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RÉGIONALISATION DES CONCENTRATIONS EXTRÊMES DE SÉDIMENTS EN SUSPENSION DANS LES RIVIÈRES D'AMÉRIQUE DU NORD

Thèse présentée pour l'obtention du grade de
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Résumé

Les fortes concentrations de sédiments en suspension réduisent la qualité de l'eau et peuvent dégrader les habitats aquatiques. Des réseaux de mesure en rivière existent, mais peu de stations enregistrent quotidiennement les données de concentrations de sédiments en suspension (CSS). Ainsi, les événements extrêmes sont difficiles à prévoir pour de nombreux cours d'eau ne disposant pas de données. L'objectif de cette thèse est d'adapter aux concentrations extrêmes en sédiments en suspension pour les cours d'eau d'Amérique du Nord (Canada et USA) le concept de la régionalisation. La régionalisation en hydrologie consiste à transférer de l'information des sites jaugés vers les sites non jaugés afin d'estimer les valeurs des extrêmes hydrologiques. Ainsi, elle est couramment utilisée pour les débits de crue ou d'étiage.

Les données de CSS quotidiennes pour 179 stations au Canada et aux États-Unis constituent la base de ce travail, en utilisant également les débits et diverses caractéristiques physiographiques et météorologiques des bassins versants de ces stations. Dans cette thèse quatre objectifs spécifiques sont abordés. Le premier consiste en une modélisation probabiliste des événements extrêmes de CSS par l'analyse fréquentielle locale, permettant de caractériser l'amplitude et la fréquence de ces événements. Le second, porte sur l'étude des événements extrêmes de CSS, afin d'analyser les cycles saisonniers d'occurrence des événements de forte concentrations, mais aussi les corrélations avec les débits et avec les propriétés physiographiques et climatiques des bassins versants. Le troisième objectif est d'utiliser des approches de régionalisation couramment utilisées pour les débits afin d'estimer les concentrations de CSS extrêmes pour des sites non jaugés. L'évaluation de la qualité

d’estimation des approches testées se faisant par ré-échantillonnage avec les données disponibles. Des approches utilisant soit les caractéristiques physiographies soit des critères saisonniers pour délimiter des groupes de stations « homogènes » sont comparées. Enfin le quatrième et dernier objectif porte sur le développement d’une nouvelle approche de régionalisation afin de pallier aux limitations des approches existantes, pour l’estimation des CSS extrêmes. L’approche non paramétrique des arbres de régressions est ici utilisée à cette fin.

Parmi les conclusions les plus importantes de cette thèse, il à été montré qu’une approche régionale aboutit à une meilleure estimation des événements extrêmes qu’un seul modèle global incluant tous les sites. La grande spécificité locale des événements extrêmes de CSS à été mise en évidence d’une part par la variabilité d’un site à l’autre des distributions statistiques retenues pour modéliser les CSS extrêmes, et d’autre part par l’importance des caractéristiques physiques du voisinage immédiat des stations de mesure dans la modélisation des événement extrêmes. Il a été aussi montré que les débits seuls ne permettent pas d’expliquer les concentrations extrêmes observées dans la majorité des stations. Les caractéristiques physiographiques et climatiques des sites de mesure sont plus efficaces pour prédire les concentrations extrêmes. Il s’avère également que les lois Exponentielles et Log-Normales sont, pour la plupart des stations, les plus adaptées pour modéliser les maximums annuels de CSS. L’échantillonnage par maximums annuels et par dépassement de seuil (ici le 99i$^{\text{éme}}$ percentile à été utilisé) donne des résultats très similaires, mis à part pour les courtes périodes de retour où l’échantillonnage par dépassement de seuil semble plus performant.

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CHAPITRE 1 : Introduction

Les sédiments sont une composante naturelle des écosystèmes aquatiques. Cependant en trop grande quantité ils posent des problèmes, pour la vie aquatique ainsi que pour les infrastructures humaines. Le transport en suspension représente environ 70% de tous les sédiments transportés par les cours d'eau (Knighton 1998). On considère que des concentrations supérieures à 200 mg/L sont nocives pour de nombreuses populations de poissons (Waters 1995). Les cours d'eau peuvent transporter des concentrations importantes de solides en suspension pendant les crues. Ces fortes concentrations peuvent être associées avec le transport d'une grande quantité de polluants tels que métaux lourds ou pesticides (Müller *et al.* 1999, Meybeck *et al.* 2003, Walling 2005). Les sédiments en suspension représentent le principal vecteur de transport de polluants dans les systèmes hydriques. En effet, les sédiments des rivières sont considérés par l'agence de protection de l'environnement américaine (USEPA) comme le principal polluant des cours d'eau (USEPA, 2002). Pour ces raisons les concentrations ou les charges de sédiments en suspension sont mesurées depuis des décennies. Cependant, le nombre de stations mesurant en continu des données a fortement baissé depuis la fin des années 1980 dans les réseaux de stations nord-américaines.

Le transport de sédiments dans les cours d'eau est un phénomène complexe qui varie beaucoup dans l'espace, d'une région ou d'un bassin à un autre, et dans le temps, selon les saisons et les années. Dans la plupart des cours d'eau, le transport de sédiments n'est pas continu au cours du temps. On estime que la quantité totale de sédiments charriés en une année par un cours d'eau est transportée sur 10% ou moins des jours de l'année (Meade *et al.*, 1990). Cet intervalle de temps est encore moindre à mesure que le cours d'eau est petit, et qu'il se situe dans une zone aride. Pour qu'il y ait transport de sédiments, il faut à la fois que des sédiments soient disponibles et que l'agent de transport soit présent. Ainsi il est fortement lié aux débits les plus élevés, mais le débit seul ne permet pas toujours de prédire efficacement les quantités transportées (Knighton 1998, Dodds et Whiles, 2004). Les recherches menées sur les transports de sédiments ont surtout porté sur l'estimation des bilans sédimentaires des bassins, les quantités totales ou charges transportées pendant des périodes allant de l'année au mois. Le lien entre concentration et débit par le biais d'une relation log-linéaire a beaucoup été utilisée, mais d'autres nouvelles approches de modélisation ont été développées, prenant en compte un nombre plus important de facteurs autres que les débits, tels que les types de sols, l'occupation des terres, ou la topographie (Hrissanthou 2005, De Vente et Poesen 2005).

Il existe peu d'études sur les extrêmes de concentrations de sédiments en suspension (CSS) dans les cours d'eau et aucune à notre connaissance portant sur l'estimation de ces extrêmes sur des bassins non jaugés. Si quelques chercheurs ont déjà considéré l'utilisation de l'analyse fréquentielle pour modéliser les événements extrêmes de CSS (Watts *et al.*, 2003, Galéa *et al.*, 2004, Soler *et al.*, 2007), les seules applications de régionalisation pour le transport de sédiments ont jusqu'alors porté sur l'estimation des charges annuelles (Feraresi, 1990, Bray *et al.*, 1993). Nous proposons d'adapter certaines approches de régionalisation développées pour les débits de crue aux concentrations extrêmes de sédiments en suspension et de proposer une nouvelle approche. Le principe de base de l'approche de régionalisation en hydrologie est d'ajouter à l'information locale limitée d'un bassin cible une information spatiale provenant de bassins ayant un régime hydrologique similaire (Ouarda *et al.* 1999). On peut ainsi d'une part estimer des paramètres pour des bassins non jaugés (par exemple des quantiles de débit) mais aussi compléter l'information qui peut être disponible de manière partielle pour les stations jaugées (des courtes séries chronologiques). L'intérêt de transposer ces méthodes est qu'elles ont fait l'objet d'avancées méthodologiques importantes au cours des 20 dernières années (GREHYS 1996a). Nous utiliserons une base de données sur les basins versants incluant des variables autres que celles couramment utilisées pour la régionalisation des débits, incorporant notamment des données sur les sols, la couverture végétale, l'occupation des terres des indices climatiques et la topographie. Notre hypothèse de base est que l'analyse fréquentielle régionale permet une estimation des concentrations extrêmes de sédiments en suspension dans un site non jaugé en utilisant les propriétés des sites de mesure.

Les objectifs principaux de cette thèse sont :

1. Modéliser les concentrations extrêmes de sédiments en suspension observée dans les cours d'eau Nord-Américains grâce à l'analyse fréquentielle, qui permet de caractériser la fréquence d'occurrence et l'amplitude de ces événements extrêmes. Les deux types d'échantillonnages couramment employés pour mener des analyses fréquentielles que sont les maximums annuels et les dépassements d'un seuil seront comparés pour les CSS extrêmes.

2. Contribuer à la connaissance sur les événements de CSS extrêmes en rivière, d'une part, en utilisant une base de données physiographique exhaustive sur les bassins versants nord-américains ainsi que sur le voisinage immédiat des sites de mesure, pour déterminer les facteurs qui influencent le plus les concentrations extrêmes, et d'autre part, contribuer à améliorer la connaissance du cycle d'occurrence des événements extrêmes de CSS et leur relation avec les débits.

3. Tester des approches de régionalisation afin de procéder à l'estimation des CSS extrêmes. Au vu de la littérature scientifique sur la régionalisation des débits, on sélectionnera des approches éprouvées pour évaluer le potentiel d'estimation de telles méthodes pour des CSS extrêmes en des sites non jaugés.

4. Proposer une nouvelle méthode de régionalisation appliquée au CSS extrêmes, visant à contourner les éventuelles limites liées à certaines approches de régionalisation couramment utilisées. Parmi les approches non paramétriques existantes, qui permettent de se libérer d'un certain nombre de contraintes par rapport aux approches paramétriques, on proposera l'utilisation de la technique des arbres de régression, ainsi que ses modalités d'application dans un contexte de régionalisation.

La thèse est organisée de la manière suivante. Dans le chapitre 2, une première partie consiste en une revue de littérature qui présentera le transport de sédiments en suspension et l'impact des fortes concentrations sur l'environnement aquatique. Dans une seconde partie sont présentées des approches de modélisation du transport de sédiment ainsi que les principes et applications de la régionalisation en hydrologie. Le chapitre 3 est un résumé des travaux de recherches contenus dans quatre articles (en langue anglaise) qui constituent le cœur de cette thèse. Pour chacun de ces articles, les objectifs spécifiques, la méthodologie utilisée et les principaux résultats seront présentés avec des références fréquentes aux articles, qui constituent les chapitres 4, 5 6 et 7 de cette thèse. L'auteur principal des articles a réalisé toutes les analyses et conclusions, les co-auteurs agissant à titre de conseillers pour les développements méthodologiques et de correcteurs. Au chapitre 8 la conclusion permet de résumer les principaux résultats obtenus et proposer de nouvelles pistes de recherches.

CHAPITRE 2 : Revue de Littérature

2.1 Le transport des sédiments en suspension et l'impact des fortes concentrations sur l'environnement aquatique

Les eaux courantes sont le principal vecteur de transport des produits de l'érosion à la surface des continents en milieu tempéré (Coque, 1998). Les berges et le lit du cours d'eau sont également sujets à l'érosion par la force de cisaillement de l'eau courante, mais aussi par des mouvements de masse de plus ou moins grande envergure. Certains auteurs estiment que l'érosion du lit et des berges produit 50% des sédiments transportés (Knighton, 1998). Ces sédiments peuvent être transportés sous différentes formes ; on en distingue trois catégories (Bravard et Petit, 1997) :

- Transport en solution : éléments de taille microscopique dissous dans l'eau
- Transport en suspension : éléments transportés avec l'écoulement, de taille généralement comprise entre 0,0005 mm et 0,062 mm
- La charge de fond : éléments les plus gros charriés au fond du lit du cours d'eau

On estime que le transport en suspension représente environ 70% de tous les sédiments transportés par les cours d'eau vers les océans (Knighton, 1998). Il correspond à un état d'équilibre mécanique entre les forces de gravité et les échanges turbulents de quantités de mouvement. Les particules transportées sont principalement les argiles, sables, lœss et matières organiques. Le transport en suspension est généralement composé de deux fractions, contrôlées par des processus distincts. La fraction la plus fine (<0.062 mm), composée des argiles et limons, provient du lessivage des versants (wash load) et est contrôlée par la disponibilité en sédiments fins à la surface du bassin versant. La fraction la plus grossière, composée des sables fins, émane généralement du lit et des berges, sa concentration est reliée à la capacité de transport de la crue. Dans cette thèse n'est considérée que la concentration résultante en sédiment en suspension, mesurée dans le cours d'eau sans distinction à priori de l'origine des grains qui la constitue, issus soit du bassin versant (phase directe) soit de la remise en suspension des sédiments du lit (phase indirecte).

2.1.1 Variabilité temporelle

Le transport de sédiments en suspension est un phénomène très discontinu dans le temps. La quantité de sédiments transportés dans un cours d'eau dépend de deux facteurs (Gordon *et al.*, 1999) : la quantité de sédiments disponibles sur les versants et dans le cours d'eau et l'aptitude du cours d'eau à transporter ces sédiments. Une fois que les sédiments se trouvent dans le cours d'eau, tous ne sont pas transportés immédiatement vers son exutoire. La charge peut se déposer, quand l'énergie de la rivière n'est plus suffisante pour les déplacer, puis être remise en mouvement lors des crues. On estime que les océans ne récupèrent que le quart des sédiments produits par l'érosion (Knighton, 1998). Les processus de transport sont donc fonction de la combinaison des conditions hydrodynamiques et des caractéristiques des éléments disponibles. Cette combinaison est instable, susceptible de se modifier d'un moment à l'autre et d'un point à l'autre, du fait de la variation des facteurs (Coque, 1998). On observe ainsi une variabilité temporelle du transport en suspension à différentes échelles, journalière, saisonnière et interannuelle.

La variabilité temporelle du transport solide est liée à la variabilité temporelle des débits. Ce lien entre concentrations et débits a beaucoup été étudié, surtout dans le but de prévoir les concentrations à partir des débits (Muller *et al.*, 1999, Cherifi *et al.*, 1999, Seeger *et al.*, 2004, Zonta *et al.*, 2005). C'est durant les crues que le transport est le plus important, surtout pour les plus grandes d'entre elles. Les forces nécessaires au transport atteignent leur maximum avec l'accroissement du débit et de la vitesse. Une rivière peut ainsi transporter en quelques jours ou en quelques heures plus d'alluvions que pendant tout le reste de l'année et mobiliser des matériaux très grossiers qu'elle ne saurait mobiliser autrement (Coque 1998). Meybeck *et al.* (1999, 2003) ont observé que la variabilité temporelle est souvent fonction de la taille des bassins; plus la taille des bassins est importante plus les variations sont faibles. Cette variabilité est poussée à l'extrême dans les zones arides, voire désertiques. Les cours d'eau sont le plus souvent intermittents et les rares précipitations entraînent une forte érosion et des concentrations très élevées de sédiments (Coppus *et al.*, 2002, Bond *et al.*, 2004, Griffith *et al.*, 2006). Les premières crues qui se présentent après une période de sécheresse peuvent engendrer des concentrations importantes, même si leur débit de pointe est moins important que celui des crues suivantes (Bravard et Petit, 1997, Cherifi, 1999).

On observe souvent que la concentration en sédiments est plus élevée lors de la montée de la crue que lors de la décrue. Sur un graphique montrant l'évolution chronologique de la concentration en fonction des débits, on observe fréquemment un comportement horlogique, appelé hystérèse (Bravard et Petit, 1997). Ce phénomène d'hystérèse implique donc que la concentration à débit égal va être différente dans le temps, à la montée et à la descente de la crue. Différent types de boucle d'hystérèse ont étés mis en évidence par Wood (1977) ou Asselmann (2000). Il existe aussi des variantes saisonnière à la relation concentration / débit. Dans les régions tempérées océaniques la charge en suspension est plus importante en été qu'en hiver. Les pluies d'été sont généralement plus intenses et plus agressives. Par ailleurs en hiver le manteau neigeux ou le gel du sol peuvent limiter le ruissellement de surface et retenir les sédiments (Bravard et Petit, 1997). Cependant les pratiques agricoles peuvent modifier ce schéma, par exemple si les sols sont laissés à nus en hiver mais protégés par les cultures en été.

Enfin, de nombreux travaux ont mis en évidence des tendances au long terme à la diminution des quantités de sédiments transportés par les cours d'eau. Walling et Fang (2003) ont ainsi mis en évidence sur 145 cours d'eau à travers le monde, que plus de la moitié voyaient leur charge solide diminuer au fil des ans. Benedetti (2002, 2003) a également observé cette diminution dans le nord du bassin du Mississipi. Dans la plupart des cas, cette baisse peut être attribuée à l'adoption de mesures limitant les pertes de sols des terres utilisées par l'agriculture ou la construction de barrages (Walling, 2006).

2.1.2 Variabilité spatiale

De nombreux travaux ont porté sur les facteurs contrôlant la production de sédiments fins selon les types de sols et l'occupation des terres (Walling, 1999, Higgit et Lu, 1999, Rondeau *et al.*, 2000, Asselman *et al.*, 2003, Kasai *et al.*, 2005, Ahearn *et al.*, 2005, Restropo *et al.*, 2006). Il en ressort que c'est l'association complexe du climat, du type de sol et de la structure géologique ainsi que la couverture végétale qui va déterminer le type d'érosion que l'on va rencontrer dans une région et la quantité de sédiments disponibles. Il s'avère que les facteurs déterminants varient d'une région à l'autre, mais de manière générale, quelque soit le climat, la couverture végétale est un facteur limitant l'érosion.

Certaines régions sont plus ou moins riches en sédiments, on retrouvera des concentrations en rivière plus élevées dans les milieux arides (Coppus *et al.*, 2002, Bond *et al.*, 2004, Griffith *et al.*, 2005). Doods et Whiles (2004) ont ainsi mis en évidence un gradient croissant d'est en ouest des concentrations moyennes mesurées dans les rivières américaines, depuis les provinces maritimes du Canada jusqu'aux montagnes Rocheuses. Au Canada et dans le nord des États-Unis, les cours d'eau sont englacés pendant les mois d'hiver. Les grandes quantités d'eau soudainement libérées au printemps combinées à l'effet de la glace ont un fort pouvoir érosif (Morse et Hicks, 2005).

Au niveau des bassins versants, même dans une région présentant les mêmes conditions de climat, de sols et de végétation, on peut observer une grande variété de formes et de processus de surface. Ainsi même des bassins proches géographiquement peuvent avoir une morphologie et des bilans sédimentaires très différents. Dans le cas des bassins de grande superficie, ils peuvent être composés de milieux différents avec des concentrations variant de l'amont vers l'aval (Lu, 2005). Enfin, au niveau du cours d'eau le transport n'est pas uniforme le long de la section mouillée. Le champ de vitesse et la forme du chenal vont déterminer des zones d'écoulement et de transport de sédiments plus ou moins rapide, ainsi que des zones où au contraire les sédiments vont s'accumuler (Knighton, 1998).

Certains auteurs estiment que jusqu'à 80% des sédiments pourrait être produits de manière directe ou indirecte par les activités humaines (Owens *et al.*, 2005). L'urbanisation provoque une perturbation de l'érosion des sols, notamment en imperméabilisant le substrat et donc en augmentant le ruissellement de surface (Dodds et Whiles, 2004). Les pratiques d'exploitation forestière ont aussi des répercussions sur l'érosion. Le déboisement intensif d'une région et la construction de routes peut accroître le ruissellement naturel des eaux et accélérer l'érosion du sol. Ces activités entraînent un accroissement des charges de sédiments dans les cours d'eau environnants, comme cela été montré dans plusieurs études (Ashmore *et al.*, 2000, Piegay *et al.*, 2004, De boer *et al.*, 2005). Ce sont surtout les activités agricoles qui ont le plus fort impact sur la production de sédiments (Gordon *et al.*, Owen *et al.*, 2005). Les sols cultivés sont beaucoup plus érosifs que ceux d'une forêt ou d'une prairie. Les pratiques agricoles peuvent aggraver l'érosion, en éliminant la végétation naturelle qui retient le sol en la remplaçant par des plantes cultivées qui laissent davantage le sol à nu, ou en modifiant la structure du sol de façon à réduire sa capacité d'absorber l'eau et le rendre plus vulnérable à l'érosion. De nombreuses recherches ont été menées afin de mieux comprendre et quantifier l'érosion par les pratiques agricoles (Sogon *et al.*, 1999, Russel *et al.*, 2001, Gruszowski *et al.*, 2003). Ces travaux ont souvent été menés dans des zones de grandes cultures agricoles intensives d'Europe de l'ouest ou des plaines nord-américaines (Mabit *et al.*, 1999, Walling, 2005) dans le but d'essayer de lutter contre cette perte des sols qui nuit à la productivité des terres cultivées.

2.1.3 Méthodes et réseaux de mesure

Le transport de sédiments par les cours d'eau est difficile à mesurer de part sa grande variabilité à la fois dans l'espace et dans le temps (Gordon *et al.*, 1999). Des mesures prises à différents endroits d'une même rivière peuvent donner des concentrations en sédiments différentes (Gao, 2008). Dans les plus petits cours d'eau, les concentrations peuvent aussi fluctuer de manière relativement importante au cours de la journée. Pour les matières en solution et en suspension on utilise des mesures de concentration, soit une masse de solides rapportée à un volume d'eau (généralement exprimée en milligrammes par litre). La méthode de mesure la plus simple est de prélever des échantillons d'eau en différents endroits du cours d'eau puis après évaporation on pèse le résidu solide. Il existe deux protocoles de mesure : les SSC (« suspended sediment concentration ») et TSS (« total suspended solids »). On retrouve souvent les deux termes de manière interchangeable dans la littérature. Dans les deux cas, il s'agit de la mesure du poids du résidu sec d'un volume d'eau connu, mais avec des protocoles expérimentaux différents. Les SSC et TSS peuvent avoir des valeurs différentes, surtout si les sédiments sont grossiers (en présence de sables). Les TSS semblent sous-estimer les fortes valeurs, ils sont plus adaptés pour les réservoirs tandis que les SSC sont plus adaptées pour mesurer les concentrations en milieu naturel (Gray et Glysson, 2000).

Un comité inter-agences américain à été crée en 1939, dans le but de proposer une uniformisation des méthodes et protocoles de mesures (Edward et Glysson, 1999). Il a donné naissance en 1946 au Subcommittee on Sedimentation of the Federal Inter-Agency River Basin Committee, qui établit de manière uniforme pour les États-Unis les méthodes de sélection des sites, les protocoles de mesure et les équipements d'échantillonnage. Les mêmes standards ont étés employés pour développer le réseau canadien (Day, 1992). Pour une description détaillée des méthodes et protocoles de mesure employés on peut consulter le manuel de techniques de l'United States Geological Survey (USGS) d'Edward et Glysson (1999). La méthode du prélèvement est traditionnellement utilisée, du moins dans les débuts des programmes de mesures (Gray et Glysson, 2002). C'est aussi la méthode la plus onéreuse en termes de ressources car elle nécessite des visites quotidiennes sur les sites de mesure. Cette méthode est de plus remplacée par des méthodes optiques : on va chercher à mesurer le degré de turbidité de l'eau et ainsi évaluer indirectement la teneur en solides en suspension. Cette mesure de turbidité peut être faite grâce à un néphélomètre (« optical back-scatter » OBS) qui va mesurer la réfraction d'un rayon lumineux dans l'eau et ainsi évaluer sa turbidité. Les principales limitations de ce protocole de mesure sont sa sensibilité différentielle en fonction de la granulométrie des sédiments en suspension et les mesures peuvent être aussi affectées par la couleur de l'eau (Gao, 2008). Ces dispositifs permettent de réduire les coûts car ils peuvent être déployés de manière semi-autonomes (Day, 1992, Ongley, 1992). De nombreuses techniques ne nécessitant pas d'intervention ont été développées, mais du fait de leurs limitations, les protocoles de mesures emploient différentes méthodes de manière concomitante (Gray et Glysson, 2002).

La première station de mesure en continu des concentrations de solides en suspension a été installée en 1889 sur le Rio Grande par l'USGS (Osterkamp, 1991). Le réseau américain en 2003 comptait 1593 stations dont 15% avec 10 années ou plus de données quotidiennes. Le programme de mesure canadien des sédiments en suspension a été développé sur le modèle des États-Unis avec le même type d'équipement et de méthodes (Day, 1991). Il a commencé en Saskatchewan en 1948. Le réseau a compté 850 stations environ, dont 250 sont encore actives (Day, 1992). Il subsiste de grandes régions pour lesquelles on dispose de peu de données, en particulier dans les zones nordiques et au Québec. Les réseaux de mesure se sont fortement développés à partir de 1945, de nombreuses stations ont été implantées. À partir des années 1960 les réseaux ont été modernisés et le nombre de stations a diminué fortement (Osterkamp, 1991, Ongley, 1992, Day, 1992). Dans le but de diminuer les coûts d'exploitation, des politiques de rationalisation ont vu le jour au Canada et aux États-Unis. Les programmes basés sur des enregistrements quotidiens, pendant plusieurs dizaines d'années, ont laissé la place à des mesures suivant différentes méthodes, plus espacées dans le temps, en utilisant les relations avec les débits pour consolider l'information. Les longs enregistrements disponibles initialement ont en effet permis d'étudier le phénomène de transport plus en détail, et ainsi de développer des procédés de mesure plus efficaces. Day (1988) a réalisé une étude sur les longues séries de concentration du programme canadien. Il conclut qu'au bout de 10 ans les caractéristiques moyennes sont bien définies. Peu d'information supplémentaire est apportée pour un nombre d'années plus grand. Il souligne que les très longues séries peuvent poser un problème pour les études sur les sédiments, car les caractéristiques des bassins sont susceptibles de changer au cours du temps, surtout dans les zones fortement anthropisées.

2.1.4 Impacts environnementaux liés aux fortes concentrations et normes en vigueur

Les sédiments transportés par les rivières ont des impacts sur l'environnement et les activités humaines, c'est pour cette raison qu'ils sont mesurés dans les cours d'eau (Day, 1988, Osterkamp, 1991, Ongley, 1992). Les dommages physiques, chimiques et biologiques causés par les sédiments en Amérique du nord sont estimés à 16 Milliards de dollars annuellement (Gray et Glysson, 2002). Outre les problèmes posés par les fortes concentrations de sédiments en suspension pour les infrastructures d'approvisionnement en eau potable ou industrielle, les impacts majeurs concernent la qualité de l'eau et les habitats aquatiques.

Les sédiments transportés par les rivières sont l'un des principaux vecteurs du transport de polluants surtout dans les régions les plus urbanisées. Les substances chimiques toxiques peuvent se fixer aux particules de sédiments puis transportées et déposées dans un autre milieu. Cet aspect a fait l'objet de nombreuses études pour quantifier et prévoir le phénomène. Le fleuve Saint Laurent au Québec (Ashmore *et al.*, 2000, De Boer *et al.*, 2005) et la Seine en France (Meybeck *et al.*, 1999) drainent des territoires fortement urbanisés et transportent de grandes quantités de polluants, avec une tendance à la hausse. Müller et Wesseld (1999), Zonta *et al.* (2005) ont analysé le lien direct qui existe entre les crues, les quantités de sédiments et de polluants transportés pour des cours d'eau en Allemagne et en Italie. Les fortes crues, comme celle de la rivière Odra en 1997, entraînent une dispersion importante de métaux lourds et d'autres polluants transportés par les sédiments, atteignant jusqu'à 1/3 des quantités annuelles mesurées. Panin *et al.* (2001) ont montré le rôle de l'érosion et des sédiments en suspension dans la dissémination des particules radioactive libérées par l'explosion de la centrale nucléaire de Chernobyl plus de 10 ans après l'accident. Les sédiments en suspension sont en mesure de transporter quatre types d'éléments (Gordon *et al.*, 1999, Meybeck, 2005) ; Les nutriments du sol (phosphore et composés azotés, tel que l'ammoniaque, qui proviennent souvent des engrais utilisés en agriculture), hydrocarbures (huile, essence et solvants), insecticides et métaux (fer, manganèse, plomb, cadmium, zinc, et mercure, aussi bien que des métalloïdes, tels que l'arsenic et le sélénium).

Les sédiments fluviaux ont plusieurs effets directs sur les habitats aquatiques, de part leurs caractéristiques et la toxicité des éléments qu'ils peuvent véhiculer. Ils peuvent compromettre certains habitats de manière importante, mais ils représentent aussi une source de nourriture pour les organismes des écosystèmes aquatiques en fixant de la matière organique (Dodds et While, 2004). La présence de sédiments en suspension réduit le taux de pénétration de la lumière dans l'eau, ce qui influence les pratiques d'alimentation et de rassemblement des poissons et peut faire baisser leur taux de survie (Newcombe et Jansen, 1991, Waters, 1995). En absorbant la chaleur du soleil les particules font accroître la température de l'eau, ceci peut avoir des répercussions possibles sur certaines espèces poïkilothermes. Les sédiments, en se déposant et en s'accumulant, peuvent enfouir et étouffer les œufs dans les frayères et diminuer la concentration d'oxygène disponible. Ils peuvent aussi déloger les plantes, les invertébrés et les insectes du lit fluvial. Cette baisse de densité des invertébrés peut avoir un effet sur les poissons qui s'en nourrissent et réduire la taille et le nombre de ces derniers. Les fortes concentrations peuvent également poser des problèmes pour l'alimentation en oxygène des poissons (Waters, 1995). Sur le ruisseau Catamaran dans le Nouveau Brunswick, St-Hilaire *et al.* (2005) ont estimé des baisses potentielles du taux de survie des alevins de saumon atlantique de 95% à 69% selon les sites, conséquemment à l'augmentation de sédiments fins liés à l'exploitation forestière. On considère que les élevages de poissons peuvent être affectés à partir d'une concentration de 80 mg/L et qu'au-delà de 200 mg/L les concentrations deviennent nocives pour plusieurs populations de poissons. Un cours d'eau avec une concentration supérieure à 400 mg/L fournit un habitat pauvre (Waters, 1995, Dodds et Whiles, 2004).

Des normes de concentration maximales existent au Canada et aux États-Unis dans le cadre du contrôle de la qualité des eaux. Au Québec, le ministère de l'environnement du développement durable et des parcs recommande la limite de 25 mg/L pour la protection de la vie aquatique (Ministère de l'environnement, 2001). Les sédiments en suspension sont considérés comme un polluant parmi d'autres : Les apports en sédiments ne doivent pas dépasser le niveau naturel de plus de 25 mg/L pendant 24 heures. Pour des apports entre 24 heures et 30 jours, la moyenne des apports ne doit pas dépasser de plus de 5 mg/L le niveau naturel. Aux États-Unis, il n'existe pas de norme pour l'ensemble du territoire. La plupart des états utilisent des normes exprimées en NTU (Nephelometric Turbidity Unit), seuls quelques états utilisent les concentrations et les normes varient entre 30 mg/L et 158 mg/L (USEPA, 2002). Depuis quelques années, dans le but d'harmoniser les politiques de qualités des eaux, l'United States Environmental Protection Agency (USEPA) a introduit le concept de TDML (« Total Maximum Daily Load ») qui représente la quantité maximale de sédiment qu'un cours d'eau peut recevoir tout en respectant les normes de qualités. L'USEPA doit approuver chaque TDML établi par les états pour les cours d'eau en fonction des connaissances scientifiques sur ces derniers (USEPA, 1999).

2.2 Modélisation et régionalisation du transport sédimentaire

Depuis des décennies des chercheurs ont tenté de modéliser le transport de sédiments en suspension. La plupart des applications concernent l'estimation des charges transportées annuellement ou encore l'estimation des valeurs moyennes du transport en suspension. Les approches classiques utilisent la relation entre les concentrations et le débit par biais de courbes de calibration ou « rating curves » mais récemment d'autres approches de modélisation ont également étés développées. Néanmoins, très peu de travaux néanmoins concernent l'estimation des valeurs extrêmes.

2.2.1 Modélisation du transport en suspension

La procédure la plus courante pour transformer des mesures de concentrations intermittentes en données continues est d'utiliser la relation qui existe entre les concentrations et les débits (Cohn, 1995). Cette relation permet à la fois d'interpoler les données existantes, et d'extrapoler pour des événements de plus grande ampleur (Fergusson, 1986, Horowitz, 2001). La relation entre le débit *Q* et la concentration de sédiments en suspension *C* est souvent exprimée de la manière suivante (« suspended-sediment rating curve ») :

$$C = a Qb$$

Où *a* et *b* sont des paramètres à ajuster.

La transformation en logarithme permet d'obtenir une relation linéaire. La principale utilisation de cette relation avec les débits est de calculer la charge sédimentaire, c'est-à-dire la quantité de sédiments transportée par un cours d'eau pendant une période donnée. La charge *L*, pendant une période *T* est obtenue en intégrant le produit du débit et de la concentration.

Dans le cadre du programme National Stream Water Quality Accounting Network (NASQAN) de surveillance de la qualité des eaux en rivière aux États-unis, des données ont été recueillies sur 40 cours d'eau à des pas de temps fins. Ces données ont permis à Horowitz *et al.* (2001) d'utiliser les relations débit / concentration pour estimer les charges annuelles de solides en suspension des cours d'eau mais aussi de polluants transportés. Holtschlag (2001) s'est basé sur des méthodes de régression avec les débits pour interpoler les concentrations journalières à partir de mesures prises à des intervalles irréguliers. Il a proposé des facteurs limitant le biais d'une telle interpolation. Le bilan de ces travaux menés sur les grands bassins américains montre que les estimations de charge sont fiables pour les longues séries de données (au moins 20 ans) et pour les bassins versants de moyenne et grande taille (Cohn, 1995, Horowitz, 2003). Cependant il existe de nombreuses critiques et incertitudes liées à l'utilisation de cette relation. Fergusson (1986) est le premier à mettre en évidence que l'estimation des charges à partir de la relation avec les débits est sous-estimée du fait de la transformation en logarithme, en particulier pour les fortes concentrations. Il propose d'ajouter des facteurs permettant de limiter le biais inhérent à cette méthode. Mais plus tard Walling et Webb (1988) ont montré à partir de données expérimentales sur des cours d'eau anglais que malgré la correction du biais via les diverses méthodes existantes, les estimations de la charge par cette méthode restent peu précises. Ils suggèrent d'incorporer une pondération des valeurs les plus élevées de concentration ainsi que d'autres facteurs explicatifs. Webb *et al.* (1997) ont utilisé des données de concentration hebdomadaires sur des cours d'eau en Angleterre et ont aussi montré que l'estimation des charges était peu fiable en utilisant uniquement la relation avec le débit, surtout pour des périodes inférieures à un an, du fait du phénomène d'hystérèse.

Du fait des problèmes liés à l'utilisation de ces courbes d'étalonnage entre concentration et débit, de nombreux modèles physiques ont été développés là encore dans le but principal d'estimer les volumes de sédiments transportés par les cours d'eau, aux pas de temps annuels ou mensuels. En plus des débits, ces modèles peuvent prendre en compte un très grand nombre de variables, sur l'occupation des sols, la pente et la topographie, les précipitations, les formes de surface, et les propriétés pédologiques du substrat. La plupart des modèles basés sur les processus physiques sont composés de trois sous-modèles : hydro-climatiques pour les précipitations et les débits, d'érosion, utilisant le plus souvent l'équation universelle de perte de sol (« Universal Soil Loss Equation », USLE) ou ses dérivées, et de transport, utilisant les propriétés hydrauliques du cours d'eau (Hrissanthou 2005). Parmi les applications récentes, on peut citer Schwartz *et al.* (2003) qui, à partir d'une base de données sur les sols, l'occupation des terres, les précipitations, le débit et l'élévation, ont développé un modèle de prédiction du flux moyen annuel de sédiment pour les sites du programme NASQAN. De tels modèles ont été développés et utilisés en Espagne par Periago et Soto (2004), en Italie par Van Rompaey *et al.* (2005) et en Grèce par Hrissanthou (2005). De Vente et Poesen (2005) ont réalisé une revue de littérature des modèles couramment utilisés et surtout des variables d'entrée de ces modèles. On peut également trouver cette information dans Osterkamp et Toy (1997), Restropo (2006).

Des avancées récentes laissent entrevoir des perspectives de modélisation et de prévision à des échelles et des pas de temps plus réduits. On peut citer les travaux de Sikumavar (2005, 2006). Sur le bassin du Mississippi, il a testé une approche déterministe multi fractale pour estimer la charge annuelle mais aussi la concentration. Il s'agit avant tout de travaux préliminaires mais il obtient des résultats très encourageants pour estimer la charge du Mississippi au niveau de Saint Louis. Le potentiel de l'approche fractale pour la modélisation a été souligné par plusieurs chercheurs au cours des dernières années (De Boer *et al.,* 2005). Kisi (2005) utilise une approche non paramétrique par réseaux de neurones pour modéliser la relation débit – concentration, et obtient des résultats plus précis qu'en utilisant les « rating curves » traditionnelles. Enfin on peut citer l'approche de Li *et al.* (2006) qui vise à estimer par co-krigeage les charges en suspension au pas de temps journalier en utilisant le débit.

2.2.2 La régionalisation en hydrologie

La régionalisation (ou analyse fréquentielle régionale) en hydrologie consiste à estimer la distribution d'une variable hydrologique pour des sites non jaugés, en utilisant l'information provenant de sites jaugés similaires. La principale application concerne les crues ou les étiages, en cherchant à modéliser l'amplitude et la fréquence d'occurrence des événements extrêmes. Le plus souvent il s'agit d'estimer le quantile de débit correspondant à la période de retour *T*, pour un bassin non jaugé en utilisant l'information régionale. Les approches de régionalisation utilisées en hydrologie comprennent en général deux étapes (Ouarda *et al.,* 1999) :

1. Définition et détermination des régions hydrologiquement homogènes, c'est-à-dire des groupes de stations qui ont un comportement hydrologique comparable.
2. Estimation régionale, le transfert à l'intérieur d'une même région de l'information des sites jaugés à un site non jaugé ou partiellement jaugé .

Historiquement, les premières approches pour constituer des régions homogènes consistaient à délimiter des régions sur la base de la proximité géographique. Les stations dont les caractéristiques étaient très différentes des stations voisines étaient éliminées, notamment à l'aide d'un test proposé par Darlymple (1960). L'approche géographique peut être justifiée si les facteurs qui expliquent le paramètre étudié présentent une forte cohérence spatiale, tels que le type de sols, l'altitude ou le climat. En revanche, pour les crues ou d'autres variables hydrologiques, ce sont souvent des facteurs qui ne présentent pas de continuité spatiale, tels que l'aire du bassin, sa forme, ou encore l'occupation des sols, qui ont le plus d'influence (Ouarda *et al.,* 1999).

D'autres approches ont par la suite étés développées, basées non pas sur un critère géographique mais sur les caractéristiques communes des bassins versants. Des régions fixes non contiguës regroupant un nombre variable de stations peuvent ainsi être délimitées. La création de ces régions peut être basée sur des caractéristiques statistiques communes, en utilisant les tests développés par Hosking et Wallis (1993) basés sur les L-Moments. Plus fréquemment, les régions sont délimitées par des méthodes de classification basées sur les caractéristiques physiographiques des bassins (Nathan et McMahon, 1990, GREHYS, 1996a) ou bien des indices décrivant la saisonnalité de la variable d'intérêt (Burn, 1997, Ouarda *et al.*, 2006). Plus récemment, des approches de type voisinage ont été utilisées avec une plus grande efficacité pour certaines régions, définissant non pas des régions fixes mais pour chaque station un ensemble (voisinage) de stations ayant des caractéristiques proches (GREHYS, 1996b). Parmi les méthodes utilisées dans ce type d'approche, les plus courantes sont la méthode des régions d'influence (Burn, 1990, Burn *et al.*, 1997) et l'analyse canonique des corrélations (Cavadias, 1990, Ouarda *et al.*, 2001, Haché *et al.*, 2002).

Il n'existe pas de consensus sur la meilleure approche de régionalisation. Les travaux du GREHYS (1996b) traitant d'étude comparative des différentes méthodes de régionalisation pour les rivières canadiennes concluent qu'il est difficile de départager les différentes méthodes de constitution des régions homogènes, et que la méthode dépend fortement des données utilisées. Ils démontrent que la méthode d'analyse canonique des corrélations semble donner de meilleurs résultats avec les données de débit au Québec. À l'inverse, Merz *et al.* (2004) montrent dans une étude sur 575 stations autrichiennes que les approches qui privilégient la proximité géographique sont plus performantes que celles basées sur les caractéristiques des bassins, dans une zone géographique restreinte (l'Autriche) avec une forte densité de stations. Ouarda *et al.* (1999) considèrent que ce sont les approches de type voisinage qui sont les plus performantes, et elles ont été appliquées fréquemment au Canada (Burn 1990, Ribeiro-Corréa *et al.* 1995, Ouarda *et al.* 2001, Haché *et al.* 2002).

Pour l'étape de l'estimation régionale au sein de régions ou voisinages crées, les deux principales méthodes sont l'indice de crue et la régression directe sur les quantiles (GREHYS, 1996a). La méthode de l'indice de crue est l'une des plus anciennes pour l'estimation régionale, introduite par Dalrymple en 1960. L'hypothèse de base est que les données des différents sites d'une région sont homogènes, et suivent la même distribution à un facteur d'échelle près. Cette méthode repose sur la standardisation des données par un indicateur de tendance centrale, l'indice de crue, et le calage d'une distribution régionale pour l'ensemble des sites. La méthode de régression directe sur les quantiles est la plus utilisée dans les travaux de régionalisation sur les débits. Parmi les travaux les plus récents de régionalisation des crues, Ouarda *et al.,* 2000 et 2001, Haché *et al.,* 2002 l'ont utilisé dans leurs études sur le Québec et l'Ontario. Elle permet d'établir une relation directe entre les variables hydrologiques et des variables physiographiques ou météorologiques. Elle a l'avantage d'être d'usage simple et de permettre d'utiliser des distributions différentes pour représenter les débits de crue dans différents sites de la même région (Ouarda *et al.,* 1999). De plus la méthode n'est pas sensible à l'hétérogénéité qui peut exister dans la région considérée.

2.2.3 Approches régionales appliquées au transport solide

Comme on l'a vu précédemment, la régionalisation en hydrologie consiste en l'estimation d'événements hydrologiques extrêmes pour des bassins non jaugés. Elle repose donc sur une approche de modélisation probabiliste de la variable hydrologique d'intérêt. Peu de travaux de recherches ont jusqu'à présent utilisé une telle approche fréquentielle pour décrire le transport de sédiments fins. Pourtant, plusieurs travaux ont montré que l'étude en fréquence/magnitude des concentrations de sédiment en suspension est plus importante que les charges annuelles pour établir l'impact des sédiments sur les habitats aquatiques (Newcombe et MacDonald, 1991, Newcombe et Jensen, 1996).

Parmi les quelques travaux utilisant l'analyse fréquentielle pour modéliser le transport de sédiments en suspension, Van Sickle (1981) a associé des périodes de retour empiriques aux événements de forte charge pour des bassins de l'Oregon. Simon *et al.* (2004) ont évalué les conditions de transport correspondant à une période de retour de 1.5 années pour 2900 sites aux États-Unis, visant à estimer les conditions de transport correspondant au débit plein bords ('bankfull discharge'). Pour les concentrations, Watts *et al.* (2003) ont modélisé avec une distribution Pareto généralisée les trois plus fortes concentrations enregistrées annuellement dans le bassin de la Lower Swale (UK), dans le but d'estimer le stress des fortes concentrations sur les populations de poissons. Galea *et al.* (2004) ont adapté au débit solide l'approche QDF (débit - durée - fréquence) utilisée habituellement pour les débits de crue. Ils procèdent à une modélisation des débits de pointe et des concentrations en sédiments associées, en utilisant une loi Pareto généralisée pour les concentrations et une loi exponentielle pour les débits. Ils montrent que les concentrations ne sont pas simplement proportionnelles aux débits mais croissent plus rapidement. Ils proposent ainsi cette méthode pour estimer à la fois la concentration et le volume de sédiments pour chaque événement de crue dans 28 cours d'eau du bassin du Tibis-Béga en Roumanie. Leurs travaux constituent une première étape qui mènera dans un second temps à une approche régionale. Plus récemment, Soler *et al.* (2007) ont modélisé les maximums annuels de concentration, ainsi que les dépassements du $90^{\text{ème}}$ centile, dans un cours d'eau espagnol utilisant des distributions Log-Normale et Gumbel.

En ce qui concerne l'estimation régionale de variables décrivant le transport de sédiment, beaucoup de recherches ont analysé le lien entre concentrations et caractéristiques des bassins versants (Restropo *et al.*, 2006, Robertson *et al.*, 2006) ou celles du voisinage immédiat des sites de mesures (Jarvie *et al.*, 2002, Siakeu *et al.*, 2004) mais très peu visant à l'estimation régionale. Quelques travaux, même si n'étant pas *stricto sensu* de l'analyse fréquentielle régionale, utilisent le principe d'estimation en utilisant de l'information régionale. Mimikou (1990) a proposé une estimation régionale des paramètres de « rating curves » reliant concentration et débit pour les 6 plus grands cours d'eau de Grèce en utilisant les caractéristiques physiographiques des bassins versants. Une méthode de régionalisation des bilans sédimentaires annuels de cours d'eau dans le nord de l'Italie a été développée par Feraresi (1990). Il retient deux approches; la première consiste à transférer les paramètres de calibration d'un modèle physique d'érosion et de transport des sites jaugés vers les sites non jaugés, puis de calculer grâce au modèle le paramètre d'intérêt en chaque site non jaugé. Mais les modèles physiques nécessitent beaucoup de paramètres pour décrire avec précision les phénomènes d'érosion et de transport. De plus, cette approche est difficilement applicable hors des bassins versants instrumentalisés. La seconde approche, utilisée par Feraresi (1990), est d'estimer directement la charge annuelle des cours d'eau, par régression multiple en utilisant les caractéristiques physiographiques des bassins versants proches comme variables explicatives. Cette méthode est moins précise que la première mais plus facile à mettre en œuvre. Bray et Xie (1993) ont aussi estimé les charges annuelles et mensuelles pour des cours d'eau non jaugés dans l'est du Canada en utilisant une approche similaire. Après avoir déterminé cinq régions présentant des caractéristiques physiographiques homogènes, ils ont estimé les charges annuelles et mensuelles par régression multiples avec des variables hydro-climatiques et géomorphologiques. Plus récemment, Whiting (2006) a développé une approche d'estimation des niveaux naturels de charge en suspension pour 46 cours d'eau dans la région des grands lacs, basée aussi sur les caractéristiques des bassins. Ce travail étant préliminaire à l'établissement des normes TMDL (« total maximum daily load ») acceptables pour ces cours d'eau.

CHAPITRE 3 : Résumé des travaux de recherche

3.1 Analyse fréquentielle des maximums annuels de concentration en sédiments en suspension en Amérique du Nord

Comme ce fut décrit dans le chapitre précédent, l'analyse fréquentielle locale est une étape requise avant de procéder à la régionalisation. Il s'avère, à l'étude de la littérature scientifique, que très peu de travaux se sont penchés sur la modélisation fréquentielle des concentrations extrêmes. Le but de cet article constituant la première partie est de réaliser une analyse fréquentielle locale des maximums annuels de CSS pour les sites ayant de longues séries chronologiques d'enregistrement en continu de CSS. Les objectifs sont triples, premièrement colliger sur tout le continent nord-américain les longues séries de CSS disponibles, deuxièmement caractériser les maximums annuels en termes de distribution spatiale, saisonnalité et relation avec les débits, enfin troisièmement modéliser avec des distributions statistiques les séries de maximums annuels de CSS.

3.1.1 Méthodes

Les stations avec 10 années ou plus de données journalières sont retenues dans les bases de données américaines du l'USGS (http://co.water.usgs.gov/sediment/) et canadiennes d'Environnement Canada (http://www.wsc.ec.gc.ca/) sur les sédiments (Figure 4.1). Ce seuil de 10 années a été choisi car la taille des échantillons est critique pour l'analyse fréquentielle et plusieurs auteurs recommandent ce seuil minimal de 10 années (Perrault *et al.*, 1994, Rao et Hamed, 2001). Une attention particulière à été apportée pour la détection des valeurs manquantes dans les séries, les années avec 60 valeurs journalières manquantes ou plus on étés éliminées. Les données erronées ont étés également recherchées dans les séries originales afin de les éliminer. Les méthodes utilisées pour l'ajustement de distributions statistiques sont celles développées pour les crues, et décrites en détail dans plusieurs ouvrages, tels que celui de Rao et Hamed (2001). Les grandes étapes sont :

1. La vérification des hypothèses de stationnarité, homogénéité, et d'absence d'auto-corrélation dans les séries de maximums annuels, en utilisant les tests statistiques non paramétriques de Kendall, Wilcoxon et Wald-Wolfowitz.

2. L'ajustement de différentes distributions statistiques (Tableeau 4.1) sur les séries de maximums annuels en utilisant pour chacune des distributions la méthode d'estimation de ses paramètres la plus appropriée (ex. méthodes du maximum de vraisemblance, méthode des moments etc.).

3. La sélection de la meilleure distribution pour chaque station, en utilisant les critères d'information d'Akaike (AIC) et Bayésien (BIC).

3.1.2 Résultats

Sur 208 stations avec des séries de CSS de 10 ans ou plus (Figure 4.1), 179 stations passent les tests d'hypothèses préalables à l'analyse fréquentielle. Le nombre de stations échouant un ou plusieurs de ces trois tests est présentés dans le tableau 4.2. Le test de Kendall, visant à détecter des tendances dans les séries, met en évidence des tendance à la baisse des concentrations maximales annuelles dans de nombreux bassins américains des contreforts des montagnes Rocheuses (Montana, Wyoming) ainsi que dans les zones arides des états du Colorado, Nouveau Mexique et Utah. Dans ces derniers états, on retrouve les rivières

Colorado et Rio Grande, très aménagées pour des besoins en ressource en eau. Les plus fortes concentrations se retrouvent aussi dans ces zones, les plus arides, mais aussi dans la zone plaines et prairies.

Le dénombrement de l'occurrence des maximums annuels pour chaque mois a été réalisé afin de caractériser la saisonnalité de ces événements. La majorité des maximums annuels de CSS en Amérique du Nord sont observés au printemps et à l'été, tel que le montre la figure 4.5. Pour le plus grand nombre de stations, les maximums annuels de concentration se produisent au printemps, pour les stations situées dans une zone allant du nord-ouest américain et canadien, jusqu'aux provinces maritimes à l'est du canada et les états du nord-est américain. On observe une seconde zone avec des maximums annuels se produisant le plus fréquemment en été, ce sont les stations situées dans les bassins du Rio Grande et Colorado. Enfin, pour les stations de Californie, les maximums annuels se produisent le plus souvent en hiver, de novembre à mars.

La corrélation avec les débits a été analysée, pour vérifier si on peut estimer les maximums annuels de CSS en utilisant le débit correspondant. Pour prendre en compte le phénomène d'hystérèse, le débit maximal sur une période de plus ou moins 5 jours de la date de l'événement de CSS a été utilisé pour tester la corrélation. Même si le débit maximal annuel tend à se produire durant la même saison que la concentration maximale annuelle (85% des cas), il s'avère qu'il existe une corrélation significative entre les CSS maximum annuel et le débit correspondant dans seulement 92 stations sur 208. Sur la figure 4.8 on peut voir que les corrélations sont généralement plus fortes avec la pointe de débit se produisant après l'évènement de maximum annuel de CSS.

Les distributions statistiques présentées dans le tableau 4.1 ont été ajustées aux séries des maximums annuels de CSS. Les résultats des valeurs des critères AIC et BIC pour la sélection de meilleures lois sont présentés dans la figure 4.9. Les distributions Log-Normale à 2 paramètres, Exponentielle, Weibull et Gamma sont retenues pour 80% des stations. Une fois les séries de CSS maximum modélisées par ces distributions, il devient possible d'extraire un nombre de paramètres d'intérêt pour divers usages. Deux exemples du type d'utilisation possible sont donnés; la figure 4.12 montre les concentrations maximales annuelles pour une période de retour correspondant à 2 années, et la figure 4.13 la période de retour associée à une concentration égale à 1000 mg/L, létale pour de nombreuses espèces de poissons.

3.1.3 Conclusions

Ce premier travail a permis de créer la base de données de CSS qui servira pour la suite des recherches et caractériser les événements extrêmes de CSS par le biais de l'analyse fréquentielle. Outre l'identification de 3 types de saisonnalités, il a été montré que les débits seuls ne sont pas suffisants pour modéliser les concentrations maximales annuelles dans l'ensemble des stations. Les séries de CSS maximums annuels modélisées par des distributions de probabilité permettent d'extraire de l'information sur la fréquence d'occurrence et l'amplitude des événements extrêmes, information qui va servir par la suite pour les approches d'estimation régionale.

3.2 Régionalisation des concentrations extrêmes de sédiments en suspension en Amérique du nord

Cette seconde partie vise à utiliser des approches de régionalisation pour les CSS extrêmes. On utilise les stations pour lesquelles les maximums annuels de CSS se produisent au printemps, qui constituent le plus grand groupe saisonnier homogène, comme vu précédemment. Le but de cette partie est d’estimer les CSS extrêmes en utilisant les caractéristiques des bassins versants. Les objectifs sont doubles : identifier les attributs des bassins versants corrélés avec les CSS extrêmes et comparer la performance d’estimation en utilisant un modèle d’estimation englobant tous les sites avec deux modèles régionaux.

3.2.1 Méthodes

Les stations pour lesquelles les maximums annuels de CSS se produisent au printemps, entre les mois de février et juin, sont utilisées mais en retirant celles fortement régulées car la présence d’infrastructures de régulation au fil de l’eau telle que les barrages peuvent modifier fortement le transport sédimentaire. Les 72 stations retenues (tableau 5.1) s’étendant des Rocheuses jusqu’à la côte Atlantique (Figure 5.2). Une base de données sur l’occupation des sols, le climat, la topographie et les types de sols des bassins versants correspondant aux stations retenues a été crée, dont la liste complète est présentée dans le tableau 5.2. En parallèle, 2 quantiles de concentration, correspondant à des périodes de retour 2 et 20 ans (C2 et C20) ont été extraits par analyse fréquentielle locale afin de tester l’estimation régionale sur ces deux quantiles. Les corrélations entre ces 2 quantiles et les attributs des bassins versants ont été analysées afin de sélectionner les attributs les plus pertinents. Enfin, pour l'estimation régionale de ces deux quantiles C2 et C20, un modèle régressif incluant toutes les stations a été créé afin d'être comparé avec 2 approches régionales. La première approche régionale (CW) consiste à regrouper les stations sur la base de la ressemblance des caractéristiques physiographiques de leurs bassins. On utilise un algorithme de classification ascendante hiérarchique (CAH) sur les attributs des bassins corrélés avec les 2 quantiles d'intérêt pour déterminer des groupes de stations, identifiés grâce à l'arbre de classification produit (dendrogramme visible sur la figure 5.4). La seconde approche (CM) se base sur la délimitation de régions définies sur la base des dates d'occurrence des maximums annuels de CSS. Pour chaque station les fréquences moyennes mensuelles d'occurrence des maximums annuels de CSS ont été calculées, et un algorithme de CAH a également été utilisé sur ces fréquences mensuelles pour déterminer des régions. Dans ces deux approches CW et CM, pour chaque région délimitée un modèle régressif a été construit pour estimer les quantiles C2 et C20. Un algorithme de régression pas à pas (« stepwise ») a été utilisé pour réduire le nombre de variables sélectionnées et minimiser le risque de colinéarité entre les variables explicatives des modèles. Pour estimer la précision des estimations, chaque site est tour à tour considéré non jaugé pour calculer un biais et un RMSE relatif entre la valeur locale et l'estimation utilisant l'information régionale (équations 5.2 et 5.3).

3.2.2 Résultats

Les attributs des bassins les mieux corrélés avec les quantiles C2 et C20 sont présentés dans le tableau 5.3. Ils incluent notamment le pourcentage d'argile dans les sols, la variable la plus fortement corrélée avec les CSS, ainsi que la couverture forestière et des indices décrivant l'intensité des précipitations. Un modèle régressif global, incluant tous les sites, donne des résultats moins performants que les deux approches régionales, avec des RMSE relatifs proches de 100% pour C2 et supérieurs à 100% pour C20 (tableau 5.6).

L'approche basée sur les caractéristiques physiographique des bassins donne des résultats similaires à ceux de l'approche basée sur la saisonnalité, avec des erreurs en termes de RMSE relatif proche de 75% (table 5.6). L'approche CW donne des régions non contiguës d'un point de vue géographique (figure 5.5), dont certaines sont de taille réduites, de 9 ou 12 stations pour les régions 1 et 4. Elle présente néanmoins l'avantage de la facilité d'attribution d'un site non jaugé à une région, car elle est basée uniquement sur les caractéristiques des bassins versants. L'approche CM donne des régions de taille plus homogènes (figure 5.7) et présentant une contiguïté spatiale. Les trois régions constituées sont en effet le groupe de stations pour lesquelles les maximums annuels se produisent en mars et avril dans le nord-est, un deuxième groupe avec les maximums annuels se produisant autour des mois de mai et juin, localisées principalement dans l'ouest, et enfin un troisième groupe où les maximums annuels se produisent en début ou fin de printemps selon les années.

3.2.3 Conclusions

Cette partie des travaux a permis de mettre en évidence les principales caractéristiques des bassins versants influençant les fortes concentrations en CSS. Elle a permis de montrer également que l'estimation régionale est plus performante qu'un seul modèle appliqué a tous les sites. Les deux approches régionales testées ont chacune leurs atouts et leurs faiblesses, l'approche basée sur la physiographie permet d'assigner facilement un site non jaugé à une région mais certaines régions crées sont de petite taille. À l'inverse l'approche basée sur la saisonnalité donne des régions plus homogènes mais il peut se poser le problème d'assignation d'un site non jaugé à l'une de ces régions, ne disposant pas d'information sur la saisonnalité des CSS en un site non jaugé. Les erreurs d'estimation sont globalement plus importantes que dans la régionalisation des crues ou des étiages. Ces erreurs sont à relier au faible nombre de stations disponibles, comparativement aux études sur les débits, et à la forte variabilité du transport en suspension et notamment des événements extrêmes de CSS. Aussi les bases de données utilisées pour décrire les bassins peuvent introduire un biais supplémentaire du fait de la différence temporelle entre les dates des mesures hydrologiques et les dates d'établissement des bases de données sur les sols et leur occupation. De plus, l'occupation du sol est susceptible d'être fortement modifiée au cours du temps par les activités humaines.

3.3 Estimation régionale des CSS extrêmes et d'indicateurs du régime de transport en Californie avec les caractéristiques des bassins versants et du voisinage des stations

On a vu dans la première partie que les stations sites en Californie ont des maximums annuels de CSS se produisant durant la période hivernale. L'objectif de cette partie est de procéder dans cette zone à l'estimation régionale de quantiles de CSS, mais aussi d'indicateurs décrivant le régime sédimentaire des cours d'eau. Pour l'estimation régionale de ces variables on utilise à la fois les caractéristiques des bassins versants mais aussi les caractéristiques locales des stations, définies par la zone de 5 km autour de chaque site.

3.3.1 Méthodes

Les données quotidiennes de CSS de 19 stations Californiennes, non ou peu régulées (figure 6.1), sont utilisées pour calculer le 99$^{\text{éme}}$ centile des CSS, estimer les quantiles de CSS correspondant aux périodes de retour 2, 10 et 20 ans, ainsi que pour calculer des indicateurs du régime sédimentaire. Ces indicateurs comprennent la quantité de sédiment en suspension calculée pendant 2% du temps (M_2) sur les séries chronologiques complètes, mais aussi annuellement, pour lesquelles sont associées des périodes de retour de 2, 10 et 20 ans via une analyse fréquentielle. Tous ces descripteurs du transport de sédiment en suspension sont estimés via des modèles régressifs pas-à-pas régionaux, dont l'efficacité est estimée via une étape de ré-échantillonnage de type Jack-Knife permettant de calculer un RMSE, biais et RMSE relatifs pour chaque variable estimée (équations 6.3, 6.4, 6.5). Outre le bassin versant, une nouvelle échelle spatiale de définition des attributs physiographiques (tableau 6.2) d'un site de jaugeage est introduite, il s'agit de la zone de 5 km autour des stations utilisées. Pour chaque station, pour procéder à l'estimation régionale on dispose ainsi d'une base de données des attributs physiographiques pour l'ensemble du bassin versant et une autre base de données des attributs de la zone de 5 km autour de cette station (figure 6.2).

3.3.2 Résultats

Les valeurs maximales annuelles de CSS dans les 19 stations Californiennes retenues présentent une très grande variabilité entre les stations mais aussi entre les valeurs prises d'année en année dans chaque station, comme l'indique la figure 6.3a. L'étude des corrélations entre ces maximums annuels et le débit maximal correspondant, sur une période de plus ou moins 3 jours centrée autour de l'événement de CSS, montre que ces corrélations sont significatives pour seulement 10 stations sur 19 (tableau 6.3).

Pour le 99ème centile et les 3 quantiles de CSS, le tableau 6.4 indique que les corrélations avec les caractéristiques locales des stations sont plus nombreuses et souvent plus fortes que celles avec les caractéristiques des bassins versants. L'estimation régionale utilisant les caractéristiques locales des stations de mesure donnent de meilleurs résultats qu'en utilisant les attributs de l'ensemble des bassins versants. Les RMSE sont réduits de près de moitié, en utilisant les caractéristiques physiographiques locales plutôt que l'ensemble des bassins, et les RMSE relatifs sont réduits de 8% à 70%, dépendant de la variable considérée (tableau 6.5). En utilisant les attributs du voisinage des stations, l'estimation régionale des différentes variables décrivant les CSS extrêmes atteint l'ordre de 50% en termes de RMSE relatif.

Pour les indicateurs du régime sédimentaire considérés dans cette étude, on retrouve des corrélations similaires avec les attributs du bassin et ceux de la zone de 5 km autour des stations (tableau 6.6). L'estimation régionale de ces indicateurs (M_2 sur l'ensemble des chroniques de CSS et annuels, avec période de retour 2, 10 et 20 ans) donne des résultats comparables en utilisant les attributs des bassins ou de la zone locale des stations. Le tableau 6.7 donne les résultats de l'estimation régionale après Jack-Knife, on voit que l'erreur d'estimation varie de 3% à 7% selon les variables considérées.

3.3.3 Conclusions

Dans cette partie on a observé que pour les stations de Californie, qui ont un rythme saisonnier différent dans le transport de sédiments en suspension du reste du continent, l'estimation régionale de différentes caractéristiques du transport de CSS est possible avec des erreurs d'estimation limitées. L'utilisation des caractéristiques physiographiques dans un voisinage de 5 km des sites de mesure au lieu de la totalité des bassins versants permet d'obtenir de meilleurs résultats, avec des erreurs d'estimation atteignant 50% pour le 99$^{\text{ème}}$ centile et les quantiles de CSS.

Il a notamment été vérifié que l'utilisation des débits seuls ne permet pas d'estimer les concentrations extrêmes dans toutes ces stations californiennes. De plus, les racines de l'erreur quadratique moyenne (RMSE) d'estimation régionale pour les quantiles de plus longue période de retour sont moindres que pour des quantiles correspondant à des périodes de retour courtes. Ces éléments semblent indiquer que les concentrations extrêmes de sédiments en suspension observées sont limitées non pas par l'agent de transport mais par le stock de sédiments disponibles sur les versants ou le lit des cours d'eau.

Le régime de transport de CSS décrit par la quantité de sédiment transportée en 2% du temps peut lui aussi être estimé régionalement en utilisant des caractéristiques physiographiques. À l'inverse des CSS extrêmes, l'utilisation des caractéristiques de l'ensemble du bassin versant et celles du voisinage des stations de mesure donnent des résultats similaires pour l'estimation, avec des erreurs d'estimation inférieures à 7%.

3.4 Une première application des arbres de régression pour l'analyse fréquentielle régionale des concentrations extrêmes de sédiments en suspension

Les résultats des parties précédentes ont été intégrés pour proposer une nouvelle approche de régionalisation. L'analyse fréquentielle des CSS extrême à été développée dans la partie 3.1, en utilisant les maximums annuels. Ici, un échantillonnage par dépassement d'un seuil (« peaks-over-threshold ») est testé à des fins de comparaison entre les deux approches. Dans les parties 3.2 et 3.3, des techniques classiques de régionalisation ont été appliquées pour l'estimation des CSS extrêmes dans des sites non jaugés. Certaines limites de ces techniques ont été mises en évidence, telles que les incertitudes liées à la délimitation de régions homogènes ou bien les problèmes liées à l'utilisation de la régression multiple en présence de colinéarité. Ici l'approche non paramétrique des arbres de classification et de régression (CART) est testée. Elle permet à la fois la création de groupes de stations homogènes et l'estimation régionale au sein de ces groupes. Comme on a vu dans la partie 3.3 que les caractéristiques du voisinage des sites peuvent influencer les CSS extrêmes, on utilise conjointement les caractéristiques des bassins et celles du voisinage des stations pour l'estimation régionale.

3.4.1 Méthodes

Les stations utilisées dans la partie 3.2, ayant des maximums annuels de CSS au printemps sont utilisées, à l'exception des bassins de moins de 100 km^2 (figure 7.1). Les caractéristiques physiographiques (tableau 7.1) des bassins versants ont été complétées par celles du voisinage de 20 km autour de chaque station de mesure, cette distance ayant été choisie car les bassins versants sont de taille plus grande que ceux de Californie utilisés dans la partie 3.3. Un échantillonnage des dépassements du 99ème centile des concentrations de CSS a été réalisé. Pour s'assurer de l'indépendance des événements retenus, deux critères ont été utilisés; deux événements consécutifs doivent être séparés de 5 jours au minimum et la concentration entre les deux doit s'abaisser en dessous du 99ème centile. Le test de Wald-Wolfowitz a été utilisé pour vérifier l'absence d'auto-corrélation dans les séries. L'occurrence des dépassements du seuil a été modélisée par une distribution de Poisson, et l'amplitude des événements par la distribution Pareto Généralisée. Les quantiles correspondant à des périodes de retour 2 et 20 ans ont été calculés en utilisant l'équation 7.1.

Les arbres de régression et de classification sont un outil statistique permettant d'explorer les relations entre une variable réponse y et une matrice des variables explicatives X. Il s'agit d'une approche non paramétrique, qui vise à scinder de manière binaire et récursive les observations en groupes telle que la somme des résidus est minimisée (équation 7.2). Le résultat est un arbre de classification ou de régression (dans notre cas), dans lequel pour chaque nœud terminal la valeur prédite y_p est constante. Le principal problème associé à la méthode est le sur-apprentissage (« over-fitting ») sur les données d'entraînement. Ainsi il est nécessaire d'élaguer (« prune ») l'arbre créé avec l'ensemble des données. La méthode classique consiste en une validation croisée aléatoire en utilisant des sous-ensembles des données de départ pour déterminer l'arbre optimal (avec la règle du *1-SE*, proposée par Breiman *et al.*, 1984). Une autre approche visant à optimiser les résultats d'estimation régionale est proposée dans ce travail. Elle consiste à utiliser une procédure de ré-échantillonnage de type Jack Kife, visant à calculer la performance d'estimation de l'arbre élagué à différents niveaux. Le niveau de coupure sélectionné est celui menant aux meilleurs résultats pour l'estimation régionale.

3.4.2 Résultats

Les quantiles de CSS extrêmes, obtenus par l'analyse fréquentielle basée sur les maximums annuels (AM) ou les dépassements du 99$^{\text{ème}}$ centile (POT) sont très similaires et fortement corrélés (figures 7.2 et 7.3). On relève une corrélation de 0.99 entre les quantiles AM et POT correspondants à une période de retour 20 ans, avec des différences de l'ordre de 3%. Pour les quantiles correspondant à une période de retour 2 ans, la corrélation est de 0.98 entre les quantiles AM et POT, mais les quantiles POT sont en moyenne 20% plus élevés que les quantiles AM.

Pour l'estimation régionale, des variables physiographiques sont sélectionnées sur la base de leurs corrélations avec les quantiles sélectionnés (tableau 7.2). Cette fois sont combinées des variables à l'échelle du bassin (pourcentage de pâturages) et des variables à l'échelle du voisinage des stations (longitude, pourcentage d'argile dans les sols et intensité des précipitations), illustrées dans la figure 7.4. Ces variables sont utilisées en combinaison avec les quantiles de CSS pour créer des arbres de régression à des fins d'estimation régionale.

Les résultats d'estimation régionale en utilisant des arbres de régression élagués selon la méthode couramment utilisée (règle du *1-SE*) sont mitigés, avec des RMSE relatifs de 100% à 300% selon les quantiles (tableau 7.3). Il s'avère que les niveaux de coupure optimaux déterminés par cette méthode sont extrêmement variables selon les stations et les variables, comme le montre la figure 7.5. Cette forte variabilité dans la taille des arbres est la cause des erreurs d'estimation élevées. En utilisant une procédure de ré-échantillonnage qui teste plusieurs niveaux de coupure fixés préalablement, les résultats d'estimation sont plus stables et meilleurs que dans le cas de l'approche précédente. Le niveau de coupure 2 est optimal pour l'estimation régionale (figure 7.6), avec des RMSE relatifs entre 84% et 144% sur l'ensemble des variables, avec des erreurs plus élevées associées aux quantiles de courtes périodes de retour (tableau 7.4).

3.4.3 Conclusions

Cette dernière partie permet de montrer que l'échantillonnage par maximums annuels ou par dépassement d'un seuil donne des résultats très comparables dans le cas des valeurs extrêmes de CSS. La modélisation POT permet une meilleure estimation des quantiles de courtes périodes de retours, car basée sur un plus grand nombre d'évènements. Dans les travaux futurs, on peut envisager l'utilisation de cette approche POT sur des séries de CSS plus courtes que 10 ans, le seuil retenu jusqu'ici, afin d'obtenir un nombre de stations plus important.

Les arbres de régression, jusqu'alors peu utilisés en hydrologie, permettent la régionalisation de quantiles de CSS extrêmes, en utilisant une approche novatrice d'élagage des arbres visant à éviter leur sur-spécialisation. L'optimisation des résultats d'estimation via cette méthode doit passer par une meilleure définition et sélection des caractéristiques physiographiques des sites, incorporant notamment les débits, et l'utilisation d'approches visant à améliorer l'efficacité de l'élagage des arbres de régression.

CHAPITRE 4 : Analyse fréquentielle des maximums annuels de concentration en sédiments en suspension en Amérique du nord

FREQUENCY ANALYSIS OF MAXIMUM ANNUAL SUSPENDED SEDIMENT CONCENTRATIONS IN NORTH AMERICA

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Abstract

Suspended sediments are a natural component of aquatic ecosystems, but when present in high concentrations they can become a threat to aquatic life and can carry large amounts of pollutants. Suspended sediment concentration (SSC) is therefore an important abiotic variable used to quantify water quality and habitat availability for some species of fish and invertebrates. This study is an attempt to quantify and predict annual extreme events of SSC using frequency analysis methods. Time series of daily suspended sediment concentrations in 208 rivers in North America were analysed to provide a large-scale frequency analysis study of annual maximum concentrations. Seasonality and the correlation of discharges and annual peak of suspended sediment concentration were also analysed. Peak concentrations usually occur in spring and summer. A significant correlation between extreme SSC and associated discharge was detected only in half of the stations. Probability distributions were fitted to station data recorded at the stations to estimate the return period for a specific concentration, or the concentration for a given return period. Selection criteria such as the Akaike and Bayesian information criterion were used to select the best statistical distribution in each case. For each selected distribution, the most appropriate parameter estimation method was used. The most commonly used distributions were exponential, lognormal, Weibull and Gamma. These four distributions were used for 90% of stations.

Résumé

Les sédiments en suspension sont une composante naturelle des écosystèmes aquatiques, mais qui peuvent devenir une menace pour la vie aquatique et véhiculer de grandes quantités de polluants lorsqu'ils sont présents en forte concentration. La concentration en sédiments en suspension (CSS) est par conséquent une variable abiotique importante utilisée pour quantifier la qualité de l'eau et la disponibilité des habitats pour certaines espèces de poissons et d'invertébrés. Cette étude est une tentative pour quantifier et prévoir les événements extrêmes annuels de CSS à l'aide de méthodes d'analyse fréquentielle. Les séries temporelles de CSS journalière de 208 rivières d'Amérique du Nord ont été analysées pour développer une analyse fréquentielle à grande échelle des maximums annuels de concentration. La saisonnalité des évènements extrêmes de CSS et la corrélation entre débit et pic annuel de CSS ont également été analysées. Les pics de concentration interviennent habituellement au printemps et en été. Une corrélation significative entre les CSS extrêmes et les débits associés n'a été détectée que pour la moitié des stations. Des distributions de probabilité ont été ajustées aux données enregistrées aux stations afin d'estimer la période de retour d'une concentration spécifique, ou bien la concentration correspondant à une période de retour donnée. Les critères de sélection Akaike et Bayésien ont été utilisés pour sélectionner la meilleure distribution statistique dans chaque cas. Pour chaque distribution sélectionnée, la méthode d'estimation des paramètres la plus appropriée a été utilisée. Les distributions les plus communément utilisées sont les lois Exponentielle, Lognormale, Weibull et Gamma. Ces quatre distributions sont retenues pour 90% des stations.

4.1 Introduction

Sediments in rivers are considered to be the most widespread pollutant in North America by the US Environmental Protection Agency (Gray & Glysson, 2002). Physical and chemical alterations to rivers and biological damages caused by sediments in North America were estimated to cost approximately US$16 billion per year (Gray & Glysson, 2002). Suspended sediments are composed of inorganic materials such as sand, clay and silt and also organic material such as algae, small aquatic animals, and non living material from aquatic organisms and terrestrial sources (Waters, 1995; Whiles & Dodds, 2002). Suspended sediments can account for 70 to 99% of the quantity of sediments transported by streams (Knighton, 1998; Babiński, 2005); the remainder is transported by saltation or intra-sediment movement. Transportation of sediments in streams is a complex phenomenon that varies from one region to another, depending on the type of soils, geomorphologic processes and seasons. The total amount of sediments carried by a stream during a year is usually transported during 10% or less of the days in one or several extreme events (Ashmore & Day, 1988). Meybeck *et al.* (1999, 2003) have shown that the temporal variability of suspended sediment transport decreases with the size of the watershed. Semi-arid watersheds show the greatest variability in sediment transport; the scarce rainfall events can cause very high concentrations of sediments in a short amount of time (Coppus & Imeson, 2002; Griffith *et al.*, 2005).

Even if they are a natural component of aquatic ecosystems, high suspended sediment concentrations (SSC) can be a threat to aquatic life and may impair water quality by carrying a large amount of pollutants which may lead to greater drinking water purification costs (Meybeck *et al.*, 2003; Dodds & Whiles, 2004; Walling, 2005). Suspended organic particles are the major source of nutrition for many aquatic organisms, particularly filter-feeding macro invertebrates and some fish (Whiles & Dodds, 2002). High fluvial sediment concentration has several direct effects on aquatic habitats. Fine-grained sediment transport in rivers is associated with contaminant transport, since sediments are the main vector of pollutants carried by rivers (Ashmore *et al.*, 2000). Chemical substances such as nitrogen, hydrocarbons, heavy metals or pesticides bind with suspended solids and are carried along with the flow. Thus, high concentrations of sediments possibly carry high amounts of elements that are toxic for several species. High concentrations of suspended sediments affect the biota by reducing the density, productivity and abundance of primary producers and macro-invertebrates (Wood & Armitage, 1997). Negative impacts on fish include smothering of eggs, interfering with respiration, limiting visibility for sight feeders, and loss of habitat and prey communities (Newcombe & Jensen, 1996; Wood & Armitage, 1997). Suspended solids also absorb the heat from sunlight and high concentrations may cause water temperature rise. Altogether this leads to a decrease in the survival rate of fish adults and embryos (Dodds & Whiles, 2004). Concentrations above 80 mg/L start to affect some fish populations, and concentrations above 200 mg/L are assumed to be harmful to most North American fish (Waters, 1995).

Thus, it can be seen that SSC is an important abiotic variable to quantify water quality and habitat availability. To our knowledge, this study is a first attempt to quantify and predict high SSC using frequency analysis methods that are often applied to flood prediction. Quantifying fish habitat availability in rivers requires data for a number of abiotic variables, including suspended sediment concentrations (St-Hilaire *et al.*, 2005; Newcombe & Jansen, 1996; Wood & Armitage, 1997). In this first approach, annual SSC maxima are considered.

Using frequency analysis, it is possible to quantify these extreme concentrations and estimate the associated return periods. To achieve this, the specific objectives of this study were:

(a) To collate SSC time series from stations in Canada and the USA covering a range of drainage basins that is representative of the different river systems in the continent;

(b) To characterise the annual maximal SSC in terms of regional patterns, seasonality and relationship with flow; and

(c) To perform local frequency analysis on the selected time series.

The remainder of the paper is broken down as follows: Section 2 provides the methodology used for local frequency analysis; Section 3 presents the study area and the data; Section 4 provides the results of local frequency analysis, the statistical distributions selected and some examples of estimated quantiles and return periods. Finally, the results are discussed in Section 5 and conclusions are drawn.

4.2 Methodology

4.2.1 Frequency analysis

Frequency analysis is a statistical approach commonly used in hydrology to relate the magnitude of extreme events (e.g. floods or low flows) to a probability of occurrence. The theory and application of frequency analysis is well known and described in detail in many textbooks (e.g.Rao & Hamed, 2001). A brief summary is provided in this section. The main objective of frequency analysis is to infer the probability of exceedence of all possible events, in this case suspended sediment concentrations, from observed values (a sample of the parent population). This can be done by fitting to the observed data (in this case, a homogenous, stationary time series of independent annual maxima) a statistical model that represents the relationship between the magnitude of the event and the exceedence probability. The parameters of the model (i.e. the parameters of the probability distribution) are estimated from the sample. Using the fitted probability distribution, it is possible to predict the probability of exceedence for a specified magnitude (i.e. quantile) or the magnitude associated with a specific exceedence probability.

Frequency analysis includes the following steps:

(i) Verification of hypotheses (homogeneity, stationarity and independence) and detection of outliers;
(ii) Fitting of statistical distributions and parameter estimation;
(iii) Selection of the best distribution to represent the data; and
(iv) Calculation of quantiles for different return periods.

4.2.2 Hypotheses and requirements

Time series used for frequency analysis must comply with the hypothesis of homogeneity, stationarity and randomness (Bobée & Ashkar, 1991; Rao & Hamed, 2001). To verify these hypotheses three non parametric tests were used since the distribution of the data is unknown, but assumed non-normal, as it is most frequently the case for extreme values (Helsel & Hirsch, 2002). The tests used were the Wilcoxon test for homogeneity (Wilcoxon, 1945), the Wald-Wolfowitz test for randomness (Wald & Wolfowitz, 1943) and the Kendall test for stationarity (Mann, 1945). The Grubbs-Beck test (Grubbs & Beck, 1972) was also used to detect potential outliers.

4.2.3 Fitting of distributions and estimation methods

The first step to fit a probability distribution is to calculate an empirical probability of exceedence using sorted observations. Several formulas exist to calculate this probability. In this study, the Cunnane (1978) formula was used. Of the many statistical distributions used for extremes, 16 functions that are commonly used in hydrology were retained (Table 4.1). Depending on the distribution, several methods exist to fit a probability distribution to a sample and estimate its parameters. For most distributions, the maximum likelihood method is an excellent option for parameter estimation. For the Gumbel and generalized Pareto distributions, the method of moments is more efficient (Ashkar & Ouarda, 1996). Specific fitting methods have also been developed for certain distributions such as the log-Pearson type 3 and Gamma family of distributions (Bobée & Ashkar, 1991).

4.2.4 Adequacy testing

There are different methods to compare and select the distribution that best fits a given sample. It is possible to visually examine the quality of the fit between the empirical probability of exceedence and a distribution, both plotted on probability paper. However, this method is based only on the judgement of the hydrologist and can be somewhat subjective. The $\chi 2$ and Shapiro-Wilk (for the normal distribution) tests can be used to verify the hypothesis concerning the parent distribution of the sample. The χ2 test has the disadvantage of being considered not very powerful, i.e. the probability that the test will not reject a distribution that does not represent the sample adequately is relatively small. However, if the test fails for a certain distribution, it is almost certain that this distribution does not fit the data adequately. Two selection criteria were used, both based on the likelihood function: the Akaike (1974) and the Bayesian (Schwartz, 1978) information criteria, respectively given in equations (4.1) and (4.2):

$$AIC = -2Log(L) + 2k \tag{4.1}$$

$$BIC = -2Log(L) + 2kLog(N) \tag{4.2}$$

where *AIC* is the Akaike information criterion, *BIC* is the Bayesian information criterion, *L* is the likelihood function, *k* is the number of parameters and *N* is the sample size. Equations (4.1) and (4.2) both include k, the number of parameters. Thus, parsimony is taken into account when selecting the best distribution using these two criteria. The best fit is the one associated with the smallest BIC and AIC values (Rao & Hamed, 2001). The BIC criterion tends to penalize three parameter distributions more severely than the AIC and sometimes the optimal fitted distribution differs from one criterion to another. In the case of different selections by the AIC and BIC criterion, the distribution identified by the BIC criterion was selected to emphasize parsimony.

4.3 Study area and extraction of annual maximum of SSC

4.3.1 North American data sets

Data used in this study are taken from stations located on rivers in Canada and in the USA. In Canada, the databases were provided by Environment Canada (HYDAT Database Version 2.04). In the USA, the data were provided by US Geological Survey sediment database (http://co.water.usgs.gov/sediment). The main criterion to select the stations was record length. Stations with 10 years or more of both daily suspended sediment concentration and flow were included. Within this selected subset, numerous stations were lacking data for several months. Only the years with a maximum of 60 missing days were kept, if these missing days excluded the season during which the maximum of SSC usually occurs. For several stations located in Canada or in northern USA, there are often fewer hydrometric data of good quality during winter months, when rivers are covered with ice (December–March). For these stations experiencing a cold winter season with ice cover and low flow, the data were kept even if all winter month were lacking, based on the hypothesis that the likelihood of an extreme SSC event occurring this period is very small. This concerns stations located in Manitoba, Alberta and Saskatchewan for Canada; and Wyoming, Idaho, Nebraska, Minnesota, Iowa and Wisconsin for the USA.

Using these selection criteria, a database was constructed that contained 68 stations in Canada and 140 in the USA (208 in total). Figure 4.1 displays the geographic distribution of the stations and the major watersheds in North America. The selected rivers provide a relatively good geographical coverage and represent different climate and landscape regions.

There are a few regions where no stations corresponding to the selection criteria were found: the north-western and the south-eastern parts of the USA as well as northern Ontario and the province of Quebec are not represented in the final database. Within the selected subset, the minimum length of record is 10 years (for 25 stations) and the maximum is 40 years for the Mississippi river at Saint Louis (Missouri). Average record length is 17.5 years (Figure 4.2). Figure 4.3 shows the distribution of drainage area of the selected rivers. It can be seen that a large spectrum of river types and watershed sizes are represented, from 2.5 km2 for the smallest drainage area to more than 500 000 km2 for the Mississippi river. Half of the selected rivers have a drainage area smaller than 10 000 km2.

4.3.2 Extraction of annual maximum and screening for outliers

Annual maximum values of SSC were extracted from daily time series. Canadian and US data sets were already screened for the detection of outliers, but working with extreme events requires caution about the input data. The Grubbs-Beck test (Grubbs & Beck, 1972) was applied on series of log-transformed annual maximum suspended sediment concentrations for all the stations. This test highlights the events with a small probability of occurrence, under the hypothesis that the logarithm of the sample is normally distributed (Bobée & Ashkar, 1991). The test identified 23 potential outliers of annual maximum SSC. Only one annual maximum was considered as a true outlier and the value was removed (a value of 7 000 000 mg/L for Cheyenne River, South Dakota). For the remaining 22 annual maximum SSC identified by the Grubbs-Beck test, the annual maximum was compared with other years and also with the corresponding flow data. There is no evidence of unrealistic concentrations: in most cases, SSC with a similar order of magnitude was measured during other years for the same station and the suspected values were associated with a very high flow event, which made it credible.

As expected, the values of annual maximum SSC show great variability from one river to another, from 51 mg/L recorded on 27 September 1977 in Narrow Mountain Brook, New Brunswick, to 780 000 mg/L recorded on 9 August 1968 in Paria River, Arizona. The greatest annual maximum SSC are found on the edges of the Great Plains, in particular in the basins of the Colorado and the Rio Grande rivers. The lowest annual maximum SSC are found in the Canadian Maritime Provinces and in north-eastern USA. The spatial distribution of annual maximum concentrations is very similar to that of mean suspended sediment concentration as shown by Dodds & Whiles (2004). There is also great variability in SSC from year to year in the same river. A coefficient of variation was computed for annual series of maximum SCC for each station. The mean value for all stations is 0.63 (median is 0.53). In most cases, rivers with high annual maximum concentration of SSC have a high coefficient of variation.

4.4 Results

4.4.1 Stationarity, independence and homogeneity tests

All time series of annual maximum SSC were tested for stationarity (Kendall test), independence (Wald-Wolfowitz test) and homogeneity (Wilcoxon test), as a prerequisite for frequency analysis. Table 4.2 shows the number of stations that failed these tests at significance levels of 5% and 1%. Stations that failed one or several tests at the 1% level were eliminated for frequency analysis (29 stations in total). There are 179 stations passing these tests at the 1% level. Fifty-one stations failed the Kendall test at the 5% level and twenty-six at the 1% level, showing a possible trend in some series of annual maximum of SSC (Figure 4.4). In all cases it is a decreasing trend except for Deerlick River in Alberta and Pearl River in Louisiana. These 51 stations include all the stations with the longest time series, i.e. with over 30 years of data. The average length of series that exhibit a trend is 22 years. They also include the largest river basins of the study area such as Rio Grande, Sacramento, Colorado, Green River, Red River, and Mississippi. Numerous stations with a very small drainage area also exhibit a trend, for example Deerlick Creek in Alberta (9 km2) and Third Creek in North Carolina (12 km2).

4.4.2 Seasonality of annual maximum SSC

The time and the season of the year when annual maximum occur for all 179 stations remaining were investigated. Figure 4.5 shows the frequency per month of annual maximum SSC for all stations. In North America, the annual maximum SSC occurs more often in spring, during the months of April, May and June. Peaks of SSC in spring are usually associated with snowmelt but could also be produced by rainfall events on soils not yet protected with a fully grown vegetation cover (Lecce *et al.*, 2006). High concentrations in summer months are generally caused by thunderstorms inducing high rainfall intensity (Steegen *et al.*, 2000; Lecce *et al.*, 2006). Figure 4.6 shows, for each station, the season of the year when most annual SSC maxima are recorded. Figure 4.6 is based on histograms computed for each station; the mode of the histogram was extracted and used as a basis of comparison between stations. In Canada, all annual maximum SSC values occur in spring and summer, except for two stations in the Maritime Provinces. Most stations in the Canadian prairies are characterized by annual maximum occurring in the summer or late spring. Besides the main seasonal trends described above, in the USA annual maximum also occur during the fall and winter seasons, especially for rivers located in California where most maximum occur during the winter. In this region of Mediterranean climate, water and sediment discharge patterns are driven by episodic winter rainfall events (Warrick *et al.*, 2004).

When visually assessing the time series of annual SSC, some stations appeared to exhibit a bimodal behaviour, with annual maximum occurring in spring and also in fall. These stations are usually located in Canada and in northern USA. Since homogeneity of the data is a requirement for frequency analysis (Rao & Hamed, 2001) the Wilcoxon test (Wilcoxon, 1945) was used on a seasonal basis to find out if all annual SSC maximum for a given station come from the same population. In spite of some of the variations shown in Figures 4.5 and 4.6, the hypothesis of a homogenous population was found to be acceptable for all stations at both 5% and 1% significance levels.

4.4.3 Correlation of annual maximum SSC with flow

Estimation of SSC or calculation of loads is often done with rating curves that establish the relationship between concentration and discharge (Asselman, 2000; Horowitz, 2003). Several methods exist for developing sediment rating curves. The most common is the use of a power function (regression) that relates SSC to water discharge. Since the relationship between the annual extremes of SSC with flow is of interest, it was investigated for all available stations (208). For 151 stations (85%), the annual maximum SSC occurs in the same season as the maximum flow. For 49 stations it occurs during the same month. The geographic repartition of the timing of annual peak flows for the selected stations is very similar to Figure 4.6, which shows the most frequent season of occurrence of extreme SSC. In most cases for which a difference was found, the annual maximum SSC occurs at the end of spring (June) and the maximum annual flow at the beginning of summer (July). The correlations between each annual maximum of SSC and daily flows for a period covering 5 days before and 5 days after the occurrence of maximum SSC were examined. The plot of the relationship between the annual maximum SSC events and the corresponding maximum flows usually shows a somewhat linear relationship, but in some cases a lot of scatter exists. Figure 4.7 is an example of two plots. Dry Creek, California (left) exhibits a good relationship between flow and maximum SSC, whereas Big Creek, Illinois (right) does not.

A Kendall τ rank correlation coefficient was computed between SSC annual maximum time series for each station and flow. This coefficient is more appropriate than the Pearson coefficient because it is based on rank and therefore less sensitive to outliers (Helsel & Hirsch, 2002). There are significant correlations between annual maximum SSC and flow for 92 stations at the significance level of 5% and 119 stations at the 10% level. For stations with a significant correlation, τ varies from 0.3 to 0.85. The mean value of τ is 0.56. Most of these significant correlations are found for stations located in California and along the Rio Grande. However, there are a few rivers in the Rio Grande basin that do not exhibit such strong correlation or no significant correlation at all. This could be explained by the high degree of regulation by dams and reservoirs in Rio Grande basin, where high SSC could be more related to water releases from dams than to natural flow conditions. For the rest of the continent, the repartition of station with a significant correlation does not exhibit any specific spatial pattern. Figure 4.8 shows box plots of correlation coefficients for different lead and lag periods between annual SSC maximum and discharge, from 5 days before the SSC event to 5 days after. Correlation is greater between annual maximum SSC and discharge occurring after the SSC event (median $\tau > 0.5$ for correlation with maximum discharge lagging the annual peak of SSC, median $\tau < 0.5$ for correlation with discharge leading).

The average period between the SSC event and a peak of discharge (lag or lead) is 0.7 days. It can be seen that in most cases for annual maximum SSC, there is a clockwise hysteretic effect with high concentration of suspended sediments preceding a high discharge event. There are no particular geographic patterns for the stations that have a lead or a lag. Most large basins have a longer delay between peak SSC and the corresponding flow, with lag values from 3 to 5 days but there is no significant correlation of the lag with the size of drainage area.

4.4.4 Best fitted probability distributions

The HYFRAN software (www.ete.inrs.ca/activites/groupes/chaire_hydrol/hyfran.html) combined with codes of the FRESH software (Ouarda *et al.*, 2003), were used to fit the statistical distributions. As stated earlier, the 16 distributions of Table 4.1 were fitted to each sample of maximum annual SSC for the stations that met the requirements for frequency analysis. Figure 4.9 shows the distributions that were selected as the best fit to the 179 series using AIC and BIC as well as graphical validation. The log-normal distribution was selected for 52 stations, the Exponential distributions for 41 stations, the Weibull for 29 stations and the Gamma for 24 stations. The remaining 36 stations were best fitted by one of the following six distributions: log-Pearson type 3, GEV, normal, Gumbel, Leaks, generalized Pareto and lognormal with three parameters. Figure 4.10 shows two examples of distribution fit; the exponential model for Turtle River in Manitoba (Canada) and the lognormal model for Beaverhead River in Montana (USA). When considering the four lowest scores on AIC and BIC criteria, 24 of the 36 stations can actually be fitted by one of the four most popular distributions. Only 12 stations did not include the four most popular distributions. The $\chi 2$ test was implemented for these 12 stations to analyse the possibility to fit either the exponential, lognormal, Weibull or Gamma distributions. In all cases, one or several of the four distributions tested could fit the data series at the 5%, and some at the 1% significance level.

Figure 4.11 shows the locations of the best fitted distributions. There is no geographical area where a particular distribution is predominant. There is no particular spatial pattern in the selected distributions. Some rivers that are very close geographically can have annual maximum SSC fitted with different probability distributions. There are even cases where several gauging stations located in the same river system were fitted with different distributions, e.g. Fraser River in British Columbia (lognormal, Gumbel, Weibull) and Rio Grande in New Mexico (Weibull, Gamma, exponential). We found no significant relationship between the selected distributions and the size of the drainage area or the length of the data series.

With series of annual maximum of SSC modelled by a probability distribution, it becomes possible to extract additional information on extremes. First, it is possible to calculate the annual maximum SSC for different return periods such as 2, 5, 10, 20 or 50 years. However, the right tail of the distribution is the one with the largest confidence interval meaning that extrapolating for high return periods is less accurate. Another type of information that could be computed is the return period for specific values of concentrations, for example lethal or stressful values of suspended sediment concentration for a specific fish species. Examples of the type of results this study can produce are shown in Figures 4.12 and 4.13. Figure 4.12 shows a map of quantiles corresponding to T = 2-year return period. Although Figure 4.12 shows some important spatial variability in quantiles, it can be seen that the Maritimes Region of Canada is characterized by SSC < 500 mg/L for a 2-year return period and that the highest SSC quantiles are found in the Rio Grande and Colorado basins. Figure 4.13 shows a map of the return period for a concentration of 1000 mg/L. This threshold can be lethal for certain species of fish such as juvenile coho salmon (Oncorhynchus kisutch) found in the western part of the continent (Waters, 1995), and larval striped bass (Morone saxatilis) found in the eastern part of the continent (Auld & Schubel, 1978).

In Figure 4.13, there is a return period greater than 100 years for the Rio Grande station below Cochiti Dam (station no. 8317400 in New Mexico). Compared to other stations of the same region, this station exhibits very low mean SSC (25.7 mg/L) as well as small loads (average of 50 000 t/year, US Geological Survey data averaged on the period 1975–1988). This is a good illustration of the effect of dams on mean sediment delivery and extremes as this station is located immediately downstream of Cochiti Dam, one of the ten largest earth fill reservoirs of the USA. Studies have shown that Cochiti Dam traps an estimated 80% of sediment inflow (Ortiz & Meyer, 2002). As a comparison, the Rio Grande station located upstream of Cochiti dam (Rio Grande at Otowi Bridge, no. 8313000) has a return period of one year for the same SSC (1000 mg/L). This station exhibits a mean concentration of SSC of 1180 mg/L and carries 2 000 000 t of sediments per year (USGS data averaged on the period 1956–1996).

4.5 Discussion and conclusions

Frequency analysis of maximum annual SSC provides a useful tool to extrapolate values of concentration for different return periods, depending on the information required. To our knowledge, this is the first attempt to use such a probabilistic approach on extreme concentrations of suspended sediments at a sub-continent scale. By fitting statistical distributions to series of annual maximum of sediment concentration it is possible to calculate return periods and quantiles for 179 rivers in North America, reflecting a wide variety of sizes, climates and ecosystems. Annual maximum SSC were modelled using different probability distributions. The lowest scores of AIC and BIC were found for four two-parameter distributions that could fit 80% of the data series.

The Lognormal and Exponential distributions are the most adequate for half of the stations (90). The Weibull and Gamma models follow with respectively 29 and 21 stations. These four distributions all belong to the Gumbel family of extreme values distributions. The Exponential distribution is a special case of the Weibull or Gamma distributions, with a shape character equal to 1. The remaining 20% of annual maximum SSC series were best fitted using seven other distributions including the GEV and log-Pearson type 3 (three parameters) and two-parameter distributions like the normal or Gumbel. If distributions with the four lowest AIC and BIC values are considered, the exponential, lognormal, Weibull and Gamma distributions can model 90% of the stations. These selected distributions do not exhibit any geographic pattern. In some cases, SSC series from neighbouring river basins are not fitted with the same statistical distributions. Even series from the same river system were sometimes fitted with different distributions. This shows the site-specificity of extreme SSC occurrence and magnitude. This feature of sediment transport was described in previous studies. Lecce *et al.* (2006) suggested that concentrations may be difficult to predict because of local factors associated with vegetation, Asselman (2000) showed high spatial differences in the relationship between discharge and SSC for different locations in the Rhine River. There is no apparent link between selected distributions with drainage area or length of time series. At this point it is hypothesized that the characteristics, such as land cover vegetation and soil type of each watershed or even the physiographic conditions in a relatively small portion of the basin in the vicinity of the station (Jarvie *et al.*, 2002; Siakeu *et al.*, 2004) may explain the lack of spatial consistency in selected distributions.

There is a statistically significant correlation between flow and annual maximum sediment concentrations for only half of the stations. For the stations with a significant correlation, the greater correlation is with the discharge peak occurring after SSC annual maximum. Different types of hysteresis occur, some clockwise and others anticlockwise. Usually, clockwise hysteresis indicates that the stream channel itself represents a significant source of SSC coming from stored material deposited after prior events and/or base flow while counter-clockwise loops suggests that sediment is delivered by hillslope processes or distant sources (Wood, 1977; Meade *et al.*, 1990; Lecce *et al.*, 2006). However, other explanations have been proposed: the length and duration of events (Wood, 1977) or the supply of sediment from distant hillslope sources (Steegen *et al.*, 2000). In small basins, peak concentration is more likely to lead peak discharge (Knighton, 1998) and the lead period is usually short (Banasik *et al.*, 2005). In large basins the lag between peak flow and SSC can be larger due to location of sediment sources within the watershed. Sediment transport is mainly associated with discharge, but also with sediment availability. This means that in some cases, large amounts of sediment are available and can be transported by flows that are above average, but not extreme. For example, in arid environments such as deserts, storms during summer and fall can occur when there are large quantities of fine materials on the hill slopes (Coppus & Imeson, 2002). The wash load of the slopes associated with the remobilisation of deposits within the stream could lead to great concentrations of suspended sediments (Knighton, 1998). An illustration can be found in the arid Rio Grande region; many rivers within that region exhibit strong correlation between annual maximum SSC and high discharge events while some stations have no significant correlation. In addition to natural fluctuations of sediment concentrations linked with flow, rare events such as volcanic eruptions and a number of anthropogenic activities such as road building, logging, or mining may produce large amounts of fine sediments that have the potential to disturb the sediment regime and increase SSC in a water body.

Annual maximum concentrations of suspended sediment exhibit a trend in 51 stations at the 5% significance level. A more thorough investigation of the causes of these trends for the selected rivers would require an analysis of the physical characteristics of the watersheds which is beyond the scope of this initial study. Benedetti (2002) has shown a similar decreasing trend in peak SSC values in the Mississippi River. According to his study, the most likely causes for the observed trends are agricultural land management practices aimed at reducing soil erosion and the construction of dams and reservoirs. Walling & Fang (2003) also linked the decreasing trends of SSC and load in the Mississippi and Colorado rivers with the construction of reservoirs.

Studies of water quality to establish habitat availability for several aquatic species have shown that the duration of high suspended sediment concentration events is as important as the concentration itself. Newcombe & Jensen (1996) stated that concentration alone can be insufficient as an indicator of suspended sediment effects. In order to eventually incorporate sediment in aquatic habitat suitability models, one way of combining concentration and duration could be to use a peak-over-threshold (POT) approach. Using this approach, it is possible to model the events above a certain threshold of concentration as well as duration of these events. However, the POT approach requires the selection of the threshold and the development of criteria to retain peak values since independence of the data is a prerequisite of frequency analysis (Lang *et al.*, 1999). In the case of SSC, even relatively low thresholds that are exceeded for a long time will have an impact on habitat (e.g. St-Hilaire *et al.*, 2006; Ouellette *et al.*, 2006). Sub-lethal impacts of sediments on fish populations can appear at low concentration levels if there is a long duration of exposure (Waters, 1995).

This study is the first prerequisite step to perform a regional analysis, which would aim to estimate SSC quantiles and return periods of extreme concentration for ungauged rivers. Using quantiles of concentration or loads at gauged sites, coupled with a database on the watershed characteristics such as land use, soil types and topography, it could be possible to adapt methods developed for regionalisation of floods (e.g. GREHYS, 1996). This approach could be used to model several aspects of extreme transportation of sediments on ungauged rivers, including concentration and loads. But regionalization of SSC extremes is probably a greater challenge than for other hydrometric variables (flood or low flows) because of its site specificity.

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Tableau 4.1: Probability distribution functions used

Name	Probability density function	Domain	Number of param.
Exponential	$f(x)=\frac{1}{(x-m)\sigma\sqrt{2\pi}}\exp\left\{-\frac{\left[\ln(x-m)-\mu\right]^{2}}{2\sigma^{2}}\right\}$	$x > m$	2
Leaks	$f(x)=e^{-\lambda}$ **if** $x = 0$	$x > 0$	2
	$f(x)=\frac{\lambda}{\beta}\exp(-\lambda-\frac{x}{\beta})\frac{I_1\left(2\sqrt{\frac{\lambda x}{b}}\right)}{\sqrt{\frac{\lambda x}{b}}}$ **if** $x > 0$		
Gamma	$f(x)=\frac{\alpha^{\lambda}}{\Gamma(\lambda)}x^{\lambda-1}e^{-\alpha x}$	$x > 0$	2
Generalised Gamma	$f(x)=\frac{\lvert s\rvert\alpha^{s\lambda}}{\Gamma(\lambda)}x^{s\lambda-1}e^{-(\alpha x)^{s}}$	$x > 0$	3
GEV	$f(x)=\frac{1}{\alpha}\left[1-\frac{k}{\alpha}(x-u)\right]^{\frac{1}{k}-1}\exp\left\{-\left[1-\frac{k}{\alpha}(x-u)\right]^{1/k}\right\}$	$x > u+\alpha/k$ if $k < 0$ $x < u+\alpha/k$ if $k > 0$	3
Gumbel	$f(x)=\frac{1}{\alpha}\exp\left[-\frac{x-u}{\alpha}-\exp\left(\frac{x-u}{\alpha}\right)\right]$	$-\infty < x$ $x < +\infty$	2
Halphen A	$f(x)=\frac{1}{2m^{\upsilon}K_{\upsilon}(2\alpha)}x^{\upsilon-1}\exp\left[-\alpha\left(\frac{x}{m}+\frac{m}{x}\right)\right]$	$x > 0$	3
Halphen B	$f(x)=\frac{2}{m^{2\upsilon}ef_{v}(\alpha)}x^{2\upsilon-1}\exp\left[-\left(\frac{x}{m}\right)^{2}+\alpha\left(\frac{x}{m}\right)\right]$	$x > 0$	3
Inverse Halphen B	$f(x)=\frac{2m^{2\upsilon}}{ef_{v}(\alpha)}x^{-2\upsilon-1}\exp\left[-\left(\frac{m}{x}\right)^{2}+\alpha\left(\frac{m}{x}\right)\right]$	$x > 0$	3
Lognormal two parameters	$f(x)=\frac{1}{x\sigma\sqrt{2\pi}}\exp\left\{-\frac{(\ln x-\mu)^{2}}{2\sigma^{2}}\right\}$	$x > 0$	2

Tableau 4.2: Probability distribution functions used (suite)

Name	Probability density function	Domain	Number of param.
Lognormal three parameters	$f(x) = \frac{1}{(x-m)\sigma\sqrt{2\pi}} \exp\left\{-\frac{[\ln(x-m)-\mu]^2}{2\sigma^2}\right\}$	$x > m$	3
Log-Pearson type 3	$f(x) = \frac{\alpha^\lambda}{x\Gamma(\lambda)}(\ln x - m)^{\lambda-1} e^{-\alpha(\ln x - m)}$	$x > e^m$	3
Normal	$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left\{-\frac{(x-\mu)^2}{2\sigma^2}\right\}$	$-\infty < x$ $x < +\infty$	2
earson type 3	$f(x) = \frac{\alpha^\lambda}{\Gamma(\lambda)}(x-m)^{\lambda-1} e^{-\alpha(x-m)}$	$x > m$	3
Weibull	$f(x) = \frac{c}{\alpha}\left(\frac{x}{\alpha}\right)^{c-1} \exp\left[-\left(\frac{x}{\alpha}\right)^c\right]$	$x > 0$	2
Generalised Pareto	$f(x) = \frac{1}{\alpha}\left(1 - \frac{k}{\alpha}x\right)^{(1/k-1)}$ **if** $k \neq 0$ $f(x) = \frac{1}{\alpha}e^{-x/\alpha}$ **if** $k = 0$	$k \leq 0$ $0 \leq x < +\infty$ $k > 0$ $0 \leq x \leq \alpha / k$	2

Tableau 4.3: Number of stations failing each considered test depending of the significance level

Test	5%	1%
Kendall	**52**	**24**
Wald-Wolfowitz	**30**	**14**
Wilcoxon	**44**	**20**
One or multiple tests	**75**	**29**

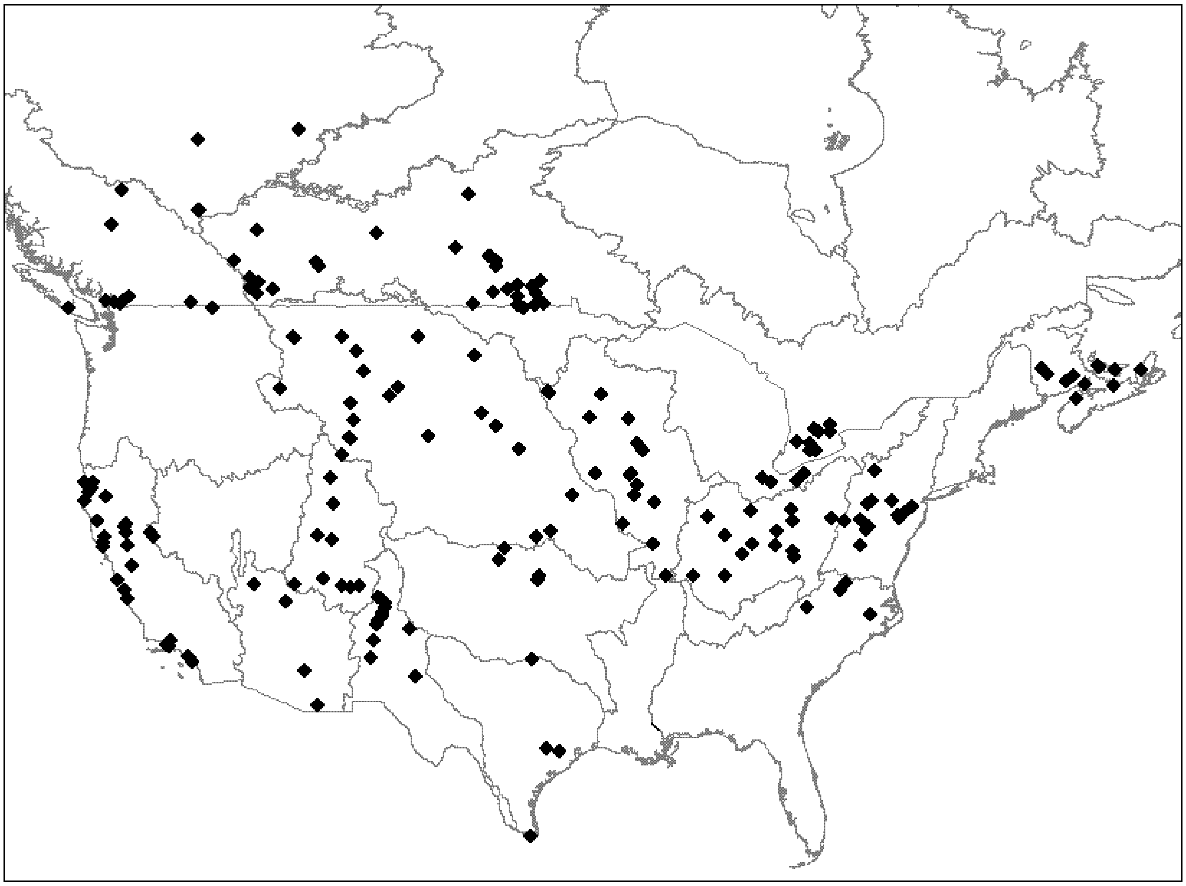

Fig. 4.1: Location of the 208 stations

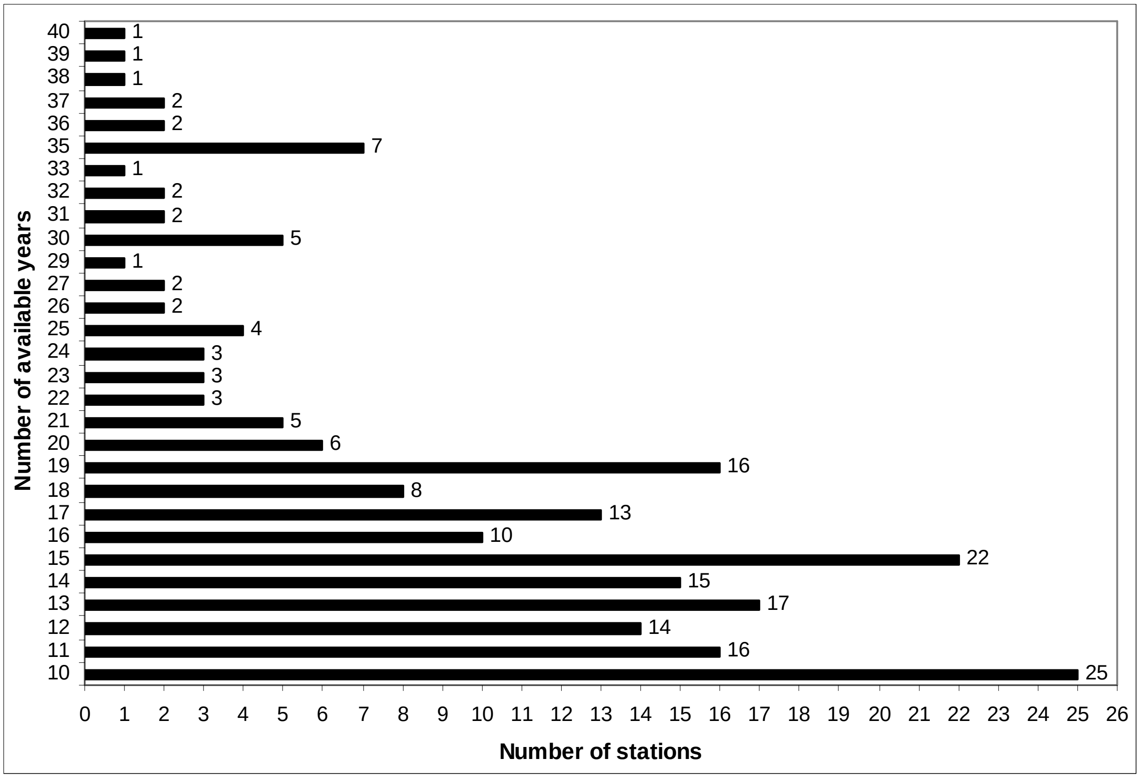

Fig. 4.2: Length of data series

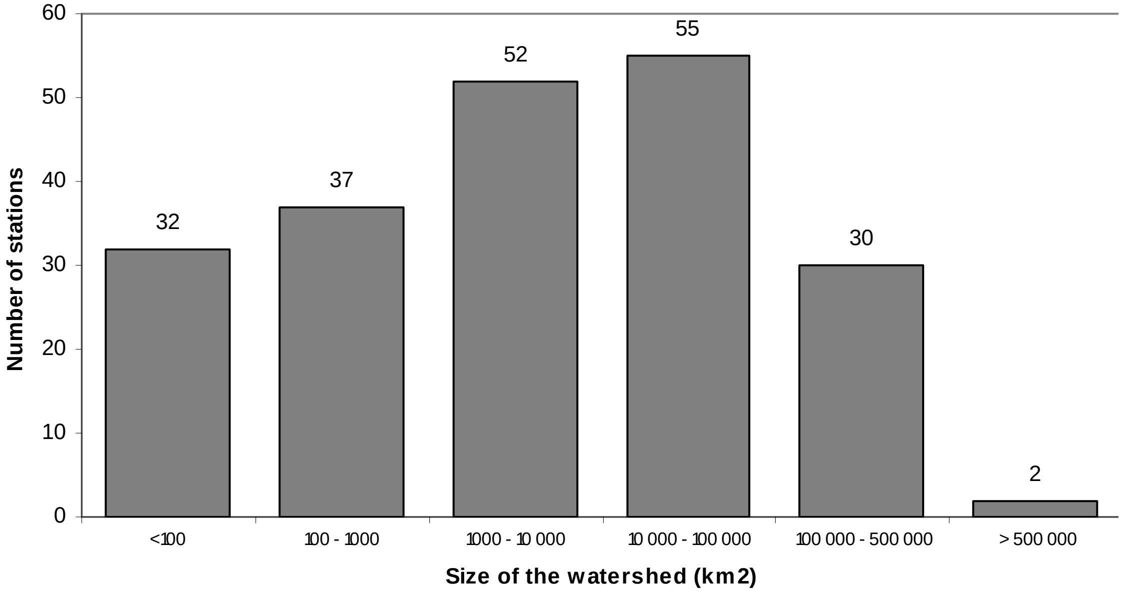

Fig. 4.3: Size of the watersheds

Fig. 4.4: Stations with a trend

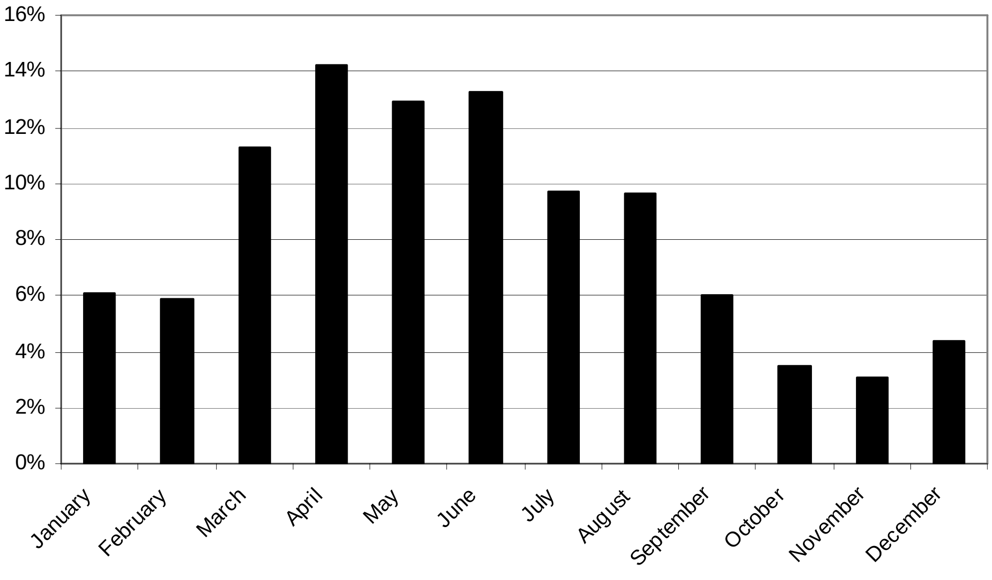

Fig. 4.5: Frequency of annual maximum SSC

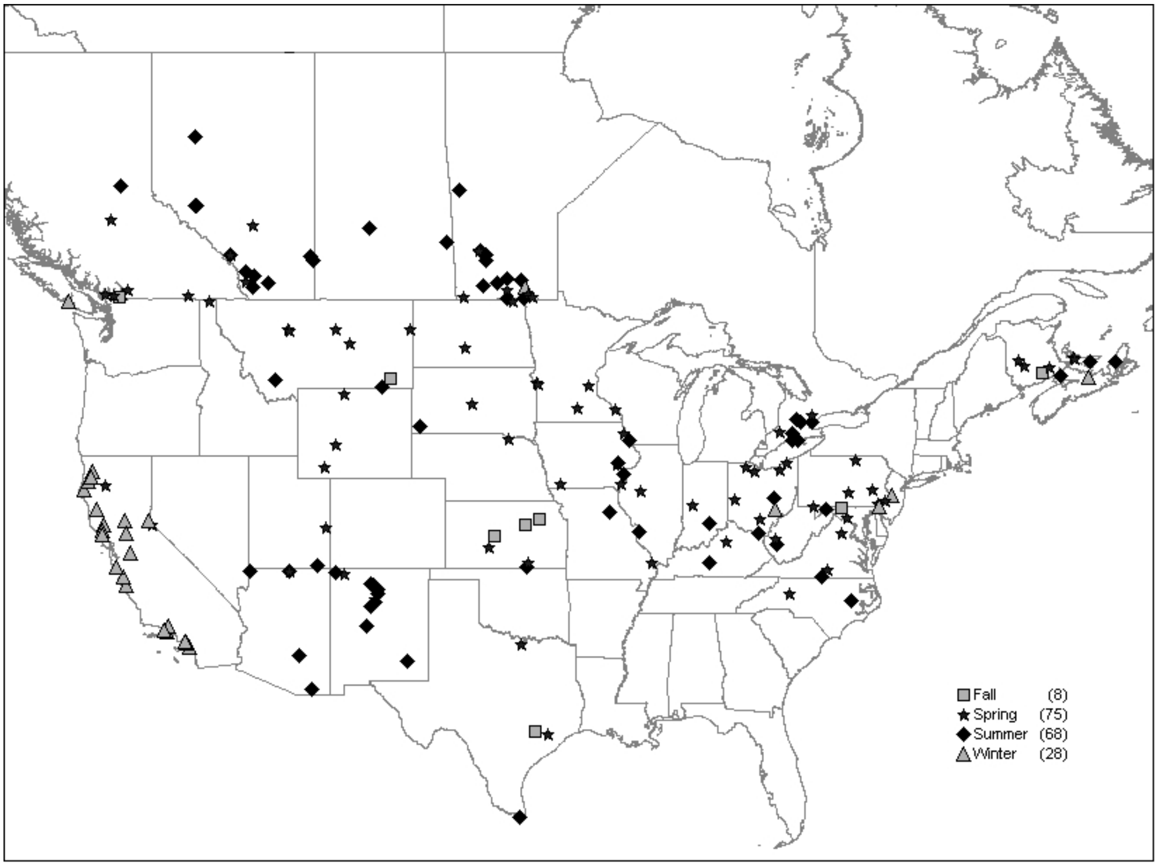

Fig. 4.6: Season of maximal occurrence of annual maximum SSC

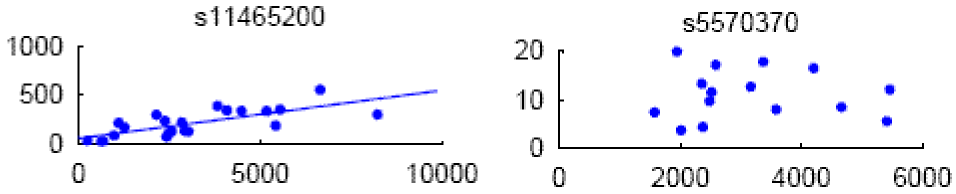

Fig. 4.7: Relation between annual maximum (horizontal) and corresponding flow (vertical) in Dry Creek, California (left) and Big Creek, Illinois (right)

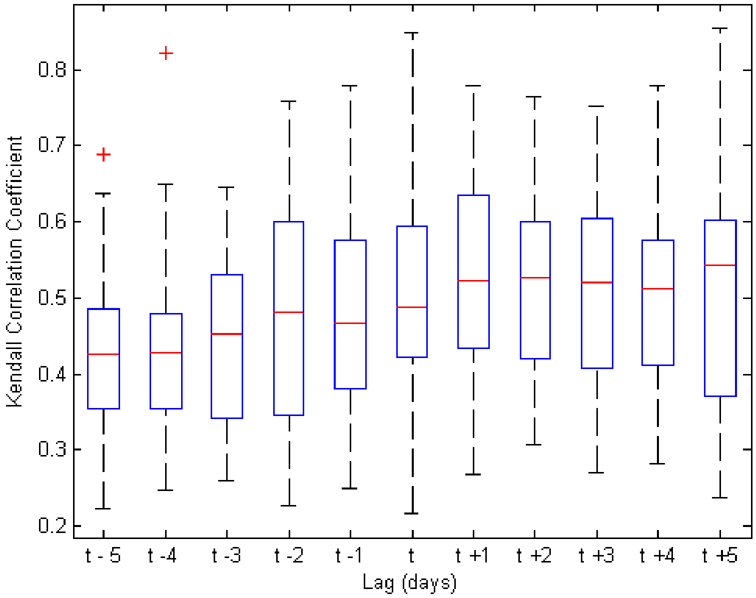

Fig. 4.8: Box plot (25th, 50th, and 75th percentiles) of Kendall correlation coefficient for different lags days between discharge and annual maximum SSC (*t* = event of SSC)

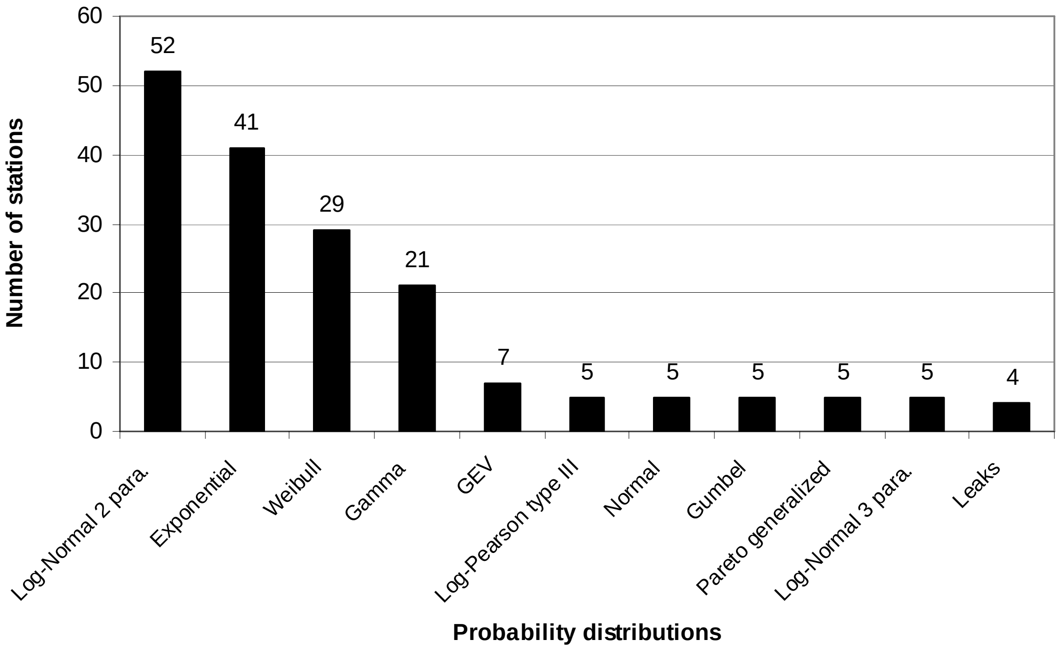

Fig. 4.9 : Probability distributions fitted

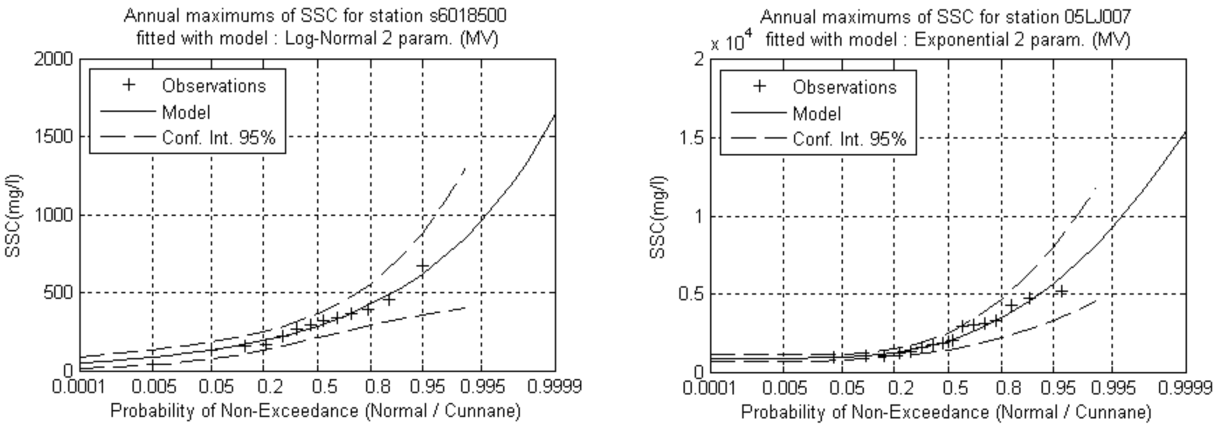

Fig. 4.10: Examples of distribution fit for stations 6018500 (left) and 05LJ007 (right)

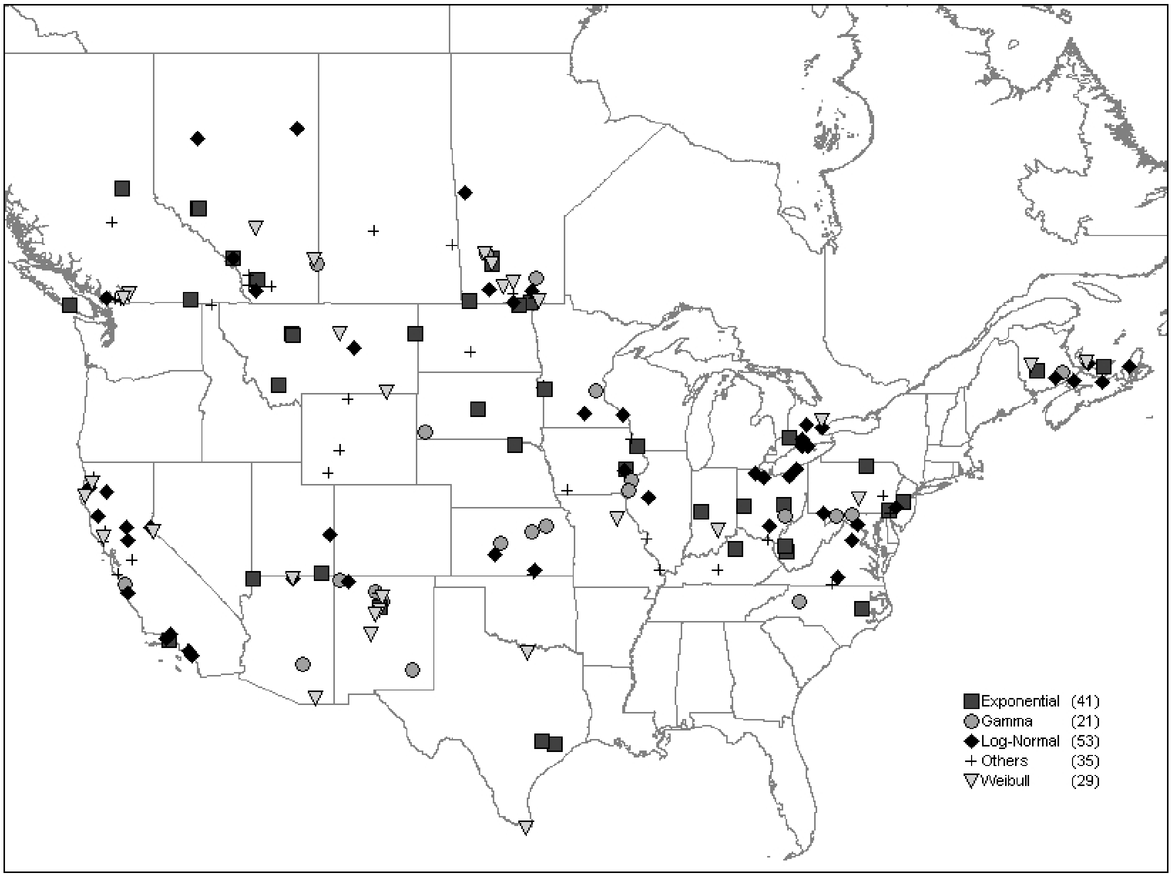

Fig. 4.11: Best fitted probability distributions to annual extreme SSC

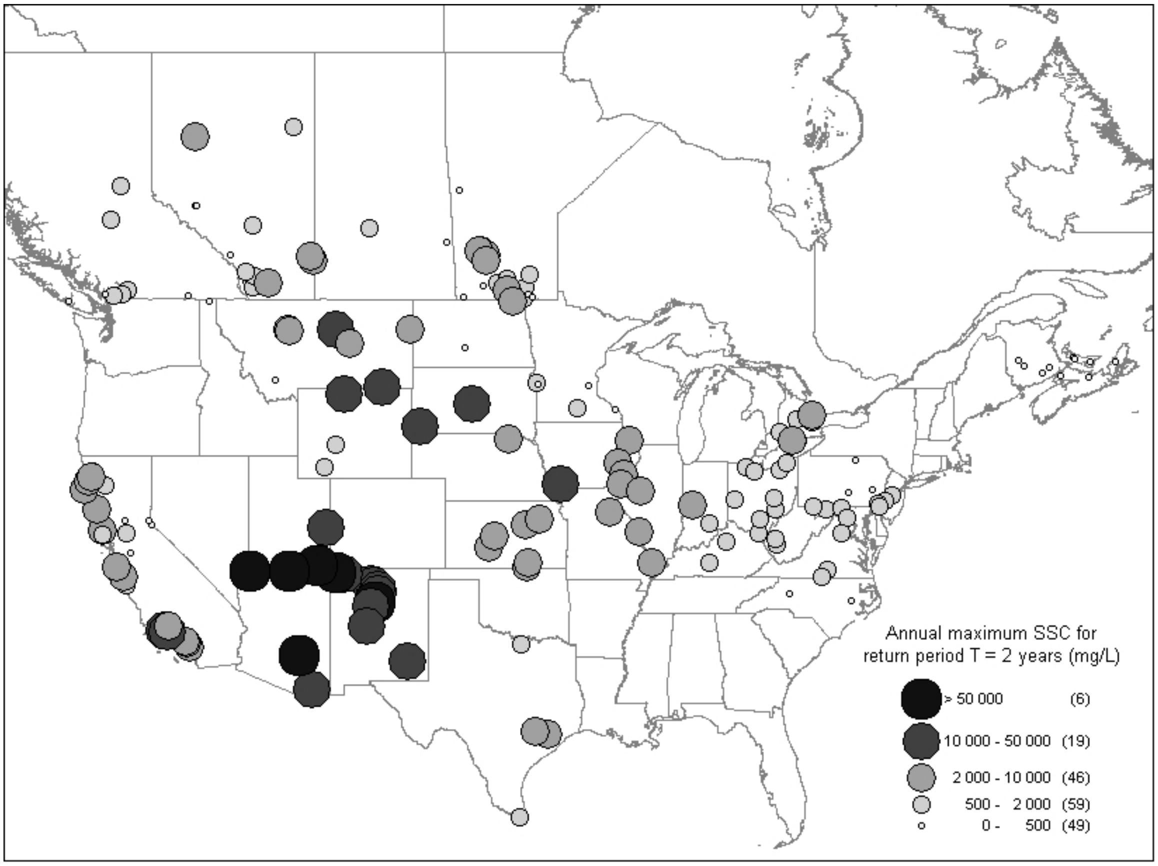

Fig. 4.12: Concentration quantiles corresponding to a 2-year return period

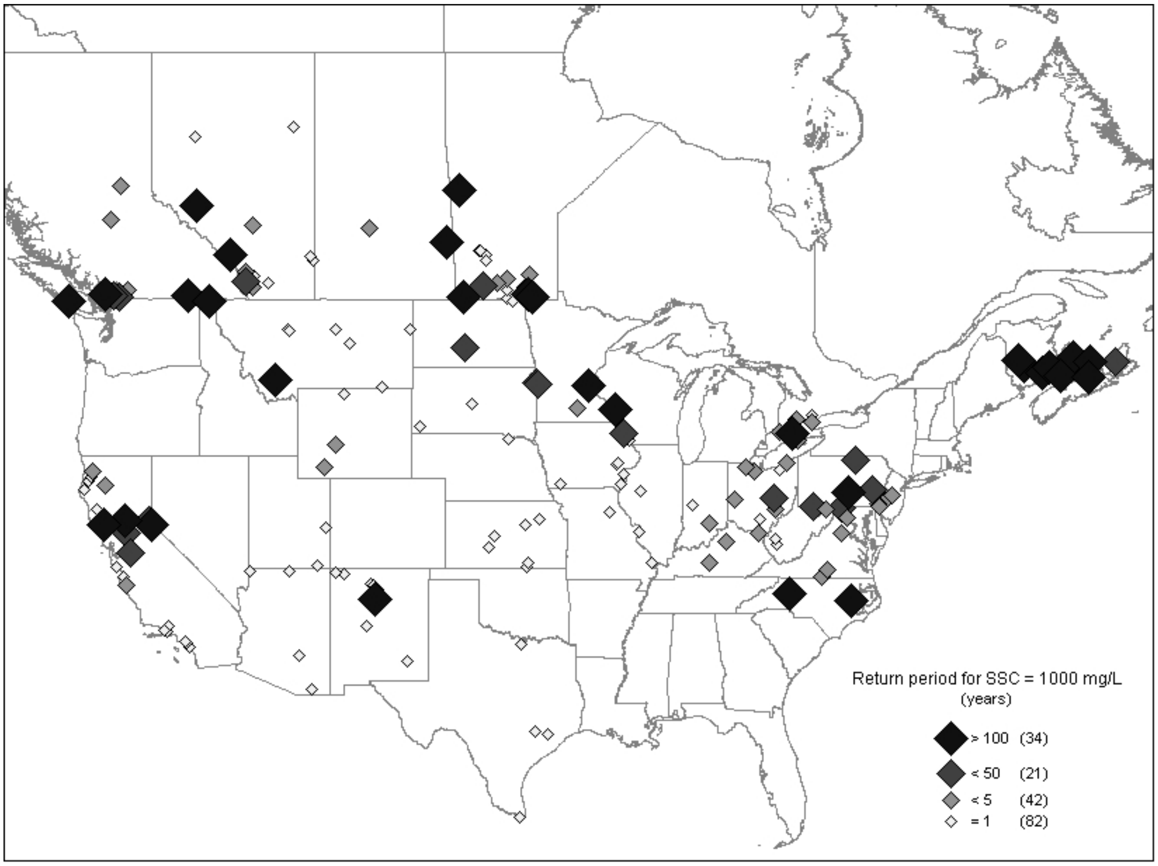

Fig. 4.13: Return period for an annual maximum concentration of 1000 mg/L

CHAPITRE 5 : Régionalisation des concentrations extrêmes de sédiments en suspension en Amérique du Nord

REGIONALISATION OF EXTREME SUSPENDED SEDIMENT CONCENTRATIONS IN NORTH-AMERICA

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Abstract

The number of stations monitoring daily suspended sediment concentration (SSC) has been decreasing since the 1980s in North America while suspended sediment is considered as a key variable for water quality. The purpose of this study is to test the possibility of regionalisation to estimate extreme SSC in ungauged basins using the watershed characteristics. Annual maximum of SSC for 72 rivers in Canada and USA were modelled with probability distributions in order to estimate quantiles corresponding to different return periods. Regionalisation techniques, originally developed for flood prediction in ungauged basins, were tested using the climatic, topographic, land cover and soils attributes of the watersheds. Two approaches were compared, using either physiographic characteristics or seasonality of extreme SSC to delineate the regions. Multiple regression models between SSC quantiles and watershed characteristics were built in each region, and compared to a global model including all sites. The most important variables for predicting extreme SSC are the percentage of clay in the soils, precipitation intensity and forest cover. The relative efficiency of each method to estimate extreme SSC was assessed by considering a Jack-Knife procedure. Regional estimates of SSC quantiles were compared with the local values. Results show that regional estimation of extreme SSC is more efficient than a global regression model including all sites. The seasonality-based approach yields better results for estimation of the longer return periods.

5.1 Introduction and literature review

High suspended sediment concentrations (SSC) are harmful to certain species of fish and aquatic organisms (Newcombe and Jensen 1996, Suren *et al.*, 2005), increase the cost of drinking water treatment and possibly carry large amounts of pollutants (Waters, 1995). High concentrations affect the biota by reducing the density, productivity and abundance of primary producers and macro invertebrates (Wood & Armitage, 1997). Concentrations above 80 mg/L start to affect some fish populations, and concentrations above 200 mg/L are assumed to be harmful to most North American fish (Waters, 1995).

From 1982 to 2002, the number of sediment monitoring stations in the USA has decreased by 71% (Osterkamp & Parker, 1991, Gray & Glysson, 2002) and the same trend is observable for stations in Canada (Day, 1992). In the mean time, the need for reliable, cost-effective, spatially and temporally consistent data on sediment has never been greater for engineering, environmental and regulatory considerations since suspended sediment is more and more considered as a key variable for water quality (Gray & Glysson, 2002, Horowitz, 2003, Meybeck *et al.*, 2003). To palliate this lack of measurements, it is necessary to develop reliable estimation methods for suspended sediment transport.

Estimation of SSC is often done with rating curves that establish an empirical relation between sediment concentration and discharge. Several studies have shown that rating curve models tend to underestimate high SSC values (Fergusson, 1985, Asselman, 2000, Horowitz *et al.*, 2003) even when a bias correction method is applied (Walling & Webb, 1988). Improvements in estimating SSC have been noted when data sets were subdivided into seasonal or hydrological groupings (Asselman, 2000, Horowitz *et al.*, 2003) or with the use of truncated rating curves relating only the highest quantiles of SSC and river flow (Meybeck *et al.*, 2003, Simon *et al.*, 2004). Inaccurate prediction of extreme SSC can be related to the scattered relation that could exist between sediment and discharge caused by hysteresis effect (Smith & Croke, 2005). Weak correlations between SSC and discharge have been reported in several studies. Tramblay *et al.* (2008) have shown that correlation between annual maximum SSC and corresponding discharge (taking into account the possible lag time caused by hysteresis) was significant in only 92 out of 208 rivers in North America. These results suggest that for many rivers, suspended sediment transport is rather supply limited than discharge limited. Discharge alone is therefore not sufficient to estimate magnitude of extreme SSC in numerous rivers.

Aside from discharge, several studies have established significant correlations between some watershed characteristics (including topography, geology, climate, and land use) and sediment yield (Slaymaker, 1982, Bray & Xie, 1993, Ludwig & Probst, 1998, Restropo *et al.*, 2006), mean SSC values (Jarvie *et al.*, 2002, Robertson *et al.*, 2006, Siakeu *et al.*, 2004, Dodds & While, 2004) or extreme SSC (Tramblay *et al.*, 2007). Robertson *et al.* (2006) used a regression tree analysis to create groups of rivers in the Great Lakes region in order to estimate several water quality parameters, including suspended sediments. Jarvie *et al.* (2002) constructed multiple regression models to explore the linkages between land characteristics and SSC in central England. To our knowledge no studies used this approach for extreme SSC.

In this study an alternate way of estimating extreme SSC is considered, based on a probabilistic approach. Frequency analysis is a statistical approach commonly used in hydrology to relate the magnitude of extreme events (e.g. floods or low flows) to a probability of occurrence (Rao & Hamed, 2001). Only a few studies used a probabilistic modelling approach for SSC. Van Sickle (1981) developed a peak-over-threshold Poisson model for annual sediment yield for two small Oregon streams. Watts *et al.* (2003) computed exceedance probabilities of SSC for 1–6-day durations using peaks-over-threshold techniques for reaches of the Lower Swale, UK. Simon *et al.* (2004) estimated suspended sediment transport conditions at the 1.5-year recurrence interval for rivers in the USA. Galéa *et al.* (2004) proposed the transposition of the discharge-duration-frequency analysis concept (or QdF) to the wash load in the Bega sub-basin in Romania. Soler *et al.* (2007) fitted the log-normal distribution to annual maximums and partial duration series of SSC for the Vallcebre basin in Spain. Application of the frequency analysis approach and results for annual maxima of SSC in 179 rivers of North America are detailed in Tramblay *et al.* (2008).

In this study, the feasibility of regionalisation techniques is tested for extreme SSC using some approaches developed originally for the regionalisation of floods. The goal of flood regionalisation is to estimate flood quantiles in ungauged catchments using the watershed characteristics (GREHYS 1996). The two main steps are the identification of groups of hydrologically homogeneous basins and the regional estimation within each delineated region to estimate flood characteristics at the site of interest. In this study, two approaches are compared to identify hydrologically homogeneous regions. The first approach is based on grouping catchments according to their physiographic similarity. This approach is commonly used in the regionalisation of floods (Nathan and McMahon, 1990, GREHYS, 1996). The other approach tested is based on the similarity in seasonality of occurrence of extreme SSC. Regionalisation methods based on seasonality have been recently gaining increased popularity among hydrologists (Ouarda *et al.*, 2006). In these seasonal regional models, the delineation of homogeneous regions is based on the seasonal behaviour of flood flows in the various stations (Burn 1997, Ouarda *et al.*, 2006). The two main objectives of this study are:

1. To identify the most significant physiographic variables affecting extreme SSC. These variables can subsequently be used in regionalisation methods.
2. To compare the estimation performance of two regionalisation models versus a unique (i.e. encompassing all study sites) for extreme SSC. The first approach considers seasonality of extreme SSC and the second uses the physiographic characteristics of the watershed to delineate regions.

5.2 Study area and data collection

5.2.1 Selected stations

Data from 140 gauging stations in North America constitute the basis of the project (2505 station-years). In North America, the annual maximum SSC occurs more often in spring, during the months of April, May and June except for rivers located in California and Rio Grande or Colorado systems (Tramblay *et al.*, 2008). Stations having annual maxima of SSC occurrence in spring were chosen because they represent the largest population of stations having long records (10 years or more) of SSC in North America (Tramblay *et al.*, 2008).

Peaks of SSC in spring are usually associated with snowmelt but could also be produced by rainfall events on soils not yet protected with a fully grown vegetation cover (Lecce *et al.*, 2006). High concentrations in summer months are generally caused by thunderstorms inducing high rainfall intensity (Meade *et al.*, 1990, Lecce *et al.*, 2006).

In Canada, data were retrieved from the Environment Canada HYDAT Database. In the USA, data were provided by the US Geological Survey Sediment Database. Figure 5.1 shows the number of stations with SSC records available for each year. Most of the data are available for the 1970s and 1980s. Subsequently, a major decline can be observed in the number of available stations, a consequence of the monitoring networks rationalization in the USA and Canada (Osterkamp and Parker, 1991, Day, 1992). The selection criteria for stations were record length, number of missing data, hypotheses test results, watershed size and regulation level. All stations have 10 years or more of daily SSC data. Drainage area ranges between 20 km^2 and 200 000 km^2. These stations cover a wide range of climates and landscapes. Average record length is 17 years and median record length is 15 years.

Data series were screened to ensure they include no more than 20 missing days during the "spring season" (February to July). Stations on basins with major dams or reservoirs were excluded since sediment transport can be greatly affected by regulation in rivers (Walling & Fang, 2003, Walling, 2006). Metadata from Environment Canada HYDAT Database contain information about regulated rivers in Canada. In the USA, the database of the National Inventory of Dams (NID) from the US Army Corps of Engineers was used to detect the presence of large dams or reservoirs on the main stem in the selected rivers within 30 miles of each station. Time series of flow discharge were also analyzed to detect major shifts in the data that could be caused by dam construction, using the Wilcoxon and Kendall non parametric tests. 38 stations were excluded because of evidence of strong flow regulation.

Annual maxima of SSC occurring in spring (February to July) were extracted from the data, and the hypotheses of homogeneity, stationarity and independence were verified since they are a prerequisite for frequency analysis. The non-parametric tests of Wilcoxon for homogeneity, Wald-Wolfowitz for autocorrelation and Kendall for stationarity were used at the 1% significance level. 15 stations had a significant trend detected by the Kendall test and 8 series showed autocorrelation detected by the Wald-Wolfowitz test. Homogeneity was tested to detect shifts in the chronological distribution as well as on a seasonal basis to test whether events of early spring (February to April), had the same median amplitude than late spring events (May-July). Only 10 stations were found to have a non homogeneous population of early spring/late spring events of extreme SSC. In total, 30 stations failed one or several of these tests. After this selection process, 72 stations listed in Table 5.1 met all requirements and were retained for this comparative study (Figure 5.2).

5.2.2 GIS database

A GIS database was created to retrieve land cover, topography, soils types and climate characteristics for all river basins considered in this study. Boundaries of watersheds for the selected gauging stations were found in Hydrologic Units of the USA database (USGS) and using the National Scale Framework database of the department of Natural Resources of Canada. Some small watersheds not included in these reference layers were manually delimitated using a digital elevation model at small scale. Then, several layers of spatial information about elevation, land cover, soil types and climate were integrated in order to retrieve several catchment characteristics. The attributes of basins were chosen based on their availability and the previous studies on correlations of watershed characteristics with SSC (Ludwig & Probst, 1998, Jarvie *et al.*, 2002, Robertson *et al.*, 2006, Siakeu *et al.*, 2004, Dodds & While, 2004, Restropo *et al.*, 2006) and extreme SSC (Tramblay *et al.*, 2007).

The digital elevation model of the HYDRO1K database from USGS at a resolution of 1 km was used for elevation and slope data. For the USA, land cover was provided by the NLCD 1992 USGS database, with a 21-class land cover classification scheme over the United States. For Canada, land cover was provided by the Department of Natural Resources, the 1995 dataset contains 31 classes. Some classes are different in Canada and USA, such as cropland, which in described in the USA system by 5 classes (Pasture/Hay, Row Crops, Small Grains, Fallow) and 3 in the Canadian classification (Low, Medium and high biomass). To obtain a homogenous classification, the original classes were aggregated in seven categories of land use: Forest, Grassland, Cropland, Wetland, Urban and Bare Rock (Table 5.2). Soil data for the USA were extracted from the STATSGO (1994) database of USDA. Soil data for Canada come from the Soils Landscape of Canada database (SLC, version 2.0, 1994 and 3.1, 2006). Selected parameters were identical in Canadian and USA databases. All parameters were spatially averaged within the boundaries of each watershed. Several parameters were extracted as shown in Table 5.2.

Climate data were retrieved from USHCN (NOAA) and Environment Canada database. Stations with 30 years or more of data were selected. Several climate indices were computed (Table 5.2). The index of precipitation intensity (INTPREC) is given by the mean annual precipitation divided by the maximum monthly precipitation (the long term mean value of precipitation for the wettest month of each year) for the entire period of record (Restropo *et al.*, 2006). Several indices were taken from the STARDEX project (www.cru.uea.ac.uk/projects/stardex/). Days with precipitation (PRECP1) are the number of days per year with more than one millimeter of precipitation. Rainfall intensity (SDII) is the ratio of the total annual precipitation divided by the number of days with precipitation. Maximum daily precipitation (PDAYMAX) is the mean precipitation of the wettest day of the year. All indices are averaged over 30 years of observation, and interpolated with ordinary kriging (Goovaerts 1997).

5.3 Methods

The three main steps are:

1) Local estimation of quantiles at gauged stations,

2) Delineation of homogenous region and

3) Construction of the regression model for each homogenous region.

For each station, annual maxima of SSC were fitted with theoretical probability density functions to estimate local quantiles. The complete methodology for this local frequency analysis is described in details in Tramblay *et al.* (2008). Then, using these quantiles and the watershed characteristics two methods were tested for regionalisation of extreme SSC, following these two steps: the delimitation of "homogeneous" regions and regional estimation using a cross validation procedure to assess the relative efficiency of the method.

5.3.1 Clustering based on watershed characteristics

A clustering approach was tested for the delineation of homogenous regions based on the similarity of catchment attributes. Hierarchical clustering is a method for simultaneously investigating grouping in data over a variety of scales, by creating a cluster tree (GREHYS, 1996, Ouarda *et al.,* 2006). Hierarchical clustering proceeds successively by either merging smaller clusters into larger ones, or by splitting a larger cluster to smaller ones. This regionalisation technique is often applied in regional flood estimation (Nathan and McMahon, 1990; Burn *et al.,* 1997, Rao and Srinivas, 2006). Correlations between annual maximum of SSC quantiles given by local frequency analysis with catchment attributes were first investigated using Pearson correlation coefficient at the 5% level. Then, using the most significantly correlated variables, all catchments were projected in a multidimensional Euclidian space defined by theses physiographic attributes aggregated in principal components. The second step of delimitating homogeneous regions consists in combining clusters according to an index of similarity. The Ward linkage algorithm was chosen because it tends to form spherical clusters of equal size and gives the best results for identification of homogeneous regions in several regional flood frequency studies (Nathan and McMahon, 1990; Ouarda *et al.*, 2006, 2007). The last step consists in selecting the clustering level from a specific selected distance that can be determined either by the targeted number of groups or the cluster sizes. Several clustering levels were tested, in order to select the number of clusters leading to the optimal regional estimation results.

5.3.2 Clustering based on seasonality of extreme SSC

In this alternative approach, the timing of events is used instead of watershed characteristics to define catchment similarity. The main advantage of this approach is that seasonality is described using the date of annual maxima, which are more accurate than measurements related to the magnitude of events (Ouarda *et al.*, 2006). The approach is based on relative monthly frequencies. The dates of annual maximum SSC occurrences are grouped into calendar months and the relative frequencies of occurrence are calculated for every month. In each site, the relative monthly frequencies of extreme SSC provide a detailed description of the intra-annual seasonality pattern that can be used instead of physiographic attributes to establish homogenous regions. These monthly frequencies were used as clustering variables in a hierarchical cluster analysis, to construct regions. Applications of seasonality-based measures for regional flood frequency analysis can be found in Black and Werrity (1997), Burn (1997), Burn *et al.* (1997), Cunderlik and Burn (2002), Cunderlik *et al.* (2004) and Ouarda *et al.* (2006).

5.3.3 Quantile estimation

For regional estimation of quantiles, multiple linear regressions between SSC quantiles and watershed characteristics were built. Direct estimation of quantiles through multiple linear regression is the most common method used in regional estimation because of its flexibility (GREHYS 1996). In each region, a relation between SSC quantile and physiographic characteristics of the watersheds of this form was established:

$$C(T) = \beta_0 V_1^{\beta_1} V_2^{\beta_2} ... V_p^{\beta_p} e^{\varepsilon} \qquad (5.1)$$

Where *C(T)* is the quantile corresponding to a return period *T*, *βi* are the parameters to estimate, V_i are the explanatory variables and *e* is a normal error. The *βi* parameters were estimated with the least square method after logarithmic transformation of equation (9). The explanatory variables were selected based on the correlations between SSC quantiles and physiographic characteristics of each station. A stepwise regression procedure was used in order to optimize the number of significant explanatory variables. A unique model for all sites, relating quantiles to watershed characteristics, was also computed to serve as a basis of comparison with the different regionalisation techniques tested.

5.3.4 Performance estimation

Estimation of the reliability for the different approaches was performed using a Jack-Knife re-sampling procedure to calculate error statistics. In each region, every site is in turn considered ungauged and removed from the database. The remaining sites are then used to build a regression model to estimate the SSC quantile at the station that has been removed. Then, using the difference between the local SSC quantile and the Jack-Knife estimate, it is possible to compute the relative bias (RBIAS) and relative root mean square error (RRMSE) on estimated quantiles for each site :

$$RBIAS[\%)] = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{C_T^i - Ce_T^i}{C_T^i}\right)\times 100 \qquad (5.2)$$

$$RRMSE[\%)] = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{C_T^i - Ce_T^i}{C_T^i}\right)^2} \times 100 \qquad (5.3)$$

Where Ce_T^i is the regional estimate of the *T*-year quantile at site *i* with Jack-Knife, C_T^i is the *T*-year local quantile at site *i*, and *N* the number of sites in the region. These two performance indicators were computed for each regionalisation method tested in this study to compare their relative efficiency.

5.4 Results

5.4.1 Selection of quantiles and physiographic variables

The choice of distributions for modeling series of annual maximum SSC was based on the lowest score of the Bayesian information criterion (Schwartz 1978). Six two-parameter statistical distributions were chosen to fit the 72 series of annual maximum SSC; Exponential, Weibull, Log-Normal, Gamma, Leaks and Normal distributions. As previously noted by Tramblay *et al.* (2008), there is no apparent link between selected distributions and drainage area, length of time series or geographic location of basins.

In order to test the regionalization methods, two quantiles were chosen. The quantile corresponding to a return period of two years, C2, was selected. This value is, for most stations, equivalent to the median annual maximum concentrations. C2 can also represent the extreme concentrations for a return period close to the bankfull discharge situation that varies from one region to another (Leopold *et al.*, 1964, Simon *et al.*, 2004). The quantile corresponding to a return period of 20 years, C20, was also chosen to show extreme concentration values. Given the length of available time series, C20 is among the highest quantiles that can be extrapolated with a relatively good confidence interval. In flood frequency analysis, it is often recommended to limit extrapolation to return periods less than twice the length of the original data series (Rao & Hamed, 2001). Since our SSC records have a median length of 15 years, C20 is an extrapolated quantile that falls within the recommended limits.

The highest concentrations are found in the Plains, the lowest in the Maritime Provinces of Canada and North-Eastern USA states. Both estimated quantiles show a great spatial variation even for rivers close to each others. SSC are known to be highly variable depending on regions, climate and lithology (Meade *et al.*, 1990, Ludwig & Probst, 1998, Simon *et al.*, 2004, Dodds & Whiles, 2004, Mano *et al.*, 2006). The lowest concentrations are found in Kelley river in Ontario (01DL001) with C2 = 22 mg/L and C20 = 57 mg/L (Log-Normal distribution). The watershed of 68 km^2 is dominated by forest (100%), and characterized by one of the lowest K-Factor values (0.04) and percentages of clay in the soils (10.7%) of all stations. The highest concentrations are in Bad River in South Dakota (06441500), with C2 = 37720 mg/L and C20 = 126860 mg/L (Exponential distribution). The watershed of 8226 km^2 is dominated by grassland (79%) and has the highest percentage of clay (47%) of the whole database.

Correlation between C2, C20 quantiles and watershed characteristics were investigated in order to select the most significant variables to be used to test the regionalization approaches. Among the 32 variables extracted from the GIS database, many were correlated.

Table 5.3 presents the Pearson correlation coefficient between C2 and C20 and the 12 physiographic variables with significant correlations at a 5% level. The strongest correlations are found with the percentage of clay in the soils (CLAY) and indices of precipitation intensity (SDII and INTPREC). These correlations are consistent with those found in previous studies such as Restropo *et al.*, 2006 and Tramblay *et al.*, 2007. These 12 variables were used as the basis for all approaches described below.

5.4.2 Clustering of watershed characteristics

This approach is based on watershed characteristics. The 12 parameters correlated with C2 and C20 were first combined into orthogonal factors through principal component analysis (PCA) in order to reduce the number of variables as well as the colinearity between them. Figure 5.3 show the projection of the selected variables in the PCA space defined by the 3 first components. The three first principal components (91.05% of total variance) were used as input variables in the clustering algorithm (Euclidian distance and Ward aggregation method). Several thresholds for cutting the classification tree were tested, based on the hierarchical clustering dendrogram (Figure 5.4), creating two, three, four and six clusters. The best results in terms of RBIAS and RRMSE for regional estimation and size of clusters were found in the case of four clusters. Figure 5.5 shows the spatial localization of the four identified clusters. Figure 5.6 presents the boxplot of the distribution for six physiographic characteristics describing the formed regions (including the variables cropland cover and annual precipitation that were not included in the 12 variables used in the clustering algorithm). For each of the four identified regions, regression models were built. The results of Jack-knife re-sampling as well as the physiographic parameters used in the regression models are shown in Table 5.4.

1. Region 1 groups nine rivers with the largest watersheds, 20000 km^2 and above, with a low proportion of cropland (less than 40%) and forest (less than 20%) as well as relatively low annual precipitation and rainfall intensity. These rivers have the highest median value of SSC; they are all located in the prairies region. For this region, estimation of C20 has the smallest errors (RRMSE less than 50%).

2. Region 2 is the most heterogeneous, in terms of size and watershed characteristics. It is formed by 37 watersheds having a wide range of land-use, ranging from 10% to 95% for forest cover and from 0 to 90% of cropland. This region has the greatest geographical spread including stations in West Alberta to North-Carolina. Estimation of SSC for these stations yields the highest errors, with RBIAS larger than -23% and RRMSE above 90% for C2 and C20.

3. Region 3 is formed by the 14 smallest watersheds, with the highest forest cover (above 40%) and the lowest SSC values with median C20 under 1000 mg/L. These stations show a very contrasting annual precipitation and K-factor, they are located in Alberta, the Maritimes province of Canada, and north-eastern USA states. This region has the most similar estimation results for C2 and C20 with RRMSE less than 60%.

4. Region 4 is constituted by 12 small watersheds, all having more than 90% of their land occupied by cropland with annual precipitation less than 1000 mm per year but

with the highest rainfall intensity (above 10 mm/day). The median K-factor of this region is the smallest of the 4 regions (0.05). The geographic locations of these rivers range from the Maritimes provinces of Canada to the Midwest. Estimation of C2 in this region gives the best results with RBIAS = -8% and relative RRMSE of 41%.

5.4.2 Clustering of monthly frequencies

The best estimation results were obtained when considering three clusters of stations. Figure 5.7 shows the three identified regions. Figure 5.10 shows the mean monthly frequencies of annual maximum SSC for the three regions. The maximum frequency of occurrence of extreme SSC in the 21 stations of region 1, all located in north-eastern USA and Canada, is centered in early spring, during the month of March. The 19 stations of region 3 have the maximum occurrence of annual maximums SSC around May, for rivers located in the Western Prairies, before the Rocky Mountains. For the 32 stations of region 2, the mean monthly frequencies show a bimodal behavior with a peak of occurrence in March and a second peak in June. It appears that for the rivers located near the Atlantic coast, extreme values of SSC are almost uniformly distributed from early spring to late summer. For the other bi-modal stations located inland, there is usually one clearly defined peak of SSC, occurring from year to year either in early or late spring, depending on the flow regime of the considered year.

Some rivers close to each others, as shown on Figure 5.7, are part of different regions. In the Prairies region, Roseau River stations in Manitoba (stations 05OD001 and 05OD004) are in Region 1, while nearby Pembina River (05099600) in North-Dakota is in Region 2. Figure

5.8 shows the averaged daily concentrations on 12 years for Roseau River (05OD004) - left - and the averaged daily concentrations on 14 years for Pembina River- right - (The averaged daily concentrations for station 05OD001 was not plotted because it is identical to station 05OD004). There are many more events of high SSC in late spring and summer in the case of the Pembina River than for the Roseau River. SSC are greater for Pembina River with C2= 6185 mg/L than Roseau River, with C2= 146 mg/L. These two stations have similar watershed sizes, but the Pembina River watershed is occupied by 81% of cropland, with an average 20% of clay in the top soil layers whereas the Roseau River watershed has only 21% of cropland, 10% of clay and 15% of the watershed covered by wetlands, that retain sediments. These differences could explain both the difference in magnitude of extreme SSC and the greater rainfall erosion sensitivity in late spring for the case of Pembina River.

Three other rivers located in the Midwest have a different seasonal pattern than the surrounding rivers. Des Moines River in St. Francisville, Missouri (5490600) is in region 1 with 14 years of SSC records, East Nishnabotna River in Iowa (6809500) and Platte River in Nebraska (6805500) are in region 3 with respectively 10 and 11 years of SSC data. When comparing these three daily series of SSC with other stations in the vicinity with longer records and similar physiographic features, the seasonal pattern appears to be very similar, with annual maximums of SSC occurring both in early or late spring depending on the year. The short record length could be the main cause of the differences in cluster assignment. These three rivers were reassigned to region 2.

Table 5.5 shows the estimation results and the variables selected in the regional models. Region 1 with annual maximum of SSC occurring in early spring, and with the lowest SSC concentrations, has the highest RRMSE, above 90%. Region 2 has very similar estimation results for C2 and C20, with RRMSE less then 60%. Region 3, with rivers located in the west, has good results for the estimation of C20 with RRMSE less than 50%.

5.4.6 Comparison of the different approaches

The performance indicators (RBIAS and RRMSE) were computed for the two methods for all stations (Table 5.6) in order to compare them with those of a unique regression model including all stations. The unique regression including all sites was built with the correlated explanatory variables: forest cover (FOREST), precipitation intensity (SDII), mean depth of snow (SNOW) and the percentage of clay in the soils (CLAY). As shown in tables 5.4 and 5.5, the explanatory variables of percentage of clay (CLAY), indices of precipitation intensity (SDII & INTPREC) and the forest cover (FOREST) are the most often selected variables by the stepwise algorithm. Therefore these variables are the most efficient for predicting extreme SSC in the models.

For all methods, the RBIAS and RRMSE are higher for C2 than C20, showing that estimation is less precise for short return periods. It can be seen that the two regional approaches outperform the general regression model with lower RBIAS and RRMSE. The relative RMSE is lowered by 20% for C2 and by more than 30% when using a regional approach instead of a unique model. The two regional approaches give very similar results, with RRMSE of 75% for C2, but the estimation is slightly better for C20 with the seasonal approach (RRMSE = 68%) than with the physiographic-based approach (RRMSE = 77%).

The mean RBIAS is negative for all the approaches showing that all the methods tested tend to overestimate extreme SSC. Estimation errors were consistent for each station, from one method to another. Figures 5.9 and 5.10 show for the two regional approaches the regionally estimated quantiles versus the local quantiles produced by local frequency analysis. There is no systematic bias for high or low SSC values, but the seasonality-based approach tends to overestimate the quantiles for low concentrations. Correlations of estimation errors for each station with watershed characteristics and C2 and C20 were investigated. A positive but weak correlation of RBIAS with C2 and C20 was found to be significant at 5% level for all approaches (mean R = 0.3), which confirms that errors tend to be greater for high values of SSC. No consistent correlations of errors were found with watershed characteristics.

5.5 Conclusions and discussion

This paper investigated the adequacy of some regionalisation techniques originally developed for floods to estimate extreme SSC in ungauged catchments in North-America. Two quantiles with return periods 2 and 20 years were chosen to test the methods, but it is possible to use the same approach for other extreme values such as engineering thresholds (e.g. for water intakes) or lethal SSC values for some aquatic species. Regional estimation of extreme SSC yields better results than using a unique model for all sites. In the two regional approaches tested, reduced homogeneity in the delineated regions leads to greater estimation errors. The number of stations considered in this study is small, compared to their geographic extension. There is a need for a larger number of stations in the monitoring networks to produce better estimates.

All approaches tend to overestimate extreme SSC. The percentage of clay in the soils, as well as the percentage of forest cover in the watershed and rainfall descriptors appears to be the most important variables to estimate extreme SSC with regression models. Robertson *et al.* (2006) previously reported that the primary natural factor influencing the distribution of suspended sediment is the clay content of the soil. The uncertainty associated with estimation of quantiles of SSC is greater for short return periods (2-years) than with longer return periods (20-years). This highlights the high inter-annual variability feature of sediment transport (Meade *et al.*, 1990, Meybeck *et al.*, 1999), linked with the changing hydrological conditions (vector for transport) from year to year, whereas for large return periods it could be hypothesized that the highest concentrations are supply-limited and therefore easier to predict using watershed characteristics. As for the correlations with discharge that are not often significant, this finding also demonstrates that suspended sediment transport is often supply-limited rather than limited by discharge.

For the 72 stations selected, three distinctive seasonal patterns were identified; one set of rivers with annual peak of SSC occurring in early spring, during the months of April and March corresponding to northern rivers with a nival regime. For these rivers, estimation of the snowmelt-induced annual maximum SSC gives poor results. One second set of rivers, mainly located in the prairies in the West, have annual peak of SSC occurring in late spring, coinciding with the first rainfall events of the year after the winter season. The third set of rivers, mainly in the north-eastern USA states and the Midwest, are showing a variation in the time from year to year when annual peak of SSC occurs. The magnitude of extreme events of SCC in early or late spring for these stations appears to be homogeneous for most of the rivers (using Wilcoxon rank on median test). This may be an indication that despite different transport vectors (snowmelt versus rainfall events), extreme SCC in this region are more closely linked with the available stock of sediment.

Using seasonality alone is probably not sufficient, for example two basins close to each other but with a different altitude will have slightly different seasonal pattern, one with occurrence of snowmelt driven discharge events, the other not. Approaches based on physiographic characteristics seem to be promising, but they could be improved in the selection of the homogeneous regions by incorporating seasonality measures. Establishing relations between watershed characteristics and seasonality patterns could also help to define the homogenous region or neighbourhood to which ungauged basins belong.

There are higher errors in estimating extreme SSC than for the regionalisation of floods. The phenomenon of sediment transport is more complex than river discharge. Daily scale suspended sediment transport is known to vary in a great range over time and space (Meybeck *et al.*, 2003), being one of the most variable hydrological indicators as stated by Mano *et al.* (2006). Lecce *et al.* (2006) observed that suspended sediment loads and concentrations may be difficult to predict, in part because of the local and seasonal factors associated with vegetation. One of the main difficulties is that the time series of SSC available in North American rivers are usually shorter than those available for river discharge, in part due to the decline of the sediment monitoring networks in the 1980s. The first consequence is that local frequency analysis of annual maximum SSC is based on short records (sometimes only 10 years) for some rivers. This could affect the precision of estimated quantiles for the shortest series, since extreme SSC could vary enormously from year to year (Meade *et al.*, 1990). One way of reducing this uncertainty could be to use partial duration series or peak over threshold sampling to describe the behaviour of extreme SSC.

Beside the errors linked with short record length and the limited number of monitoring stations, a large part of the uncertainties is probably due to the databases used to characterise the catchments attributes. As described earlier, the number of stations with long record has declined after 1980. Discharge data and meteorological records are often available for the same period than SSC records but land cover and soil characteristics databases were only elaborated in the 1990s. It is possible that for several basins land cover has changed over time. Higgitt & Lu (1999) showed that the first difficulty of assessing land use impact on sediment delivery in China was caused by the lack of synchronism between land use and sediment records. The time discrepancy between available SSC records and the physiographic characteristics of watersheds might be the first cause of the error observed in estimation of extreme SSC for some rivers, since the estimation relies on watershed characteristics.

Several studies aiming to establish a link between land use, erosion and sediment yield (Slaymaker, 1982, Higgitt & Lu, 1999, Walling, 1999, Jarvie *et al.*, 2002, Walling & Fang, 2003, Siakeu *et al.*, 2004) have shown that the interactions between soil types, land use, sediment production and transport can be quite complex, in particular in areas with changing land use and agricultural practices. The last 50 years are characterized by a significant increase in urbanisation in many areas of North America. Siakeu *et al.* (2004) reported a reduction of sediment transport in Japan caused by the reduction of agricultural land cover due to urbanisation as well as by erosion protection measures introduced in the 1970s. In a study on several rivers in the world, Walling (2006) observed an increase of sediment load attributed to forest clearance for agriculture or the development of logging or mining activities in some cases, while in other rivers a decrease in sediment load was observed. The decreasing trend was reflecting the implementation of soil conservation and sediment control measures (e.g. sediment trapping by reservoirs). Even where land use did not change drastically over time, erosion mitigation measures could modify the supply of fine sediments (Siakeu *et al.*, 2004, Walling, 2006).

New attempts in modelling extreme sediment concentrations and loads should take into account this temporal change, maybe by including such variables as population density as a proxy to determine the regions where substantial land use change has occurred or is likely to occur in a near future. The site-specificity of suspended sediment transport could also be analyzed by using sub-watershed characteristics in the locality of the gauging stations, as suggested by Jarvie *et al.*, (2002). In addition to watershed attributes, future modelling of these extreme events could include more hydrologic characteristics describing single events of discharge or rainfall, such as flood or precipitation quantiles, or duration of extreme events of suspended sediment transport.

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Tableau 5.1: Stations selected for analysis

ID	LAT	LON	NAME	C20 (mg/L)	C2 (mg/L)	Drainage area (km2)
01AK005	46.04	-66.70	MIDDLE BRANCH NASHWAAKSIS	132.6	39.1	15.3
01AP004	45.70	-65.60	KENNEBECASIS RIVER AT APOHAQUI	507.7	229.2	1094.6
01BU002	45.94	-65.17	PETITCODIAC RIVER NEAR PETITCODIAC	188.2	99.3	186.3
01CB004	46.39	-63.66	WILMOT RIVER NEAR WILMOT VALLEY	823.9	418.0	77.3
01CB005	46.35	-63.63	NORTH BROOK NEAR WALL ROAD	801.0	162.3	6.6
01CE003	46.20	-62.65	BRUDENELL RIVER NEAR BRUDENELL	599.2	172.3	26.5
01DL001	45.59	-64.45	KELLEY RIVER (MILL CREEK) AT EIGHT MILE FORD	57.8	22.0	68.3
01DP004	45.50	-62.78	MIDDLE RIVER OF PICTOU AT ROCKLIN	173.6	43.9	76.6
01FB005	46.23	-61.14	APRIL BROOK AT GILLISDALE	695.4	189.4	1.2
02GA035	43.65	-80.57	EAST CANAGAGIGUE CREEK NEAR FLORADA	1647.0	675.1	11.5
02GA036	43.67	-80.60	CANAGAGIGUE CREEK NEAR FLORADALE	1539.7	743.6	18.6
02GC007	42.68	-80.54	BIG CREEK NEAR WALSINGHAM	1388.1	615.0	824.1
02GC026	42.71	-80.84	BIG OTTER CREEK NEAR CALTON	6232.3	2231.6	835.7
02HC025	43.81	-79.63	HUMBER RIVER AT ELDER MILLS	3736.2	2126.5	540.6
05AA023	49.81	-114.18	OLDMAN RIVER NEAR WALDRON'S CORNER	1163.7	194.9	1444.9
05AK001	50.74	-110.10	SOUTH SASKATCHEWAN RIVER AT HIGHWAY NO. 41	6433.5	2698.1	52806.4
05HG001	52.14	-106.64	SOUTH SASKATCHEWAN RIVER AT SASKATOON	2857.1	717.6	106110.0
05LJ007	50.94	-99.52	TURTLE RIVER NEAR LAURIER	5620.4	1980.1	836.5
05LJ034	50.72	-99.58	PACKHORSE CREEK NEAR MCCREARY	9964.6	2914.1	5.8
05LJ047	51.14	-99.92	EDWARDS CREEK DRAIN BELOW JACKFISH CREEK	7219.9	2855.3	359.2
05LJ801	50.73	-99.55	WILSON CREEK NEAR MCCREARY	14812.1	5901.4	7.9
05OD001	49.19	-97.00	ROSEAU RIVER NEAR DOMINION CITY	465.5	280.3	4820.2
05OD004	49.09	-96.69	ROSEAU RIVER AT GARDENTON	292.0	146.0	4391.7
05OF017	49.38	-98.25	SOUTH TOBACCO CREEK NEAR MIAMI	9397.2	5599.4	264.5
07AF003	53.16	-117.26	WAMPUS CREEK NEAR HINTON	1144.8	305.5	5.8
07AF004	53.16	-117.24	DEERLICK CREEK NEAR HINTON	909.1	244.0	5.6
07AF005	53.15	-117.23	EUNICE CREEK NEAR HINTON	715.7	208.6	8.8
1463500	40.13	-74.46	DELAWARE RIVER AT TRENTON, NJ	1391.6	474.1	67830.5
1517000	41.49	-76.58	ELK RUN NEAR MAINESBURG, PA	1248.6	421.4	7.5
1567000	40.28	-77.07	JUNIATA RIVER AT NEWPORT, PA	1007.4	380.3	27.4
1567500	40.22	-77.24	BIXLER RUN NR LOYSVILLE, PA	476.2	303.3	8701.6
1638500	39.16	-77.32	POTOMAC R AT POINT OF ROCKS, MD	1209.9	678.5	1099.8

1664000	38.32	-77.49	RAPPAHANNOCK RIVER AT REMINGTON, VA	1747.1	819.2	64.1
2066000	36.55	-78.44	ROANOKE (STAUNTON) RIVER AT RANDOLPH, VA	1423.8	709.8	1790.2
2075500	36.38	-79.05	DAN RIVER AT PACES, VA	1428.6	941.6	7619.2
2084160	35.33	-77.13	CHICOD CR AT SR 1760 NEAR SIMPSON, NC	586.8	228.5	6399.6
2116500	35.51	-80.23	YADKIN RIVER AT YADKIN COLLEGE, NC	2487.7	1514.0	105.2
2118000	35.50	-80.39	SOUTH YADKIN RIVER NEAR MOCKSVILLE, NC	1515.9	1024.9	5790.4
3070420	39.46	-79.35	STONY FORK TRIB NR GIBBON GLADE, PA	1174.8	621.0	19213.2
3144500	40.07	-81.60	MUSKINGUM R AT DRESDEN, OH	1446.9	590.8	20.5
3150000	39.38	-81.51	MUSKINGUM R AT MCCONNELSVILLE, OH	2092.3	675.2	16796.2
3199000	38.04	-81.50	LITTLE COAL RIVER AT DANVILLE, WV	3650.8	1613.0	18807.2
3200500	38.20	-81.50	COAL RIVER AT TORNADO, WV	4344.8	1582.6	826.0
3212500	37.49	-82.47	LEVISA FK AT PAINTSVILLE, KY	4322.6	2346.9	2254.3
3217000	38.34	-82.57	TYGARTS CREEK NEAR GREENUP, KY	1857.4	1148.9	2416.8
3234500	39.12	-82.52	SCIOTO R AT HIGBY, OH	2372.4	1500.2	689.0
3245500	39.10	-84.18	L MIAMI R AT MILFORD, OH	3549.7	1703.0	13078.2
3308500	37.16	-85.53	GREEN RIVER AT MUNFORDVILLE, KY	2712.0	1168.7	13750.7
3328500	40.47	-86.16	EEL RIVER NEAR LOGANSPORT, IN	1828.2	1139.3	4792.3
3365500	38.59	-85.54	EAST FORK WHITE RIVER AT SEYMOUR, IN	1392.8	871.0	512.2
3403000	36.48	-83.46	CUMBERLAND RIVER NEAR PINEVILLE, KY	2991.5	1587.0	1826.2
4198000	41.18	-83.09	SANDUSKY R NR FREMONT, OH	2211.2	1120.6	3218.5
4206000	41.08	-81.33	CUYAHOGA R AT OLD PORTAGE, OH	1025.0	507.0	1044.6
4208000	41.23	-81.37	CUYAHOGA R AT INDEPENDENCE, OH	3733.4	1435.7	1812.4
5099600	48.55	-97.55	PEMBINA RIVER AT WALHALLA, ND	18568.3	6183.9	5206.8
5406500	43.08	-89.44	BLACK EARTH CREEK AT BLACK EARTH, WI	1926.7	590.2	203.8
5474000	40.45	-91.16	SKUNK RIVER AT AUGUSTA, IA	7709.6	4217.3	11246.3
5490600	40.27	-91.34	DES MOINES RIVER AT ST. FRANCISVILLE, MO	7158.7	3379.0	37495.8
5570370	40.27	-90.08	BIG CREEK NEAR BRYANT, IL	5455.9	2994.9	203.5
6088300	47.37	-111.38	MUDDY CREEK NEAR VAUGHN, MT	13536.9	4159.6	4850.5
6088500	47.33	-111.32	MUDDY CREEK AT VAUGHN, MT	21899.4	7370.1	5102.4
6115200	47.38	-108.41	MISSOURI RIVER NEAR LANDUSKY, MT	23328.1	10850.6	116795.8
6130500	46.59	-107.53	MUSSELSHELL RIVER AT MOSBY, MT	25332.8	8522.3	25308.8
6279500	44.45	-108.11	BIGHORN R AT KANE, WY	34374.8	21562.0	43071.1
6324710	45.25	-105.24	POWDER RIVER AT BROADUS, MT	45374.1	31147.1	23301.2
6400500	43.18	-103.33	CHEYENNE R NEAR HOT SPRINGS, SD	54525.0	36154.8	22496.1
6441500	44.19	-100.23	BAD R NEAR FORT PIERRE, SD	126860.9	37720.8	8226.8
6465500	42.44	-98.12	NIOBRARA RIVER NR. VERDEL, NE	13042.0	5136.5	32678.6

6805500	41.01	-96.09	PLATTE R AT LOUISVILLE, NE	12299.2	8190.2	69664.6
6809500	41.00	-95.14	EAST NISHNABOTNA RIVER AT RED OAK, IA	44516.5	21902.4	2240.8
6817000	40.44	-95.00	NODAWAY RIVER AT CLARINDA, IA	25428.6	14792.8	2051.0
7040100	36.27	-90.08	ST. FRANCIS RIVER AT ST. FRANCIS, AR	3922.5	2494.9	1212.1

Tableau 5.2: Physiographic parameters extracted from the GIS database

LANDCOVER	FOREST	% of forest cover
	CROPLAND	% of cropland and cultivated
	WETLAND	% of wetland cover
	URBAN	% of urban and residential
	BARE-ROCK	% of bare rock surfaces
	WATER	% of open water
TOPOGRAPHY	MIN_A	Minimum altitude (m)
	MAX_A	Maximum altitude (m)
	DENIV	Altitude range (m)
	ALT_MED	Median altitude (m)
	MED_SLOPE	Median Slope (%)
	PERIMETER	Perimeter of drainage area (km)
	SIZE	Size of drainage area (km2)
CLIMATE	PRECP1	Days with precipitation (days)
	INTPREC	Precipitation peakedness
	PANNU	Precipitation total (mm)
	SDII	Rainfall intensity (mm/day)
	PDAYMAX	Maximum daily precipitation (mm)
	SNOW	Mean depth of snow (inches)
	FROST	Number of frost days (days)
SOILS	KFFACT	K Factor
	OM	Fraction of organic Materials (%)
	PERM	Permeability of the soil (in. per hour)
	DRAIN	Soil drainage group
	ROCKVOL	Rock (> 2mm) volume on surface (%)
	SAND	Volume percent of sand (%)
	SILT	Volume percent of silt (%)
	CLAY	Volume percent of clay (%)
	BD	Bulk density (g/cm3)
	ROCKD	Mean depth to bedrock (cm)
	POROS	Soil porosity (%)

Tableau 5.3: Pearson Correlation coefficient of variables significantly correlated with C2 and C20

VARIABLES	LogC20	LogC2
SIZE	0.310	0.297
FOREST	-0.465	-0.481
SDII	-0.559	-0.546
SNOW	-0.284	-0.320
FROST	0.313	0.272
INTPREC	0.630	0.581
DENIV	0.432	0.414
ALT_MED	0.451	0.387
ROCKD	0.350	0.402
KFFACT	0.315	0.379
CLAY	0.701	0.655
BD	0.351	0.397

Tableau 5.4: Estimation results per region defined by physiographic variables

REGIONS	QUANTILES	Median SSC	RBIAS	RRMSE	Variables selected in regression models
REG1	C2	8522	-21%	61%	SNOW KFACT
	C20	23328	-8%	45%	SDII DENIV
REG2	C2	1148	-24%	91%	KFACT CLAY
	C20	2211	-23%	91%	KFACT CLAY
REG3	C2	274	-6%	52%	SIZE FROST INTPREC ROCKD
	C20	958	-8%	57%	SIZE INTPREC ROCKD BD
REG4	C2	1487	-8%	41%	SIZE INTPREC CLAY
	C20	3939	-10%	66%	SIZE CLAY

Tableau 5.5: Estimation results per region defined by monthly frequencies

REGIONS	**QUANTILES**	**Median SSC**	**RBIAS**	**RRMSE**	**Variables selected in regression models**
REG1	C2	292	-30%	103%	FOREST ROCKD CLAY
	C20	748	-27%	92%	FOREST SDII CLAY
REG2	C2	1436	-12%	59%	SNOW INTPREC ALT_MED CLAY
	C20	2488	-12%	54%	INTPREC ALT_MED CLAY
REG3	C2	2914	-21%	74%	FOREST SDII FROST CLAY
	C20	9965	-11%	49%	FOREST SDII SNOW ALT_MED

Tableau 5.6: Estimation errors for the different regionalization approaches tested

Approaches :	**C2**		**C20**	
	RBIAS	RRMSE	RBIAS	RRMSE
Physiographic variables (CW)	-18%	75%	-16%	77%
Monthly frequencies (CM)	-19%	75%	-16%	68%
Global regression (REG)	-25%	96%	-32%	117%

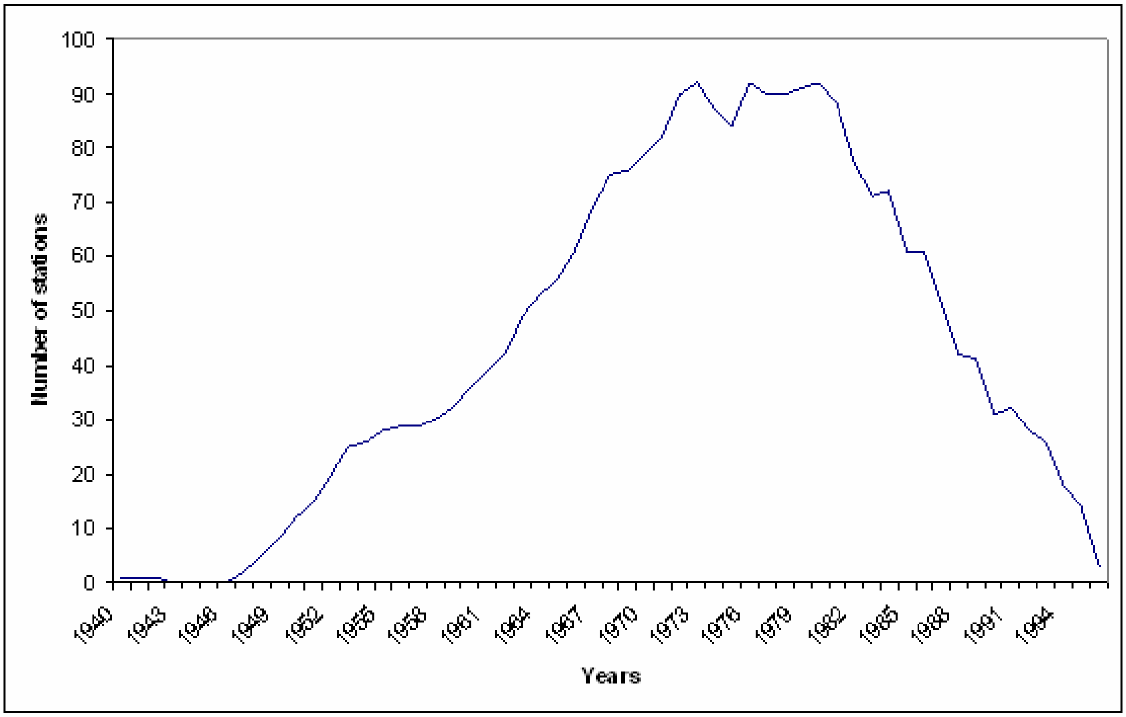

Fig. 5.1: Number of stations available per year

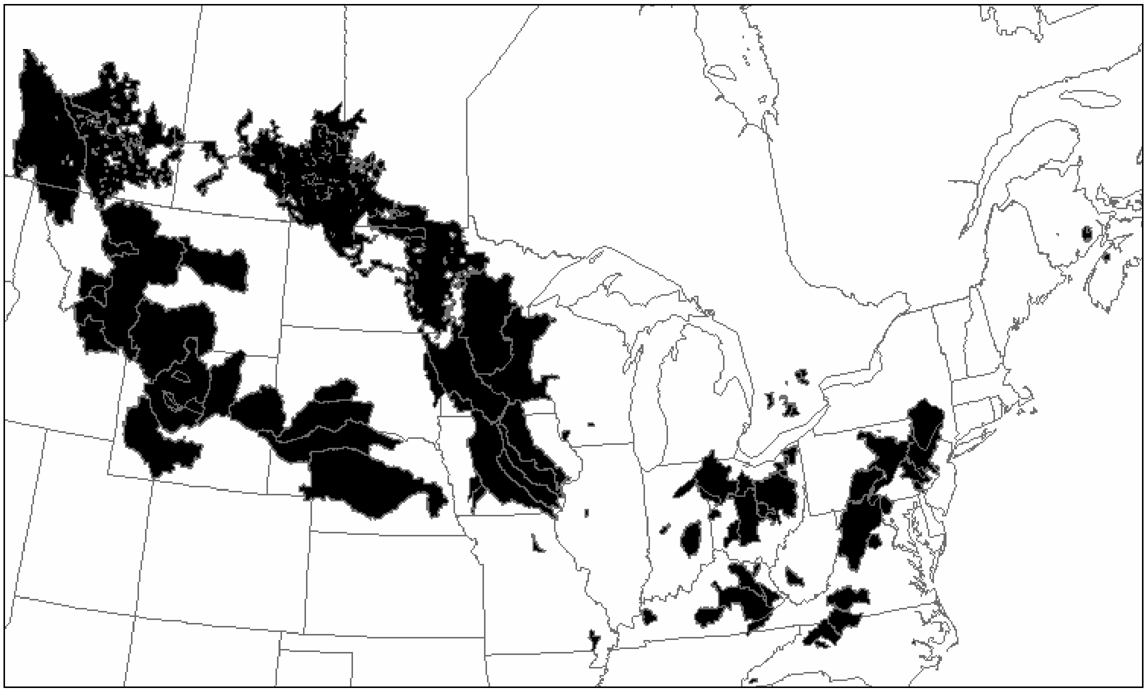

Fig. 5.2: Watersheds of the 72 selected stations

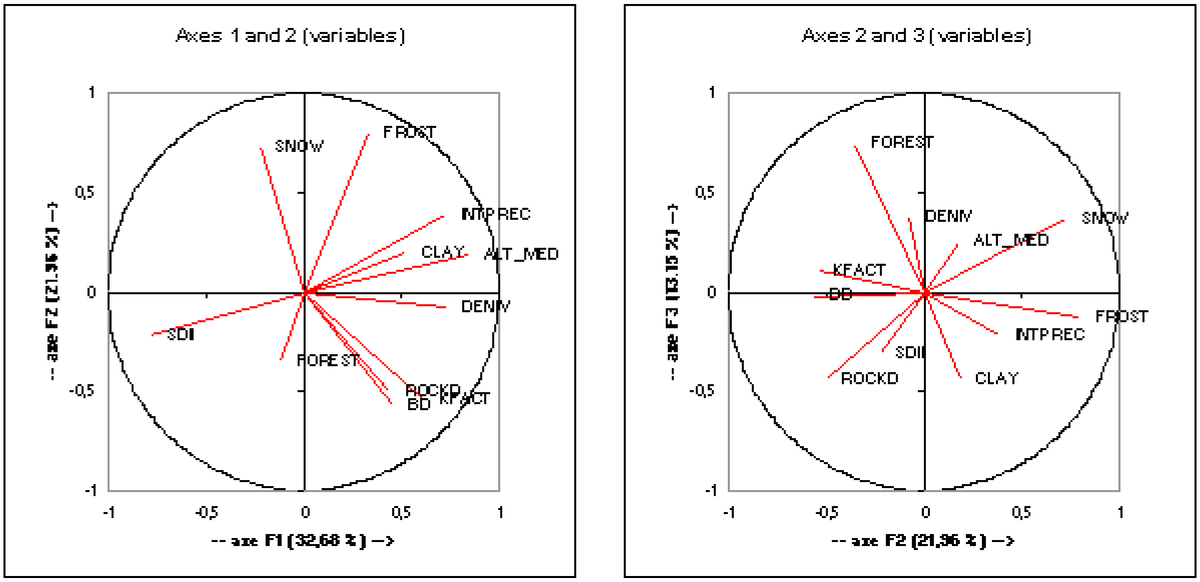

Fig. 5.3: Projection of the variables on the PCA axes 1 and 2 (left) on axes 2 and 3 (right)

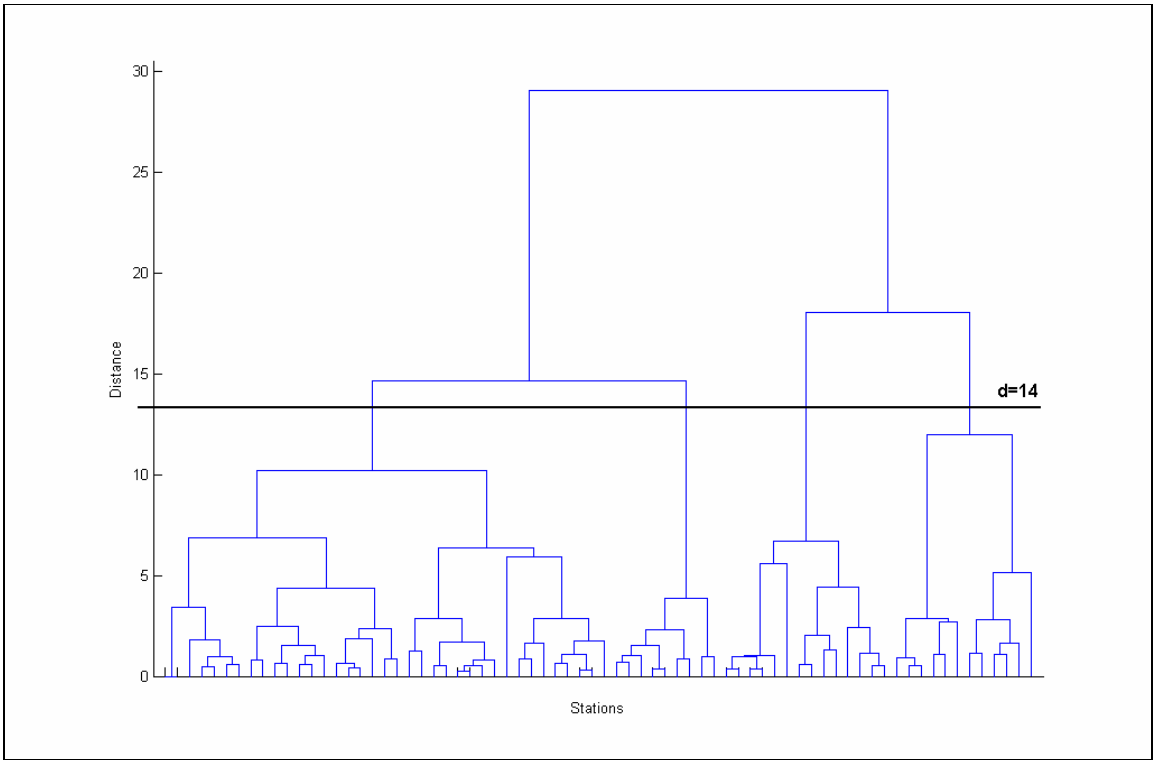

Fig. 5.4: Dendrogram of the hierarchical clustering on watersheds characteristics

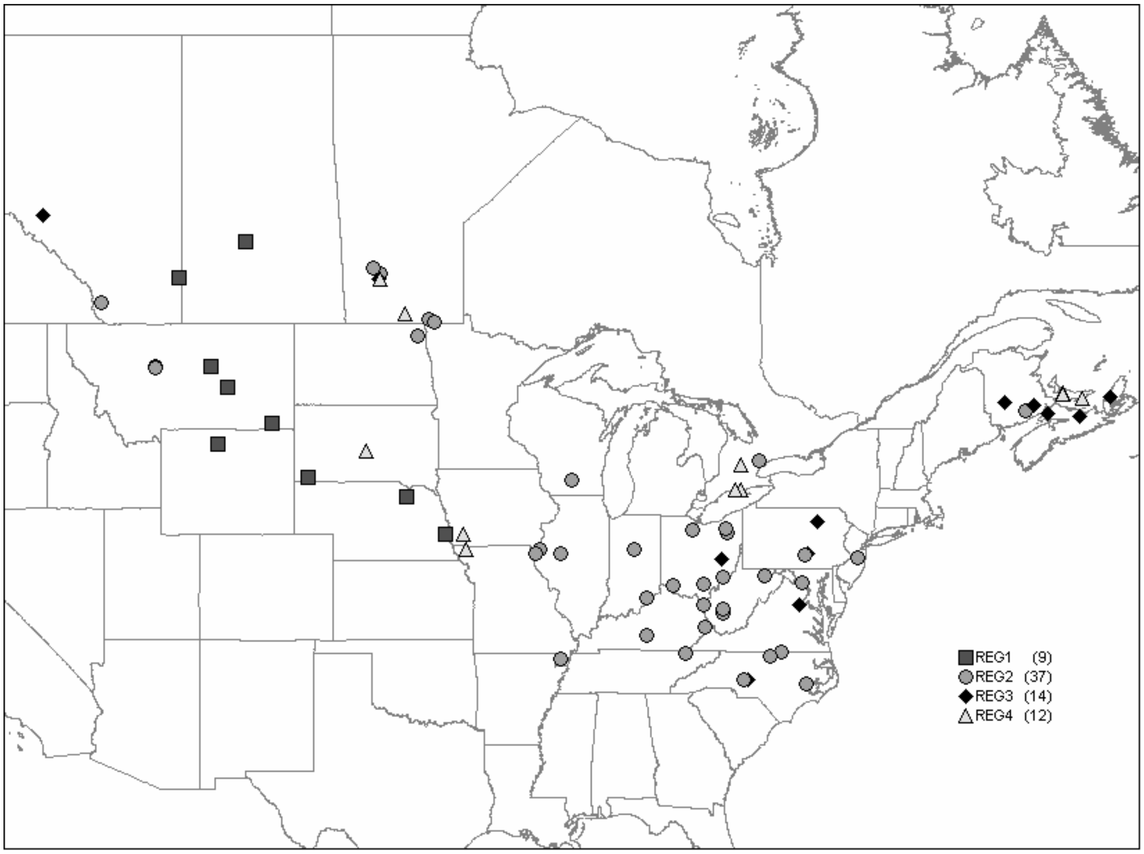

Fig. 5.5: Map of 4 regions identified by the clustering of watershed characteristics

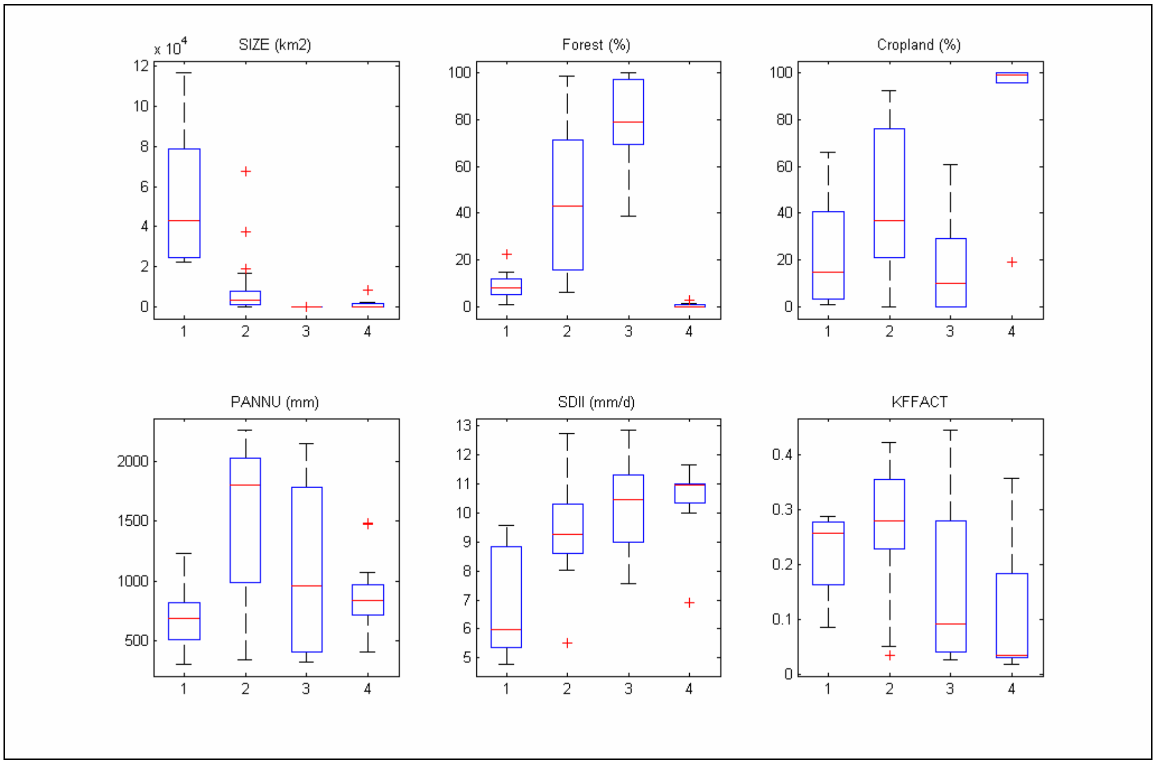

Fig. 5.6: Boxplot of variables describing the 4 regions created by the clustering on watersheds characteristics

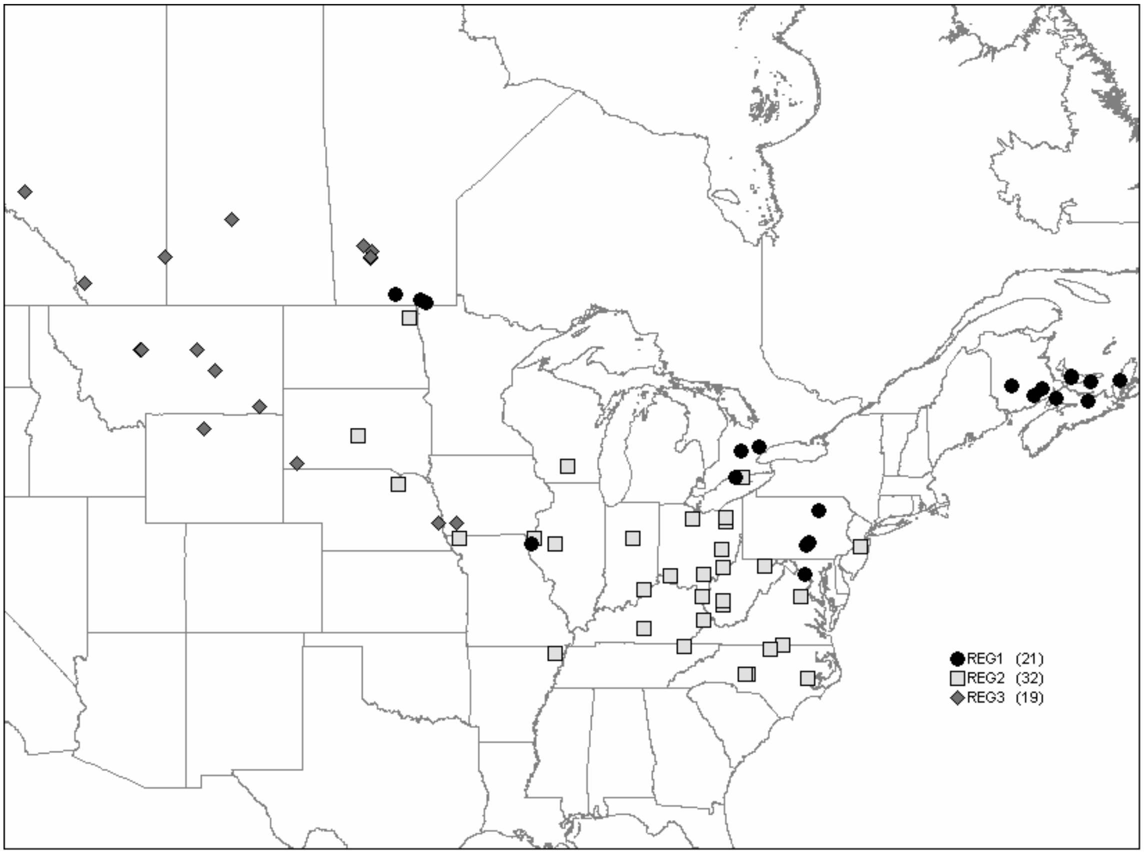

Fig. 5.7: Map of the 3 regions identified by clustering of monthly frequencies

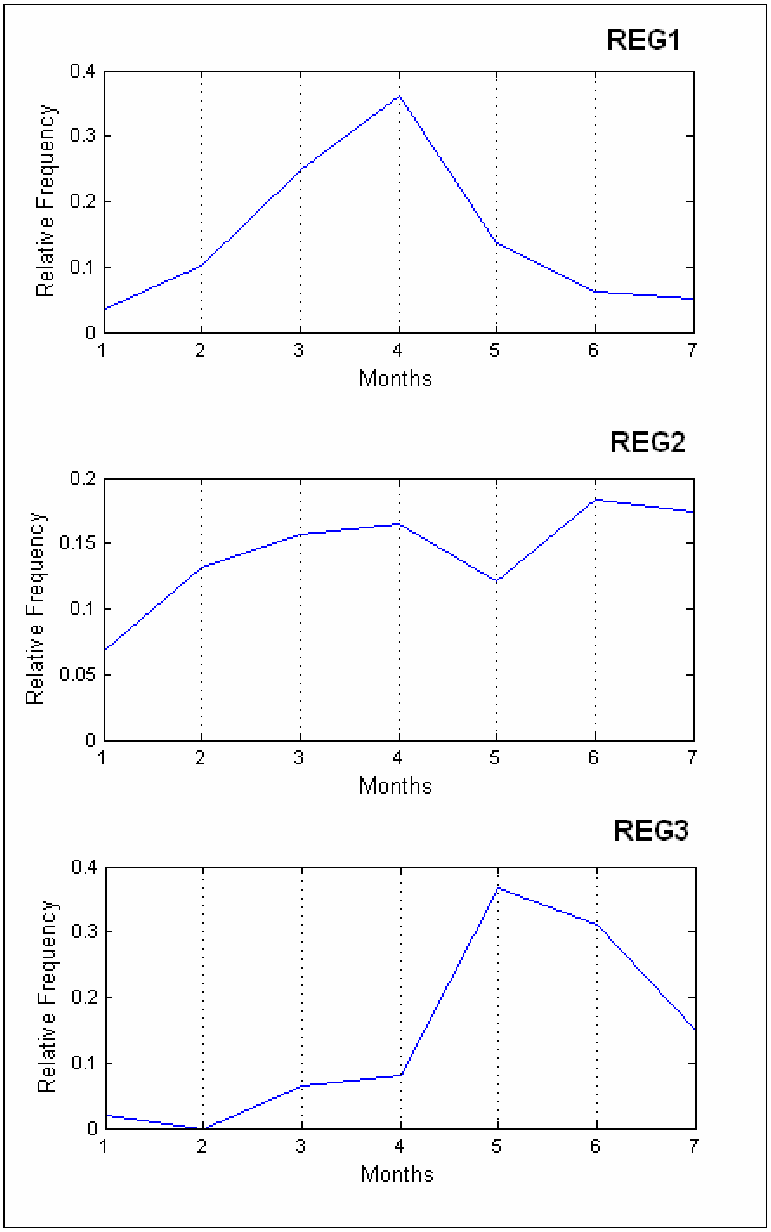

Fig. 5.8: Mean monthly frequencies of annual maximum of SSC for the three regions

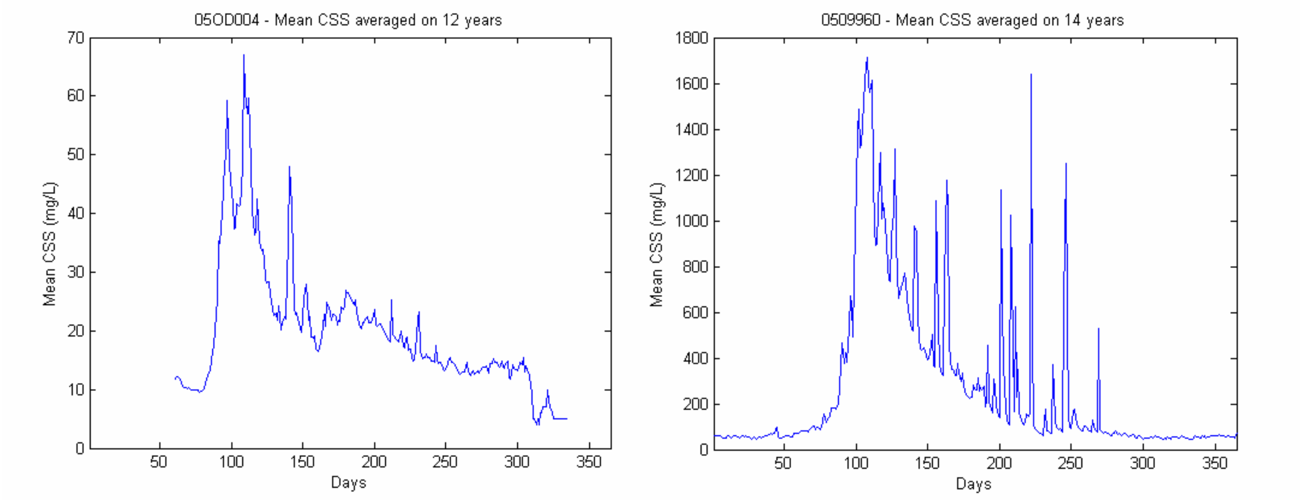

Fig. 5.9: Mean daily CSS for stations 05OD004 (a) and 05099600 (b)

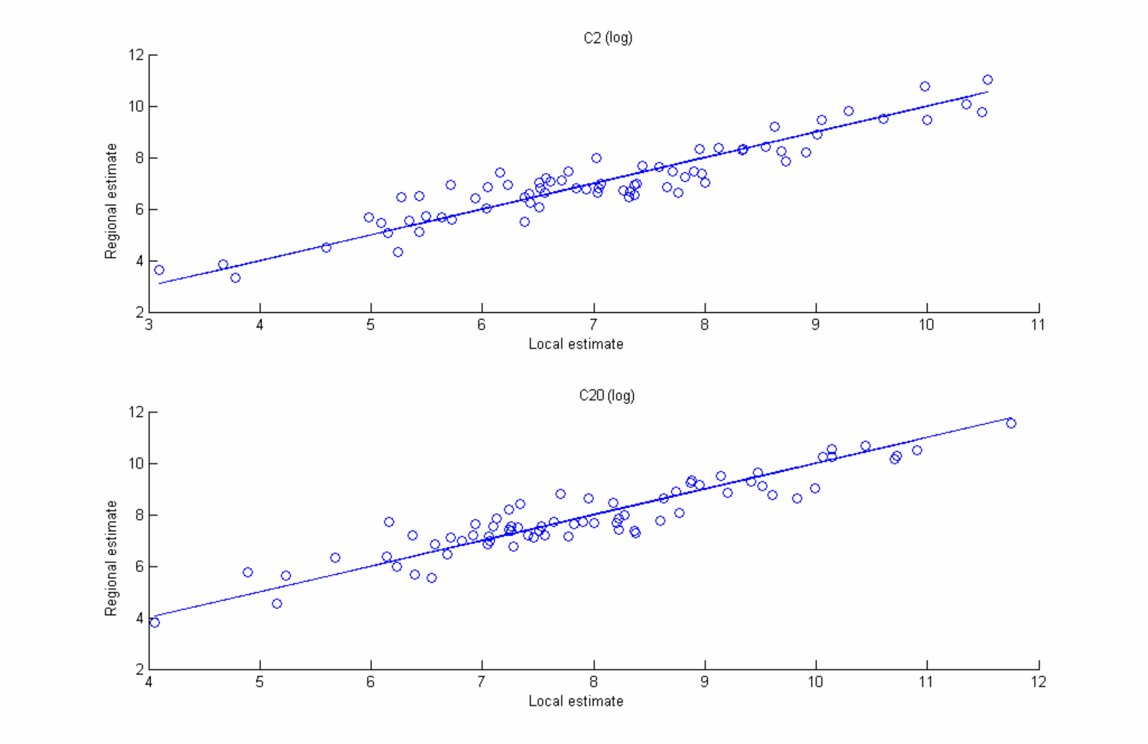

Fig. 5.10: Local versus regional estimations of quantiles C2 and C20 for the physiographic-based approach

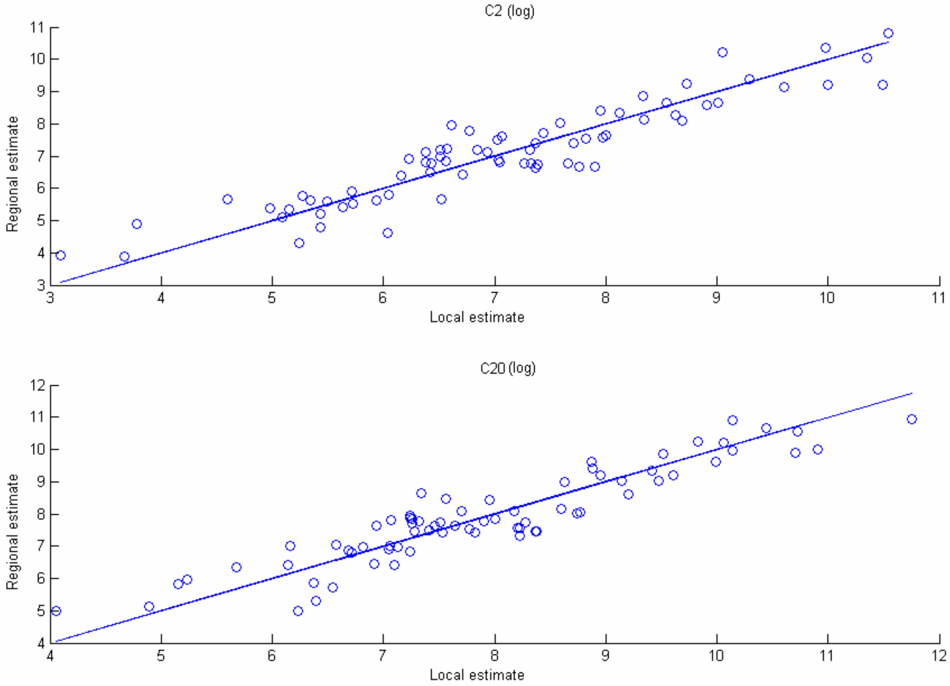

Fig. 5.11: Local versus regional estimations of quantiles C2 and C20 for the seasonality-based approach

CHAPITRE 6 : Estimation régionale des CSS extrêmes et d'indicateurs du régime de transport en Californie avec les caractéristiques des bassins versants et du voisinage des stations

REGIONAL ESTIMATION OF EXTREME SUSPENDED SEDIMENT CONCENTRATIONS AND SEDIMENT TRANSPORT REGIME INDICATORS IN CALIFORNIA WITH CATCHMENT AND STATION-LOCALITY CHARACTERISTICS

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Abstract

In Mediterranean-climate regions the sediment budget is mainly dominated by suspended sediment. The total amount of suspended load carried by a stream during a year is usually transported during one or several extreme events related to flood and intense rainfall, leading to very high suspended sediment concentrations (SSC). In this study several indicators of suspended sediment transport are considered: annual maximum SSC, the 99th percentile of SSC series, and the percentage of annual suspended flux discharged in 2% of the time (M_2) computed for each year and also on the whole time series. Analyses of relationships between physiographic characteristics and the selected indicators were undertaken at two scales: the watershed and localities of 5-km radius draining of each sampling site. Then, using watershed and station-locality characteristics of gauging sites, multiple regression models were built to test the regional estimation for these indicators of suspended sediment transport. To assess the reliability of the estimates, a Jack-Knife re-sampling procedure was used to compute relative bias and RMSE for the models. Results show that the estimation is more reliable for all SSC indicators using station-locality attributes rather than watershed attributes. There is less than 60% uncertainty on the estimation of extreme SSC when using the station-locality characteristics. For the flux duration indicators, we obtain a similar estimation performance when using either the characteristics of the whole watershed or only the station-locality of the sites. The regional estimation of M_2 using physiographic characteristics is much more precise that for extreme SSC, with less than 10% uncertainty on the estimated values.

6.1 Introduction

Extreme suspended sediment concentrations (SSC) affect water quality and are a threat to aquatic life. Estimation of SSC is essential for characterizing water quality and water resources management (Achite & Ouillon, 2007, Gao *et al.*, 2007). It is also necessary in the case of an ungauged stream for establishing criteria for the maximum daily amount of sediment a stream can receive and still meet the water quality standards (i.e. maximum concentrations or total maximum daily loads, TMDLs). Since the number of sediment monitoring stations in the USA has decreased by 71% from 1982 to 2002 (Osterkampf & Parker, 1991), reliable estimation methods are necessary to palliate the paucity of on-site measurements. Beside extreme concentrations, Moatar *et al.* (2006) observed that suspended sediment transport regime of rivers affects the imprecision of computed fluxes of sediment and pollutants in rivers. Therefore, regional estimation of the flux duration indicators describing sediment transport regime could optimize river surveys (Moatar & Meybeck, 2007). M_2, the maximum percentage of annual suspended sediment load carried in 2% of the time, is a robust indicator of sediment transport regime used by Meade *et al.* (1990) or Moatar *et al.* (2006), and is strongly associated with the uncertainty associated with the prediction of river fluxes (Moatar & Meybeck, 2007).

Only a few studies of suspended sediment transport have been conducted in drainage basins characterized by a marked contrast between dry and humid conditions such as the Mediterranean region (Rovira & Batalla, 2006, Salles *et al.*, 2006, Achite & Ouillon, 2007). In California, the west coast is subjected to a semi-arid Mediterranean type climate where river discharge is driven by episodic winter rainfall (Curtis *et al.*, 2006). There is a strong seasonal cycle with almost all of the annual precipitation occurring between November and April (Ahearn *et al.,* 2005) which produces ephemeral, torrential discharges in creeks and rivers of this region (Warrick *et al.*, 2004). In Mediterranean-climate regions the sediment budget is mainly dominated by suspended sediment (Nadal-Romero *et al.*, 2007) and the total amount of suspended load carried by a stream during a year is usually transported during one or several extreme events related to flood and intense rainfall (Inman and Jenkins, 1999, Cherifi & Loudiki, 1999, Meybeck *et al.*, 2003). Several studies have shown the importance of the quantitative role of rare or extreme events on the long-term average flux of suspended sediments (Meade *et al.*, 1990, Meybeck *et al.*, 2003). Rovira and Battala (2006) studied the Tordilla River (Spain) and found that more than 90% of the annual suspended sediment load was transported during flood events and annual sediment loads showed a high degree of variability that could be primarily related to the number and magnitude of floods. In California, Warrick *et al.* (2004) observed for the Santa Clara River that more than half of the annual sediment load is carried during the top 1-5 days of flooding.

The estimation of suspended sediment concentration and subsequent load estimation is usually done with rating curves between sediment concentrations and discharge. Ferguson (1985), Asselman (2000) or Horowitz *et al.* (2003) observed that these models tend to underestimate high SSC. Quilbé *et al.* (2006) and Salles *et al.* (2006) reported significant differences in the load estimates derived from discharge depending on the method used. Suspended sediment is often rather supply limited than discharge limited, leading to weak or no correlation with discharge (Tramblay *et al.*, 2008). The physical and anthropogenic factors controlling sediment availability and transport could interact differently in each event. Langlois *et al.* (2005) observed in a mountain stream of Lake Tahoe (Nevada) no clear relationship between stream discharge and SSC peaks, even when the event data were subdivided in terms of rising or falling stage. Overall, in Mediterranean regions, several study reported a high degree of scatter in the SSC/discharge relation, illustrated by no significant or little correlations, leading to sediment rating curves that can substantially underestimate or overestimate the concentrations (Rovira & Batalla, 2006, Alexandrov *et al.*, 2007, Nadal-Romero *et al.*, 2007, Soler *et al.*, 2007, Zabaleta *et al.*, 2007).

Aside from discharge, several correlations have been established between watershed characteristics (including topography, geology, climate, and land use) and sediment yield (Ludwig & Probst, 1998, Restropo *et al.*, 2006), mean SSC values (Jarvie *et al.*, 2002, Robertson *et al.*, 2006, Siakeu *et al.*, 2004, Dodds & While, 2004) or extreme SSC (Tramblay *et al.*, 2007). Modelling attempts of sediment yield have been carried out using regression with watershed characteristics by Ferraresi (1990), Bray and Xie (1993) and Restropo *et al.* (2006). Mimikou *et al.* (1990) proposed a regional estimation of the rating curve parameters based on physiographic attributes. For SSC, Robertson *et al.* (2006) used a regression tree analysis to create groups of rivers in the Great Lake region in order to estimate several water quality parameters, including SSC, from soils and land cover data. Jarvie *et al.* (2002) and Siakeu *et al.* (2004) compared the correlations between SSC and characteristics of the watersheds versus characteristics of sub-basins in the station-locality of the gauging stations with 10 km or 20 km radius. Ahearn *et al.* (2005), in their study about the impact of land use on weekly samples of sediment transport in Sierra Nevada, reported that many studies linked land use to river water quality but none have been conducted in Californian watersheds.

Only a few studies considered a probabilistic modelling approach for SSC, such as Van Sickle (1982), Watts *et al.* (2003), Simon *et al.* (2004), Soler *et al.* (2007) and Simon & Klimetz (2008). Indicators of sediment transport considered in the present study include annual maximum SSC, the 99th percentile of SSC series, and the percentage of annual suspended flux discharged in 2% of the time (M_2). Application of the frequency analysis approach and its results for annual maxima of SSC in North America is detailed in Tramblay *et al.* (2008). The same approach was used in the present study to estimate quantiles at gauged stations.

The main objectives of this study are to:

1. Compare the correlations between the selected indicators of suspended sediment transport and physiographic characteristics at the watershed and the locality of station scales.
2. Test the reliability of regional estimation for indicators of suspended sediment transport using either local (i.e. in the vicinity of the station, hereafter station-locality) or watershed characteristics.

6.2 Datasets and methodology

6.2.1 Selection of stations in California

Stations in California with 10 years or more of daily data of SSC and discharge were selected from the US Geological Survey Sediment Database. Fully regulated rivers were excluded since sediment transport can be greatly affected by regulation in rivers (Meade *et al.*, 1990, Snoussi *et al.*, 2002, Walling, 2006). In California, in many rivers the discharge is influenced by the presence of dams, reservoirs, diversion for irrigation and water supply. For several small streams low flows consists mainly of return flow from irrigated areas. The database of the National Inventory of Dams (NID) from the US Army Corps of Engineers and metadata from USGS stations database were used to detect the presence of major dams or reservoirs in the selected river basins. Of 39 stations having long records, only 19 were found to be not or only moderately regulated, all located in Western California. The stations selected were the ones with no major dam or storage facilities within 30 miles of the gauging station. Table 6.1 lists the selected stations, with catchment sizes ranging from 100 to 20.000 km^2. Figure 6.1 show the watersheds for the 19 selected stations, all coastal except for Klamath River.

6.2.2 Physiographic characteristics

A GIS database was created to retrieve the physiographic characteristics of the 19 river basins considered in this study. Several layers of spatial information about elevation, land cover, soil types and climate were integrated in order to retrieve these characteristics. The digital elevation model of the HYDRO1K database from USGS at a resolution of 1 km was used for elevation and slope data. Land cover was provided by the NLCD 1992 USGS database, with a 21-class land cover classification scheme over the United States. Soils data was extracted from the STATSGO (1994) database of USDA. Climate data were retrieved from USHCN (NOAA) stations with 30 years or more of data. Several climate indices were computed. Several climate indices were selected from the STARDEX project (www.cru.uea.ac.uk/projects/stardex/). Days with precipitation (PRECP1) are the number of days per year with more than one millimeter of precipitation. Rainfall intensity (SDII) is the ratio of the total annual precipitation divided by the number of days with precipitation. Maximum daily precipitation (PDAYMAX) is the mean precipitation of the wettest day of the year. All indices are averaged over 30 years of observation, and interpolated with ordinary kriging.

6.2.3 Watershed and station-localities identification

Boundaries of watersheds for the selected gauging stations were found in Hydrologic Units of the USA database (USGS). Physiographic characteristics were extracted for the whole catchment and for the portion of the station-locality of 5 km radius located in the drainage basin. The definition of watershed and station-locality is illustrated on figure 6.2. All parameters were spatially averaged within the boundaries of each watershed and the station-localities. Then for this study, two ensemble of physiographic parameter are compared for the estimation of SSC and flow duration indicators, one at the catchment scale, and one another at the locality of stations scale.

6.2.4 At-site frequency analysis of selected indicators

For SSC and discharge, annual maxima were extracted. The percentage of the annual load carried during 2% of the time (M_2), corresponding to 7 days, was extracted for each year. The hypotheses of homogeneity, stationarity and independence were verified for all the series since they are a prerequisite for frequency analysis. The non-parametric tests of Wilcoxon for homogeneity, Wald-Wolfowitz for autocorrelation and Kendall for stationarity were used at the 1% significance level. For each station, series of annual maxima of SSC, discharge, and annual M_2 values were fitted with theoretical probability density functions to estimate local quantiles for different return periods. The complete methodology for this local frequency analysis is described in details in Tramblay *et al.* (2008). The selection of the most appropriate probability distribution was based on the lowest score of the Baysian Information Criterion (BIC):

$$BIC = -2Log(L) + 2kLog(N) \qquad (6.1)$$

Where L is the likelihood function, k is the number of parameters and N is the sample size.

6.2.5 Regional estimation

For regional estimation of quantiles, multiple linear regressions between quantiles and watershed characteristics were built. Direct regression with quantiles is the most common estimation approach in regionalisation (GREHYS, 1996). A relation between each quantile and physiographic characteristics of the watersheds of this form was established:

$$C(T) = \beta_0 V_1^{\beta_1} V_2^{\beta_2} \ldots V_p^{\beta_p} e^{\varepsilon} \qquad (6.2)$$

Where $C(T)$ is the quantile corresponding to a return period T, βi are the parameters to estimate, V_i are the explanatory variables and e a normal error. The βi parameters were estimated with the least square method after logarithmic transformation of equation (6.2). The explanatory variables were selected based on the correlations between the quantiles and physiographic characteristics using Spearman correlation coefficient. A stepwise regression procedure was used in order to optimize the number of significant explanatory variables.

6.2.6 Assessment of the reliability of the regional estimations

Estimation of the reliability of the regional estimates was performed using a leave-one-out re-sampling procedure to calculate error statistics. Every site is in turn considered ungauged and removed from the database. The remaining sites are then used to build a regression model to estimate the quantile at the station that has been removed. Then using the difference between the local quantile and the Jack-Knife estimate, it is possible to compute the relative bias (RBIAS), relative root mean square error (RRMSE) and root mean square error (RMSE) on estimated quantiles for each site :

$$RBIAS[\%)] = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{C_T^i - Ce_T^i}{C_T^i}\right)\times 100 \tag{6.3}$$

$$RRMSE[\%)] = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{C_T^i - Ce_T^i}{C_T^i}\right)^2}\times 100 \tag{6.4}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(C_T^i - Ce_T^i\right)^2} \tag{6.5}$$

Where Ce_T^i is the regionally estimated *T*-year quantile at site *i*, C_T^i the *T*-year local quantile at site *i*, and *N* the number of sites in the region. These three performance indicators were computed for each regional model built in this study to compare their efficiency.

6.3 Results

6.3.1 Correlation between SSC and discharge

The relation between SSC and discharge was investigated since it is traditionally the most common way to estimate SSC. For each annual maximum of SSC, the corresponding maximal discharge during the whole period covering 3 days before and 3 days after the SSC event was extracted. On average, the lag between the annual peak of SSC and corresponding event discharge is 1.7 days. For over half of the events (55.06%), the peak of SSC occurs the same day as the peak of discharge. 28% of the events have the peak of discharge occurring before the peak of SSC, showing a clockwise hysteretic effect, and 16.5% of events with anti-clockwise hysteretic effect. Including all stations, the total number of events considered is 266. A high degree of scatter can be seen in the relation between annual maximum SSC and the corresponding discharge for several stations. For each station the correlation between annual maximum SSC event and the corresponding maximal discharge was investigated using the Spearman correlation coefficient at the 5% significance level. Results shows that the correlation is significant in only 10 stations out of 19 (table 6.3). The mean correlation coefficient for stations that have a significant correlation is 0.81. Therefore, using discharge alone is not sufficient to estimate extreme SSC for all selected stations in California.

6.3.2 Variability of suspended sediment transport and local frequency analysis

Annual maximums of SSC for the selected stations show a great variation from year to year as well as a variation in space, from a station to another. Figure 6.3a shows the range of values of annual maximums SSC for each station. The highest concentrations are found in the southern rivers. Calleguas and Sespe Creeks, Santa Clara River, number 4, 5 and 6 on the figure 6.3a, are the river exhibiting the greatest variation of the annual maximum values of SSC. They are also the stations with the highest recorded concentrations; exceeding 2 g/L. Meade *et al.*, 1990, Inman and Jenkins (1999) and Warrick *et al.* (2004) previously reported very high sediment production rates for these southern Californian Rivers as well as very high SSC during storm events.

The same great variability is observed for the annual values of the maximum percentage of suspended load carried in 2% of the time (M_2). Figure 6.3b shows the value of M_2 computed for each year. For most stations M_2 is above 40%, showing that for the selected Californian stations a large part of the annual load of suspended sediment is carried during 2% - or less - of the time. The annual values could vary of 30% from years to years. The stations with the highest values with M_2 above 90%, and the least inter-annual variability, are the Santa Clara River, Calleguas and Sespe Creeks, the rivers that have also the highest recorded SSC values.

Series of discharge (Q), annual maximum SSC and maximum percentage of annual load carried during 7 days of the year (i.e. M_2), were modelled with probability distributions. The complete list of tested distributions is available in Tramblay *et al.* (2008). For each station, the distribution with the lowest Bayesian information criteria (BIC) was selected. The selected distributions for all series include the 2 parameters Log-Normal, Exponential, Gamma, Weibull, Generalized Pareto and Gumbel distributions. Discharge series were best modelled by Generalized Pareto (7 stations) and Log-Normal (5 stations) distributions. For SSC series, 8 stations were fitted with Log-Normal and 8 with Exponential distributions. For the annual values of M_2, 6 station series were best fitted with the Weibull distribution. The selected distributions show neither specific spatial pattern and are not a function of a specific land use, exhibiting the site specificity feature of suspended sediment transport.

In order to study the correlations with physiographic characteristics and test the regional estimation, 3 quantiles of return period 2, 10 and 20 years were extracted from each fitted distribution of annual maximum SSC and M_2. The quantile corresponding to the 2 years return period is, for most stations, equivalent to the median of the series of annual maximum SSC or M_2. The Spearman correlation coefficient is 0.98 between the median of annual maximum SSC and the quantile of SSC of return period 2 years. The others quantiles of longer return periods (10 and 20 years), characterising the less frequent events, are among the highest quantiles that can be extrapolated with a good confidence interval since the lengths of data series were small. The 99th percentile of the SSC distribution was also extracted from the station series, as well as a unique M_2 value per station computed on the whole series.

6.3.3 Regional estimation of extreme SSC

The quantiles corresponding to return periods of 2, 10, 20 years (respectively C2, C10 and C20) and the 99th percentile (CSS99) of SSC show several significant correlations with physiographic characteristics at the watershed scale and the station-locality scale. Table 6.4 shows the Spearman correlation coefficients between extreme SSC indicators and catchment or station-locality characteristics. The statistically significant correlations at the 5% confidence level are indicated in bold. There are no statistically significant correlations with discharge quantiles. On the whole, the correlations are stronger with the SSC quantiles corresponding to longer return periods. At the watershed scale, extreme SSC are strongly correlated with the presence of residential, bare rock, orchard and vineyards types of land use. Forest cover, annual precipitation and the number of days with precipitation show also good negative correlations with extreme SSC. At the station-locality scale, the correlation coefficients with land use characteristics are weaker, but some other classes of agricultural land use (pasture/hay, row crops, small grains) that were not strongly correlated with SSC at the watershed scale show significant correlations at the station-locality scale. This indicates that the presence of such agricultural activities in the vicinity of the station could lead to greater concentrations. All topographic attributes, such as altitude and slope, are better correlated with extreme SSC at the station-locality scale. The correlations with annual precipitation and some soils attributes such as rock volume on the surface, permeability and drainage quality of the soils are also stronger at the station-locality scale.

To test the regional estimation using watershed and station-locality attributes, regressions models were built using the attributes correlated with extreme SSC indicators. Stepwise regression algorithm was used in order to reduce the number of variables included in the regression models. The watershed-based regression model used to estimate extreme SSC indicators is described in equation 6.3 and the station-locality-based regression model is described in equation 6.4.

$$C(T) = \theta_0 FOREST^{\theta_1} PRECP1^{\theta_2} PANNU^{\theta_3} RESIDENTIAL^{\theta_4} e^{\varepsilon} \tag{6.3}$$

$$C(T) = \beta_0 ROCKVOL_L^{\beta_1} DRAIN_L^{\beta_2} PANNU_L^{\beta_3} RESIDENTIAL_L^{\beta_4} e^{\varepsilon} \tag{6.4}$$

Where *C(T)* is the quantile corresponding to the return period *T*, or the percentile to estimate, βi and θi are the regression parameters and e a normal error term. These models were used to proceed to the regional estimation of SSC quantiles C2, C10 and C20 and the 99th percentile of SSC series (CSS99). The estimation results using either the watershed or the station-locality characteristics, in terms of RMSE, RBIAS, and RRMSE after Jack-Knife re-sampling, are presented in the table 6.5. The coefficient of determination (R^2) was also computed for each regression model. Results show that the estimation is more reliable for all SSC indicators using station-locality attributes rather than watershed attributes. RMSE, RBIAS and RMSE are up to 40% lower in the case of the station-locality-based estimates of extreme SSC and the coefficients of determination of the regressions are greater by 0.02 to 0.34. In particular for the 99th percentile of SSC (CSS99), RRMSE drops from 122% when using watershed characteristics to 51% when using the station-locality characteristics. Uncertainty in the estimation are greater when considering short return periods such as 2 years (C2), with RRMSE around 100% for the watershed estimation but 60% for the station-locality estimation. Figure 6.4 shows the plot of the regional estimates versus the local values of the quantiles and the 99th percentile. When considering the station-locality attributes rather than the whole watershed attributes there is less scatter in the estimation. For the 2 stations with the highest SSC recorded, the Calleguas Creek (11106550) and Santa Clara River (11108500), regional estimation tends to underestimate the concentration for all quantiles and the 99th percentile, using either watershed or station-locality attributes. These two catchments are located in the vicinity of the city of Los Angeles, it is hypothesized that urbanisation in general and residential land use in particular have been increasing significantly in these areas since the 1990s.

6.3.4 Estimation of flux duration indicators

The flux duration indicators considered include the maximum percentage of annual load carried during 2% of the time, computed on the whole time series of SSC (M_2), and for each year with the return periods 2, 10 and 20 years (respectively M2-2, M2-10 and M2-20) extracted from the probability distributions. Table 6.6 shows the Spearman correlation coefficients between the different duration indicators with watershed and station-locality characteristics. The flux duration indicators are correlated with many physiographic characteristics both at the watershed and station-locality scale; in particular with quantiles of discharge, climatic and soils characteristics. The size of the watershed is only moderately correlated to M_2 quantiles, with a significant correlation only with M2-2. There are good correlations with forest and shrubland types of land use. There are correlations with a greater number of land uses classes at the watershed scale than at the station-locality scale. Almost all climatic characteristics, including mean value of rainfall or snow (PANNU, SNOW), descriptors of precipitation intensity (SDII, PDMAX) and winter temperature (TJAN, FROST) are correlated with the flux duration indicators considered. The soils characteristics showing strong correlations with the indicators include the bulk density (BD), porosity (POROS), distance to bed-rock (ROCKDEPM) at both scale, whereas the thickness of the soils layers (THICK) and the K-factor are only correlated at the station-locality scale. In general there are more significant correlations at the watershed than in the station-locality.

The estimation of these flux duration indicators is made using multiple regressions models built using the variables correlated shown in Table 6.6. The two models used to predict the

M_2 quantiles at the watershed scale (equation 6.5) and the station-locality scale (equation 6.6) are:

$$M(T) = \theta_0 BAREROCK^{\theta_1} SHRUBLAND^{\theta_2} PANNU^{\theta_3} PDAYMAX^{\theta_4} e^{\varepsilon} \tag{6.5}$$

$$M(T) = \beta_0 Q2^{\beta_1} FOREST_L^{\beta_2} PANNU_L^{\beta_3} ROCKDEPTH_L^{\beta_4} e^{\varepsilon} \tag{6.6}$$

Where *M(T)* is the quantile corresponding to the return period *T*, *βi* and *θi* are the regression parameters and *e* a normal error. Stepwise regression algorithm was also used to select the parameters to include in the regressions. For the estimation of M_2, only the parameters BAREROCK and PANNU are included in the regression model at the watershed scale, and the variables Q2, FOREST and PANNU for the model at the station-locality scale. The estimation results for the flux duration indicators after re-sampling lead to errors less than 10%, with RMSE ranging from 3,2% to 7,2% for the watershed-based estimation and from 3,4% to 6,8% for the station-locality-based estimation (Table 6.7). All performance indicators (RRMSE, RMSE, RBAIS and R^2) indicate that the estimation yields very similar results using either the attributes of the whole watershed or of the station-locality. On figure 6.5, where are plotted the regionally estimated values of the flux duration indicators (M2-2, M2-10, M2-20 and M2) against the local values, two groups of stations could be identified on several graphs (M2-10, M2-20 and M2). These two group are corresponding to the southern stations, with a high percentage of the annual load carried in 2% (above 90%), and the northern stations with lower values (less than 90%).

6.4 Conclusions and discussion

Extreme suspended sediment concentration in Californian rivers show a great variation in space and time, and are correlated with several physiographic characteristics. In the 19 selected rivers in the context of this study with a wide range of catchment sizes, extreme SSC are better correlated with the local physiographic characteristics of the gauging stations, with a radius of 5 km around them, than with the physiographic characteristics for the whole catchment area. Therefore, estimation of extreme SSC quantiles for different return periods and the 99th percentile of the SSC distribution give better results when using the physiographic characteristics of the station-locality in multiple regression models. For the indicators considered in this study, there is less than 60% uncertainty on the estimation of extreme SSC when using the station-locality characteristics.

In contrast with extreme SSC, the flux duration indicators considered in this study are also correlated with several physiographic characteristics, both at watershed and the station-locality scale. Unlike extreme SSC, there is similar estimation performance for M_2 indicators when using either the characteristics of the whole watershed or only the station-locality of the considered measuring sites. For the various flux duration indicators considered, M_2 computed on the whole time series or quantiles of different return periods derived from annual values, the regional estimation using physiographic characteristics is much more precise than for extreme SSC with less than 10% uncertainty on the estimated values.

Extreme rates and variability of suspended sediment transport are observed in the selected Californian Rivers in this study. The high inter-annual variability of the annual maximum

SSC and load carried during 2% of the time adds uncertainty to the probabilistic modelling in absence of very long record for all stations. As observed by Meade *et al.* (1990), some extreme events may belong to different populations than the more typical year-to-year peak flows and therefore may not be predicable by extrapolation based on magnitude and frequencies of the more normal events. Beside this characteristic of sediment transport in semi-arid environments, the estimation errors observed are probably in large part caused by the databases used to retrieve the physiographic characteristics of the catchment and the station-locality.

Most of the suspended sediment data used in this study was collected before the 1990s (except for station 11525600 with records until 1994) while land use, derived from satellite images, and soil information databases were available more recently. Higgitt & Lu (1999) showed that the first difficulty of assessing land use impact on sediment delivery was caused by the time discrepancy between available SSC records and the physiographic data. It is hypothesized that several river basins considered in this study, in particular the ones close to urban areas, have seen a significant modification in their land use, or the implementation of soil conservation and sediment control measures, leading to either an increase or a decrease in the supply of fine sediments (Walling, 2006). Another feature specific to these semi-arid catchments is the occurrence of wildfires that produce a large increase in sediment exports that Lane *et al.* (2006) estimated to amplify by a factor 8-9 in year 1 after the fire in Australian catchments with similar climatic conditions.

The importance of the local characteristics of a particular measuring site for suspended sediment transport characterization and estimation has been previously investigated for mean SSC in Jarvie *et al.*, 2002, and Siakeu *et al.*, 2004. In the present study, results indicate that the physiographic characteristics of the station-locality of the stations are more important than the whole catchment characteristics to predict extreme SSC. For the estimation of suspended sediment flux duration indicators, using either the whole catchment or only the physiographic characteristics of the station-locality yields very similar results. The high site-specificity feature of suspended sediment transport has been reported in several previous studies by Meade *et al.* (1990) or Asselman (2000), but has not been yet studied for extreme SSC or suspended sediment transport regime.

The results indicate that extreme SSC are closely linked to the availability of local sources of sediment, as previously stated by Jarvie *et al.* (2002) for mean SSC. The importance of the local characteristics to study extreme SSC has to be linked with the different statistical distributions modelling series of extreme SSC even for sites close to each others (Tramblay *et al.*, 2008). The main conclusion that could be drawn from this work for future sediment regionalisation studies is the importance to consider the local physiographic characteristics of the measuring stations. One should not only focus solely on the catchment scale. There is also a need to test different sizes of station-locality to define the optimal "locality" of a given gauging station for sediment transport characterization. Future studies should verify that the optimal station-locality size to characterise suspended sediment transport varies depending of the localization of the considered stations within the different climatic/geomorphologic regions.

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Tableau 6.1: Selected stations

ID	USGS CODE	LAT	LON	NAME	SIZE (km2)	AVAILABLE YEARS
1	11046550	33,293	-117,394	SAN JUAN CREEK AT SAN JUAN CAPISTRANO	545	1971-1986
2	11048500	33,405	-117,483	SAN DIEGO CR AT CULVER DR NR IRVINE	123	1973-1985
3	11078000	33,446	-117,543	SANTA ANA R A SANTA ANA *	4319	1968-1988
4	11106550	34,105	-119,022	CALLEGUAS C CAMARILLO STATE HOSPITAL	638	1968-1978
5	11108500	34,236	-118,421	SANTA CLARA R A LOS ANGELES-VENTURA *	2937	1968-1978
6	11113000	34,270	-118,553	SESPE CREEK NR FILLMORE	594	1967-1978
7	11151870	36,142	-121,285	ARROYO SECO NR GREENFIELD	436	1963-1984
8	11152500	36,375	-121,402	SALINAS R NR SPRECKELS *	10885	1969-1979
9	11160500	37,024	-122,042	SAN LORENZO R A BIG TREES *	341	1972-1982
10	11179000	37,351	-121,574	ALAMEDA C NR NILES *	1391	1960-1973
11	11472150	39,373	-123,203	EEL R NR DOS RIOS	1724	1967-1977
12	11473900	39,422	-123,193	MF EEL R NR DOS RIOS *	1739	1966-1976
13	11475000	40,131	-123,375	EEL R A FORT SEWARD *	5650	1966-1976
14	11477000	40,293	-124,056	EEL R A SCOTIA *	8126	1960-1980
15	11481000	40,544	-124,034	MAD R NR ARCATA *	1109	1960-1974
16	11481500	40,542	-123,485	REDWOOD C NR BLUE LAKE	218	1973-1988
17	11523000	41,181	-123,320	KLAMATH RIVER AT ORLEANS *	21558	1968-1979
18	11525600	40,404	-122,495	GRASS VALLEY C NR LEWISTON *	135	1976-1994
19	11530000	41,030	-123,402	TRINITY R A HOOPA *	5244	1960-1979

* = Partial regulation

Tableau 6.2: Physiographic parameters

LANDCOVER	RESIDENTIAL	High or low density residential
	COMMERCIAL/IND.	Commercial or Industrial
	BARE ROCK	Bare Rock/Sand/Clay
	FOREST	Forest
	SHRUBLAND	Shrubland
	ORCHARD/VINE.	Orchards/Vineyards/Other
	PASTURE/HAY	Pasture/Hay
	ROW CROPS	Row Crops
	SMALL GRAINS	Small Grains
TOPOGRAPHY	MIN_A	Minimum altitude (m)
	MAX_A	Maximum altitude (m)
	DENIV	Altitude range (m)
	ALT_MED	Median altitude (m)
	MED_SLOPE	Median Slope (%)
	PERIMETER	Perimeter of drainage area (km)
	KM2	Size of drainage area (km2)
CLIMATE	PRECP1	Days with precipitation (days)
	PANNU	Precipitation total (mm)
	SDII	Rainfall intensity (mm/day)
	PDAYMAX	Maximum daily precipitation (mm)
	SNOW	Mean depth of snow (inches)
	FROST	Number of frost days (days)
	TJAN	Mean January temperature (deg. Celsius)
SOILS	KFFACT	K Factor
	OM	Fraction of organic Materials (%)
	PERM	Permeability of the soil (in. per hour)
	THICK	Cumulative thickness of all soil layers (in.)
	DRAIN	Soil drainage group
	ROCKVOL	Rock (> 2mm) volume on surface (%)
	F_SAND	Volume percent of sand (%)
	F_SILT	Volume percent of silt (%)
	F_CLAY	Volume percent of clay (%)
	BD	Bulk density (g/cm3)
	ROCKDEPM	Mean depth to bedrock (cm)
	POROS	Soil porosity (%)

Tableau 6.3: Spearman correlation coefficient (rho) between discharge and SSC and associated P-value

ID	P-value	rho
s11481500	0,00000	0,88929
s11523000	0,00000	0,94545
s11530000	0,00031	0,73804
s11113000	0,00165	0,85455
s11160500	0,00203	0,90000
s11048500	0,00824	0,80606
s11106550	0,00875	0,82846
s11473900	0,01841	0,74545
s11481000	0,02889	0,59121
s11108500	0,03413	0,82143
s11046550	0,05958	-0,51485
s11179000	0,12232	-0,60994
s11472150	0,13282	0,51515
s11475000	0,17822	0,46667
s11078000	0,36641	0,28671
s11477000	0,38129	0,21228
s11152500	0,70332	0,16667
s11525600	0,90620	0,03846
s11151870	0,96068	0,01471

Tableau 6.4: Spearman correlation coefficients between SSC indicators, watershed and station-locality characteristics (in bold the significant correlations at the 5% level)

Correlations with watershed characteristics					Correlations with station-locality characteristics				
	C2	C10	C20	CSS99		C2	C10	C20	CSS99
Residential	0,444	**0,702**	**0,695**	**0,676**	Residential	0,276	**0,574**	**0,571**	**0,559**
Commercial/Ind.	0,226	0,378	0,354	**0,474**	Commercial/Ind.	0,206	0,408	0,432	**0,456**
Bare Rock	0,442	**0,651**	**0,681**	**0,616**	Forest	**-0,481**	**-0,714**	**-0,672**	**-0,612**
Forest	-0,414	**-0,574**	**-0,532**	**-0,511**	Shrubland	0,286	**0,486**	**0,504**	0,237
Shrubland	0,265	**0,514**	**0,530**	0,400	Orchard/Vine.	**0,627**	**0,627**	**0,627**	**0,493**
Orchard/Vine.	0,439	**0,654**	**0,632**	**0,593**	Pasture/Hay	**0,525**	**0,525**	**0,525**	**0,545**
MIN_ALT	**-0,478**	**-0,599**	**-0,603**	**-0,577**	Row Crop	**0,649**	**0,748**	**0,742**	**0,632**
PRECP1	-0,354	**-0,642**	**-0,646**	**-0,514**	Small Grains	**0,503**	**0,503**	**0,503**	0,385
PANNU	-0,319	**-0,609**	**-0,623**	**-0,479**	MIN_ALT	**-0,502**	**-0,635**	**-0,614**	**-0,623**
SDII	**0,504**	0,289	0,240	0,286	MAX_ALT	-0,434	**-0,565**	**-0,531**	**-0,624**
TJAN	0,358	**0,618**	**0,616**	**0,467**	MEAN_ALT	**-0,458**	**-0,591**	**-0,596**	**-0,658**
ROCKVOL	**-0,502**	**-0,456**	-0,409	-0,396	MEDIAN_ALT	-0,425	**-0,551**	**-0,561**	**-0,609**
					MEAN_SLOP	-0,325	**-0,493**	**-0,472**	**-0,523**
					MEDIAN_SLOPE	-0,344	**-0,526**	**-0,519**	**-0,544**
					TJAN	0,454	**0,704**	**0,696**	**0,574**
					PANNU	**-0,456**	**-0,682**	**-0,668**	**-0,533**
					FROST	-0,235	**-0,456**	**-0,465**	-0,358
					PRECP1	-0,300	**-0,589**	**-0,589**	-0,418
					PERM	0,256	0,439	**0,512**	0,304
					DRAIN	0,453	0,379	0,302	**0,553**
					ROCKVOL	**-0,640**	**-0,663**	**-0,612**	**-0,737**

Tableau 6.5: Estimation results for SSC

Watershed					Locality				
	C2	C10	C20	CSS99		C2	C10	C20	CSS99
RMSE	3370	9435	11990	2551	RMSE	2504	6101	7838	1820
RBIAS	-29,1%	-16,1%	-14,8%	-35,6%	RBIAS	-13,8%	-7,8%	-8,9%	-12,8%
RRMSE	103,1%	68,0%	65,1%	122,5%	RRMSE	60,0%	48,8%	57,1%	51,5%
R2	0,40	0,63	0,68	0,35	R2	0,68	0,72	0,70	0,69

Tableau 6.6: Spearman correlation coefficients between flux duration indicators, watershed and station-locality characteristics

Correlations with watershed characteristics					Correlations with station-locality characteristics				
	M2 - 2	M2 - 10	M2 - 20	M2		M2 - 2	M2 - 10	M2 - 20	M2
Q20	**-0,632**	**-0,501**	-0,189	**-0,682**	Q20	**-0,632**	**-0,501**	-0,189	**-0,682**
Q10	**-0,646**	**-0,523**	-0,209	**-0,696**	Q10	**-0,646**	**-0,523**	-0,209	**-0,696**
Q2	**-0,670**	**-0,585**	-0,285	**-0,747**	Q2	**-0,670**	**-0,585**	-0,285	**-0,747**
BareRock	0,288	**0,483**	**0,469**	**0,468**	Forest	**-0,607**	**-0,617**	**-0,497**	**-0,616**
Forest	**-0,539**	**-0,713**	**-0,729**	**-0,600**	Shrubland	**0,632**	**0,526**	0,333	**0,760**
Shrubland	**0,556**	**0,738**	**0,742**	**0,658**	Pasture/Hay	**0,459**	**0,521**	0,427	**0,653**
Orchard/Vineyar	0,025	0,382	**0,507**	0,220	Row Crop	**0,533**	**0,487**	0,442	**0,533**
Pasture/Hay	0,378	**0,766**	**0,825**	**0,642**	PDAYMAX	**-0,596**	**-0,635**	**-0,542**	**-0,647**
Row Crop	0,135	**0,591**	**0,746**	0,346	SNOW	**-0,581**	**-0,663**	**-0,627**	**-0,560**
Small Grains	0,359	**0,538**	**0,530**	**0,487**	TJAN	**0,730**	**0,742**	**0,630**	**0,726**
MEDIAN_SLOPE	-0,225	**-0,496**	**-0,526**	**-0,470**	PANNU	**-0,846**	**-0,836**	**-0,673**	**-0,802**
Km2	**-0,530**	-0,214	0,074	-0,442	FROST	**-0,516**	**-0,584**	**-0,517**	**-0,509**
PRECP1	**-0,735**	**-0,773**	**-0,644**	**-0,768**	PRECP1	**-0,782**	**-0,773**	**-0,611**	**-0,818**
PANNU	**-0,718**	**-0,815**	**-0,722**	**-0,782**	KFFACT	-0,375	**-0,544**	**-0,558**	-0,439
PDAYMAX	-0,333	**-0,716**	**-0,809**	**-0,544**	THICK	**-0,575**	**-0,603**	**-0,558**	**-0,505**
SNOW	**-0,644**	**-0,634**	**-0,542**	**-0,588**	BD	**0,577**	**0,751**	**0,733**	**0,670**
TJAN	**0,758**	**0,735**	**0,589**	**0,737**	ROCKDEPM	**-0,649**	**-0,704**	**-0,643**	**-0,586**
OM	**-0,579**	-0,436	-0,253	-0,419	POROS	**-0,575**	**-0,749**	**-0,724**	**-0,665**
ROCKVOL	-0,449	**-0,463**	**-0,483**	-0,421					
BD	**0,598**	**0,578**	**0,476**	**0,507**					
ROCKDEPM	-0,446	-0,443	-0,396	**-0,493**					
POROS	**-0,649**	**-0,634**	**-0,526**	**-0,568**					

Tableau 6.7: Estimation results for flux duration indicators

Watershed					Locality				
	M2-2	M2-10	M2-C20	M2		M2-2	M2-10	M2-C20	M2
RMSE	7,27 %	3,74 %	3,2 %	5,4 %	RMSE	6,84 %	3,48 %	3,94 %	4,44 %
RBIAS	-0,98%	0,01%	0,10%	0,04%	RBIAS	-0,85%	-0,12%	-0,10%	0,06%
RRMSE	11,21%	4,12%	3,34%	6,32%	RRMSE	11,14%	3,88%	4,17%	5,33%
R^2	0,84	0,86	0,86	0,88	R2	0,87	0,90	0,73	0,93

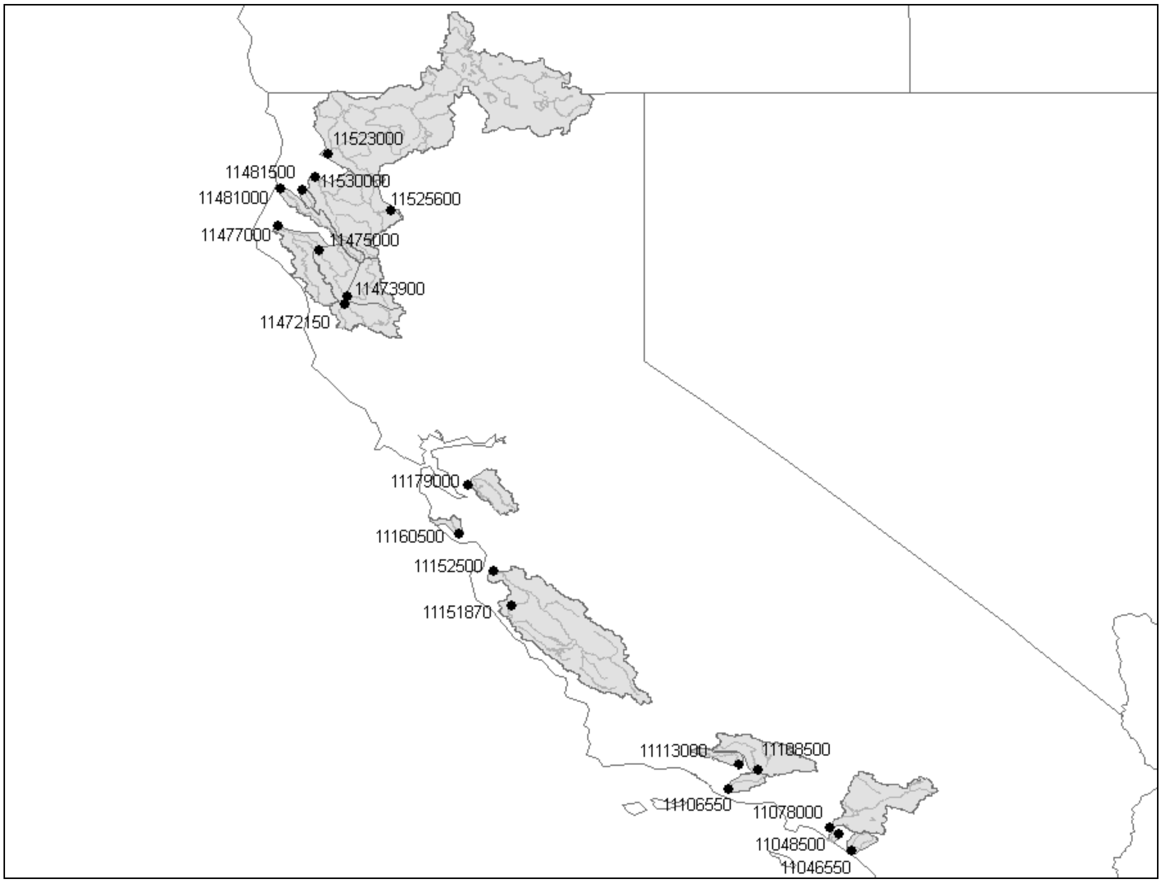

Fig. 6.1: Map of the selected watersheds

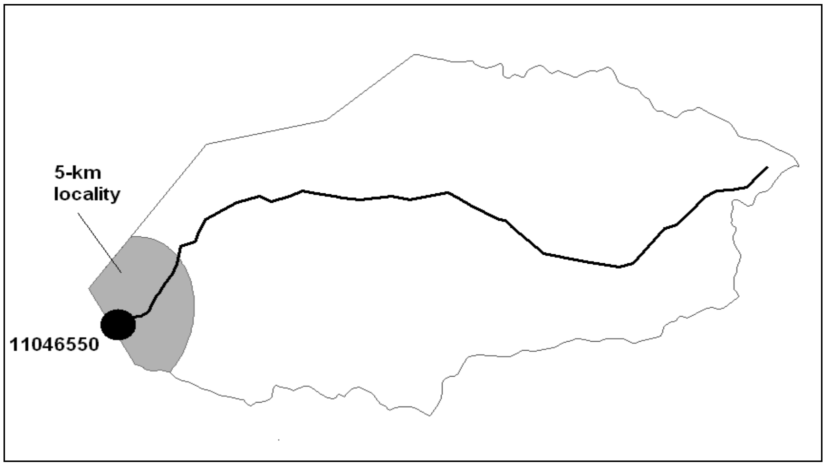

Fig. 6.2: Illustration of the 5km station-locality vs. whole watershed

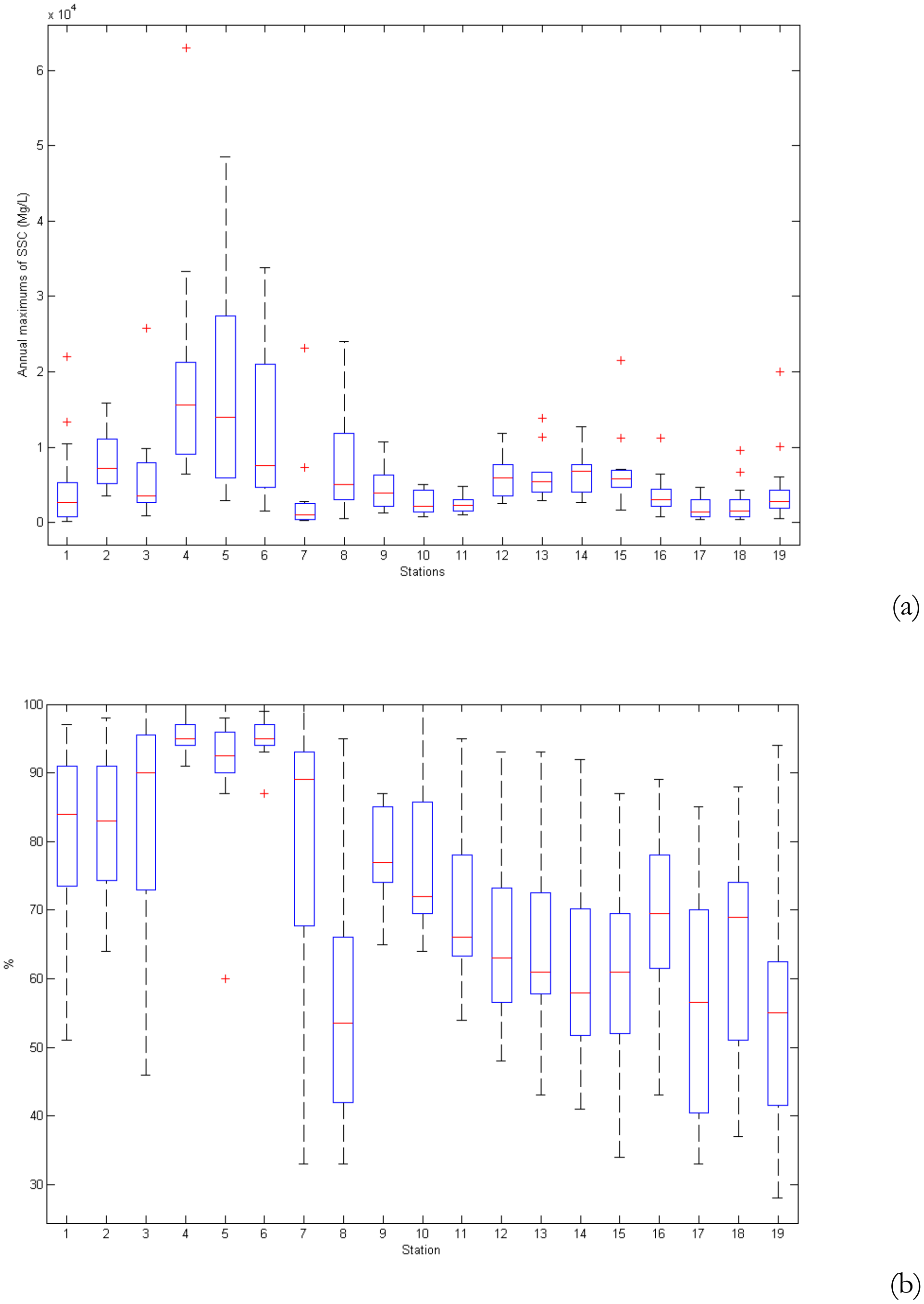

Fig. 6.3: Inter annual variability of sediment transport for the selected stations: (a) annual maximum SSC and (b) annual M_2 values

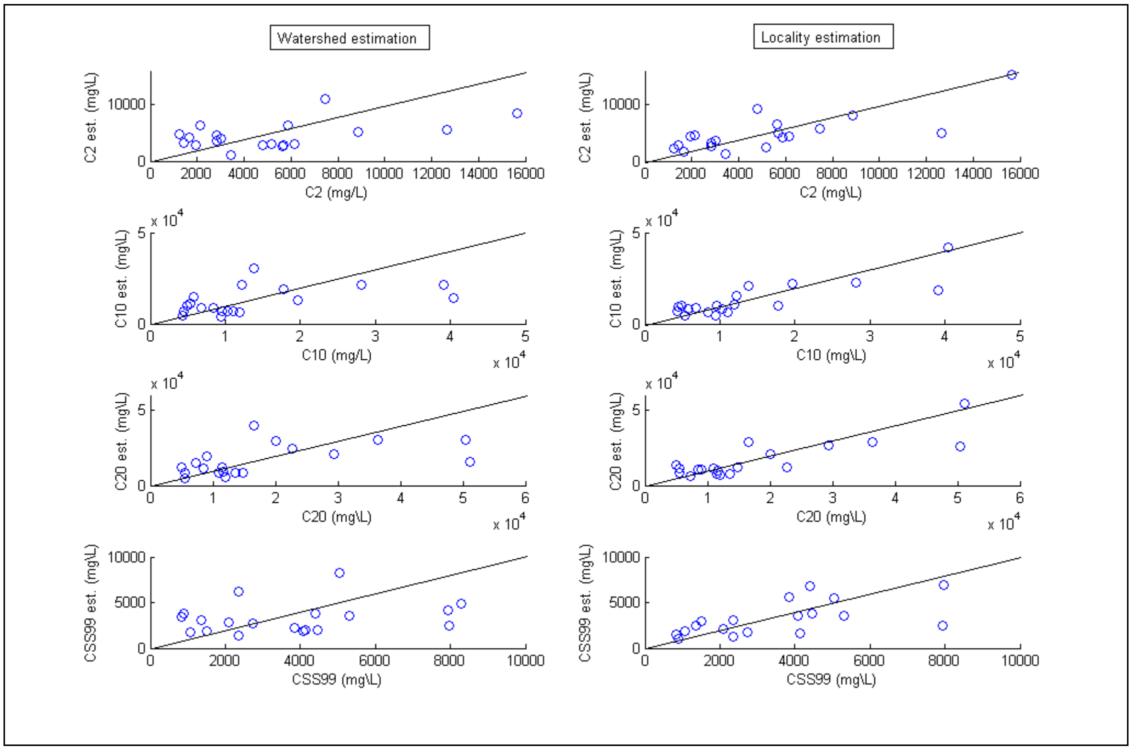

Fig. 6.4: Estimation results for SSC using watershed (left) or station-locality (right) characteristics

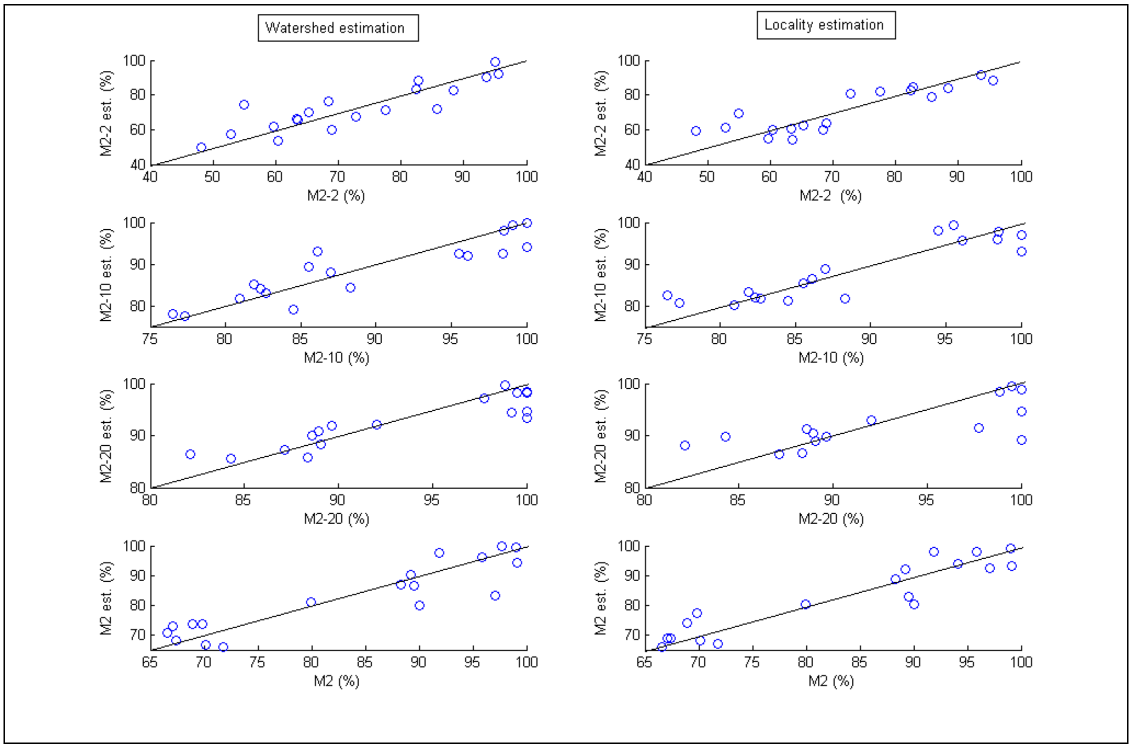

Fig. 6.5: Estimation results for flux duration indicators using watershed (left) or station-locality (right) characteristics

CHAPITRE 7 : Une première application des arbres de régression pour l'analyse fréquentielle régionale des concentrations extrêmes de sédiments en suspension

A FIRST APPLICATION OF REGRESSION-TREE APPROACH FOR REGIONAL FREQUENCY ANALYSIS OF EXTREME SUSPENDED SEDIMENT CONCENTRATIONS

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Abstract

Extreme suspended sediment concentrations (SSC) reduce water quality and are also difficult to monitor and predict, due to sampling protocol limitations and the small number of stations with long records. In this study extreme SSC are modelled using two sampling approaches; the first uses annual maximum values (AM), modelled by several probability distributions, the second uses peak over threshold (POT) sampling, considering the exceedances over the 99th percentile and modelled with Poisson and Generalized Pareto distributions. The quantiles obtained by frequency analysis are estimated for ungauged sites with watershed and station-locality physiographic characteristics using a regression-tree approach. This non parametric method combines the two "classical" regionalisation steps of 1-delimitation of homogeneous regions and 2-regional estimation, into one single procedure. Two different pruning approaches for the regression-trees are tested, one based on the commonly employed *1-SE* rule, and the other based on the selection of the pruning level that optimize the regional estimates. Results of the frequency analysis indicate that AM and POT quantiles for long return period (20-years) are very similar, with less than 3% difference, but for a shorter return period (2-years) POT quantiles are in average 20% greater. Regional estimation using the regression-tree approach gives better results when considering the pruning approach aiming at reducing estimation uncertainty, but the method need further improvements to take full benefits of its predicting capabilities.

7.1 Introduction

Suspended sediments are a key variable for water quality assessment. High suspended sediment concentrations (SSC) are a threat to aquatic life and can carry large amounts of pollutants particles such as heavy metals, or nutrients (Waters, 1995). Only a few hydrometric networks in the word monitor SSC with a high temporal resolution. Suspended sediment transport is highly variable in time, with infrequent large events that could transport enormous loads (Meade *et al.*, 1990). In North America, several stations monitoring daily SSC are still in function but their number has been decreasing dramatically since the 1980s (Gray & Glysson, 2002). Therefore knowledge on extreme values of SSC is relatively limited and there is a need to develop estimation procedures to palliate this lack of measurements.

In this study, extremes of SSC are modelled using a frequency analysis approach. The goal is to derive SSC quantiles of different return periods from the available series of daily measurements. Only a few studies have developed a probabilistic modelling approach for SSC. Watts *et al.* (2003) used peaks over threshold (POT) sampling approach to assess the risk to fish from high SSC in England. Soler *et al.* (2007) used both annual maximum (AM) and POT sampling to model SSC series in the Vallcebre experimental catchment in Spain. Modelling of annual maximum SSC with several probability distributions in North America has been carried out in Tramblay *et al.* (2008). In the case of flood frequency analysis, several studies have shown that the POT approach provides better estimates of flood quantiles (Madsen *et al.*, 1997, Lang *et al.*, 1999). In the present study, SSC quantiles obtained by frequency analysis based on both AM and POT sampling approaches are compared for 56 stations in North America.

Regionalisation is a helpful tool to estimate hydrological variables in ungauged or partially gauged sites. It usually consists in two main steps, the delineation of homogeneous regions and the regional estimation within the regions created (GREHYS, 1996). In this study, the applicability of regression-trees analysis (Breiman *et al.*, 1984) is tested to estimate extreme SSC in ungauged sites. The regression-tree method has been seldom used in hydrology and usually for classification purposes only. A study by Laaha & Blöschl (2006) used this approach for the regionalisation of low flows in Austria. Robertson *et al.* (2006) applied regression-trees for regional classification of reference water quality in USA. However, a number of other applications exist, for satellite images classification (Huang & Townshend, 2003) or ecological and biological data analysis (Breiman *et al.*, 1984, De'ath & Fabricius, 2000).

Regression-tree analysis (CART) is a statistical technique used to explore the relations between a single response variable and one or more explanatory variables. The method involves partitioning a data set into subgroups based on relations between the response variable (e.g., quantiles of SSC) and the explanatory variables (e.g., percentage of clay, rainfall intensity etc.). This is the main difference with other classification approaches producing a tree, such as clustering (Ouarda *et al.*, 2007), that considers only the relation between the explanatory variables. The results resemble a tree with the specific values or breakpoints of various explanatory variables defining its branches (Robertson *et al.*, 2006). Regression-trees have several advantages over other statistical models for regionalisation. Their structure is non-parametric, there is no global sensitivity to outliers and they are able to handle non-linear relationships well (Laaha and Blöschl, 2006). For the purpose of this study, the main advantage remains the combination of the two traditional steps of regionalisation in one single procedure. However, several potential problems exist with this approach such as the lack of smoothness of the estimated data and the need to use some tree pruning methods to avoid over-fitting (Breiman *et al.*, 1984).

The main objectives of this study are:

1. Compare the quantiles of extreme SSC obtained with annual maximum (AM) or peaks over threshold (POT) sampling and their correlations with physiographic characteristics.
2. Test the reliability of regression-trees with two different pruning approaches to estimate extreme SSC in ungauged catchments, using the physiographic characteristics of the sampling sites.

7.2 Methodology

7.2.1 Study area and GIS data

Series of daily SSC for 56 stations (15 stations are in Canada, 41 in USA) were extracted from the Hydat (Canada) and USGS-Sediment (USA) databases. All these sampling sites are located east of the Rocky Mountains, between the plains region and the Atlantic coast (figure 7.1). Catchment sizes ranges from 76 km^2 to 116,000 km^2. In these stations, high SSC events are generally observed during the period ranging from the months of March to July, associated either with snowmelt of spring rainfalls (Tramblay *et al.*, 2008). The main selection criteria for the stations were the length of time series available, 10 or more years of daily SSC, and little or no regulation of discharge. Long series are necessary to produce reliable quantiles with frequency analysis and regulation in river is known to affect greatly sediment transport (Walling, 2006).

An extensive GIS database was built to retrieve several physiographic attributes describing the soils, climate, land cover and elevation of the Canadian and American stations (Table 7.1). These attributes were retrieved and averaged at the watershed scale and for a smaller area around the locality of stations. The locality of the sampling sites is defined by the drainage area of 20-km radius of each station. The research of Jarvie *et al.*, 2002, or Siakeu *et al.*, 2004, suggested the importance of the characteristics of the locality of stations to describe suspended sediment and chemicals transport in streams. Tramblay *et al.* (2008) showed that regional estimation of extreme SSC yields better results when using the physiographic characteristics of the locality of the gauging stations rather than the whole basin. Elevation data was retrieved from the HYDRO1K database (USGS). Land cover for the USA was extracted from the NLCD database (1992), for Canada from the Department of Natural Resources database (1995). Soil data for the USA were extracted from the STATSGO (1994) database of USDA. Soil data for Canada were retrieved from the Soils Landscape of Canada database (SLC, version 2.0, 1994 and 3.1, 2006). Climatic data were obtained from USHCN (NOAA) and Environment Canada database.

7.2.2 At-site frequency analysis

Local frequency analysis is carried out using two sampling strategies commonly used for flood modelling (GREHYS, 1996): the first based on annual maxima (AM) and the second based on peaks-over-threshold (POT).

In the AM approach, series of annual maximums SSC are fitted with several statistical distributions. The selection of the most adequate distribution is based on the lowest score of the Bayesian Information Criterion (BIC) computed from the likelihood function and the number of parameters of the distributions (Schwartz, 1978). All series must comply with the hypothesis of homogeneity, stationarity and independence, tested in this study with the non parametric tests of Wilcoxon, Kendall, and Wald-Wolfowitz. Using the most accurate probability distribution fitted to each station data, different quantiles for several return periods can be extracted. The complete methodology for frequency analysis of annual maximum SSC and the list of tested distributions are detailed in Tramblay *et al.* (2008).

For the POT approach, the samples are not collected annually but include all the values of the variable that exceed a specific threshold. The POT approach is not limited to only one event per year. The choice of the threshold value is critical since meeting the independence condition for the selected peaks is a prerequisite for frequency analysis. This represents the main difficulty in the POT modelling approach and various sampling rules have been established (GREHYS, 1996, Lang *et al.*, 1999, Beguería, 2005). Usually it is assumed that the occurrence times of peaks follow a Poisson process combined with the generalised Pareto distribution for the magnitude of exceedances (Madsen *et al.*, 1997, Önöz & Bayazit, 2001, Watts *et al.*, 2003). In this study, the 99th percentile of daily SSC was used as threshold value for each station. To ensure the independence of the selected peaks, two conditions were imposed: a minimum of 5 days between successive peaks and the concentrations must drop below the threshold value between two peaks. Occurrences of peaks were modelled by a Poisson distribution of parameter λ, corresponding to the mean number of exceedances per year. The two parameter Generalized Pareto distribution (GPD) was fitted to the peak magnitudes. The GDP has the cumulative distribution function:

$$F(q) = 1 - \exp\left(-\frac{q - q_0}{\alpha}\right) \qquad \varkappa = 0$$

(7.1)

$$F(q) = 1 - \left(1 - \kappa \frac{q - q_0}{\alpha}\right)^{1/\kappa} \qquad \varkappa \neq 0$$

Where α is the scale parameter, $\varkappa$ the shape parameter of the GPD distribution and q_0 the threshold level. The scale and shape parameters of the GPD were estimated using the method of moments, to derive the T_P-year event that is the event which on the average is exceeded once in T_P years (Madsen *et al.*, 1997):

$$q_T = q_0 + \frac{\alpha}{\kappa}\left[1 - \left(\frac{1}{\lambda T}\right)^{\kappa}\right] \tag{7.2}$$

Where q_T is the quantile of return period T and λ the mean number of exceedances per year.

7.2.3 Estimation with regression-trees

Regression-tree analysis is a statistical technique used to explore the relations between a single response variable and one or more explanatory variables. In traditional linear regression analysis, the dependent variable is assumed to be a linear function of a set of independent variables. This is often an unrealistic assumption, due to the type of the relation between the variables. Regression-tree analysis (Breiman *et al.*, 1984) avoids these problems by making no assumptions about the shape of the relations between the independent variables and dependent variable (Robertson *et al.*, 2006). In our case, the response variables are the quantiles of SSC extracted for different return periods and the explanatory variables are the watershed and the local physiographic and meteorological characteristics of the considered sites.

Regression-trees are built with a process known as binary recursive partitioning (Breiman *et al.*, 1984). This method recursively partitions the observations into subsets such that the total residual sum of squares (*RSS*) is minimized. The *RSS* of each *k*th subset is calculated as:

$$RSS_k = \sum_{i=1}^{N_k} (y_p^i - y^i)^2 \qquad (7.3)$$

Where N_k is the number of samples in the *k*th subset, y_p^i and y_p the predicted and actual values of the response variable for site *i*. In each terminal node *T*, the predicted value y_p is constant. At each step, all variable samples are scanned, and the variable and its breakpoint that minimize the *RSS* criterion are chosen. The first step is to grow a large tree *Tmax* by letting the splitting procedure continue until all terminal nodes are either reaching the minimal node size specified (in our case 10 values) or contain only identical measurements. The *Tmax* tree is not the optimum size and the estimates are overly optimistic; since it is grown using the training data set, when it reaches the full structure it usually suffers from over-fitting. This results in poor performance in estimation or forecast mode. Therefore it has to be pruned using validation data to determine the optimal number of nodes (Breiman *et al.*, 1984, Laaha & Blöschl, 2006).

In most studies the method for pruning is cross validation (Breiman *et al.*, 1984, De'ath & Fabricius, 2000). The data is randomly divided into a number *N* (usually 10) of exclusive subsets of approximately equal size. Each subset is dropped in turn; a tree is built with the remaining subsets, and used to predict the responses for the omitted subset. The estimated error is calculated for each subset. These steps are repeated for each pruning level. Breiman *et al.* (1984) suggested the *1-SE* rule, where the best tree is selected as the smallest tree such that its error rate is within one standard error of the minimum error (De'ath & Fabricius, 2000). Another option consists in selecting the minimum error tree but this method may result in over-fitting by keeping too many branches.

Breiman *et al.* (1984) observed that for trees with 11 or more terminal nodes the cross validation estimates are quite accurate. However for smaller trees, the discrepancies are generally large, the random cross validation may create unbalanced test sample. For both the minimum and *1-SE* rule, the size of the selected tree will vary significantly under repeated cross validation. In the context of this study, where the objective is to estimate extreme SSC with regression-trees, two pruning methods are considered. They both rely on a Jack-Knife re-sampling procedure, and the computation of two performance measures: the relative Bias (RBIAS) and relative root mean square error (RRMSE):

$$RBIAS[\%)] = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{C_T^i - Ce_T^i}{C_T^i}\right)\times 100 \qquad (7.4)$$

$$RRMSE[\%)] = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{C_T^i - Ce_T^i}{C_T^i}\right)^2}\times 100 \qquad (7.5)$$

Where Ce_T^i is the regional estimate of the *T*-year quantile at site *i* with Jack-Knife, C_T^i is the *T*-year local quantile at site *i*, and *N* the number of sites.

The first pruning method considers the cross validation described above with the *1-SE* rule following these steps:

1. Removing the target site.
2. Fitting a regression-tree to the remaining data.
3. Determining the optimal tree size by cross validation using the *1-SE* rule.
4. Pruning the initial tree back to the optimal size derived in Equation (2).
5. Estimating for the target site with the tree pruned and computing of RBIAS and RMSE.

The second approach tested aims at reducing the uncertainties associated with the estimated quantiles. It follows these different steps:

1. Removing the target site.
2. Fitting a regression-tree to the remaining data.
3. Pruning the initial tree with several specified pruning levels (0,1,2,3,4,5).
4. Estimation for the target site with each of the trees created in 3. and computation of RBIAS and RMSE for each pruning level.
5. Selecting of the best pruning level corresponding to the lowest estimation errors.

7.3 Results

7.3.1 Comparison of AM and POT quantiles

The SSC quantiles based on AM sampling were obtained from Tramblay *et al.* (2008). They are derived from 6 distributions; Exponential, Weibull, Log-normal, Gamma, Leak and Normal fitted on the series of annual maximum SSC. These distributions were chosen for each station based on the lowest score with the BIC criterion. For the POT sampling approach, the exceedances of the 99th percentile were extracted for each station and tested for autocorrelation with Wald-Wolfowitz non parametric test. All series were found to have no significant autocorrelation signal at 5% significance level. The occurrence was modelled using a Poisson process of parameter λ; the intensity parameter, estimated as the average number of exceedances per year. The mean number of exceedances for all stations is 2.1 events per year, ranging from 0.9 to 3.5 events per year depending on the station. The mean number of exceedances is above the value of 1.65 events per year, often referred to as a general point beyond which the PDS model becomes more efficient than the AM model (Madsen *et al.*, 1997). The magnitudes of the exceedances were modelled with GDP distribution using the method of moments for parameter estimation.

To compare the results based on AM and POT sampling and thereafter test the regional estimation, two quantiles of return period 2 and 20 years were computed. For the AM approach, quantiles of return period 2 and 20 years (C2 and C20) were derived using the distribution function selected for each station. For the POT approach, the quantiles of return period 2 and 20 years ($C2_{pot}$ and $C20_{pot}$) were computed using relation (1). There is a strong correlation between the quantiles obtained by the AM or the POT approach, the Spearman correlation coefficient between C2 and $C2_{pot}$ is 0.98, and 0.99 between C20 and $C20_{pot}$. On average, there is very little difference (less than 3 %) between C20 and $C20_{pot}$ quantiles. For the quantile of return period 2 years, $C2_{pot}$ is for most stations higher than C2, on average 20% larger. Figure 7.2 show the relation between the C2 and $C2_{pot}$, figure 7.3 the relation between C20 and $C20_{pot}$. The only station where the 2 quantiles are significantly different is Big Horn River in Wyoming (06279500), with C20=63,7 mg/L and $C20_{pot}$= 34,3 mg/L.

The correlations between the quantiles C2, C20, $C2_{pot}$, C20pot and the 99th percentile of SSC series with watershed and locality of sampling sites characteristics were investigated using the Spearman correlation coefficient at the 5% significance level. Table 7.2 shows on the left side the correlation coefficient for the variable significantly correlated with the SSC variables. On the right side of the table are shown the correlations with the 20-km locality of the gauging stations. The SSC quantiles and the 99th percentile are correlated with several watershed characteristics, in particular the clay content of the soils (FRACT CLAY), the longitude of the station (LON), the percentage of land covered by grassland (GRASSLAND) and rainfall peakedness (INTPREC). Several significant correlations are found with various climatic variables (PRCP1, SDII, PANNU, and FROST). At the locality scale, the same characteristics are also correlated with the SSC quantiles and the 99th percentile with similar correlation coefficients. There are more correlations with soil characteristics at the more local scale, such as with drainage quality (DRAIN), the sand content of the soils (FRACT SAND) and the rock volume on surface (ROCKVOL).

7.3.2 Quantile estimation with regression-trees

Among all the variables showing a strong correlation with SSC quantiles and the 99th percentile, a stepwise algorithm was used prior to the creation of the regression-trees to select a restricted parsimonious subset of the variables to be included. The stepwise algorithm selected the following variables: FRACT CLAY (local scale), SDII (local scale), GRASSLAND (watershed scale) and the longitude (LON) of the stations. Figure 7.4 shows the relations between the quantile C20 and the four variables selected. The relations with the other quantiles or the 99th percentile were not plotted because of very similar shape. For the variable 'GRASSLAND', the relation with C20 is not linear, opposing in one side the catchments located in the prairies having a large percentage of their area covered with grassland-type land use and on the other side the other catchment with no or little land use of that type.

The first pruning approach described in the methodology section is used to test the regional estimation of SSC quantiles and the 99th percentile (CSS99). The four selected variables are used to create a tree for each of the variables of interest (C1, C20, $C2_{pot}$, $C20_{pot}$ and CSS99). Each of the 56 stations is in turn removed, and then the remaining stations are used to build a regression-tree for which the best pruning level respecting the rule *1-SE* is estimated by a random cross validation procedure using 30 folds. Figure 7.5 shows the box plot of the best pruning level determined by this approach for the four SSC quantiles and CSS99. The lowest pruning level (i.e. leading to a large tree including many branches) is obtained for the variables C20 and $C20_{pot}$ with a median value around 2. For the other variables, the pruning level is higher, but for all variables there is a great variation, from almost one to ten, in the best pruning level selected using this cross validation approach. Increasing the number of cross validations does not reduce significantly the range of values taken by the best pruning level. Table 7.3 gives the estimation results for the SSC quantiles and CSS99 using this approach. The best results are obtained for the return period of 20 years, whereas for the other variables the errors are quite large with RRMSE values exceeding 100%.

The second pruning approach tested considers using fixed pruning levels. Each station is removed in turn, several trees are grown with the remaining stations and their efficiency to predict the value for the site that has been removed is evaluated using trees pruned at different levels, from 0 to 5. Figure 7.6 shows the RRMSE for the quantiles and CSS99 for the different pruning levels. The RRMSE have been averaged on the 5 variables as shown on figure 7.7. The optimal pruning level leading the lowest RRMSE is 2 as seen on figure 7.6 and 7. One of the advantages of using such approach is that the results do not change at each iteration, unlike the random cross validation approach. The estimation results for the considered variables also resemble to the errors that are in theory associated with the regression-tree method: when using a pruning level of 0, meaning no pruning, the trees is grown using all the training dataset and therefore is not necessarily adapted to predict new values with a great adequacy. When the pruning level increases, it reaches an optimum value where the predictive capability is a good compromise between reducing the tree size and overfitting. When the pruning level increases more, the number of branches and terminal nodes becomes small and the estimation errors grows as the size of the trees is diminishing. Table 7.5 shows the estimation results in terms of relative BIAS and RMSE using a pruning level of 2. Estimation errors with this approach are smaller than with the cross validation using the rule *1-SE*, reducing RRMSE on all variables. Estimation errors of the 20-years SSC quantiles ranges from 84% to 93% of RRMSE. The estimation of the 2-year SSC quantiles and the 99th percentile gives similar results with RRMSE between 120 and 144%.

7.4 Conclusions and perspectives

In this study two approaches to model extreme SSC with probability distributions were tested to retrieve quantiles of extreme SSC for different return periods. Using either annual maximum or peaks over threshold sampling, with 99th percentile of concentration for threshold, yields very similar results. For quantiles corresponding to a return period 2 and 20 years the correlation between the AM and POT quantile is above 0.9. The quantiles computed for the 20-year return period are almost identical when using AM or POT sampling strategies. In the case of the quantiles computed for a 2-year return period, the quantiles obtained by POT sampling are on average 20% larger than the quantiles obtained by AM sampling. Hence, the more central values differ slightly, but more extreme quantiles (e.g. C20) are similar. The quantiles obtained show good correlations with physiographic characteristics, both at the catchment and locality of site scales. The variables most correlated with extreme SSC values are the percentage of clay, rainfall descriptors, forest and grassland covers.

The feasibility of regionalisation using a regression-tree approach was tested for the quantiles of SSC obtained by the local frequency analysis as well as the threshold value used in the POT approach, the 99th percentile of concentrations. Regression-trees is a non parametric method that can be used for both the delineation of homogeneous groups of stations for a given response variable and the estimation of the variable within the groups created. The main issue associated with the method is the pruning of the trees, necessary to avoid over-fitting. In this study two pruning approaches were considered. They both rely on a Jack-Knife re-sampling procedure, aiming at simulating the case of an ungauged catchment. The first approach is the cross validation procedure with the *1-SE* rule detailed by Breiman *et al.* (1984) and widely used. The second approach used fixed tree sizes to determine which pruning level yield the best estimation results for an ungauged site. The second approach appears to be more efficient than the 1-*SE* rule to estimate quantiles of SSC for ungauged catchments. The uncertainties are lower when using this approach, with estimation errors ranging from 144% to 84%, depending on the variable. The regional estimation with the regression-tree approach yields better results for longer return period quantiles (20 years) than for shorter ones (2 years), for both the AM or POT quantiles.

One feature of suspended sediment transport is its high inter-annual variability (Meade *et al.*, 1990). By including only one event per year in the AM approach, it may lead to underestimation of the short term variation of SSC transport while the right tail of the distribution is more correctly described. With the POT approach, in the context of this study there is an average of 2.1 events per year. Therefore, it may lead to the selection of not only rare infrequent events but also 2nd or 3rd order peaks that occur more often from year to year and then provide a better description of short return period transport conditions, as reflected by lower errors for $C2_{pot}$ estimations than for C2.

Better estimation results for longer return periods quantiles than for C2 may indicate that sediment transport is stock-limited; the suspended sediment carried in extreme events depend on the amount of sediment available in the catchment and therefore can be estimated based on its properties. In the opposite, short return period concentrations are probably more discharge dependant, therefore more difficult to predict using only the watershed characteristics. The available amount of fine sediments for a given catchment is likely to change from year to year, within a range of values depending on its geomorphologic properties and anthropogenic activities. But the discharge of a stream could be subject to even higher variations caused by intense rainfall or drought leading to extreme hydrological events.

The main issues associated with the use of the regression-tree method for regionalisation are the selection of the adequate variables and the optimization of the predictive capabilities of the trees created. Breiman *et al.* (1984) observed that the pruning of a tree is somewhat subjective and to some extend data sensitive, in particular when dealing with small datasets. He suggested that pruning approaches based on bootstrap re-sampling might be more efficient than random cross-validation for small databases. Further development has been accomplished by Breiman (2001) by the introduction of random forests, where each tree is grown on a bootstrap sample, and the forest is formed by averaging the predictions from individual trees. The main advantage of random forests is their resistance to over-fitting, meaning no pruning is necessary and their ability to handle large number of predictors. In this study a minimal selection of explanatory variable was considered, selected by a stepwise regression algorithm. Several variables show good correlations with SSC quantiles, but only a few are selected by the stepwise algorithm prior to the creation of the regression-trees. Huang and Townshend (2003) proposed a new approach of variable selection for the creation of regression-trees, which consists in implementing a stepwise selection process of the variables at each node of the tree.

Further research to improve the estimation possibilities of regionalisation using physiographic characteristics is needed to develop better physiographic descriptors. The first problem associated with the use of land cover or soils data is the possible time discrepancy between these data sets and the period of the hydrologic observations. Many areas have seen a significant change in land use, or the implementation of sediment mitigating measures that can substantially influence the sediment output of a stream (Walling, 2006). Beside this limitation, regionalisation approaches usually consider only the catchment scale with metrics such as mean values or cover percent for the attributes. In this study, and in Jarvie *et al.* (2002) or Siakeu *et al.* (2004) the local characteristics of the gauging sites are also described since suspended sediment transport is in a large part site-specific. There are good correlations both at the catchment and the 20-km locality. There is a need to investigate the influence of these local characteristics by testing different sizes and shapes of what is defining this 'locality'. New metrics to describe the land characteristics could be developed, for example considering the position in space of a given feature that could be described by a distance to the stream as suggested by Van Sickle and Johnson (2008). This may lead to a better designation of the sediment sources within the watershed and thus a better modelling of sediment transport.

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Tableau 7.1: Physiographic parameters extracted for the watershed and the locality of stations

LANDCOVER	Residential	High or low density residential
	Commercial/Ind.	Commercial or Industrial
	Bare Rock	Bare Rock/Sand/Clay
	Forest	Forest
	Shrubland	Shrubland
	Orchard/Vine.	Orchards/Vineyards/Other
	Pasture/Hay	Pasture/Hay
	Row Crops	Row Crops
TOPOGRAPHY	MIN_A	Minimum altitude (m)
	MAX_A	Maximum altitude (m)
	DENIV	Altitude range (m)
	ALT_MED	Median altitude (m)
	MED_SLOPE	Median Slope (%)
	PERIMETER	Perimeter of drainage area (km)
	KM2	Size of drainage area (km2)
CLIMATE	PRECP1	Days with precipitation (days)
	PANNU	Precipitation total (mm)
	SDII	Rainfall intensity (mm/day)
	PDAYMAX	Maximum daily precipitation (mm)
	SNOW	Mean depth of snow (inches)
	INTPREC	Rainfall peakdness
	FROST	Number of frost days (days)
	TJAN	Mean January temperature (deg. Celsius)
SOILS	KFFACT	K Factor
	OM	Fraction of organic Materials (%)
	PERM	Permeability of the soil (in. per hour)
	THICK	Cumulative thickness of all soil layers (in.)
	DRAIN	Soil drainage group
	ROCKVOL	Rock (> 2mm) volume on surface (%)
	F_SAND	Volume percent of sand (%)
	F_SILT	Volume percent of silt (%)
	F_CLAY	Volume percent of clay (%)
	BD	Bulk density (g/cm3)
	ROCKDEPM	Mean depth to bedrock (cm)
	POROS	Soil porosity (%)

Tableau 7.2: Correlations between extreme SSC with watershed (left) and locality (right) physiographic characteristics (Spearman correlation coefficient, in bold when significant at 5% level)

ALL WATERSHED						**20km-LOCALITY**					
	CSS99	C20	C2	C2pot	C20pot		CSS99	C20	C2	C2pot	C20pot
LON	**-0,68**	**-0,70**	**-0,65**	**-0,67**	**-0,70**	FOREST	**-0,44**	**-0,42**	**-0,40**	**-0,42**	**-0,43**
SIZE	**0,36**	**0,36**	**0,34**	**0,34**	**0,35**	GRASSLAND	**0,75**	**0,75**	**0,73**	**0,74**	**0,74**
FOREST	**-0,50**	**-0,47**	**-0,48**	**-0,49**	**-0,48**	PASTURE/HAY	**-0,35**	**-0,35**	**-0,32**	**-0,34**	**-0,35**
GRASSLAND	**0,76**	**0,77**	**0,74**	**0,75**	**0,76**	PRCP1	**-0,34**	**-0,33**	**-0,28**	**-0,32**	**-0,34**
PASTURE/HAY	**-0,29**	**-0,29**	**-0,29**	**-0,30**	**-0,29**	PANNU	**-0,44**	**-0,46**	**-0,42**	**-0,44**	**-0,47**
PRECP1	**-0,39**	**-0,37**	**-0,33**	**-0,36**	**-0,38**	SDII	**-0,38**	**-0,43**	**-0,40**	**-0,39**	**-0,41**
PANNU	**-0,36**	**-0,37**	**-0,30**	**-0,34**	**-0,38**	PDAYMAX	**-0,30**	**-0,33**	-0,26	**-0,29**	**-0,33**
SDII	**-0,37**	**-0,41**	**-0,38**	**-0,37**	**-0,39**	FROST	**0,37**	**0,39**	**0,33**	**0,35**	**0,39**
PDAYMAX	**-0,35**	**-0,37**	**-0,31**	**-0,34**	**-0,37**	INTPREC	**0,57**	**0,56**	**0,54**	**0,55**	**0,56**
FROST	**0,39**	**0,42**	**0,36**	**0,38**	**0,42**	DENIV	**0,29**	**0,33**	**0,31**	**0,32**	**0,34**
INTPREC	**0,63**	**0,63**	**0,60**	**0,62**	**0,63**	ALT_MEDIAN	**0,58**	**0,60**	**0,55**	**0,56**	**0,60**
DENIV	**0,46**	**0,44**	**0,40**	**0,43**	**0,44**	DRAIN	**-0,28**	**-0,28**	-0,25	**-0,27**	**-0,27**
ALT_MEDIAN	**0,58**	**0,59**	**0,54**	**0,56**	**0,59**	FRACT_SAND	**-0,29**	**-0,34**	**-0,36**	**-0,33**	**-0,33**
FRACT_CLAY	**0,62**	**0,64**	**0,61**	**0,62**	**0,63**	FRACT_CLAY	**0,66**	**0,66**	**0,65**	**0,66**	**0,67**
						ROCKVOL	**-0,34**	**-0,32**	**-0,32**	**-0,32**	**-0,31**

Tableau 7.3: Estimation results for pruning determined by cross validation

	RBIAS	RRMSE
C2	-92,69%	310,57%
C20	-32,71%	112,70%
C2pot	-49,44%	209,80%
C20pot	-40,13%	145,58%
CSS99	-71,91%	243,56%

Tableau 7.4: Estimation results for fixed pruning level = 2

	RBIAS	RRMSE
C2	-38,68%	144,69%
C20	-20,27%	84,83%
C2pot	-26,28%	111,75%
C20pot	-24,21%	93,48%
CSS99	-33,60%	120,02%

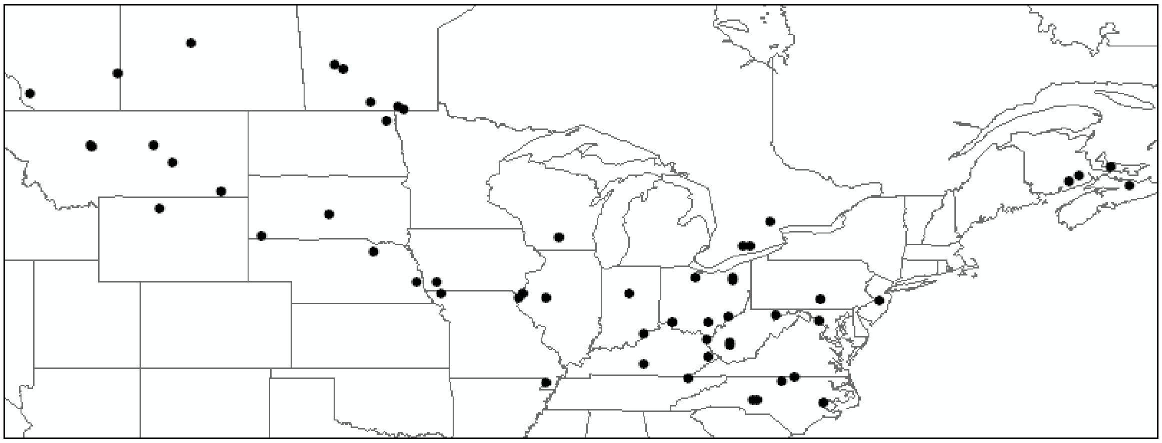

Fig. 7.1: Map of the selected stations

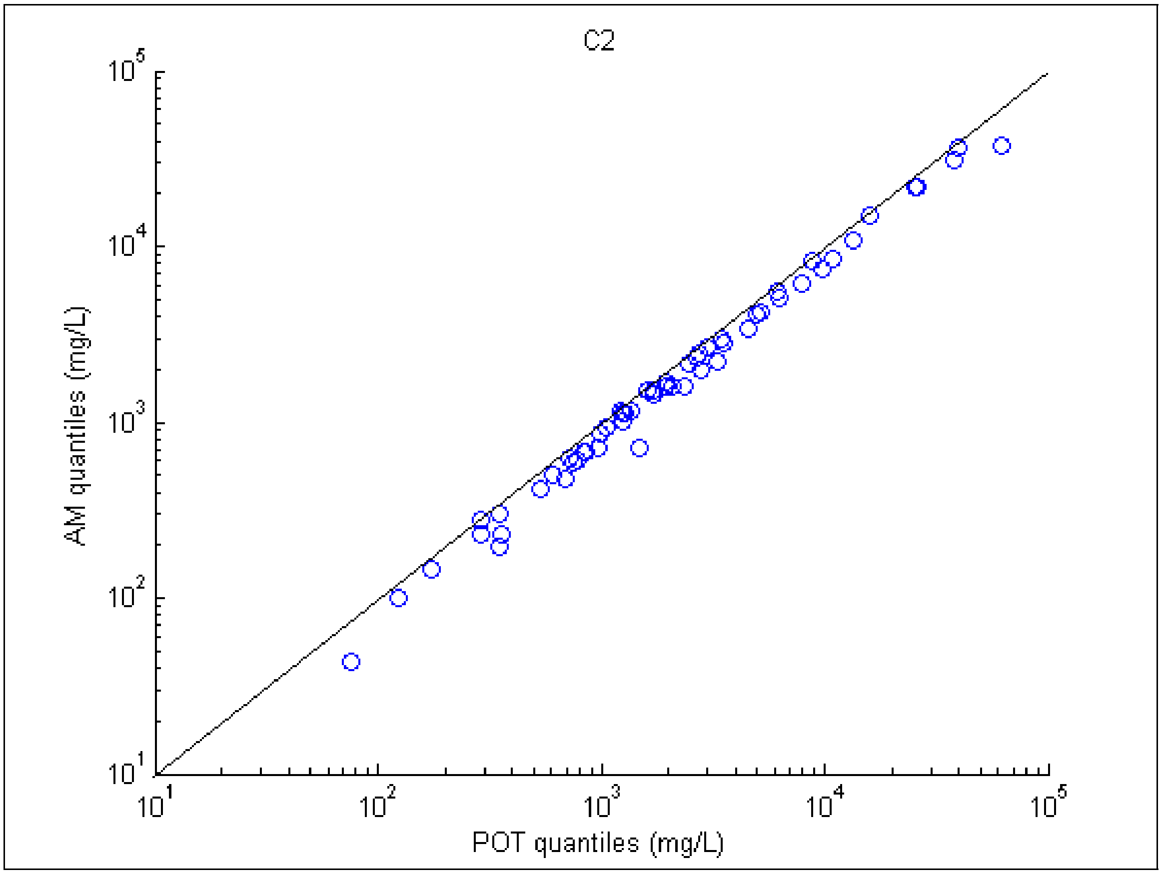

Fig. 7.2: C2 and C2pot scatter plot

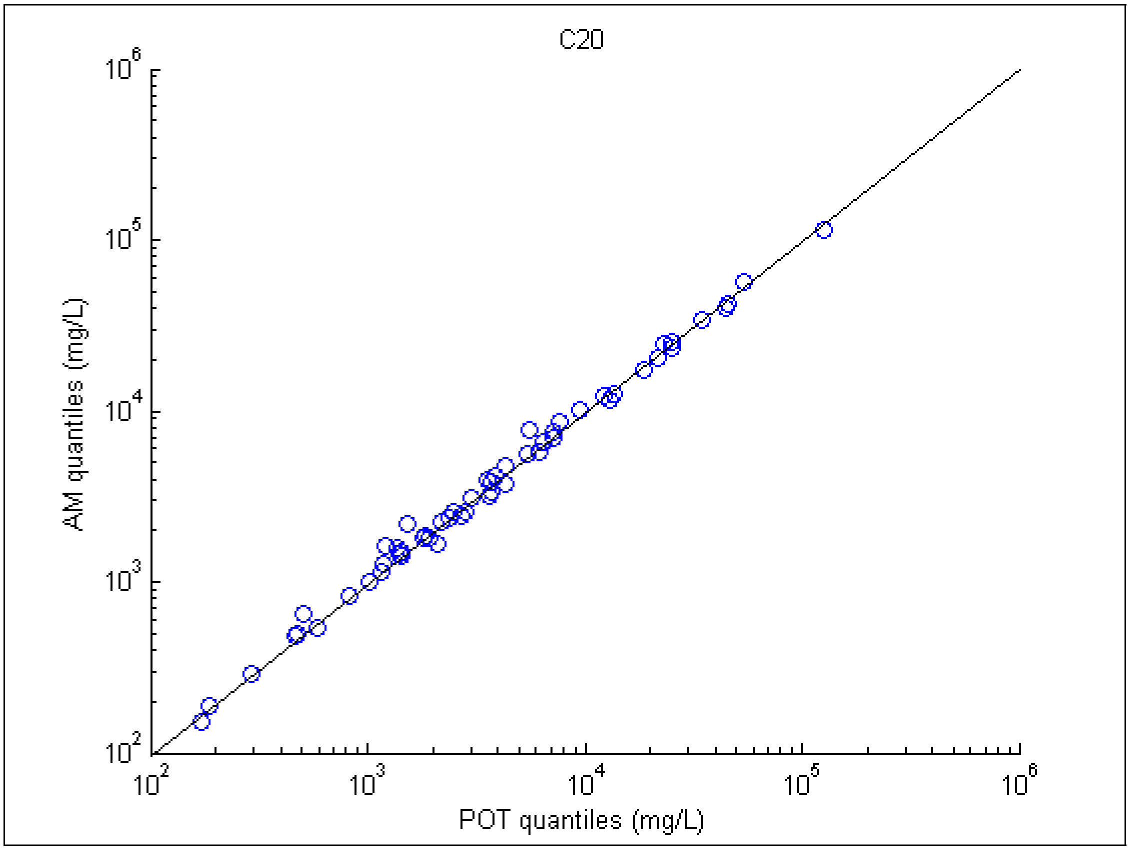

Fig. 7.3: C20 and C20pot scatter plot

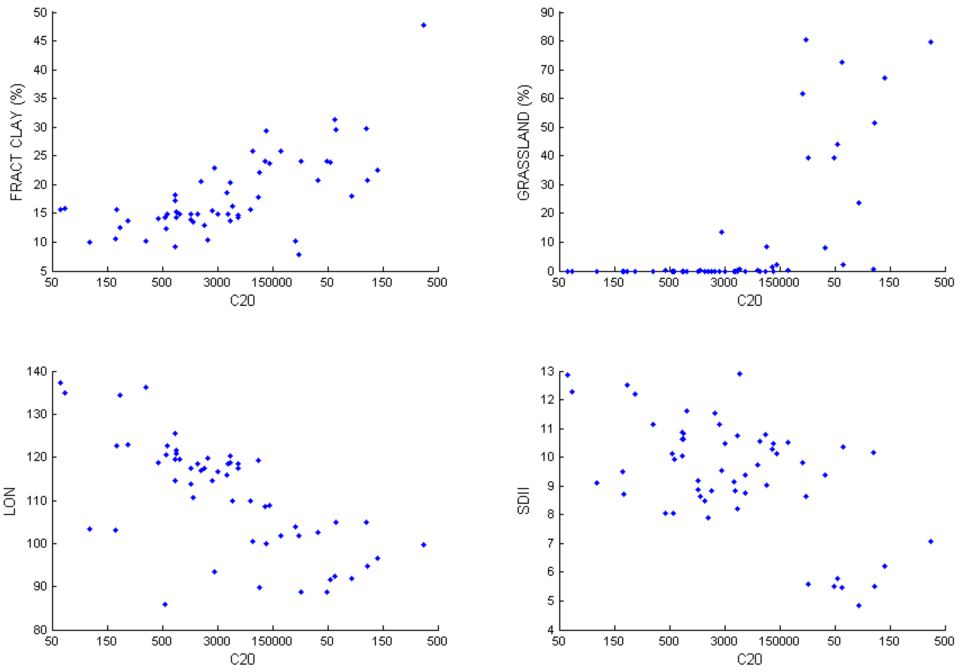

Fig 7.4: Scatter plot of selected physiographic variables with C20

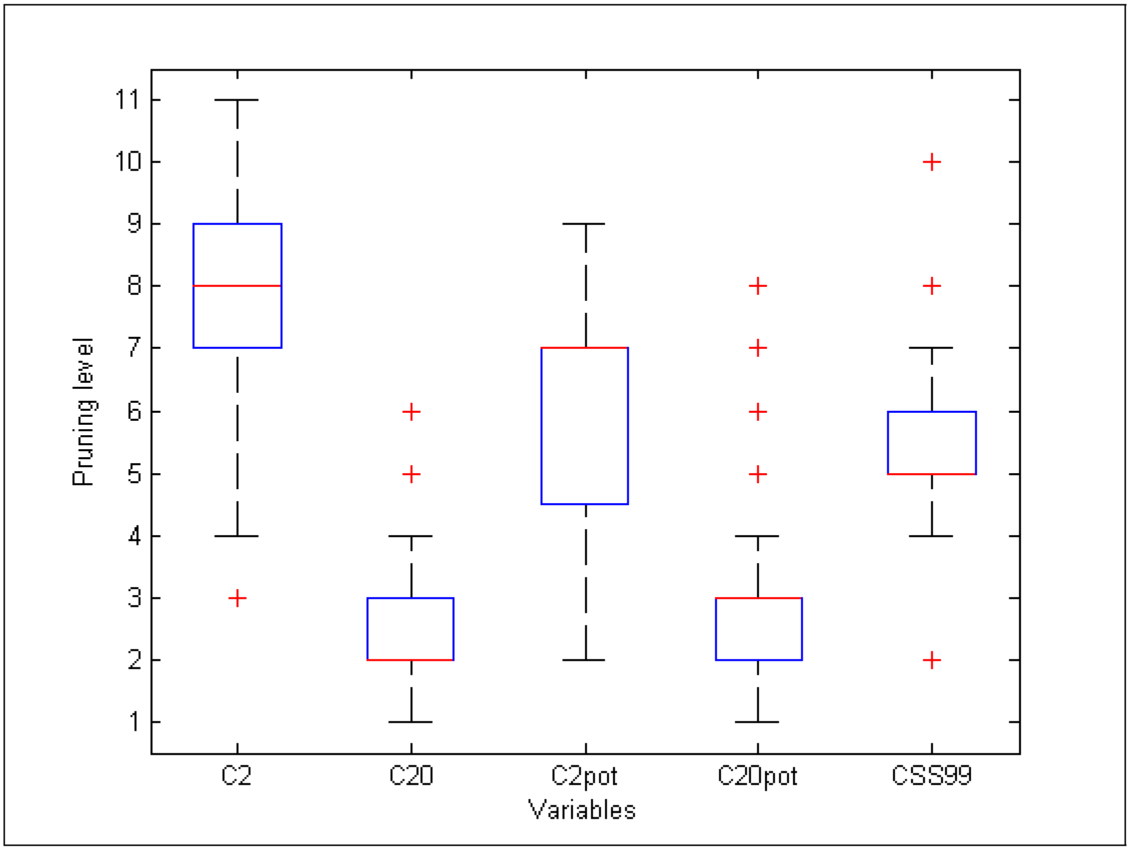

Fig. 7.5: Best pruning levels determined by cross validation for each variable (obtained with the first pruning method)

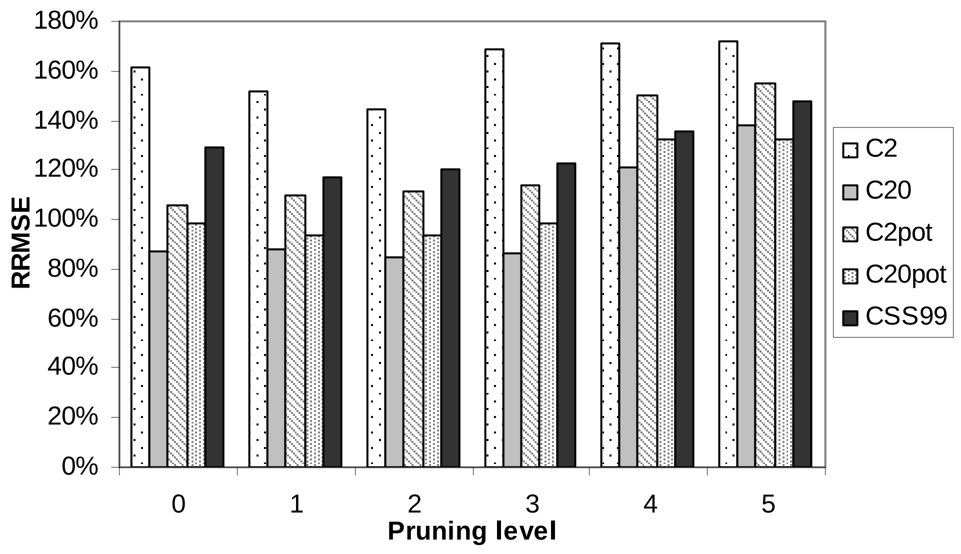

Fig. 7.6: Relative RMSE for different pruning levels for each variable (obtained with the second pruning method)

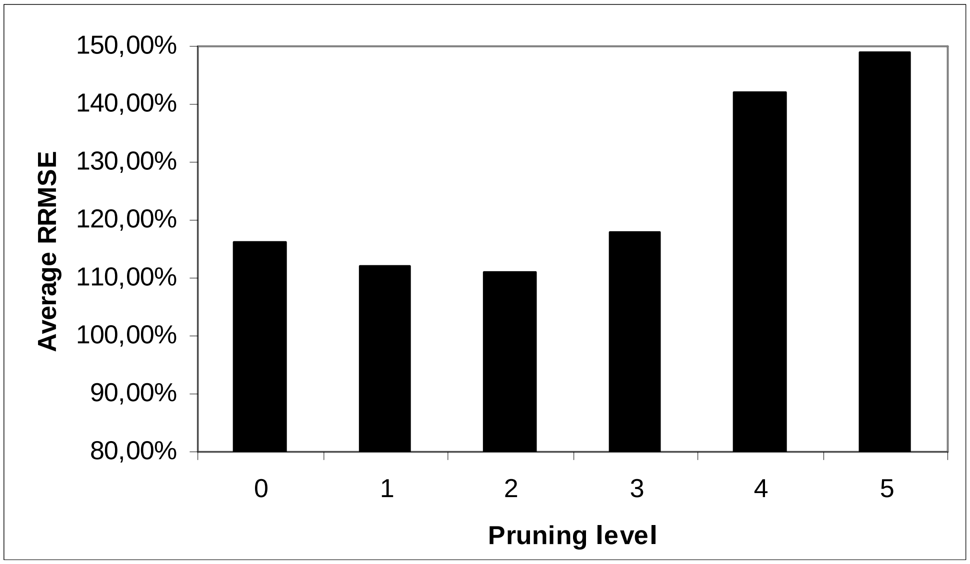

Fig. 7.7: Average RRMSE for the 5 variables depending on the pruning level (obtained with the second pruning method)

CHAPITRE 8 : Conclusions de la thèse

Le principal objectif de cette thèse était de proposer une procédure de régionalisation des concentrations extrêmes de sédiments en suspension pour les cours d'eau en Amérique du Nord. L'intérêt est de pallier au manque de données enregistrées disponibles en proposant une méthode d'estimation pour des sites non jaugés. Dans cette thèse, quatre objectifs spécifiques ont étés abordés : 1) la modélisation des événements extrêmes de CSS par l'analyse fréquentielle, 2) contribuer à la connaissance des événements extrêmes de CSS, 3) tester des approches de régionalisation, couramment utilisées pour les débits, pour la régionalisation des CSS extrêmes, 4) proposer une nouvelle approche de régionalisation pour les CSS extrêmes.

Les séries de maximums annuels de CSS ont été modélisées par des distributions statistiques afin de caractériser la fréquence d'occurrence et la magnitude de ces événements extrêmes. La sélection des lois optimales pour chaque station à été déterminée par l'utilisation du critère d'information Bayésiens (BIC) afin d'utiliser une méthode de sélection uniforme basée sur un critère objectif pour toutes les stations. Il s'avère que pour la majorité des séries disponibles, soit 179 stations, ce sont les lois Log-Normale et Exponentielle qui s'ajustent le mieux aux séries de maximums annuels de concentration. Une comparaison des méthodes d'échantillonnage par maximums annuels et par dépassement d'un seuil, ici le 99$^{\text{ème}}$ centile des séries, à été menée sur un échantillon de 72 stations. Les quantiles obtenus via ces deux approches sont très similaires, surtout pour les longues périodes de retour, tandis que pour les périodes de retour plus courtes, les quantiles estimés avec un échantillonnage par maximums annuels sont en moyenne 20% moindres que ceux obtenus par échantillonnage de dépassement de seuil.

Différentes caractéristiques des événements extrêmes de concentration ont pu être analysées. Selon la localisation des stations, les concentrations maximales sont enregistrées en différentes saisons. Les maximums annuels se produisent le plus fréquemment au printemps, pour le plus grand nombre de stations, localisées principalement dans la région des prairies ainsi que les états et provinces de l'est. Dans la zone aride au sud-ouest des États-Unis (Arizona, Nouveau Mexique, Colorado, Utah) les maximums annuels se produisent le plus souvent au courant de l'été. Enfin pour les stations de Californie les maximums annuels se produisent le plus fréquemment en hiver. Pour ces différentes zones, la saison la plus fréquente du maximum annuel de concentration est aussi la saison où se produisent le plus fréquemment les crues annuelles. Il a néanmoins été montré par l'étude de corrélations entre les maximums annuels de concentration et le débit correspondant que pour l'ensemble des stations l'utilisation des débits seuls ne permet pas de modéliser la magnitude des événements extrêmes de concentration. En revanche, l'estimation est améliorée en utilisant les caractéristiques physiques des bassins versants dont certaines sont fortement corrélées avec les CSS extrêmes, notamment le pourcentage d'argile dans les sols, la couverture forestière et l'intensité des précipitations. L'influence des caractéristiques physiographiques du territoire constituant le voisinage immédiat des stations de mesure a également été montrée sur les CSS extrêmes. En utilisant les attributs physiographiques de la zone de 5 km ou 20 km autour des stations de mesure, on obtient de meilleures corrélations entre les caractéristiques physiques et les CSS extrêmes qu'en utilisant les propriétés de la totalité des bassins versants.

Des approches couramment utilisées pour la régionalisation des débits ont étés testées pour estimer les concentrations extrêmes, décrites ici par des quantiles correspondant à différentes périodes de retour obtenus grâce à l'analyse fréquentielle, pour des sites non jaugés. Les approches testées sont la création de groupes de stations par classification ascendante hiérarchique basée soit sur leur caractéristiques physiographiques soit sur la saisonnalité des évènements de CSS extrêmes. Puis l'estimation régionale au sein de ces groupes se fait par régression multiple en utilisant les caractéristiques physiographiques corrélées aux quantiles de CSS. Les résultats indiquent que des modèles régionaux permettent une meilleure estimation qu'un seul modèle englobant tous les sites. Ainsi une approche régionale est appropriée pour l'estimation des concentrations extrêmes. Les approches de classification des stations basée sur la similarité des caractéristiques physiographiques ou sur la saisonnalité des événements de CSS donnent des résultats d'estimation comparables. Les erreurs d'estimation demeurent plus élevées que dans les travaux portant sur la régionalisation des débits mais contrairement aux débits, le nombre de stations ainsi que la longueur des séries disponibles sont plus réduits. De manière générale, les erreurs d'estimations sont plus grandes pour les quantiles correspondant aux courtes périodes de retour, mettant en évidence la très forte variabilité interannuelle des concentrations observée dans de nombreux cours d'eau. A l'inverse, les erreurs d'estimation plus modérées pour les quantiles correspondant à de longues périodes de retour pourraient indiquer que les concentrations extrêmes observées sont limitées par le stock de sédiments disponibles, sur les versants ou le lit du cours d'eau. Une estimation régionale des CSS extrêmes a également été menée pour les stations de Californie, afin de montrer la possible utilisation des caractéristiques du voisinage des stations plutôt que celles de l'ensemble des bassins.

Une nouvelle méthode de régionalisation a été utilisée pour l'estimation des CSS extrêmes en des sites non jaugés, afin de contourner les éventuelles limitations liées à certaines approches de régionalisation couramment employées. Parmi les méthodes existantes, l'approche par arbre de régression (CART) à été retenue car, outre sa nature non paramétrique, elle permet de combiner les deux étapes classiques de régionalisation, la délimitation de régions et l'estimation régionale, en une seule. En étant basée sur les caractéristiques physiographiques elle permet aussi de résoudre le problème d'assignation d'un site non jaugé à une région. Les tests réalisés avec cette méthode pour un échantillon de stations indiquent des résultats prometteurs mais des erreurs d'estimation encore importantes. Le problème majeur associé à l'utilisation de cette approche est la nécessité de troncature des arbres de régression à un niveau adéquat évitant la sur-spécialisation du modèle. Une méthode basée sur l'optimisation des résultats d'estimation à été proposée dans le but de réduire ce problème. Parmi les développements futurs possibles de cette approche, on pourrait considérer la possibilité d'intégration d'un plus grand nombre de variables explicatives, en appliquant une méthode de sélection des variables optimales pour chaque groupe de stations, ainsi que l'utilisation d'un plus grand nombre de stations.

Parmi les principales difficultés rencontrées dans les travaux de cette thèse, la première est le petit nombre de stations d'enregistrement de données de CSS disponibles. Dans le but de produire des estimations fiables par analyse fréquentielle, le nombre d'années minimal à considérer à été fixé à 10 ans, ce qui réduit le nombre de stations de mesures ayant pu être utilisées parmi celles disponibles. Les États-Unis et le Canada demeurent néanmoins les pays ayant les réseaux de mesures de sédiments en rivière les plus importants. Dans le but d'augmenter le nombre de stations pouvant être incluses dans ce type de travail, et ainsi la robustesse des méthodes utilisées, on pourrait étudier l'éventualité d'utiliser un échantillonnage de type dépassement de seuil en considérant de plus courtes périodes de retour afin d'abaisser le seuil de 10 années requises pour produire des estimations fiables.

L'autre difficulté importante réside dans l'acquisition des données physiographiques utilisées pour décrire les bassins versants. Il a été montré à plusieurs reprises que l'occupation des sols est susceptible de changer de manière importante au cours du temps, en particulier dans les zones les plus humanisées. Ainsi, il peut exister un décalage temporel entre les mesures en rivière et la date d'établissement des bases de données physiographiques. Entre les données disponibles dans les bases de données et la réalité de terrain il peut aussi exister une grande différence, très dommageable dans ce type de travaux, surtout dans un contexte de changements rapide de l'environnement. On pourrait envisager de considérer les données physiographiques de manière plus dynamique, à savoir l'utilisation de l'information disponible à plusieurs dates successives, comme par exemple les clichés d'images satellite décrivant l'occupation des terres pouvant être disponibles pour plusieurs années. L'importance des propriétés physiques du voisinage immédiat des stations de mesure sur les CSS extrêmes a été démontrée, aussi on pourrait recommander pour les travaux futurs d'utiliser les caractéristiques physiographiques de ce voisinage, et non seulement de l'ensemble des bassins, en s'assurant de la qualité et de l'adéquation des données disponibles pour ce voisinage.

Outre les caractéristiques physiographiques décrivant les bassins versants, les débits pourraient être inclus pour modéliser les CSS extrêmes, ce qui impliquerait de limiter l'applicabilité de l'approche de régionalisation uniquement aux sites où les débits sont jaugés. Cependant, ce type d'approche permettrait une prise en compte plus complète des processus impliqués dans le transport de sédiments en suspension. En utilisant les débits conjointement avec une information plus détaillée décrivant le lit du cours d'eau, sa morphologie et les propriétés granulométriques des échantillons de sédiments récoltés, il serait possible de distinguer pour les extrêmes de concentrations deux modèles distincts ; Un premier modèle, décrivant la fraction la plus fine des sédiments transportés, issus des versants en phase directe et directement reliée aux propriétés du bassin versant, un second modèle pour la fraction plus grossière issue du lit et des berges, reliée aux propriétés du lit et à la capacité de l'écoulement.

Enfin d'autres approches de régionalisation que celles utilisées dans cette thèse existent. En particulier les approche de type voisinage (régions d'influence et analyse canonique des corrélations) qui pourraient être testées pour l'estimation régionale des CSS extrêmes. Des travaux préliminaires ont montré la faible robustesse de l'approche par analyse canonique des corrélations sur un échantillon de stations de taille limitée. Étant donné que cette technique est jugée l'une des plus efficaces pour la régionalisation des débits, il serait intéressant dans des travaux futurs d'utiliser cette approche mais en incluant un plus grand nombre de stations. D'autres méthodes statistiques non paramétriques comme les arbres de régression ou les réseaux de neurones connaissent un gain d'intérêt croissant pour des applications de régionalisation. Ces méthodes semblent adaptées à l'estimation régionale des CSS extrêmes, car leur très grande variabilité spatiale et temporelle et la faible quantité de données disponibles complique l'utilisation des méthodes paramétriques standards. Comme on l'a vu dans l'utilisation d'arbres de régression pour l'estimation régionale, il demeure qu'un certain nombre d'avancées méthodologiques sont nécessaires pour améliorer la qualité des prédictions, notamment en ce qui concerne la sélection des variables à incorporer ou pour éviter la sur-spécialisation de ces modèles.

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