impacts

Differences between pristine state and present state simulations highlight the cumulative impacts on the physics of the system. Because the simulations of both states were calculated with the same grid, cumulative impacts are obtained by subtracting velocities node by node over the entire domain. The results are shown on three maps of the distributed differences of velocity. Present state hydrodynamics were already completed prior to this paper and are described in Morin *et al.* (1998a); the three simulations considered have the exact same discharges for the St. Lawrence River and for tributaries.

RESULTS

Pristine State Numerical Field Model

Geomorphologic changes between the two NFMs are of three types: anthropic, natural, and mixed; i.e., natural evolution of man-made situations. Of an obvious anthropic origin is the dredging and the deposition of dredged materials. Natural geomorphologic changes are present mainly in the eastern portion of the lake and are related to wind wave erosion and also to erosion by currents. Other morphologic changes are the results of combined man-made and natural effects, generally related to the achievement of post-dredging equilibrium.

Pristine state NFM can be analyzed properly by contrasting the changes with the present state geometry. Figure 6 contains both pristine and actual

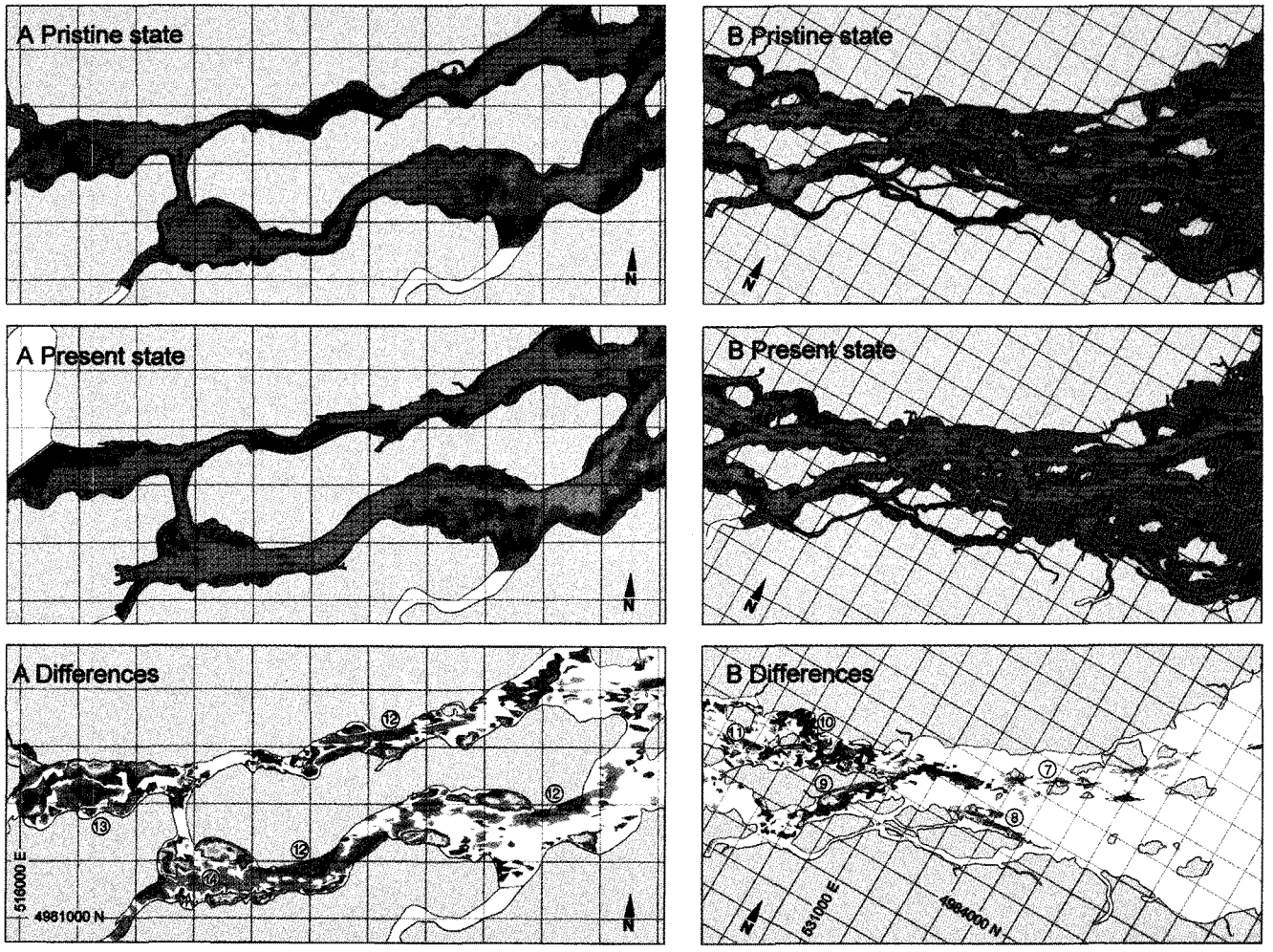


FIG. 6. Numerical field models of Lake Saint-François in pristine and present state, with their differences. A: Upstream of Lake Saint-François. B: Central portion of the lake. C: Downstream of Lake Saint-François. Numbers refer to Table 1.

elevation models along with the spatial distribution of differences between both NFMs. Transformation of the lake bottom can be viewed in three sections. The upstream part (A) has been severely dredged and a lot of material was displaced; it is possible that a large portion of this material was washed away and deposited east of Cornwall Island in the middle portion. In addition to this deposition area, modifications of the middle portion (B) of the lake are related to dredging for the Seaway. The eastern portion (C) has several areas with wind wave erosion. A detailed description of these transformations is presented in a synthetic manner in Table 1.

Hydrodynamic Simulations

Hydrodynamics

The flow within Lake Saint-François can be subdivided in three main facies. In a general manner, velocities increase with discharge. Upstream of the lake, velocities reach more than 3 m/s. In the central part, shoals with low velocity are separated by several swift flow sections of 0.6 to 0.7 m/s, while in the downstream portion, a single channel of 0.3 to 0.5 m/s transects a low velocity water body. Figure 7 shows the three simulated states of 5,000, 7,500, and 10,000 m^3/s in the pristine conditions.

At 5,000 m^3/s, most of the flow is concentrated

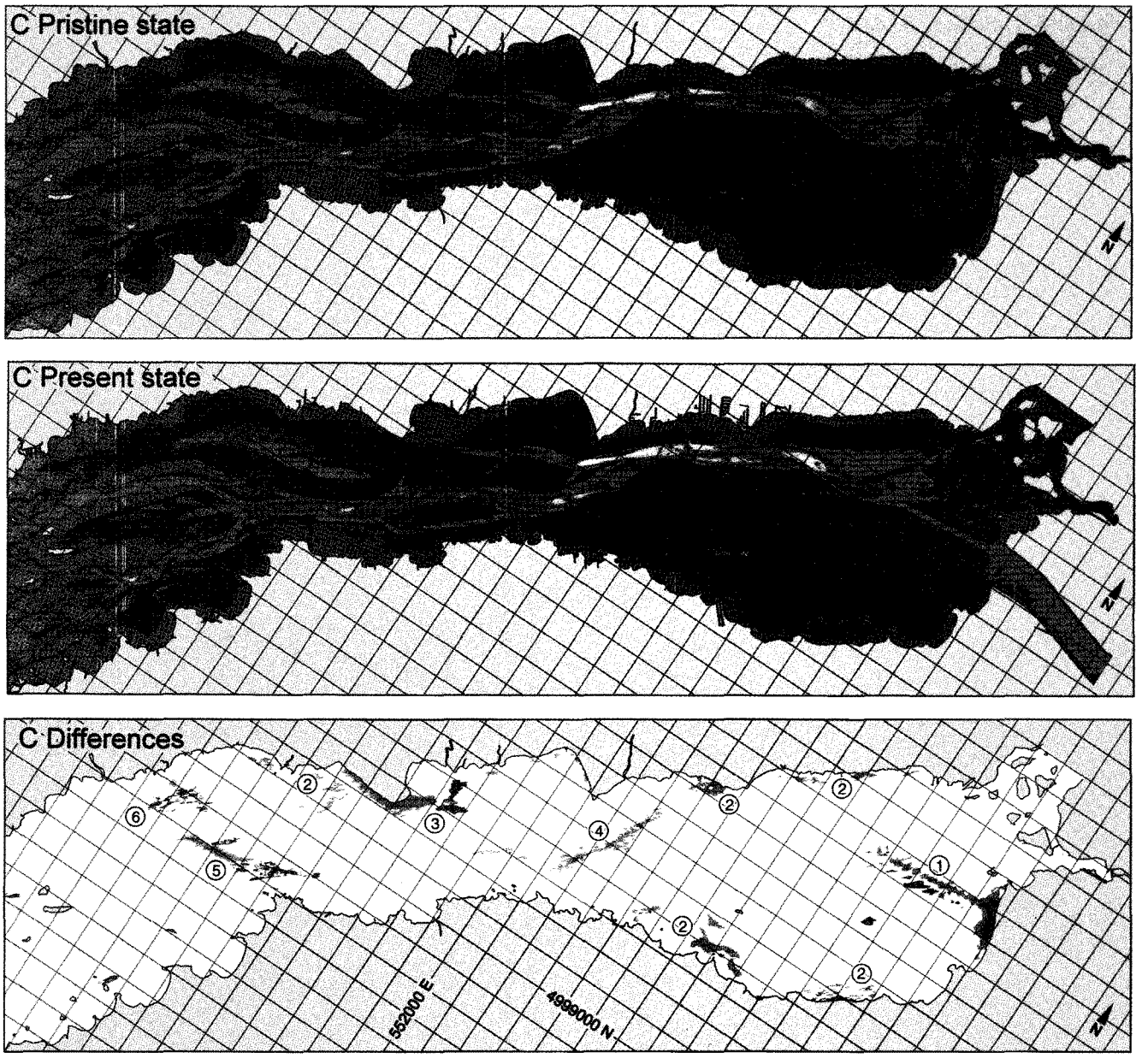

C Pristine state
C Present state
C Differences
552000 E
4999000 N
Topography (m, RIGL 55)
-48
-46
-44
-42
-40
-38
-36
-34
-32
-30
-28
-26
-24
-22
-20
-18
Differences of topography (m)
11.5
9.5
7.5
5.5
3.5
1.5
0
-1.5
-3.5
-5.5
-7.5
-9.5
-11.5
erosion
accumulation
A
B
C
Grid UTM Zone 18 NAD27
1000 m x 1000 m

TABLE 1. Description and interpretation of topographic transformations. The number and figure correspond to Figure 6 A, B, or C.

#	Fig.	Name	Process	Description & interpretation
1	C	Beauharnois canal	dredging & deposition	Beauharnois canal was built in 1932, a large part of the surrounding beaches were eroded. Navigation channel was dredged in 1958, dredged materials were deposited laterally.
2	C	Shallow water erosion	wind waves	South and north sides of the lake have important areas of wind wave erosion of sandy material. Fetches in both side are significant and are under influence of dominating winds.
3	C	Pointe Mouillée	wind waves	This area is in the same context than #2. This sandy point was eroded of about 170 m since 1900. Important amount of sand was deposited downstream. Actually, it is still the subject of an important erosion.
4	C	Port Lewis bank	currents	Substrate in this area is composed of sandy material. Strong currents produced by large flow are probably responsible for this erosion, large wind wave may also be involved.
5	C	Island bank	dredging & deposition	This area was dredged for the St. Lawrence Seaway, materials were deposited downstream. Some portions of these deposits were washed away downstream.
6	C	Lancaster basin	sedimentation	Lancaster basin was already recognized as a sedimentary basin (Lorrain *et al.* 1993).
7	B	Clark/St. Francis Islands	dredging	This area of about 6 km long was dredged for the St.Lawrence Seaway. Materials were deposited in the vicinity.
8	B	Simard Island	deposition	This site is a major dredged material depot that reaches more than 12 m in thickness.
9	B	East Saint-Régis	deposition	This site is an important area for dredged material deposition that reaches about 9 m thick.
10	B	Flanigans Point	deposition	Dredged materials were deposited between the point and the island (SW) and it is possible that an important amount was washed downstream. Large deposition area south-east of this site is covered of material possibly removed by currents from dredged area upstream.
11	B	Colquhoun Islands	dredging	A 12 m deep trench was dredged in this bank in order to access the Port of Cornwall to the Seaway. An other smaller trench was dug during early 1900's, about 500 m south (see Fig. 6: A Present State).
12	A	Cornwall Island area	dredging	Several points were removed by dredging in the north and south channel in order to increase the flow, reduce the water level and ice jams. The material removed was used to fill several small bays. Lots of dredging were performed for the Seaway on the south channel.
13	A	Long Sault Bank	dredging	This large bank probably composed of gravel was completely removed, some part of it was used for the reservoir dykes. Moses-Saunders dam was built over the minor channel of the St. Lawrence.
14	A	Polly's Gut basin	dredging & deposition	The morphology of this small basin was completely transformed by the construction of the Seaway. Important dredging took place at the entrance of the locks and materials were deposited 500 m northward. Diversion dykes were also built.

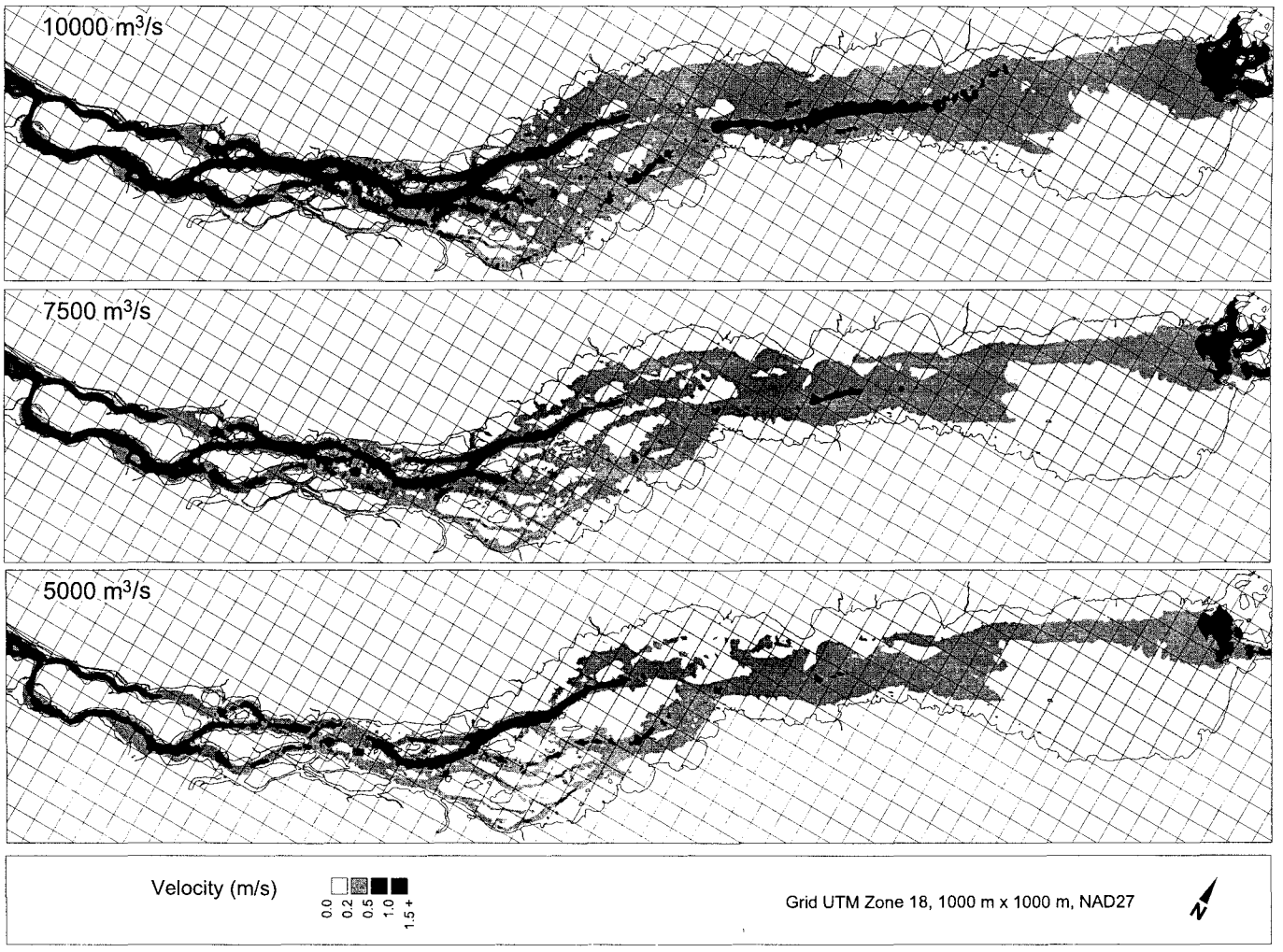


FIG. 7. Simulation of velocities of pristine state conditions for 5,000, 7,500, and 10,000 m³/s.

in the channels; shoals are either exposed or covered with reduced velocities. Singularly, several channels in the central part have the fastest velocities at this low discharge. At 10,000 m³/s, there are important velocities that reach 3.5 m/s in the upstream portion. Compared to lower discharges, there is an increase of velocities within channel constrictions. Excluding some large embayments, most of the lake is covered with water flowing at more than 20 cm/s.

Water Levels

As actual water levels are stabilized at Coteau to around 46.45 m, simulated ancient flows of 10,000, 7,500, and 5,000 m³/s are, respectively, 28 cm higher, 17 cm lower, and 92 cm lower than the present levels (Fig. 8). The present level at Coteau-Landing corresponds to a discharge of approximately 8,800 m³/s under pristine conditions. Total level fluctuation was almost constant throughout the lake at 1.20 m. Most of the variation in the water level slope is located in the upper part of the lake, from 5 to 15 km, and corresponds to the Cornwall Island area. The slope has been reduced and flattened by the removal of flow restrictions by dredging. Spatially, the impact of ancient water level fluctuations can be observed with the simulations. Simulation at 5,000 m³/s discharge shows important areas that dried up in the middle of the lake as well as on the shore (Fig. 7). At 7,500 m³/s, water level is lower than the actual level and simulation shows small areas of exposed lake bottom close to the shore. However, at 10,000 m³/s, all

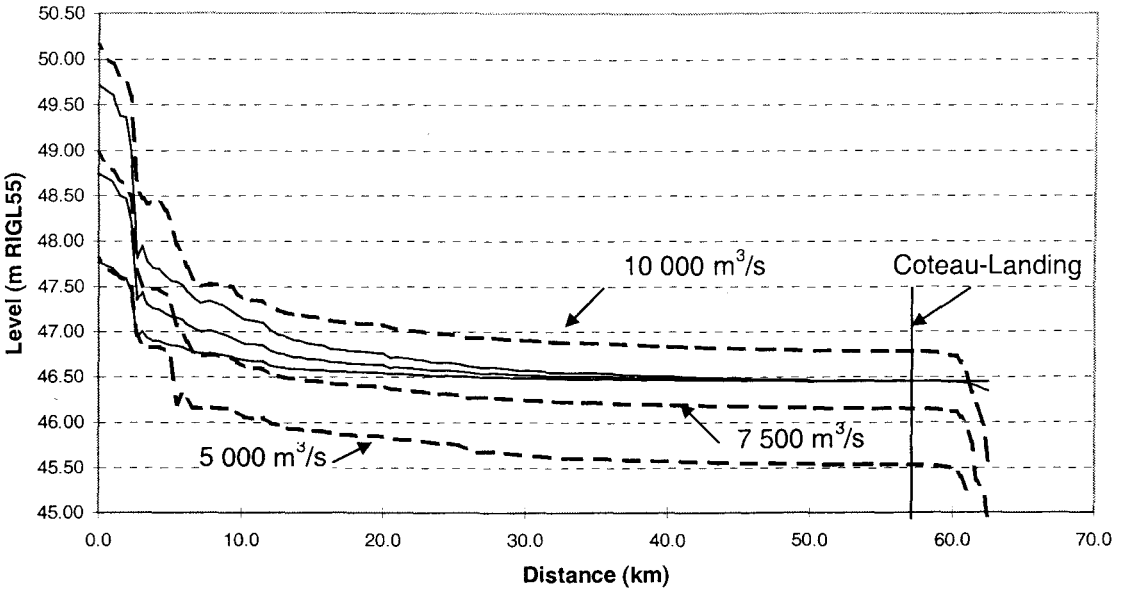


FIG. 8. Profile of water level throughout Lake Saint-François from west to east. This cross section follows the main channel of Lake Saint-Francois and passes south of Cornwall Island. Hatched lines correspond to pristine state while plain lines were simulated with actual conditions.

shoals were covered and large areas on the lake shore were certainly flooded.

Differences Between Pristine and Present States

Changes in the hydrodynamics from the pristine conditions are best contrasted with the difference between simulations of equivalent discharge. It is not possible to show herein every simulation in the present conditions (Morin *et al* 1998a). However, differences between the simulated flow fields between pristine and present conditions are presented in Figure 9. This figure shows that the most important changes in velocity are associated with the dredged areas upstream and downstream. There is a reduction of velocities in the natural channels (Fig. 9 #1) and an increase in the Beauharnois canal (Fig. 9 #2). Also, there is a general velocity decrease in the north channel (Fig. 9 #3) and an increase in the south channel of Cornwall Island (Fig. 9 #4).

Changes are significant and vary with discharge. At a discharge of 5,000 m^3/s, most of the flow field is transformed. In an area associated with relatively deep waters, velocities are slightly decreased compared to the present conditions. The most important decreases in velocity are present upstream and downstream and in the main channel of the central part. Most of the shoals show increased velocities. At 7,500 m^3/s, augmentation and reduction of velocities are mainly associated with large channels. For the 10,000 m^3/s discharge, most of the changes consist of an increase of the flow in the main channels and a slight reduction on shoals.

DISCUSSION

Causes of Velocity Changes

Hydrodynamic transformations since the pristine state are significant. The changes are either related to topographic changes as described earlier or to the water level stabilization. Because water level is stabilized to a fixed level around 46.45 m (IGLD55) regardless of the discharge, the imposed wetted section is larger for small discharges and smaller for large discharges. This causes a systematic reduction of velocities for discharges like the simulated 5,000 m^3/s, and an augmentation of velocities for discharges higher than about 8,800 m^3/s, this during the period without ice cover or plants. Difference of velocities over shoals is more complex to explain. In pristine conditions and during low discharge, shoals were either exposed or covered with very shallow water with slow velocities while during high discharge, shoals were covered with deeper

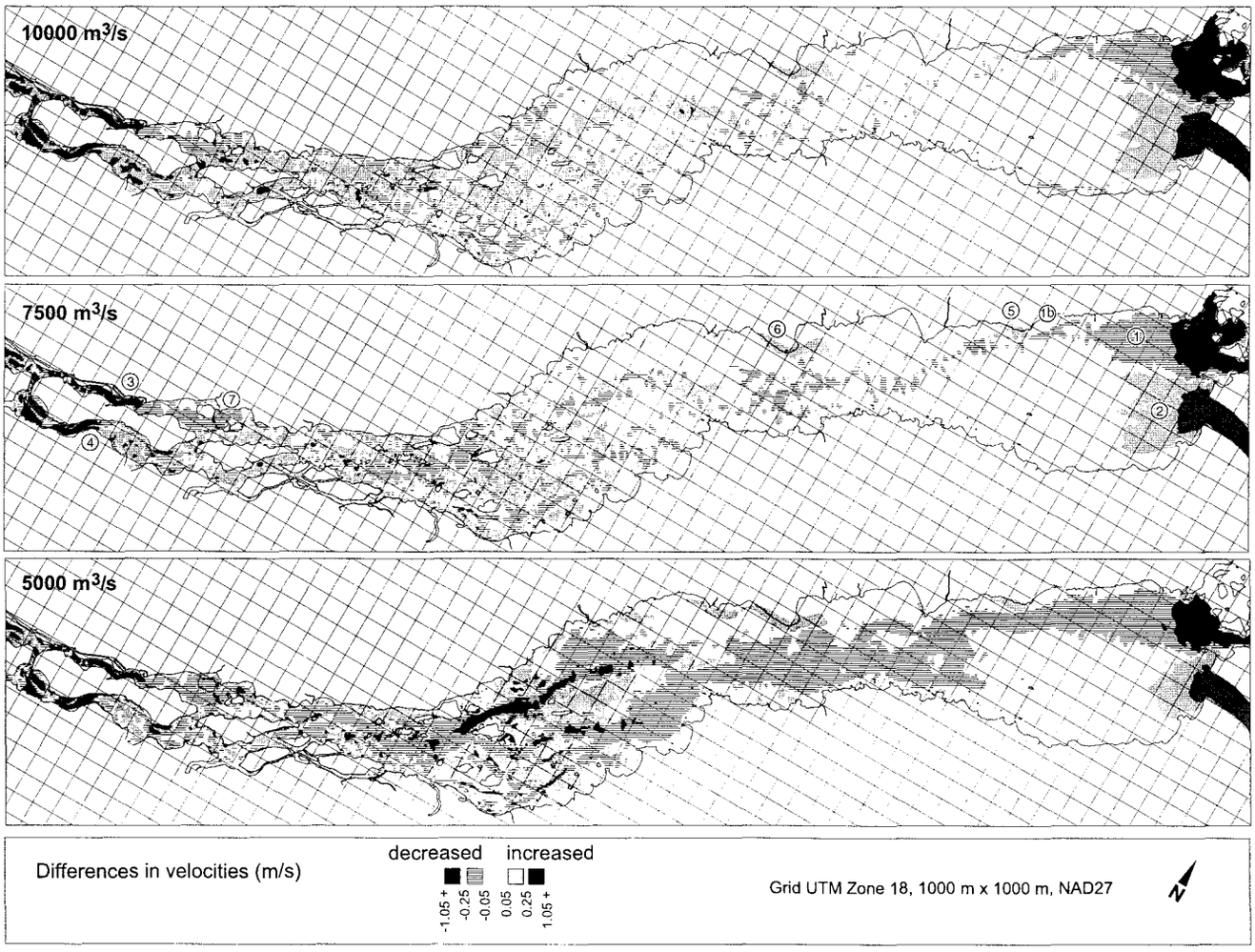


FIG. 9. Velocities differences between pristine and present state conditions for 5,000, 7,500 and 10,000 m³/s.

water and faster velocities. In present conditions, water depth over shoals is almost constant and velocities are varying in a smaller range with discharge compared to pristine conditions.

Topographic transformations are either of natural or of anthropic origins. Because natural erosion is relatively subtle in terms of accumulation and erosion differences, the impacts of these processes on hydrodynamics are generally minor. There are, however, two sites (Fig. 9 #5 and #6) where wind wave erosion and subsequent deposition have significantly modified the flow fields. Dredging, dredged material deposition, and damming had the most noticeable impacts on the flow fields and resulted in major changes in velocity direction and module. Moreover, modifications of the topography have changed the amount of water flowing in the north and south channels of Cornwall Island (Fig. 9 #3 and #4). Important dredging and straightening in the south channel resulted in changes from 64% to 71% of the total river flow passing through the south channel while the flow in the north channel decreased from 36% to 29%.

Sedimentation

It is obvious that velocity changes had an impact on sedimentation. In Lake Saint-François, because of the fluctuating nature of flow in the system, only velocity changes that are present in the entire spectrum of conditions can be validated with sediment thickness. The corollary of this is that velocity changes can be used to interpret the measured sedi-

Habitat modelling of submerged macrophytes, Lake Saint-François, St. Lawrence River

Jean Morin, Daniel Rioux, José Bechara and Michel Leclerc

Résumé : L'habitat fluvial du lac Saint-François a été décrit en terme de facteurs abiotiques 2D afin d'élaborer un modèle prédictif de la distribution des plantes submergées. Les facteurs abiotiques composant l'habitat des plantes proviennent de mesures directes et de simulations numériques représentant les conditions du printemps et de l'automne. Ces facteurs sont décrits sur l'ensemble du lac Saint-François avec une maille de l'ordre de 50 m de diamètre. Les courants, les vagues, l'accumulation de sédiments fins et la lumière au fond sont simulés à différentes conditions de référence tandis que la topométrie, la pente du fond et le diamètre du substrat proviennent de mesures directes. Chacun des 12 facteurs abiotiques définissant l'habitat des 8 espèces dominantes de ce milieu est décrit sur l'ensemble du domaine d'écoulement. Suite à une caractérisation de la distribution des espèces de plantes submergées présentes, une base de données d'habitat a été constituée en concordance avec la position des 806 échantillons de présence/absence des espèces. 698 de ces échantillons sont à la base de l'ajustement des modèles de régression logistique et 108 points sélectionnés au hasard ont servi à la validation des modèles pour chacune des espèces. Les modèles montrent des prédictions correctes variant entre 81% et 92% selon les espèces, à l'aide de moins de 8 variables abiotiques de base. Les facteurs abiotiques clés et les intensités critiques sont identifiés et interprétés permettant ainsi d'envisager la prédiction de la distribution spatiale des espèces dans le fleuve.

Mots-clés : Modélisation d'habitat macrophytes submergés, système fluvial, lac Saint-François, fleuve Saint-Laurent, régression logistique, GIS, TIN

Abstract:

The fluvial habitat of Lake Saint-François is described using 2D abiotic factors making possible the elaboration of a predictive model of spatial distribution of submerged macrophytes. The abiotic factors controlling the distribution of macrophytes were either measured or simulated using numerical models representing conditions occurring during spring and fall. They are available for the whole of Lake Saint-François on a grid mesh of the order of 50 m in diameter. Abiotic factors, like currents, waves, fine particle accumulation, and the ratio of light intensity reaching the bottom have been simulated or estimated under various reference conditions, while the riverbed slope and the mean grain size of the substrate are derived from direct field measurements. Each of the 12 abiotic factors selected to represent habitats of the 8 dominant species is described for the entire flow domain. Following a field characterisation campaign of plant species distribution, a habitat database was built in concordance with the location of the 806 observations of the presence and absence of submerged macrophyte species. From the complete set of 806 plant observations, 108 were randomly selected for validation (validation data), and the remaining samples (calibration data) were employed for parameter adjustment. The calibration and validation models show correct predictions varying from 81% to 92%, depending on species, with less than 8 basic variables. Critical abiotic factors and intensities are identified and interpreted, allowing for the possibility of predicting the spatial distribution of submerged species in this part of the river.

Key words: Habitat modelling, spatial distribution submerged macrophytes, fluvial system, Lake Saint-François, St. Lawrence River, logistic regression, GIS, TIN

Introduction

Context

Submerged aquatic plants are present all along the St. Lawrence River corridor and they are relatively abundant compared to other large rivers. This amount of submerged vegetation is mainly related to the low concentration of suspended matter in the Great Lakes waters (<10 mg l^{-1}). Macrophytes are so abundant in the river that they drastically modify the flow distribution of the fluvial system during the growth season. Precise species distribution is therefore an essential data for an accurate description of hydrodynamics, sedimentation and pollutant transport processes. However, the effort in terms of fieldwork that has to be deployed each time this basic information is needed is both time consuming and expensive. Moreover, these measurements are reliable only for the season in which they were taken. Predictive tools for plant distribution have to be developed in order to understand and predict their spatial and temporal variability. These would lead to the reliable prediction of impacts from climatic changes and from water level/discharge management on this component of the fluvial ecosystem.

Distribution of submerged macrophytes

The spatial distribution of aquatic macrophytes can be analysed using different scales where factors controlling plant distribution vary spatially. At the continental level (>100 km), variables such as latitude, altitude, climate and drainage basin geology are key factors for species location (see Duarte and Kalff 1990: Toivonen and Huttunen 1995). At the plant level (<10 m), species associations and patchy distribution are influenced by local *substratum* features, competitive interactions or differential use of resources (Chambers and Prepas 1990, Anderson and Kalff 1986, Barat-Segretain 1996). At the water body level (10 m-100 m), controlling factors can be numerous and complex. Interaction between abiotic factors and plants, interspecific competition and species succession can influence their distribution (Spence 1982).

Abiotic factors controlling the distribution of submerged macrophyte species have been identified in the abundant literature available on the topic. These studies are generally based on the isolation of one habitat variable monitored during the growth season that is later linked to local species and biomass variations. The main factors identified are depth, bottom slope, currents, waves, light penetration and sediment characteristics.

Water level fluctuations have a significant influence on the temporal and spatial variability of local abiotic factors (Crowder and Painter 1991, Howard-Williams *et al.* 1995, Geis 1985). Plant distribution and biomass in the St. Lawrence vary with water level fluctuations (Marie-Victorin 1943, Hudon 1997). Strong currents inhibit plant growth since turbulence can damage leaves, uproot the plant and prevent the stabilisation of buds, while slower currents influence sedimentation and chemical exchange. Currents tend to reduce biomass and plant species diversity, notwithstanding sediment type (Chambers *et al.* 1991). Waves have a direct influence on the occurrence of macrophytes through the mechanical stress on plants, seeds and buds (Keddy 1982, Chambers 1987). They are also an important factor in sediment dynamics (Hakanson 1977, Keddy 1982, Petticrew and Kalff 1992). Conversely, macrophytes can absorb the orbital motion of waves (Kobayashi *et al.* 1993, Camfield 1977).

Macrophytes slow down currents. This effect is a function of the friction surface of the plants and it favours the deposition of nutrient rich fine particles (Petticrew and Kalff 1992, Chambers and Prepas 1994, Wilson and Keddy 1985). This fact directly increases water transparency, thus favouring light penetration, a determining factor of habitat quality and productivity (Dale 1986, Spence 1982, Wetzel 1975). The quantity and colour of light reaching the bottom also affect plant biomass (Duarte and Kalff 1990, Chambers and Kalff 1985; 1987).

For most of the macrophytes species, the substrate is important in two ways: 1) a geochemical aspect, being the main source of nutrients, and 2) a physical aspect in terms of the required texture and stability for the penetration and anchoring of roots. Roots do not penetrate well into cohesive clays and, obviously, not at all into bedrock. Steep slopes do not favour rooting since they are generally unstable (Hakanson 1977, Duarte and Kalff 1986) and plants are also less likely to colonise eroded zones (Madsen and Adams 1989). Nutrient availability is a determining factor for total biomass (Anderson and Kalff 1986) and sediments are by far the main source of nutrients for most species (Barko and Smart 1980, Carignan and Kalff 1980). Since nutrients are associated with the deposition of fine particles, their concentration is linked to their exposure to waves and currents (Chambers and Prepas 1990). The accumulation of fine particles influences the potential of nutrient supply and the *substratum* texture (Barko and James 1998).

Modelling the spatial distribution

Considerable knowledge has been reported in the literature on the identification of factors that

control the spatial distribution of submerged plants. However, uses of these factors for predictive spatial modelling of submerged macrophytes at the lake or river reach scale are rare. In wetlands and forest studies, several authors have produced models of plant growth and productivity (see Costanza and Sklar 1985, Mitsch *et al.* 1988, Bossel 1991). Associated with a GIS (Geographic Information System), these models take into account various terrain parameters and different processes such as nutrient recycling, seed propagation and free groundwater levels. The extensive use of these models in terrestrial environments is limited by the effort needed to collect massive data on terrain characteristics. In its study of submerged macrophytes, Lehmann (1998) has used the spatial approach developed by Hakanson (1977) combined with a GIS for mapping basic environmental variables in Lake Léman (Switzerland). Bathymetric description, substrate type, calculation of the effective fetch, rough estimation of currents and water pollution were combined with non-parametric statistic models in order to map submerged plants. Results were interesting for some species, but the insufficiently precise description of environmental variables lead to low predictive power.

Two-dimensional (2D) habitat modelling uses numerical models to produce continuous fields of habitat values over a given water body. The 2D microhabitat modelling has been almost exclusively applied to salmonid species (e.g.: Bovee 1996, Leclerc *et al.* 1995, Stalnaker 1994). Used in small rivers, this type of model exploits three variables: simulated currents, simulated depth and measured *substratum* characteristic grain size. The habitat suitability index (HSI) generally used, had mitigated success in prediction accuracy (Scott and Shrivell 1987, Bourgeois *et al*, 1996). Recently Guay *et al.* (2000), successfully used a probabilistic index (HPI) based on a multivariate logistic regression to predict fish habitat preferences.

Probabilistic methods can be applied to habitat modelling of submerged macrophytes in combination with a GIS for spatial analyses and numerical models for the calculation of habitat variables. If plant presence/absence data are available, this task can be accomplished by applying multivariate logistic regression analyses, which allows for the determination of significant variables, as well as the statistical adjustment of the equation parameters. As described in the literature, the main controlling factors for macrophytes distribution are depth, waves, currents, *substratum* properties and light penetration. All of these variables can either be measured and/or simulated with 2D numerical models that are readily available and that attain a sufficient level of

precision. The main difficulties are associated with 1) the choice of proper variables which are structuring plant habitat, in order to obtain a manageable number of variables and 2) with a proper discretisation (precision of calculation mesh) of the water body in order to take into account significant field particularities.

Relevant abiotic factors within the study area

Spatial heterogeneity of abiotic factors in a given water body brings about habitat diversity. On this scale, relevant abiotic factors can be mapped, allowing for the definition of local habitat conditions. As macrophyte species are adapted to perform better in some of these habitats, the spatial distribution of macrophytes can be predicted with the proper characterisation of their "suitable" habitat. Significant abiotic factors for a given water body can be defined within the local environmental context.

Lake Saint-François is the first natural enlargement of the St. Lawrence River, downstream of the Great Lakes (Figure 1). This fluvial lake is 62 km long and 7 km wide (254 km^2), with a mean depth of 5.7 m. The topography is rather complex with numerous underwater channels and shoals. Apart from zones exceeding 6 to 8 m in depth, the bottom is covered with submerged macrophytes during the summer. Water levels in this river reach are narrowly regulated by dams located upstream and downstream, to an annual fluctuation of less than 10 cm in the eastern portion (Morin and Leclerc 1998). Lake Saint-François has a mean discharge of 7 500 $m^3 s^{-1}$. The flow is relatively stable, compared to other large rivers, with a minimum and maximum daily interannual mean of 7000 and 9000 $m^3 s^{-1}$ respectively (1960-1998). Tributaries have a small impact on the global hydrology with a total mean interannual discharge of about 150 $m^3 s^{-1}$. The main water mass, coming from Lake Ontario, is considered homogeneous. These waters show a green colour, high transparency and have low concentrations of suspended matter varying from 1 to 8 mg l^{-1}(Hudon 2000, Rondeau 1993, Kaiser *et al.* 1990, Verrette 1990). As with other studies (Sand-Jensen 1998, Chambers and Prepas 1990), Lake Saint-François sediments show a near-linear relationship between concentrations of fine particles and organic matter/nutrients (Lorrain *et al.* 1993). Dominating winds are from NW, W and SW during every season with a strong eastern (E, W, NW, and SW) component during spring.

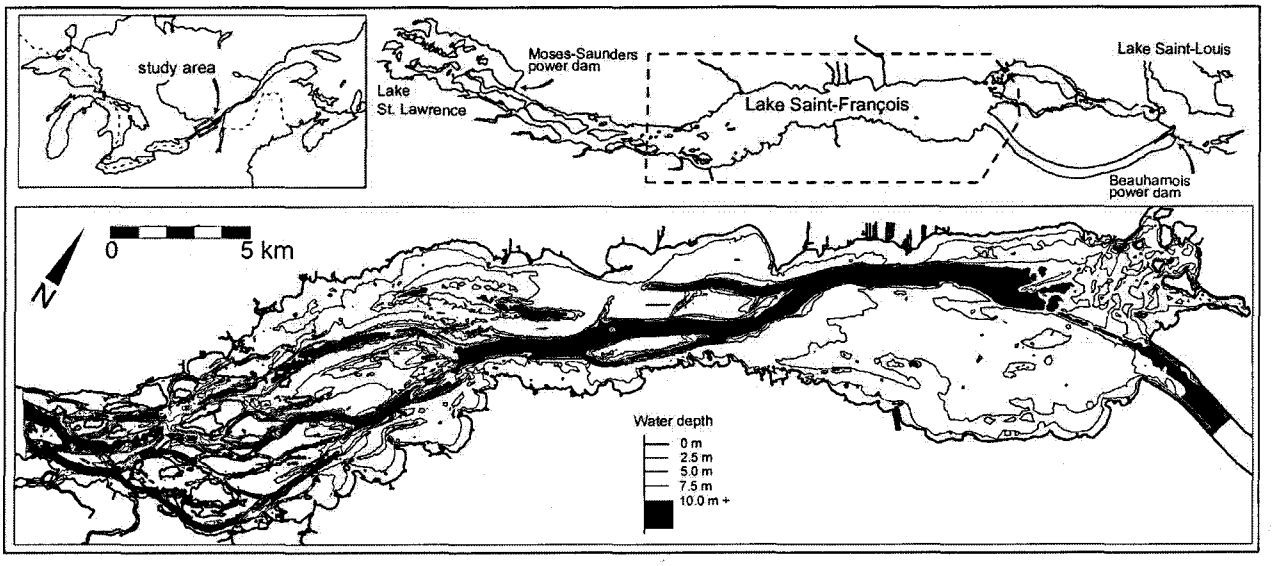


Figure 1 : Location map of the study area and bathymetry of Lake Saint-François, showing underwater channels and shoal locations.

The environmental conditions of Lake Saint-François permit the reduction of the number of possible controlling variables to a reduced set. Because of almost constant water level and stable discharge over a one-year period, we put forward the hypothesis that the number of hydrological reference conditions necessary to describe habitat can be reduced to a single representative scenario of 7500 m^3/s. Therefore, hydrodynamics (currents), water depth, light penetration and accumulated fine sediments can be reduced to this single event. This also decreases significantly the number of simulations necessary to express the interaction of waves with the riverbed. Spring and fall wind conditions have to be described in terms of dominant intensities and directions for only one hydrodynamic event. All of these variables can be simulated with numerical models, while bottom slopes, partly the depth which also depends on the water level and *substratum,* can be produced directly from the Numerical Terrain Model (NTM).

Objectives

The main objectives of this research are to 1) model the spatial distribution of species using the synoptic spatial distribution of abiotic factors for describing plant habitat and, in doing so, 2) improve the understanding of the controlling abiotic factors of dominant species in Lake Saint-François. Herein, multivariate logistic regressions are used to analyse a Habitat Data Base (HDB) that comprises a) a biological data set describing plant presence from field observations combined with the corresponding b) data on abiotic factors obtained from detailed numerical simulations. The methodological goal is to explore the potential of numerical methods for

approximating natural processes with the perspective of predicting the spatial distribution of aquatic macrophytes, but not to obtain perfect simulations in the modelling of abiotic factors.

Material and method

Habitat Data Base (HDB) and its modelling

The HDB comprises two sets of data, one biological, synthesising the species occurrences at sampling stations, and one abiotic, representing the values of abiotic factors at the corresponding locations. The abiotic factors are either derived directly from measurements (bottom slopes and *substratum*) or calculated with numerical models from detailed topographic information and selected parameterisation.

The method follows this sequence: 1) collection of biological data, 2) assemblage of the field terrain model (topography and *substratum*), 3) simulations with a 2D numerical model of selected abiotic factors with relevant parameterisation (wind, discharge, water level and suspended load), 4) assemblage of the HDB and 5) analysis of the HDB with multivariate logistic regression.

Management of georeferenced data is done with MODELEUR (Secretan and Leclerc 1998), GIS-like software, which uses finite elements as discretisation and interpolation methods. Various mesh types: triangular, rectangular or linear, can be built and used for modelling and data support. Each layer of data carried on any type of grid can be interpolated (projected) on any other grid, a feature that makes it possible to easily explore algebraic relationships between layers of information. In the present study, visualisation of results and most of the simulations are made using a Triangular Irregular Network (TIN) composed of 55 997 elements (114 562 nodes) which is herein called Global TIN (Figure 2). The Global TIN was developed to reach the needed precision for abiotic factor simulations at a spatial scale similar to that of the collected biological data. It is built with T3 elements (triangles with 3 nodes) of an average size of 40 m, that vary from 6 m to 100 m, depending on the local topographic complexity.

The logistic equations are adjusted with the HDB, which contains 698 sampling stations with species presence/absence and are validated with a separated data set of 108 sampling points. For each species, the logistic equations are used as predictive models for macrophytes mapping over the entire domain on the Global TIN.

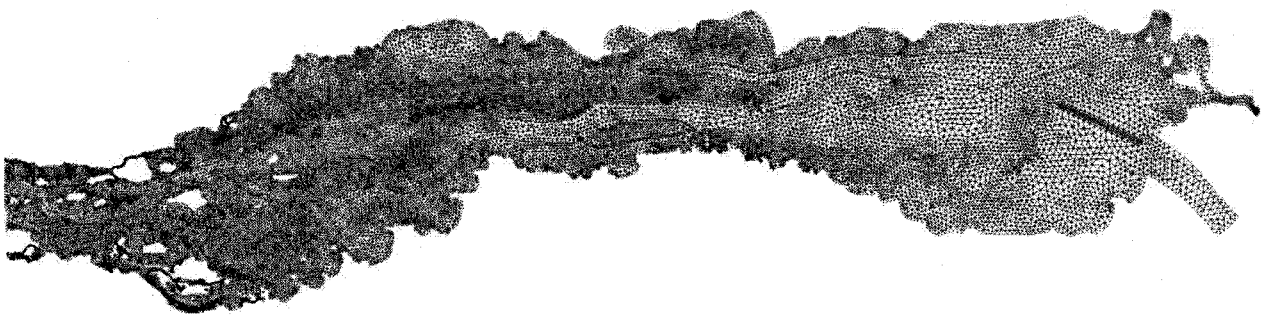


Figure 2: Finite element mesh used for simulations and data support (Global TIN) composed of 55 997 irregular triangular elements and 114 562 nodes.

Biological data collection

Data on species presence were collected in 1995 during a plant mapping survey (Morin *et al.* 1999). From September 24 to October 3, 35 transects were covered in the central and eastern portions of Lake Saint-François. Transects were observed with a Raytheon paper echosounder using a 200 kHz transducer at a 9° angle of penetration and a submersible video camera (Cosmicar HX 3.7 mm). Positions, recorded at every second, were measured with real-time differential GPS (dGPS) for horizontal precision of less than 2 m. Every 100 m along the transects, positions were marked on the echosounder chart and the plants were identified. The echosounder was used to assess the presence of submerged plants, while the submersible video camera was used to identify plant species. Observations on the plant beds with the camera lasted 1 to 5 minutes and covered 10 to 20 m in distance, thus avoiding problems associated with patchy distribution of some species assemblages. Video observations were validated with direct sampling and field samples were identified by Normand Dignard (Herbier Marie-Victorin, Québec City). A total of 806 points were characterised from video and echosounder observations of plant presence/absence and used to build the biological portion of the HDB (Figure 3). Macrophytes were observed in 576 of these locations.

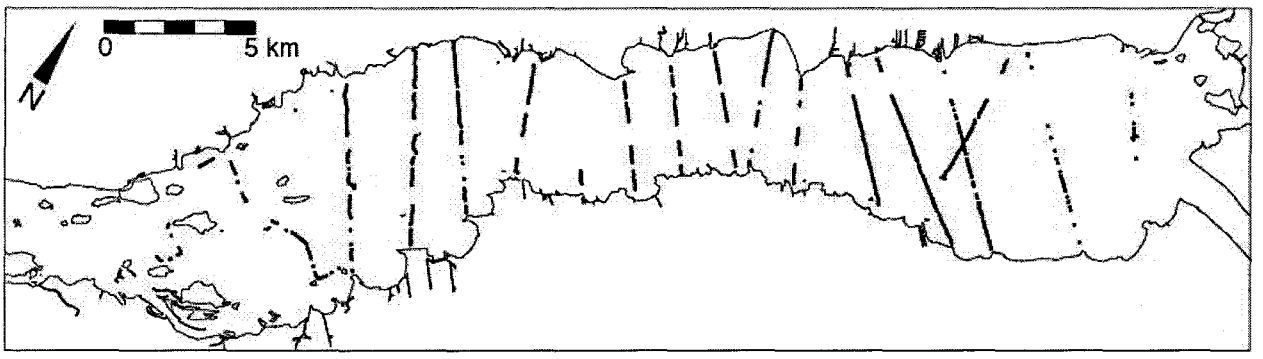


Figure 3: Location of biological sampling sites in Lake Saint-François.

Species assemblages were essentially composed of nine species *Vallisneria americana* (VA), *Myriophyllum spicatum* (MS), *Potamogeton richardsonii* (PR), *Potamogeton pectinatus* (PP) (PP), *Ceratophyllum demersum* (CD), *Elodea canadensis* (EC), *Heteranthera dubia* (HD), *Nitella sp.* (NI) and *Alisma gramineum* (AG). *Myriophyllum spicatum* was present in two growth forms, which are erect (MS) and canopy-producer (MSA), the erect-form did not reach the surface while the canopy-producers reached the surface and formed a cover. *Potamogeton pectinatus* was also present in two growth forms, lying-form (PP) (bent-down on the bottom) and erect (PPA).

Observed macrophyte assemblages were dominated by four species: VA, PR, NI and MS, which were present in 394, 207, 162 and 147 sampling stations respectively. More accessory species were present in less than 50 stations: CD (43), PP (37), EC (32), HD (30) and AG (25). Higher density growth forms like MSA and PPA were present in 13 and 7 stations respectively. Other species like *Lemna trisulca*, *Chara sp*, and *Potamogeton crispus* were observed in less than five locations.

Abiotic factors

Controlling factors and intensity are reduced to a relatively small group: bottom slope, *substratum* type, water depth, current velocity, wave action, fine particle accumulation and light availability on the bottom. These variables have to be known at sampling stations for the HDB assemblage, and on the entire domain (Global TIN) in order to be able to use logistic regression equations in a predictive mode. Abiotic variables produced herein represent spring and fall conditions and they are simulated as if there was a complete absence of submerged macrophytes. Therefore, they represent the environmental conditions for periods before and after the growing

season, which are the initial habitat characteristics, not those modified by plants during summer.

Numerical Terrain Model (NTM)

The NTM contains topographical information and substrate description. Topography is based mainly on soundings from the CHS (Canadian Hydrographic Survey). A total of 292 270 soundings, with a precision of ±0.15 m, were assembled and integrated in the digital elevation model with IGLD85 as the vertical *datum* (Morin *et al.* 1999). These measures have a mean density of about 1 point every 30 m. Topography is the key variable of the whole modelling system, since it is used to estimate and/or simulate all abiotic variables. The density of the soundings determines the precision limit of the entire data model.

Substrate mapping proceeded from data collected during several field surveys. The *substratum* map used here is based on 16 000 qualitative observations from the CHS, 234 grain size distribution data, and about 300 field observations made during plant species characterisation. These data were manually interpolated to form a continuous map of substrate classes over the entire lake. Its precision is a function of the local sampling density. In the HDB, the numerical terrain model is directly exploited with two variables: slope and substrate mean grain size.

Hydrodynamics

Currents and water levels were calculated with a 2D hydrodynamic model (horizontal). The HYDROSIM model (Heniche *et al.* 1999) uses a discretisation of the shallow water equations solved by the finite elements method. The model uses the conservative form of the quantity of movement from the Saint-Venant equations and takes into account the local friction caused by substrates. Vertically integrated, the model produces reliable predictions of the mean velocity of the water column, water level, and specific discharge for a wide range of hydrological conditions. The element used is a 6 node triangle called T6L (Triangle with 6 nodes and an internal linear interpolation scheme) where specific flows are evaluated on each node while levels are calculated at the summit nodes. T3 elements of the Global TIN were transformed into T6 elements for the hydrodynamic modelling.

The hydrodynamics have been simulated with the inter-annual average discharge (module) of 7500 $m^3 s^{-1}$ on the modified Global TIN which is very close to the mean discharge of 7247 $m^3 s^{-1}$ measured during spring 1995 (April and May). This simulation has been validated prior to its inclusion into the HDB with water levels and velocity measurements (Morin *et al* 2000). This

simulation provides the water levels required to calculate water depth; it also provides values of diffusion potential and shear stress for the transport-diffusion model (see below Sedimentation). For the HDB, the mean flow velocity (vertically integrated) was selected as the variable representing the influence of currents.

Waves

The HISWA model has been designed to model the growth and transformation of wind waves in the shallow water environment (Holthuijsen *et al.* 1989, Booij *et al.* 1993). It simulates in 2D (horizontal), wave propagation in shallow water including refraction and shoaling, growth due to wind action and dissipation by bottom friction and breaking. This model calculates various parameters such as wave energy, frequency, height and direction on a regular square grid.

In the present study, waves were calculated on a regular square grid with 277 302 elements of 50 m sides, covering the entire lake. Apart from wind intensities and directions, input parameters for simulation includes topography, water level and current data, supported by the regular grid. The orbital near-bottom velocities generated by waves appear to be the best index of stress on plants. This variable is generally used in sedimentation models to assess the grain stability on the bottom (Van Rijn 1989, Signell *et al.* 2000).

The effect of waves has been integrated into the HDB by making use of six variables. These represent the whole range of wind directions and intensity conditions during spring and fall. Hourly wind data with height compass divisions, measured at Cornwall from 1990 to 1995 were obtained from the Canadian Meteorological Service. Seasonal wind intensities were divided into three groups: moderate (10-24 km/h), strong (25-44 km/h) and extreme (45-55 km/h). Slow winds (0-9 km/h) were not considered because their effects on habitat are less important. Table 1 shows the observed frequency of wind intensities and directions for six variables. Near-bottom orbital velocities induced by waves were calculated for the 26 conditions listed. They were integrated in six variables with the ratio of the observed frequency from Table 1 and used for the HDB.

Table 1: Observed hourly frequency for wind directions and intensities in the Lake Saint-François area used to parameterise the wave model, where representative intensities: 17 km/h, 35 km/h and 45 km/h correspond to moderate (10-24 km/h), strong (25-44 km/h) and extreme intensities (45-55 km/h), respectively.

Season	Intensity	Direction					Ratio for integration in the HDB				
		SW	W	NW	N	E	SW	W	NW	N	E
Spring	17 km/h	13%	18%	7%	6%	15%	0.22	0.31	0.12	0.10	0.25
Spring	35 km/h	1.6%	1.5%	3.0%	0.7%	2.2%	0.18	0.17	0.33	0.08	0.24
Spring	45 km/h	0.1%	0.1%	0.3%	-	0.3%	0.13	0.13	0.38	-	0.38
Fall	17 km/h	14%	13%	15%	5%	12%	0.24	0.22	0.25	0.08	0.20
Fall	35 km/h	2.5%	4.0%	6.2%	-	0.9%	0.18	0.29	0.46	-	0.07
Fall	45 km/h	0.1%	0.1%	0.2%	-	-	0.25	0.25	0.50	-	-

Sedimentation of fine particles

Dispersion and accumulation patterns of suspended matter are simulated once hydrodynamic data are available. DISPERSIM is a 2D (horizontal) eulerian transport-diffusion model that is solved with a finite element formulation (Secretan *et al.* 2000). Among other water quality processes, it makes it possible to simulate transportation, concentration and possible deposition of suspended matter on the bottom. Sedimentation simulation is a function of the ratio of a selected threshold related to the critical shear stress of the grain size and the local shear-stress. Calculation is done using a triangular element of three nodes (T3) where residual concentrations and local deposition velocity are evaluated. Basic information for DISPERSIM includes water depth, flow diffusivity, velocity and shear stresses produced with hydrodynamic and wave models. For waves, the local maximum value of the near-bottom velocity is selected among the results obtained using wind directions and intensities presented in Table 1.

The threshold for fine particle sedimentation was fixed at 0.3 Pa for current induced shear-stress, which corresponds to the theoretical stability limit of medium sized sand grains (0.6 mm) (Van Rijn 1989). For wave induced near-bottom velocity, the threshold was established at 0.24 m/s, which corresponds to medium sized grain stability (0.6 mm) with waves with a period of about 3 sec (Komar and Miller 1975). This value is slightly higher than the 0.15 m/s used by Signell *et al.* (2000) as a value for resuspension of fine mud. The calculation is made on the Global TIN considering a steady state (non-transient) regime, with the hydrodynamic simulation presented

earlier (7500 $m^3 s^{-1}$). The suspended load is injected at the upstream boundary of the Global TIN. The upstream concentration is imposed to a value of 5 mg l^{-1}; it is similar to measured local values, and the maximum settling velocity is parameterised at 0.05 mm/s. This settling velocity is similar to the typical suspended load in river estuaries (Van Rijn 1989) and it corresponds to a particle with an equivalent diameter of 10 μm (Droppo and Ongley 1991, Teisson 1991, Ongley *et al.* 1981).

For the HDB, the variable used represents the local accumulation on the bottom of the materials injected upstream and transported as suspended load over the entire domain. It is obtained by multiplying the local concentrations and deposition velocities as calculated with DISPERSIM.

Light intensity on the bottom

As described earlier, DISPERSIM can be used to calculate the local concentration of suspended matter. The same simulation used for estimating the accumulation of fine particles on the bottom is used for describing the spatial distribution of suspended load concentrations. Considering that there is only one water mass in Lake Saint-François, the ratio of incidental light reaching the bottom is a function of depth and of the local concentration of suspended matter. It is calculated with the following function:

[1] $$I_z = I_0 e^{-KZ}$$

where I_0 is the intensity of light at the surface, K is the local extinction coefficient and Z is the depth. In the Great Lakes water body near Montreal, Hudon and Sylvestre (1998) have shown that the extinction coefficient is a function of both suspended matter and dissolved organic carbon (DOC). As the DOC concentration in Lake Saint-François is small, about 2.2 mg l^{-1} according to Cossa *et al.* (1998), and because spatial fluctuations of the DOC is not known, the local extinction coefficient of light is calculated with the local concentration of suspended matter only.

The extinction coefficient was considered to vary linearly with the concentration of suspended matter. It was roughly calibrated with Secchi depth (S), measured in Lake Saint-François at four locations (S=6.0 to 10.6 m), and with a simple relation between K and S: $K=1.46/S$. According to this relation, values of K for these four locations would vary from 0.13 to 0.24 m^{-1}. This relation represents a slightly smaller value for K (0.28 and 0.33 m^{-1}), measured in near shore

areas of Lake Saint-François and reported by Hudon and Lalonde (1999). The variable used in the HDB is the calculated ratio of incidental light reaching the bottom, considering a value of 1 for the incidental light (I_0).

Multivariate logistic model

In order to test the capability of the simulated and measured variables to predict plant presence or absence, a Habitat Probability Index (HPI) was developed for each species, using multivariate Gaussian logistic regression analyses, with backward stepwise selection. It can be represented as

[2] $$HPI = 1/(1+e^{-\lambda})$$

where $\lambda = P_0 + (P_1 V_1 + P_2 V_1^2) + (P_3 V_2 + P_4 V_2^2) + \ldots + (P_{2n-1} V_n + P_{2n} V_n^2)$

where V_n are independent habitat variables and P_{2n} are parameters fitted by the multivariate Gaussian logistic regressions. Logistic models are usually used to describe relationships in presence/absence data instead of linear models because they use values between 0 and 1 (ter Braak and Looman 1995). The curve is adjusted with the observations of one independent variable (V_n) and describes a sigmoid shape. It implies that the probability of plant presence increases or decreases with an abiotic factor. The distribution of the Gaussian component of the model, that results from a squared independent variable (V_n^2), is similar to a bell-shaped curve, but with a flatter top (ter Braak and Looman 1995). It describes a probability of presence that is maximum at medium values of the abiotic variable, and decreases or increases towards both extremes of the distribution.

Table 2: Threshold probability for predicted absence and presence used in the logistic regression models, calculated from the ratio of the observed presence and the total observations (N=698) in the calibration data set.

Species (Total N=698)	Presence (N)	Ratio
VA (*Vallisneria americana*	338	0.48
PR (*Potamogeton richardsonii*)	179	0.26
NI (*Nitella* sp.)	142	0.20
MS (*Myriophyllum Spicatum*)	131	0.19
CD (*Ceratophyllum demersum*)	40	0.06
PP (*Potamogeton pectinatus*)	32	0.05
EC (*Elodea canadensis*)	31	0.04
HD (*Heteranthera dubia*)	29	0.04

Logistic models were adjusted using the Non-linear Regressions and VGLZ modules included in the statistical software STATISTICA (StatSoft 2000). It enables validation of the adjusted equation parameters by selecting a number of observations of the original database. Backward stepwise selection permitted the exclusion of variables having non-significant ($p>0.05$) contribution to the total variability in presence-absence observations, thus reducing over-explanation and multi-colinearity. Results are expressed in terms of probability of presence (PoP) of a given plant species, and vary between 0 and 1. An observed presence is considered to be correctly predicted by the statistical model if its PoP is higher than a certain probability threshold, while lower values predict an absence (Legendre and Legendre 1998).

Only the species with more than 30 individual plants present were analysed: VA, PR, NI, MS, CD, PP, EC and HD. From the complete set of 806 plant observations, 108 were randomly selected for validation (validation data), and the remaining samples (calibration data) were employed for parameter adjustment. The threshold of PoP corresponds to the ratio of the observed presence over the total observations (Hosmer and Lemeshow 1989), which differs from one species to an other (Table 2). The logistic regression models are based on a total of 12 variables (Table 3) which correspond to recognised controlling factors in fluvial and lacustrine environments, as pointed out in the introduction. Once the parameters are adjusted, model accuracy can be estimated with the number of cases correctly classified in the validation data set.

Table 3: Synthetic description of the 12 abiotic factors that were used to build the HDB.

Abiotic Factors	Spatially distributed variables	Range of values within the HDB	Mean values
1 Slope	Slope of the lake bottom	0 to 0.26	0.02
2 Substrate	Mean grain size (ϕ : log of mean grain size)	-0.156 to –6.20 ϕ	-3.62 ϕ
3 Depth	Water depth at a discharge of 7500 m^3/s	0.8 to 23.4 m	6.29 m
4 Currents	Velocity, discharge of 7500 m^3/s, no plant friction	0.02 to 0.75 m/s	0.24 m/s
5 Light penetration	Ratio of incidental light reaching the bottom	0.027 to 0.964	0.45
6 Fine particle accumulation	Fine particle deposition on the bottom	0 to 0.0170 g/m^2	0.036 g/m^2
7 Waves_spring_17	Wave generated near-bottom velocity, spring 17 km/h winds	0 to 0.50 m/s	0.10 m/s
8 Waves_spring_35	Wave generated near-bottom velocity, spring 35 km/h winds	0 to 0.74 m/s	0.26 m/s
9 Waves_spring_45	Wave generated near-bottom velocity, spring 45 km/h winds	0 to 0.94 m/s	0.32 m/s
10 Waves_fall_17	Wave generated near-bottom velocity, fall 17 km/h winds	0 to 0.49 m/s	0.10 m/s
11 Waves_fall_35	Wave generated near-bottom velocity, fall 35 km/h winds	0 to 0.76 m/s	0.25 m/s
12 Waves_fall_45	Wave generated near-bottom velocity, fall 45 km/h winds	0 to 0.89 m/s	0.32 m/s

Results

General adjustment

All regression models are highly significant, as indicated by the low values of the ratio "deviance/degrees of freedom" (Table 4) and also by the correct global prediction. The global prediction of presence and absence for all species has a total of 5477 correct predictions out of 6448 (806 for eight species) observations, for a global score of 84.9%. For all species, the number of cases correctly predicted by the calibration data set is very high, varying from 77.1% to 89.0% for absences and from 86.5% to 95.0% for presences. Validation data are also well predicted for species that had more than 147 presences. For VA, MS, NI and PR, presences are correctly predicted in 75.0% to 95.0% of cases, and absences were correctly predicted for 78.8% to 88.6% of cases. The total correct predictions vary from 82 to 85% for these species. For the species with a small number of presences (≤5): PP, CD, EC and HD, absences are predicted correctly in 76.6% to 91.4% cases, while the small number of presences led to peculiar results in correct presence predictions of either 40.0% or 100%. These less abundant species can be divided into two groups, one with a high score of 88.0% to 92.1% that comprises CD and PP, and the other with a lower score of 80.9% to 81.4% composed of HD and EC.

Significant abiotic factors

The parameters of the resulting polynomial equations obtained with the Gaussian logistic regression are presented in Table 4, they are significant at $p<0.05$. The most common variables retained in the backward stepwise selection are Light penetration, Depth and Waves_fall_45km/h, being significant in seven out of eight species. Waves_fall_35km/h and Waves_spring_35km/h are significant for six species. All of the other variables are significant for three to five species, with the exception of Substrate, which is significant with only one species. Analysed globally, wave action appears significant for all species, with variations in intensities and seasons.

The intercept was highly significant ($p<0.00001$) for VA, MS, PR, PP and CD, but with lower significance for EC ($p=0.0027$) and not significantly different from zero for HD ($p=0.0591$) and for NI ($p=0.145$). Most of the variables selected by the stepwise method are highly significant ($p<0.001$). In terms of species, VA, MS, PR, CD contain either no, or only small number of,

variables with moderately significant levels (p>0.001). The adjusted models for NI, PP, HD and EC have many low significance variables with significance levels higher than 0.001, especially HD for which only three parameters out of 13 have a p-value lower than 0.001.

Species/variable relations

Significant variables are represented by one or two parameters, which makes up a portion of the global polynomial equation (Equation 2). Some general tendencies in the links between species and single abiotic factors can be pointed out. It appears that most species, with the exception of VA and PR, have a probability of presence that decreases with an increase in Water depth and Light penetration. Greater accumulation of fine particles tends to increase the PoP for most species. Regardless of the intensities, wave action during spring tends to decrease the PoP for most species, except for VA and NI that have the opposite tendency. Generally, waves during fall at 17 and 35 km/h tend to favour the PoP for most species. Again VA and NI behave in a different way since their PoP decreases with the increase of wave induced near-bottom velocity.

Plant predictive mapping

Logistic models can be used as predictors since the information on abiotic variables is available for the entire domain. For each species, the polynomial equation (Equation 2) has been parameterised with values presented in Table 4 and the calculation was performed on each node of the Global TIN. As these variables are georeferenced, the result is a spatial scalar field of probability that can be visualised with a colour scale. Figure 4 represents the spatial distribution of each species for the areas where the probability of presence is higher than the thresholds presented in Table 2. The spatial distribution of PoP in Figure 4 can be visually evaluated with the location of all presence observations for each species. Species with a relatively large number of presences in samples (n>147), such as VA, PR, NI and MS show larger surface areas of high probability when compared to species with less observed presences (n<43), like CD, EC, PP and HD. EC and HD can be pointed out as having the most important surface area of low PoP (<0.23) within the latter group.

Table 4: Parameters of polynomial equations as produced by the logistic regression on 12 basic variables for the height species considered. Percentage of data correctly predicted for calibration, validation and total correctly predicted ratio are also presented. Values between [] correspond to statistical significance (p) of the independent variable and 2 refers to the squared variables. Deviance/D.f. is the overall Goodness-of-fit of the model.

Variables/species		Vallisneria *americana* (VA)	*Potamogeton richardsonii* (PR)	*Nitella* sp. (NI)	*Myriophyllum spicatum* (MS)	*Ceratophyllum demersum* (CD)	*Potamogeton pectinatus* (PP)	*Elodea canadensis* (EC)	*Heteranthera dubia* (HD)
Intercept		-41.477 [0.00000]	-39.763 [0.00000]	10.685 [0.14541]	60.170 [0.00000]	50.124 [0.00001]	-34.779 [0.00000]	18.611 [0.00270]	-6.627 [0.05909]
Substrate		-	-	-	-	-	1.139 [0.00588]	-	-
Substrate 2		-	-	-	-	-	-	-	-
Depth		4.817 [0.00000]	9.626 [0.00000]	-	-8.307 [0.00000]	-	-	-	-0.747 [0.03166]
Depth 2		-0.265 [0.00004]	-0.880 [0.00000]	-0.127 [0.00036]	0.234 [0.00137]	-0.450 [0.00000]	-	-0.244 [0.00003]	-
Light penetration		38.968 [0.00000]	22.915 [0.00000]	-68.362 [0.00017]	-65.988 [0.00000]	-91.529 [0.00000]	71.708 [0.00036]	-43.211 [0.00001]	-
Light penetration 2		-	-	51.125 [0.00016]	-	-	-86.207 [0.00019]	-	-
Slope		-49.326 [0.00034]	-164.181 [0.00000]	-	-	-	-	-42.262 [0.03084]	-118.079 [0.02206]
Slope 2		219.879 [0.01224]	638.187 [0.00002]	-	-	-	-	-	500.494 [0.04533]
Fine sediment accumulation		18.758 [0.00255]	-	-	83.666 [0.00002]	-	-	-	126.352 [0.00064]
Fine sediment accumulation 2		-	-	181.528 [0.00093]	-333.177 [0.03269]	-	-	137.458 [0.02835]	-686.657 [0.01641]
Currents		-	-	60.976 [0.00008]	-24.063 [0.00001]	-	86.158 [0.00003]	-	-
Currents 2		-	-	-123.433 [0.00013]	40.063 [0.00000]	-123.660 [0.00002]	-107.708 [0.00036]	-	19.072 [0.00821]
Waves spring 17 km/h		-	-	-	-32.886 [0.00094]	-	135.512 [0.00664]	-	-214.304 [0.00089]
Waves spring 17 km/h 2		273.913 [0.00004]	-	-	-	-	-423.879 [0.01440]	-	131.205 [0.03774]
Waves spring 35 km/h		26.354 [0.00010]	-	72.293 [0.00626]	97.708 [0.00000]	-	-53.344 [0.00682]	117.519 [0.00064]	121.384 [0.00180]
Waves spring 35 km/h 2		-	-	-95.297 [0.00816]	-107.606 [0.00006]	-	-	-274.877 [0.00005]	-114.503 [0.00830]
Waves spring 45 km/h		37.883 [0.00000]	-	95.487 [0.00402]	-	-	-	-	-
Waves spring 45 km/h 2		-	-	-117.645 [0.00210]	-28.001 [0.01470]	-	-	-87.301 [0.00033]	-
Waves fall 17 km/h		-	-	-93.863 [0.00000]	-	-	-	-	153.853 [0.00264]
Waves fall 17 km/h 2		-294.408 [0.00001]	-	212.406 [0.00000]	-	-	-	-	-
Waves fall 35 km/h		-	34.880 [0.00004]	-	-	-	-190.775 [0.01554]	-59.081 [0.01232]	-
Waves fall 35 km/h 2		-36.999 [0.00037]	-	-	126.319 [0.00000]	-	391.228 [0.00377]	297.518 [0.00001]	46.723 [0.03855]
Waves fall 45 km/h		-33.948 [0.00219]	-	-105.913 [0.02328]	-47.625 [0.00002]	87.924 [0.00188]	198.929 [0.00275]	-	-56.958 [0.00038]
Waves fall 45 km/h 2		-	-36.601 [0.00009]	137.810 [0.01126]	-	-217.155 [0.00021]	-271.498 [0.00202]	-	-
Deviance (Deviance/D.f.)		0.639 (437/685)	0.545 (376/690)	0.545 (372/683)	0.532 (364/684)	0.141 (97/692)	0.187 (128/685)	0.227 (156/688)	0.237 (162/684)
Calibration	Presence	91.1% (308/338)	89.9% (161/179)	86.6% (123/142)	87.8% (115/131)	95.0% (38/40)	90.6% (29/32)	90.3% (28/31)	93.1% (27/29)
	Absence	81.4% (293/360)	80.0% (415/519)	80.0% (445/556)	77.1% (437/567)	89.0% (586/658)	85.6% (570/666)	78.3% (522/667)	78.2% (523/669)
Validation	Presence	87.5% (49/56)	89.3% (25/28)	95.0% (19/20)	75.0% (12/16)	100% (3/3)	40.0% (2/5)	100% (1/1)	100% (1/1)
	Absence	80.8% (42/52)	78.8% (63/80)	88.6% (78/88)	81.5% (75/92)	91.4% (96/105)	90.3% (93/103)	82.2% (88/107)	76.6% (82/107)
Total	Presence	90.6% (357/394)	89.9% (186/207)	87.7% (142/162)	87.1% (128/147)	97.7% (42/43)	83.8% (31/37)	90.6% (29/32)	93.3% (28/30)
	Absence	81.3% (335/412)	83.1% (498/599)	84.0% (541/644)	80.6% (531/659)	91.7% (700/763)	88.2% (678/769)	81.0% (627/774)	80.4% (624/776)
	Total (806)	85.9%	81.8%	84.7%	84.9%	92.1%	88.0%	81.4%	80.9%

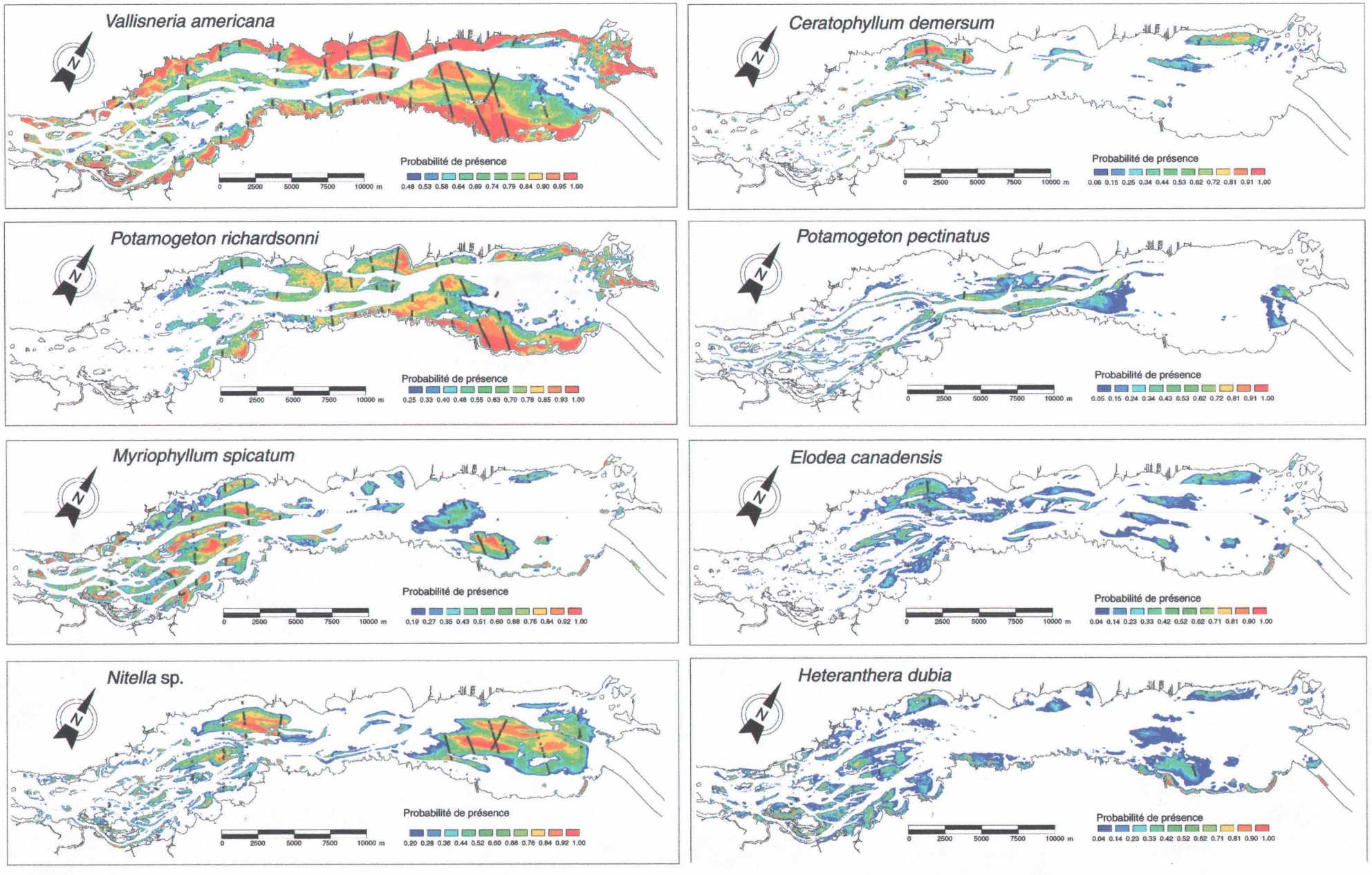


Figure 4: Predicted values of probability of presence (PoP) as calculated with the logistic regression models, parameterised withvalues presented in Table 4 and threshold values of Table 2 for all species considered. Black crosses correspond to observed presence of the species.

Discussion

Overview of model accuracy

The overall results of the regression models appear to properly represent the spatial distribution of submerged species at the scale of Lake Saint-François. The global correct prediction of presence and absence reaches a score of 84.9%. Models of dominant species (VA, PR, NI and MS) have a total score of correct predictions that varies between 81.8% and 84.9%. Models of less abundant species are grouped into a high score (>88.0%: CD, PP) and a low score (<81.4%: EC, HD). Apart from this success in correct predictions of presence/absence, the relative quality ranking for the different species models can be analysed using several characteristics: sample size used, score of correct predictions of presence and absence, statistical significance of intercepts and independent variables, and observations of the projected results.

Dominant species models, especially VA, PR and MS, appear to be the most reliable given the important number of presences in the calibration data set, the large statistical significance of intercepts and of selected abiotic factors, and the important surface area with high probability of presence (PoP). This suggests that the habitats of these species are properly described by the selected abiotic factors. NI models have similar characteristics but have low significance on intercept ($p=0.145$) and on most wave variables, suggesting singularities in its habitat. Less abundant species in the lake are already divided into two groups of high (CD, PP) and low scores (EC, HD). In the high score group, CD and PP models appear to explain a large portion of the variability. Their selected variables and intercepts have relatively high statistical significance suggesting that the habitats of these species are simpler to describe than the habitats of dominant species and of the low score group. Therefore, even if the sampling size is small, models of this high score group appear reasonably convincing. The low score group has lower statistical significance on intercept and on selected variables. When mapped on the entire domain, EC and HD models have a generally low PoP, suggesting that these species do not have a well-defined habitat in Lake Saint-François. It appears that EC and HD models are the least accurate in the present context and should be used with more caution.

Interpretation of habitat models

The VA model shows a PoP that increases with water depth and light intensity on the bottom.

All wave intensities during spring and fall are significant. Important light penetration and wave action were effectively reported as characteristic of VA habitat (Catling *et al.* 1994, Marie-Victorin 1964). Seasonal impact of wave action on VA is singular with an inverse effect compared to most of the remaining species. The PoP of VA decreases with the increase of wave action during fall, and increases during spring. This can be interpreted as a relatively positive impact on VA during spring, in regards to other species, and a relatively negative impact on VA during fall (senescence). It is possibly associated with the direct effect of wave action on propagules or other perennial structures. As VA is the most abundant species in the lake, changes in wind direction would certainly influence its spatial distribution.

The PoP of MS decreases with an increase in depth, light intensity on the bottom and currents, and increases with a higher amount of accumulated fine particles. These observations tend to confirm those of Aitken *et al* (1979) which indicated the ability of MS to reach light near the surface. The PoP of PR increases with water depth, light intensity on the bottom, wave action during fall (35 km/h) and with low values of bottom slope. NI has a PoP decreasing with water depth and light intensity but increasing with fine particle accumulation and currents. Even if p-values for waves are generally less significant, NI is influenced by waves in a similar manner as VA. The large p-value ($p=0.145$) of the intercept suggests that NI has a wide range of habitat. NI has no roots (algae), it is easily moved by currents and accumulated in lower energy areas (Round 1981). In Lake Saint-François, this species was found intertwined between stems, protected by the presence of other species and was also found forming pure dense mats in relatively deep areas of small basins.

The PoP of PP is favoured by high light intensities on the bottom and by strong currents. Waves have a complex impact that depends on season and intensity. In Lake Saint-François, PP habitat is mostly located close to the main channels, where currents are strong and sediment is coarse. Wilson (1941) and Van Wijk (1988) observed similar habitat for this species. As suggested by its regression model, CD is essentially associated with weak current areas, where light intensity reaching the bottom is relatively low. This plant species has no roots; it can be removed by currents and waves (Marie-Victorin 1964). In Lake Saint-François, CD was found mostly in protected areas within small basins.

HD and EC have fairly complex habitat models that are to be used with caution. During

fieldwork, EC and HD were never found in pure assemblages; they were secondary species, associated with different species assemblages, present in various physical contexts. Also, their logistic models have large areas of low PoP when mapped and they have large p-values in their intercept and in their variables. Because sampling can be considered as representative (every 100 m), although sampling bias cannot be totally ruled out, it suggests that the habitat of these species is not fully developed in Lake Saint-François. HD and EC are abundant in other parts of the river where the same water body is present. Downstream from Montreal, HD and EC were associated with areas recently exposed during a low water level period (Côté *et al.* 2000). This suggests that Lake Saint-François, because of its water level stability, does not offer ideal habitat conditions for these plant species.

Possible model improvements

The present habitat models are mainly based on simulated abiotic factors that can be improved in several ways. The calculation mesh used contains 55 997 elements, their number can still be increased in order to locally improve the spatial accuracy of the HDB. Greater precision can also be reached by increasing the number of events representing various habitat conditions, for example, by adding simulated reference events representing seasonal variations in currents, fine particle accumulation and light penetration. As the light extinction coefficient and the sedimentation of fine particles are based on the properties of only one sedimentation velocity, a larger *spectrum* of particle density and size can be taken into account.

In the present research, only the main water mass coming out of the Great Lakes has been simulated, but local tributaries or sewer plumes can eventually be considered for spatial changes in dissolved and suspended load characteristics. Simulated wind conditions were parameterised with averaged conditions over five years. Better results may be obtained with more detailed intensities and with wind data of seasons really observed before field measurements. As several species, like MS, NI, PP, CD and HD are influenced by current conditions that are typical of spring and fall, it is probable that the occurrence of ice during winter, which considerably modifies flow pattern, will influence the accumulation of fine particles. These conditions might have an effect on plant distribution and should eventually be considered.

Impact of plants on their habitat

As described earlier, submerged macrophytes have an important impact on abiotic factors during the growth season by modifying currents, waves, light and sediments. As shown in the results of the present study, about 85% of the variability of submerged species distribution are explained by abiotic factors representing habitat conditions during spring and fall. The low residuals leave little room for plant influence (during summer) on their own spatial distribution, at least at the scale of the water body. This is does not take into account the possible improvements that could be incorporated into the HDB, or those that could arise from more accurate parameterisation and incorporation of impacts from winter conditions.

Several authors have shown (i.e.: Spence 1982, Chambers *et al.* 1991, Petticrew and Kalff 1992) links between the biomass of submerged macrophytes and abiotic conditions prevailing during growth seasons. Even if the species distribution appears to be mainly controlled during periods preceding the growth season itself, abiotic factors are significantly modified by plants during the growth period in such a way as it would be appropriate to address spatial distribution of plant biomass with summer abiotic factors. However, integration of plant effects on abiotic factor simulation is a procedure that needs further development, since interactions with suspended load, wave action and currents are relatively complex.

Further development

The present research shows an important control of abiotic factors on spatial distribution of submerged macrophyte species and points out significant influence from seasonal wind conditions. Numerical modelling of abiotic factors combined and supported with GIS appears to be a relevant approach for describing and understanding spatial heterogeneity of aquatic systems. It also confirms the importance of abiotic factors identified in the literature, adapted to the particular environmental context of Lake Saint-François. The main advantage of this approach is that the relevant variables are simulated, allowing prediction on the entire domain and reducing field measurements of these variables to validation purposes only.

This work on spatial modelling of macrophytes should be seen as exploratory, being in an early stage of development. The application of these models to other systems is to be tested; problems are anticipated with fine particle accumulation and water mass characteristics because they have site specific characteristics and water level fluctuations because they are absent from the present

study area. Also, species not present in Lake Saint-François, including exotic ones, can have important impacts on the spatial distribution of the already present species. These impacts cannot be taken into account with the present regression models. In order to address this problem, developments are needed for quantifying functional links between significant abiotic factors and plant species, implying research inputs from several fields of study. Knowledge and quantification of processes between plants and their habitat may bring new methods for modelling spatial heterogeneity.

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