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Utilisation du concept de connectivité en hydrologie

Définitions, approches expérimentales et éléments de modélisation

par

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Définitions, approches expérimentales et éléments de modélisation

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RÉSUMÉ

Alors que certains mécanismes pourtant jugés cruciaux pour la transformation de la pluie en débit restent peu ou mal compris, le concept de connectivité hydrologique a récemment été proposé pour expliquer pourquoi certains processus sont déclenchés de manière épisodique en fonction des caractéristiques des événements de pluie et de la teneur en eau des sols avant l'événement. L'adoption de ce nouveau concept en hydrologie reste cependant difficile puisqu'il n'y a pas de consensus sur la définition de la connectivité, sa mesure, son intégration dans les modèles hydrologiques et son comportement lors des transferts d'échelles spatiales et temporelles. Le but de ce travail doctoral est donc **de préciser la définition, la mesure, l'agrégation et la prédiction des processus liés à la connectivité hydrologique** en s'attardant aux questions suivantes : 1) Quel cadre méthodologique adopter pour une étude sur la connectivité hydrologique ?, 2) Comment évaluer le degré de connectivité hydrologique des bassins versants à partir de données de terrain ?, et 3) Dans quelle mesure nos connaissances sur la connectivité hydrologique doivent-elles conduire à la modification des postulats de modélisation hydrologique ?

Trois approches d'étude sont différenciées, soit i) une approche de type « boite noire », basée uniquement sur l'exploitation des données de pluie et de débits sans examiner le fonctionnement interne du bassin versant ; ii) une approche de type « boite grise » reposant sur l'étude de données géochimiques ponctuelles illustrant la dynamique interne du bassin versant ; et iii) une approche de type « boite blanche » axée sur l'analyse de patrons spatiaux exhaustifs de la topographie de surface, la topographie de subsurface et l'humidité du sol. Ces trois approches sont ensuite validées expérimentalement dans le bassin versant de l'Hermine (Basses Laurentides, Québec). Quatre types de réponses hydrologiques sont distingués en fonction de leur magnitude et de leur synchronisme, sachant que leur présence relative dépend des conditions antécédentes. Les forts débits enregistrés à l'exutoire du bassin versant sont associés à une contribution accrue de certaines sources de ruissellement, ce qui témoigne d'un lien hydraulique accru et donc d'un fort degré de connectivité hydrologique entre les sources concernées et le cours d'eau. Les aires saturées couvrant des superficies supérieures à 0,85 ha sont jugées critiques pour la genèse de forts débits de crue. La preuve est aussi faite que les propriétés statistiques des patrons d'humidité du sol en milieu forestier tempéré humide sont nettement différentes de celles observées en milieu de prairie tempéré sec, d'où la nécessité d'utiliser des méthodes de calcul différentes pour dériver des métriques spatiales de connectivité dans les deux types de milieux. Enfin, la double existence de sources contributives « linéaires » et « non linéaires » est mise en évidence à l'Hermine. Ces résultats suggèrent la révision de concepts qui sous-tendent l'élaboration et l'exécution des modèles hydrologiques.

L'originalité de cette thèse est le fait même de son sujet. En effet, les objectifs de recherche poursuivis sont conformes à la théorie hydrologique renouvelée qui prône l'arrêt des études de particularismes de petite échelle au profit de l'examen des propriétés émergentes des bassins versants telles que la connectivité hydrologique. La contribution majeure de cette thèse consiste ainsi en la proposition d'une définition unifiée de la connectivité, d'un cadre méthodologique, d'approches de mesure sur le terrain, d'outils techniques et de pistes de solution pour la modélisation des systèmes hydrologiques.

Mots-clés : Connectivité hydrologique ; définitions ; approches et validation expérimentales ; genèse du ruissellement ; processus non linéaires ; bassins versants de tête ; climat tempéré humide ; milieux forestiers ; modélisation hydrologique ; transferts d'échelle

ABSTRACT

As core processes of the transformation of rainfall into runoff are not fully understood, the concept of hydrologic connectivity has been put forward to explain why some processes occur episodically, in a very discrete short-lived manner, as a response to intermittent atmospheric water input, storm characteristics and soil moisture storage. Even though emerging as a very powerful tool for explaining the growing numbers of nonlinear hydrologic behaviours documented around the world, the hydrologic connectivity concept raises major issues for future research in catchment hydrology in terms of its definition, its measure, its integration into hydrological models and its scaling in the space and the time domains. The aim of this doctoral work is to **precise the definition, the measure, the scaling and the prediction of processes underlying hydrologic connectivity** while focusing on the following research questions: (1) What methodological framework should guide investigations of hydrologic connectivity?, (2) How to assess hydrologic connectivity from field data?, and (3) To what extent can the ongoing knowledge acquisition on hydrologic connectivity be used to improve success with hydrological modeling?

Three study approaches are discriminated, namely: (i) a black box approach that only relies on rainfall and runoff data without examining the internal catchment behaviour; (ii) a grey box approach based on punctual geochemical data illustrating the catchment internal state; and (iii) a white box approach involving exhaustive spatial patterns of surface and subsurface topographic variables and soil moisture. These three approaches are then tested against field data from the Hermine catchment (Lower Laurentians, Quebec). It is possible to classify the Hermine catchment hydrological responses with regards to their magnitude and their timing, the switching from one response type to another depending on antecedent conditions. It is revealed that high discharge values monitored at the catchment outlet are produced by increased contributions from specific runoff sources, thus hinting towards a reinforced hydraulic linkage and an enhanced degree of connectivity between runoff sources and the stream channel. It is established that saturated areas whose spatial extent exceeds 0.85 ha are critical for high runoff generation. Soil moisture spatial patterns in temperate humid forested catchments are shown to have statistical properties that are very different from those encountered in temperate rangelands; hence the necessity of using different spatial connectivity metrics in these contrasted environments. The co-existence of "linear" and "nonlinear" contributing sources is also illustrated in the Hermine catchment. These results suggest that some concepts should be revised for hydrological modeling purposes.

The originality of the present thesis is mainly inherited from its prime focus. The pursued research objectives are in accordance with the future trend in catchment hydrology, especially as hydrologists are urged to move from site-specific experiments and results to more easily generalizable concepts that favour the study of emergent catchment properties such as connectivity. Thus, the major contribution of this thesis is the proposal of a unified definition of connectivity, a comprehensive methodological framework, technical tools and operational ideas for the better performance of hydrological models.

Keywords: Hydrologic connectivity; definitions; study approaches and experimental validation; runoff generation; nonlinear processes; headwater catchments; temperate humid climate; forested environments; hydrological modeling; scaling

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INTRODUCTION GÉNÉRALE

L'hydrologie s'intéresse à toutes les composantes du cycle de l'eau terrestre, qu'il s'agisse de l'eau atmosphérique, de l'eau de surface, de l'eau du sol, de l'humidité du sol ou de la neige, et sa particularité est d'utiliser le bassin versant comme unité d'intégration (Uhlenbrook, 2006). Les questions d'échelle sont particulièrement importantes pour la discipline puisqu'on peut travailler au niveau des petits bassins versants de tête ou des grands bassins de drainage tout comme on peut étudier des événements de très courte durée (secondes, minutes, heures) ou de longues séries temporelles (années, décennies, siècles) illustrant l'évolution de variables-clés. Le fait d'utiliser le bassin versant dans son ensemble permet d'étudier tous les réservoirs de stockage de l'eau de pluie ou de fonte de neige et ainsi d'évaluer leurs interactions. La recherche en hydrologie devrait donc permettre de répondre à de multiples questions telles que 1) comment le débit d'un cours d'eau est-il produit ?, 2) d'où vient l'eau ?, 3) quels chemins emprunte-t-elle pour rejoindre le cours d'eau ?, et 4) quelle est sa vitesse de transit ? (Joerin, 2000). Ces questions ont fait l'objet d'études exhaustives visant à améliorer notre compréhension des divers comportements hydrologiques. Plusieurs percées intéressantes ont été effectuées durant les deux dernières décennies, notamment grâce à des expériences de terrain conduites dans de nombreux bassins sous plusieurs latitudes. Toutefois, comme le soulignent plusieurs auteurs, certains processus pourtant jugés cruciaux restent peu ou mal compris (Sivapalan *et al.*, 2003b ; Beven, 2006 ; Uhlenbrook, 2006).

En conséquence, la discipline se détourne aujourd'hui des études traditionnelles axées sur l'analyse de mécanismes d'écoulement spécifiques à petite ou moyenne échelle. Il s'agit plutôt d'examiner le rôle des seuils et des phénomènes non linéaires, tant dans l'espace que dans le temps, qui affectent les processus hydrologiques de surface et hypodermiques. Les effets de seuils sont omniprésents en hydrologie, notamment si l'on considère des processus tels que l'interception (Crockford & Richardson, 2000 ; Savenije, 2004), l'écoulement de proche subsurface (Whipkey, 1965), l'écoulement préférentiel (Beven & Germann, 1982) ou les ruissellements de surface hortonien et par excès de saturation (Dunne, 1978). Ces processus sont qualifiés de non linéaires car ils ne sont pas activés lors de chaque événement pluvieux ou de fonte de neige. Ces processus sont plutôt déclenchés de manière épisodique et leur synchronisme (*timing*) est mal compris (McGrath *et al.*, 2007). Il existe néanmoins un consensus dans la littérature associée à ces effets de seuils, consensus selon lequel l'activation des mécanismes d'écoulement serait étroitement liée aux caractéristiques des événements de pluie et à la teneur en eau des sols avant l'événement. En effet, tant les caractéristiques des événements de pluie que les conditions d'humidité antécédentes déterminent dans quelle mesure le ruissellement de crue, issu de diverses zones dans un bassin versant, est acheminé jusqu'au cours d'eau principal (James, 2005 ; Bracken & Croke, 2007). Cette dynamique peut être étudiée à travers le nouveau concept de connectivité hydrologique (Pringle, 2003 ; James, 2005 ; Bracken & Croke, 2007 ; McDonnell *et al.*, 2007 ; Tetzlaff *et al.*, 2007). Si l'on suppose que la connectivité hydrologique est une mesure du lien hydrologique fonctionnel entre les diverses unités du paysage (e.g. versants, fonds de vallée, cours d'eau), ce concept devrait faciliter notre compréhension des processus qui contrôlent l'activation et la désactivation des mécanismes de genèse de l'écoulement. L'adoption de ce nouveau concept et son opérationnalisation dans les recherches hydrologiques ne se fait toutefois pas sans heurts. Il est ainsi possible d'identifier, à tout le moins, trois problématiques d'intérêt pour l'étude des processus non linéaires et de la connectivité hydrologique.

i) La mesure des dynamiques linéaires et non linéaires. Il est nécessaire de connaître le degré de connectivité hydrologique à l'intérieur d'un bassin versant pour pouvoir estimer la probabilité qu'un ruissellement épisodique se produise. Cette démarche est cependant compliquée par le fait que la connectivité est plus un concept « abstrait » qu'une quantité aisément mesurable. De plus, les essais de définition de la connectivité recensés dans la littérature sont nombreux et pas nécessairement cohérents entre eux (Ali & Roy, 2009, voir Chapitre 2). Selon Bracken & Croke (2007), cela limite considérablement l'application du concept à des études de modélisation ou de gestion des ressources d'un bassin versant. Par ailleurs, le postulat de non-linéarité entre les variations climatiques et les processus hydrologiques doit encore être prouvé et vérifié pour un grand éventail de conditions. C'est pourquoi Bracken & Croke (2007) suggèrent l'établissement d'une définition claire qui permettrait non seulement de quantifier, mais aussi de modéliser la connectivité hydrologique. Cette définition devrait, par ailleurs, être en mesure de regrouper les questions des patrons hydrologiques, des seuils et des effets de non-linéarité au sein d'une seule et même théorie hydrologique renouvelée (Sivapalan, 2005 ; Schröder, 2006 ; McDonnell *et al.*, 2007).

ii) La modélisation des dynamiques linéaires et non linéaires. La plupart des modèles hydrologiques disponibles sur le marché reproduisent mal la dynamique saisonnière de l'écoulement de crue lorsqu'ils sont exécutés sur des périodes plus ou moins longues (Peters *et al.*, 2003). Ce constat est pour le moins étonnant dans la mesure où notre compréhension des processus hydrologiques individuels est assez avancée. Par ailleurs, on se serait attendu à ce que les modèles hydrologiques basés sur des indices de similarité hydrologique, qui considèrent explicitement l'importance de la topographie et des conditions d'humidité antécédentes lors de la prévision du ruissellement de crue, soient relativement performants. Ce n'est cependant pas le cas, excepté dans des conditions très humides et en présence d'un événement pluvieux très intense (Piñol *et al.*, 1997 ; Shaman *et al.*, 2002 ; Stieglitz *et al.*, 2003). Ces résultats portent donc à croire que les structures de modélisation actuellement disponibles ne sont pas en mesure de répliquer les processus hydrologiques non linéaires observés dans la réalité, à quelques exceptions près.

iii) L'agrégation des dynamiques linéaires et non linéaires. Les récentes réflexions menées par McDonnell (2003), Sivapalan (2005), Schröder (2006) et McDonnell *et al.* (2007) sont unanimes, à savoir que les recherches futures en hydrologie ne doivent plus servir à cataloguer les spécificités des bassins versants étudiés mais plutôt à étudier leurs propriétés émergentes, plus aisément généralisables. Le concept de connectivité pourrait, par exemple, servir à cette fin. Cela nécessiterait cependant que l'on sache, précisément, à quelles échelles spatiales et temporelles cette connectivité doit être définie et comment elle se comporte lorsqu'on effectue un changement d'échelle.

Le but de ce travail doctoral est donc d'alimenter la réflexion de la communauté des hydrologues en lien avec ces trois problématiques. **L'objectif général de la recherche est de préciser la définition, la mesure, l'agrégation et la prédiction des processus liés à la connectivité hydrologique.** Cet objectif est poursuivi tout au long des six chapitres de la thèse. Tout d'abord, afin de mettre en contexte la recherche proposée, une revue de la littérature est présentée au Chapitre 1 pour faire état des connaissances actuelles et des lacunes en ce qui a trait à notre compréhension des processus qui sous-tendent la connectivité hydrologique. Les objectifs spécifiques de la recherche, découlant de l'état actuel des connaissances, sont également décrits au Chapitre 1. Les analyses spécifiques ayant conduit à des réflexions et des résultats de recherche font l'objet des Chapitres 2, 3, 4 et 5 et prennent la forme de six articles scientifiques, soit un article dans chacun des chapitres 2, 3 et 4 et trois articles dans le chapitre 5.

Le Chapitre 2 s'articule autour d'une revue critique et commentée de la littérature publiée dans *Geography Compass* en 2009 (Ali & Roy, 2009). En effet, si la connectivité hydrologique est considérée comme un élément essentiel à la compréhension de la dynamique des bassins versants, il n'y a cependant pas de consensus concernant la définition précise du concept ni la manière de mesurer la connectivité à partir de données de terrain. Ce chapitre vise donc à répondre à deux questions, soit i) quelles sont les variables à étudier ?, et ii) quel est le plan d'échantillonnage optimal pour capter les changements de connectivité hydrologique dans les bassins versants tempérés humides ? Les éléments de réponse apportés à ces questions sont une première dans le domaine et constituent ainsi une base méthodologique pour asseoir une étude sur la connectivité. Cette base méthodologique est ensuite appliquée tout au long de la thèse. La description du site d'étude et des stratégies d'échantillonnage figure ainsi à la fin du Chapitre 2. Les résultats présentés dans les chapitres subséquents (3, 4, 5 et 6) sont issus d'un seul lieu d'expérimentation, l'Hermine (Laurentides, Québec), car on vise spécifiquement la caractérisation la connectivité hydrologique dans un petit bassin versant de tête à couvert forestier situé en milieu tempéré humide. La représentativité de l'Hermine par rapport à l'ensemble des bassins expérimentaux forestiers tempérés humides décrits dans la littérature est également discutée tout au long de la thèse.

Le Chapitre 3 examine la connectivité en utilisant une approche « boite noire » (*black box*), c'est-à-dire que les changements hydrologiques sont envisagés sans étudier le fonctionnement interne du système (bassin versant) et en se servant uniquement des entrées (variables météorologiques) et des sorties (hydrogrammes de crue). Une combinaison originale de méthodes d'analyse statistique multivariée est proposée afin i) de contraster différents types de réponse hydrologique, ii) d'identifier les variables météorologiques qui influencent le plus ces types de réponse, et iii) de déterminer les valeurs « seuils » de variables météorologiques qui permettent l'activation ou la désactivation de chaque type de réponse dans le bassin versant de l'Hermine. Cet article publié dans la revue *Hydrological Processes* (Ali *et al.*, 2010c) met en évidence la possibilité d'estimer le degré de connectivité hydrologique d'un bassin versant en se servant uniquement de données aisément disponibles, soit des données de pluie et de débit.

Le Chapitre 4 étudie plutôt la connectivité en utilisant une approche « boite grise » (*grey box*), c'est-à-dire que l'on se sert de données locales sur le fonctionnement interne d'un bassin versant pour évaluer les changements de connectivité entre les versants et le cours d'eau. L'article scientifique constituant la pièce maîtresse de ce chapitre a été resoumis à *Journal of Hydrology* (Ali *et al.*, 2010b) et découle du principe que le degré de connectivité d'un bassin versant peut être évalué en identifiant les sources spatio-temporelles du ruissellement. Cette identification des sources spatio-temporelles de ruissellement est réalisée en comparant la composition chimique de l'eau du cours d'eau à celle du pluviolessivat et de la solution de sol (horizons organiques et minéraux) dont des échantillons sont récoltés dans différentes unités morphologiques du bassin versant de l'Hermine (e.g. bas de versant, haut de versant, tête de bassin). Ces compositions chimiques sont notamment examinées dans le cadre de la méthode EMMA (*end-member mixing analysis*) introduite au début des années 90 (Christophersen *et al.*, 1990; Christophersen & Hooper, 1992). L'aspect novateur de l'article scientifique du Chapitre 4 réside toutefois dans la définition de plusieurs dizaines de scénarios hydrologiques et dans l'application de la méthode EMMA à chacun de ces scénarios afin d'évaluer, dans chaque cas, i) le nombre de sources qui participent à l'alimentation du débit du cours d'eau, et ii) les contributions relatives des versants et des zones proximales au cours d'eau. Cette confrontation de scénarios a une valeur ajoutée par rapport aux approches traditionnellement décrites dans la littérature puisqu'elle permet de déterminer à quel moment la contribution de chaque source est activée et les conséquences de ces activations pour la connectivité hydrologique du bassin versant de l'Hermine.

Les trois articles scientifiques du Chapitre 5 se basent sur une approche de type « boite blanche » (*white box*), c'est-à-dire que l'on étudie des patrons spatiaux détaillés de variables topographiques et hydrologiques afin de les relier à des processus de genèse de l'écoulement et ainsi tirer des conclusions sur les changements de connectivité hydrologique. Des données spatialement discrétisées sur la topographie de surface et celle d'un horizon de sol quasi-imperméable sont notamment utilisées, de même que des données de contenu en eau du sol (humidité volumétrique, en %). Ces données d'humidité du sol qui constituent la base des trois articles du Chapitre 5 ont été recueillies à l'Hermine en 16 occasions échelonnées sur une année complète, selon un réseau de 150 sites d'échantillonnage et quatre profondeurs de sol. Premièrement, dans une optique interdisciplinaire, il est démontré que l'utilisation de l'analyse spatiale par vecteurs propres (MEM : *Moran's eigenvector maps*) originellement définie en écologie est un outil puissant afin de déterminer des échelles spatiales caractéristiques en hydrologie. Cet article accepté pour publication dans la revue *Water Resources Research* (Ali *et al.*, 2010a) est une contribution méthodologique importante. Il répond à une demande de la communauté des hydrologues en ce qui concerne la proposition de nouvelles méthodes mathématiques pour identifier les échelles spatiales naturelles de variabilité des processus, et il permet d'en apprendre plus sur l'étendue spatiale des processus hydrologiques actifs dans le bassin de l'Hermine. Deuxièmement, dans le but de proposer des outils quantitatifs de mesure des processus non linéaires en milieu tempéré humide, une panoplie de métriques spatiales sont développées et testées dans un article récemment recommandé pour publication dans la revue *Water Resources Research* après révisions afin de capturer les changements de connectivité hydrologique à l'Hermine (Ali & Roy, in review/en révision a). En effet, les travaux précurseurs sur les métriques spatiales de connectivité dérivées à partir de patrons spatiaux d'humidité du sol ont été réalisés dans des milieux de prairies tempérés secs (Western *et al.*, 1998, 2001), cependant leur transférabilité aux milieux forestiers tempérés humides n'a pas été démontrée (James & Roulet, 2007). Ce travail exhaustif avait donc pour but de trancher le débat sur l'universalité d'une mesure de la connectivité hydrologique en dépit des spécificités physiques et climatiques qui caractérisent chaque milieu. Il permet notamment de conclure que les contrastes qui existent entre les milieux de prairies tempérés secs et les milieux forestiers tempérés humides sont tels que l'étude de la connectivité hydrologique doit forcément y être abordée de manière différente. Enfin, le troisième article du Chapitre 5 a été resoumis à la revue *Hydrology and Earth System Sciences* (Ali & Roy, in review/en révision b) et se penche sur la question des conditions d'humidité antécédentes. Si ces conditions déterminent le degré de connectivité hydrologique dans un bassin versant, elles restent néanmoins difficiles à mesurer et sont généralement approximées à l'aide d'indicateurs, soit des mesures hydrométéorologiques globales. L'exercice réalisé consiste à évaluer le potentiel de ces mesures hydrométéorologiques globales d'illustrer la variabilité spatio-temporelle de l'humidité du sol qui est observée dans le bassin versant de l'Hermine. Il est ainsi démontré que les conditions d'humidité antécédentes sont hautement variables dans l'espace, d'où un plaidoyer pour l'utilisation de multiples indicateurs pour ne pas biaiser notre compréhension des systèmes hydrologiques.

Chacun des articles scientifiques précédemment cités est une contribution originale et indépendante à l'enrichissement des connaissances sur les processus hydrologiques non linéaires et la connectivité, cependant leur mise en commun est importante pour confirmer ou infirmer des hypothèses et ainsi répondre aux objectifs de recherche de la présente thèse. Cette synthèse est donc réalisée sous la forme d'un essai dans le Chapitre 6.

L'originalité de cette thèse est d'abord le fait même de son sujet, soit la connectivité hydrologique, qui est une propriété émergente des bassins versants. L'allusion aux systèmes complexes et à la notion d'émergence n'est pas anodine car l'apparition de patrons cohérents de connectivité à grande échelle témoigne de la présence de mécanismes d'auto-organisation aux niveaux inférieurs de la hiérarchie des bassins versants (voir Chapitre 1). Ainsi, cette thèse se veut une contribution à la clarification de la définition et des approches de mesure de la connectivité hydrologique sur le terrain. Ce travail doctoral a aussi l'avantage de s'appuyer sur des jeux de données exhaustifs et de bonne qualité (voir Chapitre 2), en plus d'introduire de nombreux outils d'analyse statistique (voir Chapitres 3 et 5) ou des approches conceptuelles originales (voir Chapitres 2, 4 et 5) jusqu'à présent peu ou pas utilisés en hydrologie. La combinaison de ces données et méthodes dans le cadre de cette thèse permettent ainsi de renouveler notre compréhension des comportements complexes des bassins versants.

"It is possible that as we look more closely and find a way to filter out unimportant details, we might begin to see emergent features or properties that serve as a natural skeleton to connect descriptions of hydrological responses across scales" (McDonnell *et al.*, 2007, p. 4)

CHAPITRE 1

ÉTAT DES CONNAISSANCES ET OBJECTIFS DE LA RECHERCHE DOCTORALE

"Catchment hydrology – a science in which all processes are preferential"

(Uhlenbrook, 2006, p. 1)

1.1 Théorie classique de la genèse de l'écoulement de crue

1.1.1 Les mécanismes

La théorie hydrologique classique s'articule autour des mécanismes de genèse de l'écoulement à l'échelle d'un bassin versant. L'étude de ces mécanismes a permis d'émettre des hypothèses sur la manière dont les apports en eau, illustrés par un hyétogramme, alimentent le débit d'un cours d'eau, représenté par un hydrogramme (James, 2005). Selon Joerin (2000), l'eau de pluie peut rejoindre le cours d'eau par quatre voies principales : 1) les précipitations directes à la surface du cours d'eau (*direct precipitation*), 2) les écoulements de surface (*overland flow*), 3) les écoulements hypodermiques (*throughflow*, *subsurface storm flow*), et 4) les écoulements souterrains (*groundwater flow*). Les précisions fournies ici sont issues d'une recension de la littérature et reprennent aussi les travaux récents de thèse de Joerin (2000) et James (2005).

Les précipitations directes à la surface de l'eau sont souvent négligées en tant que mécanisme alimentant le débit du cours d'eau. Cela est dû au fait qu'il ne s'agit que d'une infime contribution étant donné l'extension spatiale limitée du réseau hydrographique dans un bassin versant. Il est toutefois utile de mentionner que lors d'événements pluvieux de forte intensité et dans des conditions humides, certains segments intermittents du réseau peuvent être réactivés, rendant ainsi significatif l'apport de ce mécanisme de genèse de l'écoulement.

Les écoulements de surface concernent les eaux exfiltrées ou celles qui ne peuvent pas s'infiltrer dans le sol. Ils sont ainsi régis soit par le dépassement de la capacité d'infiltration (*infiltration excess overland flow*), soit par le dépassement de la capacité de saturation (*saturation excess overland flow*) du sol considéré (Figure 1.1 A et B).

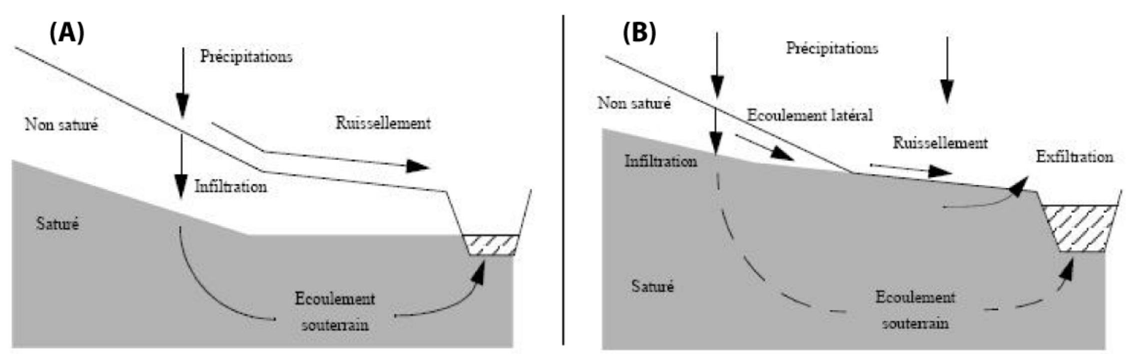


Figure 1.1 – **(A)** Ruissellement de surface par excès d'infiltration ; **(B)** Ruissellement de surface par excès de saturation (originaux de Joerin, 2000).

D'une part, le ruissellement hortonien (Horton, 1933) se produit lorsque la capacité d'infiltration du sol est dépassée. Le surplus d'eau de pluie qui ruisselle à la surface constitue la composante rapide de l'écoulement de crue tandis que l'eau infiltrée contribue à la recharge de la nappe phréatique et à l'entretien du débit de base. Le ruissellement hortonien n'est cependant pas très répandu, excepté dans les régions arides et en milieu urbain. Dans les zones où le couvert végétal est important, la capacité d'infiltration des sols est généralement très élevée, de sorte que le ruissellement hortonien est négligeable. Il peut cependant se produire dans les cas très particuliers de sols saturés, gelés ou hydrophobes (Ambroise, 1998 ; Joerin, 2000).

D'autre part, le ruissellement par excès de saturation fait intervenir le concept d'aire contributive variable (*Variable Source Area VSA concept*, voir Cappus, 1960 ; Betson, 1964 ; Hewlett & Hibbert, 1967 ; Dunne & Black, 1970a ; Beven & Kirkby, 1979 ; Ambroise, 1998). Ce concept repose sur le fait que l'eau qui transite dans le sol alimente des zones, adjacentes ou non au cours d'eau, au niveau desquelles la nappe phréatique est très proche de la surface du sol. Dans les fonds de vallée, par exemple, la saturation du sol se produit lorsque la nappe phréatique affleure à la surface, et les nouveaux apports en eau ne peuvent donc pas s'infiltrer. Hewlett & Hibbert (1967) ont fait valoir que seules les aires saturées contribuaient à l'écoulement rapide de crue. Ces aires ne sont cependant pas invariantes dans l'espace et dans le temps car l'extension des surfaces contributives dépend, d'une façon générale, de la topographie du bassin versant et des conditions d'humidité. C'est la raison pour laquelle Ambroise (2004) a introduit la distinction entre les aires et les périodes actives versus contributives. Une aire (ou une période) contributive est forcément active, mais le contraire n'est pas vrai. Les aires saturées, donc actives, ne contribuent à l'alimentation du débit que si elles sont physiquement connectées ou situées à proximité du cours d'eau. Par ailleurs, Dunne & Black (1970a) ont montré qu'en plus du ruissellement sur surfaces saturées, il fallait considérer un mécanisme d'exfiltration (*return flow*), particulièrement dans les zones proximales au cours d'eau. La présence d'une nappe phréatique et d'une frange capillaire (couche située au-dessus de la nappe et dont les pores sont quasiment tous saturés) proches de la surface favorise l'exfiltration de l'eau souterraine à proximité du cours d'eau. Cette eau devient donc disponible pour ruisseler rapidement à la surface du sol.

Les écoulements hypodermiques concernent les eaux infiltrées qui se cantonnent aux horizons superficiels du sol et se déplacent latéralement vers le cours d'eau. Le déplacement latéral, plutôt que vertical, de l'eau est alors dû au fait que la conductivité hydraulique latérale est supérieure à la conductivité hydraulique verticale. Il est d'ailleurs utile de mentionner que l'activation de tous les mécanismes d'écoulement de proche subsurface nécessite que la partie supérieure du sol ait un degré de saturation élevé. Dans ces conditions, de faibles apports en eau peuvent provoquer des hausses de près d'un ordre de grandeur de la conductivité hydraulique (Figure 1.2 A). Il s'agit là du phénomène d'accroissement de la transmissivité latérale (*transmissivity feedback*) qui force l'écoulement de l'eau du sol vers le réseau hydrographique. Ces écoulements latéraux peuvent donc se produire à deux niveaux, soit 1) dans la zone non saturée au-dessus de la nappe pérenne profonde, ou 2) dans une nappe perchée de proche surface. La formation des nappes perchées est attribuable au fait que l'infiltration verticale de l'eau de pluie à travers la matrice de sol est ralentie par la présence d'un horizon de moindre perméabilité ou d'une discontinuité texturale à quelques dizaines de centimètres de la surface du sol (Brown *et al.*, 1999). La zone au-dessus de la couche peu perméable a donc tendance à se saturer rapidement, et une augmentation minime de la teneur en eau peut produire une hausse importante de la conductivité hydraulique. Trois mécanismes d'écoulement de proche subsurface peuvent être identifiés, soit 1) l'écoulement via les macropores (*macropore flow*, *pipe flow*, *preferential flow*), 2) l'effet piston (*translatory flow*), et 3) l'intumescence de la nappe (*groundwater ridging*) (Figure 1.2 B, C et D). Tout d'abord, l'écoulement macroporeux est un écoulement préférentiel – donc rapide – de l'eau du sol qui se fait via des trous creusés par les animaux et les conduits laissés inoccupés par d'anciennes racines. Ces pores, qui peuvent former un réseau plus ou moins dense et interconnecté, ne peuvent cependant être le siège d'un écoulement que s'ils sont entourés d'une matrice de sol partiellement saturée. Ensuite, le mécanisme d'effet piston proposé par Hewlett & Hibbert (1967) est également important puisqu'il permet d'expliquer comment de l'eau contenue dans le sol avant un événement pluvieux (eau ancienne ou vieille eau) est chassée par de la nouvelle eau de pluie. C'est un mécanisme qui ne peut se manifester que lorsque le sol est pleinement saturé. Dans ces conditions, la propagation rapide d'une onde de pression permet à l'eau de pluie qui tombe en haut d'un versant d'être acheminée, presque instantanément, au pied de celui-ci.

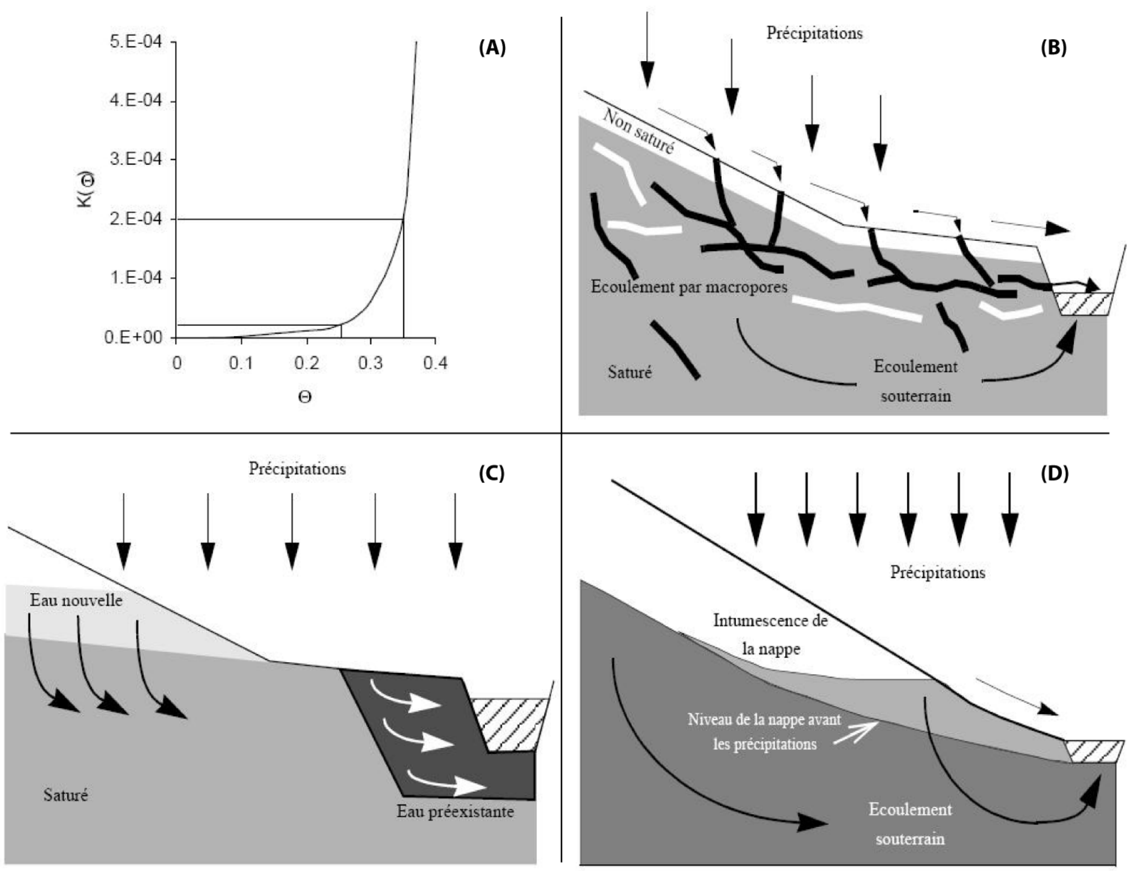


Figure 1.2 – **(A)** Courbe caractéristique de la conductivité hydraulique (K(Θ)). Le passage de la teneur en eau de 0.25 à 0.35 augmente la conductivité hydraulique d'un ordre de grandeur (soit de 2.10^{-5} à 2.10^{-4} $m.s^{-1}$) ; **(B)** Écoulement par macropores ; **(C)** Effet piston ; **(D)** Intumescence de la nappe (originaux de Joerin, 2000).

En dernier lieu, le mécanisme d'intumescence de la nappe (Sklash & Farvolden, 1979) se met généralement en place au pied de pente ou dans les fonds de vallée. S'il existe une frange capillaire près de la surface du sol, le moindre apport en eau conduit à une montée rapide de la nappe. Le résultat de ce soulèvement rapide est la création d'un gradient de charge hydraulique qui force l'acheminement rapide de l'eau de la nappe vers le cours d'eau.

Enfin, les écoulements souterrains sont le résultat de la percolation profonde de l'eau infiltrée jusqu'à la zone saturée pérenne. En général, ces écoulements sont plutôt lents. On note ainsi des retards de plusieurs jours, voire plusieurs années, avant que les eaux profondes n'atteignent l'exutoire du bassin versant (EPFL). Il n'en demeure pas moins que les écoulements souterrains sont influencés par la séquence temporelle des événements pluvieux, et leur contribution au débit peut s'avérer plus rapide lors des événements de forte intensité (EPFL ; Joerin, 2000).

1.1.2 La mesure des processus et les facteurs de contrôle

L'étude des mécanismes de genèse de l'écoulement de crue fait souvent appel à deux approches, soit le traçage environnemental et/ou les méthodes hydrométriques traditionnelles (e.g. Joerin, 2000 ; Balin, 2004 ; Burt & Pinay, 2005 ; James, 2005). Le Tableau 1.1 est issu d'une revue de la littérature et d'une réflexion personnelle concernant les caractéristiques de ces deux approches.

D'une part, les méthodes hydrométriques englobent toutes les techniques visant la quantification des précipitations, de l'évaporation, des débits, de l'infiltration de l'eau dans le sol, de l'humidité du sol ou de la hauteur de la nappe phréatique. Ces données sont utilisées de manière « directe » pour émettre des hypothèses sur les processus hydrologiques actifs. D'autre part, le traçage naturel ou environnemental, méthode de suivi des éléments chimiques transportés par l'eau, est basé sur le fait que « *la composition chimique de l'eau des sols est différente de celle de l'eau de pluie et de l'eau des rivières* » (EPFL ; Pearce *et al.*, 1986).

Tableau 1.1 – Comparaison du traçage environnemental et des méthodes hydrométriques traditionnelles pour l'identification des sources de ruissellement et l'étude des mécanismes d'écoulement. Les « lacunes » des méthodes sont mises en évidence en caractères gras. En général, il est suggéré d'utiliser une combinaison des deux approches, de manière à effectuer une validation croisée des résultats obtenus et pour obtenir un portrait plus complet des processus actifs dans un bassin versant. STE : Sources temporelles de l'écoulement ; SSTE-V : Sources spatio-temporelles de l'écoulement (discrétisation verticale) ; SSTE-H : Sources spatio-temporelles de l'écoulement (discrétisation horizontale) ; MGE : Mécanismes de genèse de l'écoulement. Les sources temporelles regroupent les catégories d'eau nouvelle (*new water* ou *event water*) et d'eau ancienne (*old water* ou *pre-event water*). Les sources spatio-temporelles d'un point de vue vertical sont identifiées selon leur profondeur par rapport à la surface du sol. Les sources spatio-temporelles d'un point de vue horizontal sont distinguées par l'attribution d'étiquettes telles que « zone riveraine », « versant », « zone amont » ou « zone aval ».

	TRAÇAGE ENVIRONNEMENTAL	**MÉTHODES HYDROMÉTRIQUES**
Principe général	Utilisation de traceurs (isotopes, cations/anions majeurs etc.) pour : ▪ Évaluer le temps de résidence de l'eau dans un bassin versant ▪ Décomposer les hydrogrammes de crue et identifier les sources de ruissellement	Utilisation d'appareils de mesure portatifs ou *in situ* pour : ▪ Mesurer les apports en eau dans un bassin versant ▪ Mesurer les volumes d'eau présents dans les sols
Exemples	Modèles de mélange / *EMMA* (*end-member mixing analysis*)	Pluviomètres/Simulateurs de pluie Humidimètres/Puits/Piézomètres
Coûts analytiques Difficulté d'utilisation	Faibles à élevés **Faible à intermédiaire**	Faibles à élevés Faible
Réactivité	**Faible à élevée**	Nulle
Universalité (potentiel de généralisation)	Faible à élevée	Élevée
Échelle spatiale	Bassin versant	Parcelle, versant ou bassin versant
Échelle temporelle	Court, moyen ou long terme	Court, moyen ou long terme
Capacité à identifier les STE	Élevée	**Nulle**
Capacité à identifier les SSTE-V	Faible à élevée	Élevée
Capacité à identifier les SSTE-H	Faible à élevée	Élevée
Capacité à identifier les MGE	**Faible si utilisation autonome**	Élevée

Le terme « traceur » désigne une caractéristique physique (e.g. conductivité électrique ou température de l'eau) ou chimique (e.g. concentrations d'ions ou ratios isotopiques) qui permet de différencier des eaux d'origines différentes (Joerin, 2000). Préalablement à une expérience de traçage, il est donc impératif d'identifier les sources susceptibles de contribuer au débit, et ainsi de choisir un jeu de traceurs qui permette de différencier facilement ces sources. L'adoption du traçage environnemental par les hydrologues ne s'est pas faite sans heurts car l'application de la méthode pose plusieurs défis :

- D'une part, s'il est avéré que le traceur idéal n'existe pas (Gaspar, 1987), les hydrologues font néanmoins face à de multiples possibilités lorsque vient le temps de choisir le « meilleur » traceur pour suivre le cheminement de l'eau. La recension de plusieurs études menées dans les vingt dernières années fournit des éléments de réponse quant aux types de traceurs disponibles et à leurs avantages comparatifs.
- D'autre part, si l'utilisation de traceurs s'illustre comme la manière la plus directe d'étudier les chemins d'écoulement de l'eau (Jenkins *et al.*, 1994b ; Kendall & Caldwell, 1998), elle doit toutefois être confrontée aux méthodes hydrométriques conventionnelles qui l'avaient précédée. La tendance récente a ainsi produit une gamme d'études utilisant les deux types d'approches et permettant d'évaluer le niveau de convergence de leurs résultats respectifs.

Les traceurs sont généralement utilisés afin de construire un modèle de mélange. La logique qui sous-tend les modèles de mélange veut que le signal hydrochimique mesuré à l'exutoire d'un bassin versant reflète la signature chimique des sources qui ont effectivement contribué à alimenter le débit de crue. Trois hypothèses principales sont donc posées (Sklash & Farvolden, 1982 ; Christophersen *et al.*, 1990 ; Jenkins *et al.*, 1994b ; Elsenbeer *et al.*, 1995) : 1) chaque source (ou composante du mélange) est caractérisée par une combinaison unique de traceurs temporellement et spatialement invariants ; 2) les concentrations des traceurs mesurées à l'exutoire sont soit les mêmes que celles de l'une des sources, soit une combinaison linéaire de celles de plusieurs sources ; et 3) la signature chimique des sources n'est pas modifiée lors du transport de l'eau jusqu'à l'exutoire. Ainsi, quelle que soit leur génération, les modèles de mélange (Christophersen *et al.*, 1990 ;

Hooper *et al.*, 1990 ; Christophersen & Hooper, 1992 ; Burns *et al.*, 2001 ; Carrera *et al.*, 2004) utilisés pour interpréter les résultats du traçage environnemental sont une conceptualisation mathématique de l'hypothèse 2).

L'application d'un modèle de mélange pour séparer un hydrogramme de crue nécessite, au préalable, la définition des sources ou des composantes. Cela se fait traditionnellement par le biais de la méthode *end-member mixing analysis* ou EMMA (Christophersen *et al.*, 1990 ; Hooper *et al.*, 1990) dont le principe est similaire à celui du modèle de mélange traditionnel exposé plus tôt, excepté que les concentrations chimiques des composantes ou des sources doivent être égales aux valeurs extrêmes des concentrations des eaux de rivière. Cette hypothèse permet une résolution graphique aisée du problème puisque dans le cas d'une séparation avec deux traceurs (donc pour trois sources), le diagramme de mélange a la forme d'un triangle. Ce triangle est situé dans l'espace des traceurs, et lorsque les composantes sont correctement définies, les concentrations des eaux du cours d'eau sont contenues à l'intérieur du triangle formé par ces composantes (Figure 1.3). Ces composantes ou sources sont alors appelées *end-members* ou pôles hydrochimiques.

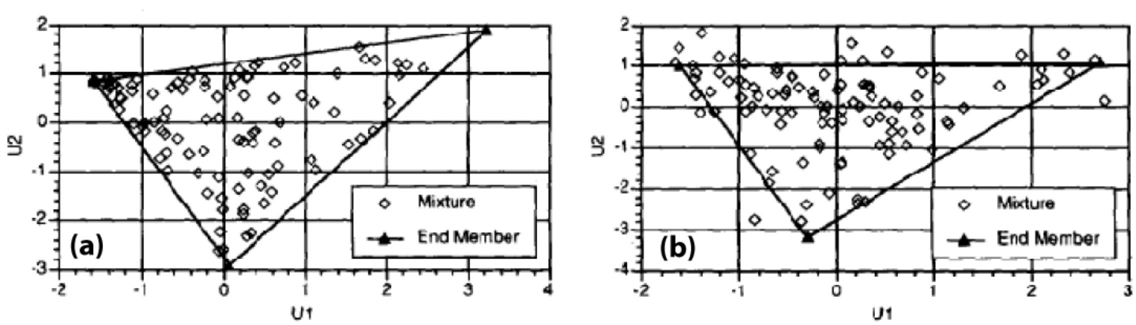


Figure 1.3. Diagrammes de mélange triangulaires obtenus suite à l'application de la méthode *End-member mixing analysis* ou EMMA (Christophersen and Hooper, 1992). La séparation basée sur deux traceurs a permis de caractériser trois composantes ou *end-members*. La situation en **(a)** représente une situation dans laquelle les composantes ont été correctement définies. À l'inverse, la localisation de plusieurs échantillons d'eau de rivière à l'extérieur du triangle en **(b)** signifie soit que les composantes sont mal définies, soit qu'il manque une composante, soit que les traceurs utilisés n'ont pas un comportement conservatif (Christophersen *et al.*, 1990).

La différenciation entre les sources de ruissellement peut se faire d'un point de vue temporel ou spatial comme le font valoir certains auteurs (e.g. McGlynn & McDonnell, 2003). Les sources temporelles regroupent uniquement les catégories d'eau nouvelle (*new water* ou *event water*) et d'eau ancienne (*old water* ou *pre-event water*). Le premier type correspond à l'eau apportée par l'événement pluvieux à l'étude, tandis que le second fait référence à de l'eau qui était déjà stockée dans le bassin versant avant le début de l'événement pluvieux à l'étude. Les sources spatiales offrent des renseignements supplémentaires en ce qui a trait à leur localisation au sein du bassin versant. La distinction peut être faite d'un point de vue strictement vertical si les sources sont identifiées selon leur profondeur par rapport à la surface du sol. Autrement, c'est une distinction latérale qui est faite, avec l'attribution d'étiquettes telles que « zone riveraine », « versant », « zone amont » ou « zone aval » afin de caractériser les sources de ruissellement.

Ainsi, avant même de se prononcer sur la convergence des résultats obtenus en utilisant le traçage environnemental ou les mesures hydrométriques traditionnelles, il faut se demander jusqu'où on peut aller en utilisant l'une ou l'autre des approches, et si les limites qui conditionnent l'application des deux approches sont les mêmes (Tableau 1.1). Si les mesures hydrométriques n'ont jamais permis de faire la distinction entre l'eau nouvelle et l'eau ancienne, par exemple, c'est parce qu'elles n'offrent pas la résolution temporelle adéquate pour ce faire (Genereux & Hooper, 1998). D'un autre côté, si l'utilisation du traçage environnemental rend rarement compte de la variabilité géographique des sources d'écoulement, les mesures hydrométriques sont en mesure de combler ce vide (Genereux & Hooper, 1998). La tendance récente consiste à combiner l'utilisation du traçage environnemental à celle des méthodes hydrométriques, et elle est directement héritée des lacunes du traçage environnemental. En effet, l'une des principales limites de la séparation d'hydrogramme est qu'elle n'offre que peu de renseignements sur les mécanismes d'écoulement, à moins d'utiliser la juste combinaison de traceurs chimiques et isotopiques (voir Buttle & Peters, 1997 pour une revue de la littérature à ce sujet). De plus, une incertitude peut être associée aux résultats des modèles de mélange à cause de la variabilité et de la réactivité des traceurs chimiques (Joerin, 2000). Le recours à des méthodes hydrométriques se justifie alors totalement, ne serait-ce qu'à des fins de validation des résultats obtenus grâce au traçage. Il n'est cependant pas question d'affirmer la « meilleure fiabilité » des méthodes hydrométriques en termes de résultats obtenus. En effet, le traçage environnemental est souvent utilisé car il intègre la variabilité qui est présente à petite échelle afin de donner une bonne indication des processus effectifs à l'échelle de tout le bassin versant (Buttle, 1994 ; Kendall & Caldwell, 1998 ; Joerin, 2000 ; Dahlgren, 2006). À l'inverse, les mesures hydrométriques ponctuelles, qu'il s'agisse de données d'humidité, de simulateurs de pluie ou de mesures piézométriques, ne peuvent être extrapolées à tout un bassin à moins d'émettre de solides hypothèses sur le comportement hydrologique à travers une gamme d'échelles spatiales (Kendall & Caldwell, 1998). Le recours au traçage plutôt qu'à l'hydrométrie doit également être solidement justifié dans certaines situations. Par exemple, il a été illustré que l'avènement du traçage avait permis de statuer sur la prédominance de l'écoulement hypodermique (e.g. Buttle & Peters, 1997). Certains hydrologistes répliquent cependant que ce résultat, loin d'être nouveau, avait déjà été démontré par un bon corpus d'études basées sur des méthodes hydrométriques (voir liste exhaustive de références dans Genereux & Hooper, 1998, p. 325) et antérieures à l'utilisation massive des traceurs (selon Genereux & Hooper, 1998, plus de dix études entre 1936 et 1978). Une divergence entre les résultats du traçage environnemental et ceux des méthodes hydrométriques peut cependant se manifester quand vient le temps d'identifier les sources spatio-temporelles – selon une perspective horizontale – de l'écoulement (e.g. Rice & Hornberger, 1998 ; Brown *et al.*, 1999).

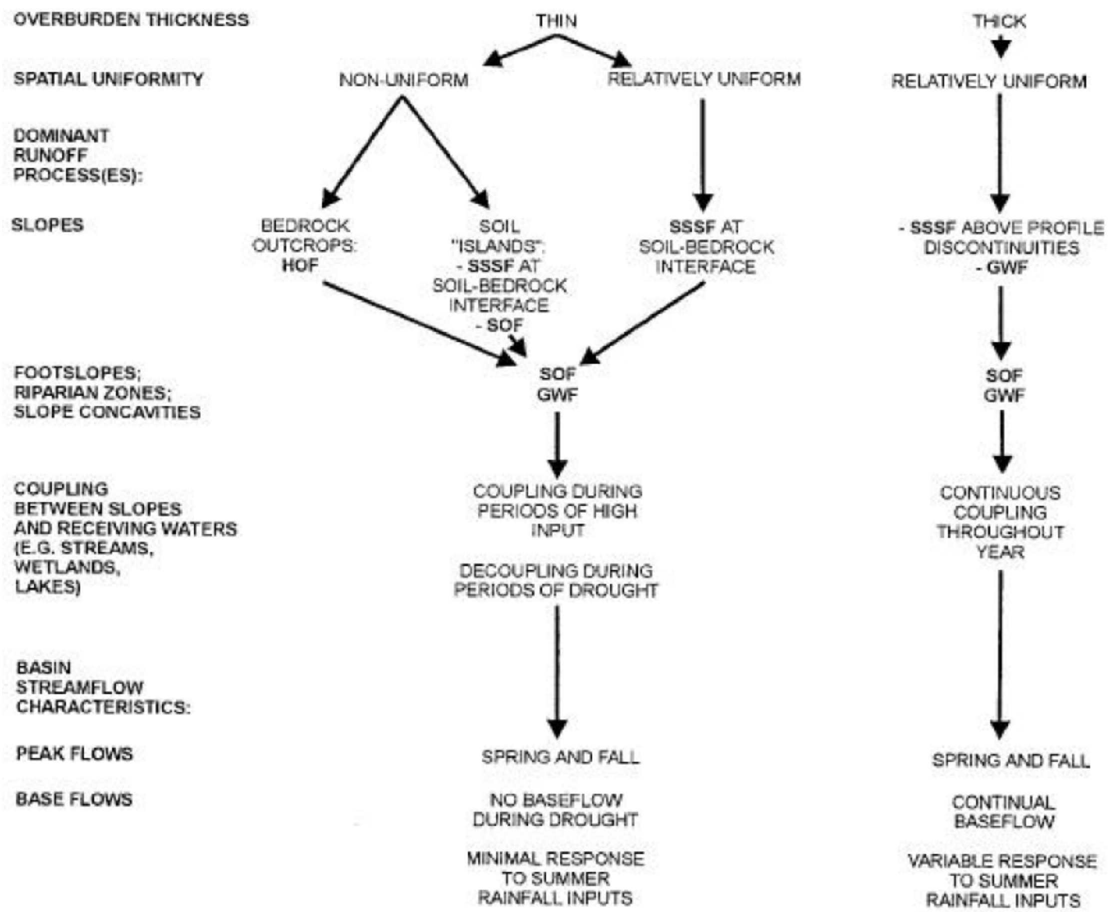


Figure 1.4 – Influence de l'épaisseur et de l'uniformité spatiale des sols sur les processus de ruissellement, le couplage entre les versants et les cours d'eau et les débits dans les bassins versants du bouclier canadien (original de Buttle *et al.*, 2000).

Il n'existe pas vraiment de théorie qui décrive, de manière systématique, les relations entre les mécanismes de genèse de l'écoulement de crue et des facteurs déterminants tels que la morphologie du bassin versant (forme, dimension, topographie, orientation des versants), ses propriétés physiques (nature des sols, couvert végétal), les caractéristiques des événements de pluie (répartition spatiale et temporelle, intensité et durée) ou les conditions d'humidité antécédentes (EPFL ; James, 2005). Il est cependant possible d'émettre des hypothèses sur les relations dominantes dans des milieux particuliers comme cela a déjà été fait pour l'épaisseur des sols dans les bassins versants du bouclier canadien (Figure 1.4). Ici ne sont examinés que deux facteurs contrôle, soit la topographie et les conditions d'humidité antécédentes.

La topographie de surface est un facteur-clé pour comprendre la réponse hydrologique des bassins versants, tout particulièrement dans les régions tempérées humides où le concept du *VSA* s'applique (Hewlett & Hibbert, 1967 ; Dunne & Black, 1970a ; Beven & Kirkby, 1979). Étant donné la facilité avec laquelle on peut dériver des données secondaires (e.g. pente locale, aires contributives) à partir des modèles numériques de terrain (Kirkby, 1997), la topographie de surface sert à approximer la distribution spatiale de l'humidité du sol, notamment en supposant que le gradient de pente reflète bien le gradient hydraulique local. En plus de ses effets sur les patrons d'humidité du sol, la topographie semble aussi contrôler non seulement l'âge de l'eau de pluie mais aussi son origine, sa chimie et les chemins d'écoulement qu'elle emprunte depuis son arrivée dans le bassin jusqu'à l'exutoire (Robson *et al.*, 1992).

D'un point de vue hydrologique, les fonds de vallée et les versants sont des unités morphologiques au comportement distinct (Flügel, 1995 ; Gallant & Dowling, 2003). De fait, les sols sont généralement plus minces sur les versants qui sont sujets à l'érosion. À l'inverse, les fonds de vallée sont des lieux d'accumulation, de sorte que les sols y sont plus épais et confèrent aux zones riveraines le rôle de zones tampon. Par ailleurs, si la topographie de surface est utile pour estimer la position des chemins d'écoulement sur les versants, l'opération est plus délicate dans les fonds de vallée à cause des faibles gradients de pente et des nombreuses dépressions (Gallant & Dowling, 2003). La réponse d'un versant à la sollicitation pluvieuse dépend, entre autres, de sa longueur, de sa conductivité hydraulique et de sa pente. En général, il est admis que plus un versant est long, plus la saturation à sa base est importante. Cependant il arrive que ce ne soit pas le cas, particulièrement lorsque le ruissellement de crue généré en haut de versant est évaporé avant qu'il ne puisse atteindre la base du versant. Afin de corriger cette conceptualisation inadéquate, le concept de longueur effective du versant a été avancé. Aryal *et al.* (2003) ont défini la longueur effective du versant comme la distance seuil mesurée à partir de la base et au-delà de laquelle on n'observe pas une augmentation du degré de saturation à la base. Ce concept, bien que rarement appliqué, n'est pas nouveau dans la mesure où il avait déjà été abordé sous l'expression « aires contributives dynamiques » (Barling *et al.*, 1994 ; Beven, 1997 ; Piñol *et al.*, 1997 ; Western *et al.*, 1999 ; Beven & Freer, 2001). L'aspect dynamique des aires contributives rend ainsi compte du fait que selon les conditions, ce n'est pas la totalité de l'aire de drainage calculée en amont d'un point qui contribue au ruissellement observé en ce point. Ce concept est, par ailleurs, particulièrement important dans les régions tempérées où, sur une base annuelle, l'évapotranspiration potentielle excède les apports en eau (Aryal *et al.*, 2003).

Récemment, l'importance de la topographie de subsurface, plus précisément celle de l'interface entre le sol et la roche-mère, a été mise en évidence (Freer *et al.*, 1997 ; Van Meerveld & McDonnell, 2005 ; Tromp-Van Meerveld & McDonnell, 2006b). C'est ainsi que pour un bassin versant forestier du bouclier canadien reposant sur un sol peu épais, Peters *et al.* (1995) ont montré que la plupart des chemins d'écoulement étaient situés à l'interface entre le sol et le matériel parental. Dans le même esprit, Freer *et al.* (1997) ont travaillé sur des versants excavés (*trenched hillslopes*) dans les bassins de Maimai (Nouvelle-Zélande) et Panola (Géorgie, États-Unis) et ont obtenu des corrélations fortes entre les gradients hydrauliques et la topographie de subsurface. Ces corrélations avaient cependant tendance à diminuer en fonction des conditions d'humidité antécédentes et de l'intensité des événements pluvieux.

Les conditions d'humidité sont importantes car elles déterminent le mécanisme dominant et les chemins d'écoulement empruntés par l'eau (James, 2005). Elles subissent d'importantes fluctuations saisonnières qui vont généralement de pair avec le débit mesuré à l'exutoire d'un bassin versant. Ainsi, la période où les stocks d'humidité sont les plus bas est la période estivale, car la grande consommation d'eau par les plantes a pour effet de pomper l'eau qui avait été stockée suite à la fonte nivale. L'automne, cependant, coïncide avec la période de sénescence, et les sols sont alors plus humides puisqu'il s'agit d'une période de moindre demande de la part des plantes et d'évapotranspiration limitée. Les fluctuations des conditions d'humidité peuvent aussi intervenir à des échelles de temps plus petites, notamment sur une base événementielle. Les conditions d'humidité qui prévalent dans un sol sont liées non seulement à l'intensité, mais aussi à la séquence temporelle des événements pluvieux (James, 2005).

Il a été possible d'observer, dans des bassins versants de plusieurs types, une évolution non linéaire de la production de ruissellement de crue en fonction des conditions d'humidité antécédentes (Western & Grayson, 1998 ; James, 2005 ; Tromp-Van Meerveld & McDonnell, 2006a). Certains mécanismes d'écoulement sont aussi activés par les conditions d'humidité. Ainsi, Sklash & Farvolden (1979) ont observé la prédominance de l'eau ancienne dans des conditions humides tandis que la contribution principale à l'écoulement de crue dans des conditions sèches est celle de l'eau nouvelle. Par ailleurs, Sidle *et al.* (1995) ont travaillé sur un bassin versant forestier japonais et montré que lors du passage de conditions sèches à des conditions humides, la contribution de l'écoulement macroporeux au ruissellement de crue passe de 0 % à 25 %. Inamdar & Mitchell (2006) ont, pour leur part, trouvé que pendant les événements de faible humidité, les contributions au ruissellement proviennent surtout des bas de vallée. Cependant au fur et à mesure de l'augmentation des taux d'humidité, on observe une plus grande expansion spatiale des aires saturées, de sorte que la contribution des versants devient plus importante. Plusieurs autres études ont également établi un lien important entre les conditions d'humidité antécédentes et les proportions relatives de ruissellement de surface et hypodermique (Mulholland *et al.*, 1990 ; McGlynn *et al.*, 1999).

La genèse du ruissellement dans les bassins versants reposant sur du till glaciaire revêt un aspect particulier. En effet, dans plusieurs régions nordiques, les dépôts de surface sont essentiellement composés de sédiments non triés (e.g. diamicton) de diverses tailles. Les sols qui s'y développent sont peu épais et se caractérisent par une conductivité hydraulique à saturation qui diminue rapidement avec la profondeur (Beldring *et al.*, 2000). Ainsi, la nappe phréatique se développe parallèlement à la topographie de surface. Cette nappe est située à quelques mètres de profondeur sur les hauts de versants, tandis qu'elle a tendance à affleurer à la surface du sol dans les fonds de vallée et à alimenter les cours d'eau. Il est donc possible de distinguer deux grandes catégories de zones, soit les versants qui constituent des zones de recharge et les fonds de vallée qui constituent plutôt des zones d'écoulement. Lors des événements, l'eau de pluie ou de fonte a tendance à s'infiltrer dans les zones de recharge et à emprunter des chemins hypodermiques pour atteindre la base des versants. Au contraire, l'eau de pluie qui tombe dans les fonds de vallée s'écoule directement vers le réseau hydrographique. La dynamique des fonds de vallée met d'ailleurs en jeu un double mécanisme, soit 1) du ruissellement de surface sur les zones déjà saturées, et 2) une redistribution de l'eau dans les zones non saturées, pour que celle-ci emprunte les chemins hypodermiques où la conductivité hydraulique est plus élevée. La forte conductivité hydraulique associée aux horizons superficiels des sols a d'ailleurs deux principales conséquences, soit 1) une réponse très rapide des aires saturées suite à une sollicitation pluvieuse, et 2) une contribution prédominante de l'écoulement de crue de proche surface (Beldring *et al.*, 2000).

"*Moving beyond heterogeneity and process complexity: A new vision for watershed hydrology"* (McDonnell *et al.*, 2007, p. 1)

1.2 Théorie renouvelée sur la genèse de l'écoulement de crue

1.2.1 Le concept de connectivité hydrologique

Les études uniquement axées sur les mécanismes de genèse de l'écoulement observés à petite échelle perdent aujourd'hui du terrain. En effet, en raison de la multiplicité et de la complexité des processus en cause, il semble exister presque autant de perceptions du comportement hydrologique qu'il y a de bassins versants étudiés. Cela va totalement à l'encontre de l'objectif qui avait été énoncé il y a plus de 20 ans pour la discipline, soit l'établissement de « lois hydrologiques » claires qui permettraient de réaliser des classifications rigoureuses des comportements hydrologiques observés sous diverses latitudes (Dooge, 1986 ; McDonnell *et al.*, 2007). Ainsi, face aux résultats mitigés et divergents des méthodes basées sur l'étude des processus à petite échelle, les hydrologues se tournent aujourd'hui vers l'étude de propriétés émergentes telles que la connectivité hydrologique.

Les multiples interprétations qui sont prêtées à la connectivité hydrologique viennent du fait qu'il s'agit d'un concept passe-partout. Bien que le concept ait d'abord été exploité par les écologistes (Tischendorf & Fahrig, 2000a, b ; Moilanen & Hanski, 2001 ; Pringle, 2001 ; Amoros & Bornette, 2002 ; Goodwin & Fahrig, 2002 ; Goodwin, 2003 ; Pringle, 2003a, b ; Calabrese & Fagan, 2004 ; Belisle, 2005), il est de plus en plus utilisé en hydrologie, notamment comme argument de choix lorsqu'il s'agit de justifier l'émergence de comportements non linéaires dans des bassins versants aussi nombreux que diversifiés. Le problème actuel est qu'il semble régner une confusion, ou à tout le moins un manque de consensus entre les hydrologues, quant à savoir ce qu'est la connectivité hydrologique, comment l'identifier et la mesurer sur le terrain, comment la relier aux recherches préexistantes et comment l'incorporer dans des cadres de modélisation (Bracken & Croke, 2007). Tant les écologistes que les hydrologues s'entendent néanmoins pour dire que la connectivité hydrologique peut opérer selon les dimensions longitudinale, latérale, verticale et temporelle des systèmes hydrologiques (Amoros & Bornette, 2002 ; Lane *et al.*, 2003). Le concept de connectivité longitudinale permet d'évaluer la variation de la conductivité hydraulique de l'amont vers l'aval du cours d'eau, de sorte que les divers degrés de connectivité sont étroitement liés au concept de continuum fluvial (*river continuum*) (Vannote *et al.*, 1980). Le concept de connectivité latérale fait plutôt référence aux liens, pérennes ou intermittents, entre le cours d'eau principal, les cours d'eau tributaires, la plaine d'inondation et les versants adjacents (Gilvear, 1999 ; Amoros & Bornette, 2002). Ainsi, les connectivités latérale et longitudinale de surface permettent un acheminement rapide de l'eau et des particules ou éléments chimiques qu'elle transporte jusqu'au cours d'eau. Toutefois, si la connectivité de surface est rompue en raison de la présence d'une zone d'infiltration accrue, c'est plutôt la connectivité verticale, ainsi que les connectivités latérale et longitudinale de subsurface, qui déterminent le transport de l'eau (Lane *et al.*, 2003). Le concept de connectivité verticale sert à évaluer les échanges entre les eaux de surface et hypodermiques, sachant que ces échanges se font principalement via l'infiltration et la percolation de l'eau dans l'aquifère alluvial ou l'exfiltration de l'eau en provenance de la nappe phréatique située sous les versants (Amoros & Bornette, 2002). Quant à la dimension temporelle, elle sert à rendre compte des variations des connectivités longitudinale, latérale et verticale sur une base événementielle, saisonnière, annuelle, etc. L'étiquette de « concept passe-partout » que l'on attribue à la connectivité hydrologique vient donc du fait qu'en hydrologie, les auteurs qui l'utilisent font rarement état, de manière explicite, de la définition (cycle de l'eau, topographie, patrons spatiaux, mécanismes d'écoulement) qu'ils adoptent et de la dimension (longitudinale, latérale, verticale, temporelle) qu'ils prennent en considération.

Afin de mieux cerner les facteurs déterminants dans l'établissement de la connectivité hydrologique à l'échelle d'un bassin versant, Bracken & Croke (2007) ont élaboré un cadre conceptuel basé sur cinq principaux éléments : 1) le climat, 2) le potentiel de ruissellement du versant, 3) la position dans le paysage, 4) le chemin d'écoulement, et 5) les zones tampon.

Le climat régnant dans la région d'étude est important à considérer puisqu'il détermine les processus de ruissellement dominants. En milieu humide, par exemple, le degré de connectivité dépend du degré d'interconnexion entre les aires saturées, soit les poches d'humidité sur les versants et le réseau hydrographique (Figure 1.5 A). Les conditions d'humidité antécédentes sont importantes car à tout moment, les poches d'humidité présentes sur les versants sont susceptibles de prendre de l'expansion suite à un événement de pluie. À l'inverse, la connectivité est beaucoup plus difficile à établir en milieu aride. Ce n'est que dans des cas exceptionnels, suite à un événement de pluie de durée et d'intensité suffisantes, qu'une mosaïque de *patches* humides se forme et que les transferts d'eau, bien que limités dans l'espace, peuvent se faire vers le réseau hydrographique (Figure 1.5 B). L'intensité, la durée et le synchronisme de l'événement pluvieux sont des paramètres importants, tant en milieu humide qu'en milieu aride. Ainsi, une pluie légère peut humidifier peu à peu un bassin de sorte que lorsqu'une pluie plus forte se produit, le ruissellement de surface est très rapidement généré et spatialement connecté du fait du manque d'infiltration dans les sols déjà saturés. Une pluie forte sur des sols secs n'aurait pas les mêmes effets car les taux d'infiltration importants empêcheraient la circulation latérale de l'eau dans les sols.

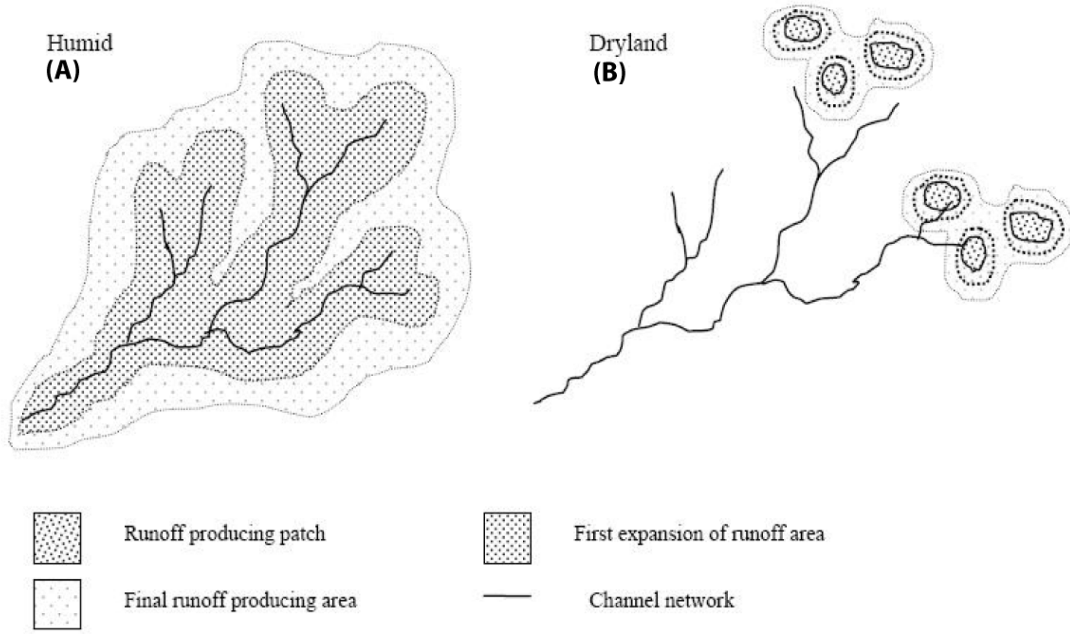


Figure 1.5 – (A) Expansion spatiale et connectivité des aires saturées en milieu humide ; (B) Mosaïque de patches humides qui doivent, nécessairement, être connectées pour produire du ruissellement en milieu aride (originaux de Bracken & Croke, 2007).

La capacité d'un versant à générer du ruissellement est le résultat d'une combinaison de facteurs, notamment la rugosité du sol, le type et la densité de végétation, la morphométrie du bassin versant et le type d'utilisation du sol. Tous ces facteurs sont importants en raison du rôle qu'ils peuvent jouer pour favoriser (ou défavoriser) l'infiltration de l'eau dans les sols, et par le fait même empêcher (ou permettre) l'établissement de la connectivité hydrologique à l'échelle d'un versant ou d'un bassin versant (Bracken & Croke, 2007). La position dans le bassin versant est également cruciale, puisqu'il s'agit d'une mesure de la distance entre le point considéré et le cours d'eau ou l'exutoire du versant ou du bassin étudié. Le degré de connectivité hydrologique a donc tendance à être élevé lorsque cette distance est courte par rapport à l'aire contributive effective (Bracken & Croke, 2007). Le concept de connectivité hydrologique peut aussi être étudié par le biais de la dynamique sédimentaire en milieu alluvial. En effet, la distribution spatiale des réservoirs et des puits de sédiments en bordure d'un cours d'eau, ainsi que la fréquence à laquelle ces sédiments sont ajoutés ou soustraits aux différents réservoirs, témoignent d'à quel point le système fluvial est déconnecté ou découplé (Harvey, 2002 ; Hooke, 2003). D'un point de vue longitudinal, les éléments qui empêchent le transfert des sédiments de l'amont vers l'aval sont qualifiés de « barrières » tandis que d'un point de vue latéral, les formes morphologiques qui restreignent la connectivité du cours d'eau et des versants sont qualifiées de « zones tampon ». L'évolution temporelle de la connectivité au sein d'un bassin dépend donc, essentiellement, de la forme et de l'étendue des barrières/zones tampon et de l'aisance avec laquelle l'eau peut les modifier ou les contourner pour se frayer un chemin jusqu'à l'exutoire (Fryirs *et al.*, 2007). Par ailleurs, les chemins d'écoulement contrôlent principalement la vitesse d'acheminement du ruissellement de crue, et ce en fonction de leur largeur et de leur profondeur. Pour ce qui est du ruissellement de surface, on distingue les chemins d'écoulement incisés (e.g. rigoles et autres ravinements) au sein desquels l'écoulement est concentré de ceux présents sous une forme plus diffuse. Les chemins d'écoulement diffus sont tout aussi importants que les chemins incisés, bien que leur quantification sur le terrain soit un peu plus délicate. Le type de chemins d'écoulement est essentiellement contrôlé par la topographie (e.g. pentes fortes) et l'utilisation du sol (Bracken & Croke, 2007). Quant à la notion de zone tampon, elle permet d'évaluer si les versants sont connectés aux cours d'eau, et dans quelle mesure la plaine d'inondation peut empêcher l'acheminement du ruissellement et des sédiments vers le réseau de drainage.

1.2.2 L’hypothèse des états préférentiels

L’hypothèse des états préférentiels est étroitement liée au concept de connectivité hydrologique. En effet, cette hypothèse avancée par Grayson *et al.* (1997) suppose que dans les milieux tempérés humides, les patrons formés par l’eau du sol fluctuent entre deux états diamétralement opposés car contrôlés par des mécanismes radicalement différents.

Bien que cette hypothèse repose sur l’existence d’un continuum d’états préférentiels, seuls les deux extrêmes sont décrits ici. D’une part, l’état humide est associé aux périodes pendant lesquelles le volume de précipitations est continuellement supérieur à l’évapotranspiration. Dans ce contexte, les patrons d’humidité du sol résultent, essentiellement, des mouvements latéraux de l’eau du sol qui emprunte des chemins tant de surface que de subsurface. Le principal facteur qui influence ces mouvements de l’eau du sol est la topographie, et on la qualifie alors de contrôle non local. En effet, c’est l’aire contributive en amont de chaque point qui détermine la quantité d’eau drainée, de sorte que les zones de grande convergence topographique sont les plus humides. Les patrons d’humidité du sol apparaissent alors comme connectés, ou à tout le moins organisés à l’échelle du bassin versant (Figures 1.5 A et C). À l’inverse, l’état sec est associé aux périodes pendant lesquelles l’évapotranspiration excède le volume de précipitations. Les mécanismes hydrologiques dominants sont alors ceux des flux verticaux d’eau dans le sol, au détriment des mouvements latéraux. Puisqu’il n’y a pas de flux latéraux d’eau, la connectivité latérale entre les points du bassin et leur aire contributive est quasi-inexistante. L’apparence *patchy*, voire même aléatoire, des patrons d’humidité du sol (Figures 1.5 B et D) reflète alors les différences de facteurs très locaux tels que les caractéristiques du sol ou de la végétation.

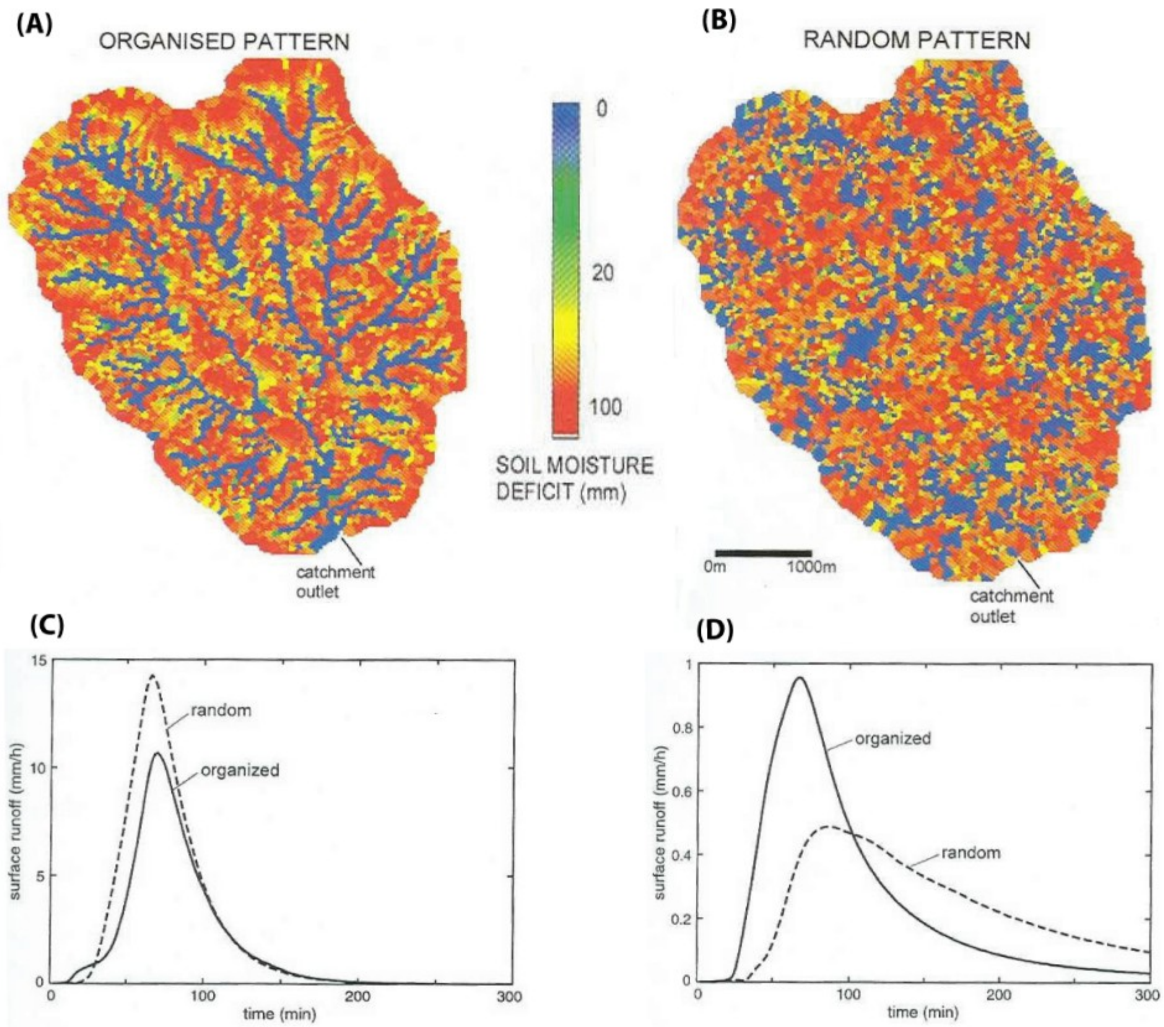


Figure 1.6 – Illustration de l'hypothèse des états préférentiels. **(A)** Patron d'humidité du sol « organisé » ; **(B)** Patron d'humidité du sol « aléatoire » ; **(C)** Ruissellement de surface simulé par le modèle *THALES* pour les deux patrons spatiaux pour un apport de 30 mm de pluie en une heure ; **(D)** Idem pour un apport de 5 mm de pluie en une heure (Grayson & Blöschl, 2001).

La transition d'un état préférentiel à l'autre, qui se fait sur une période relativement courte, consiste en un changement dans la prédominance des flux latéraux ou verticaux d'eau, et donc dans le contrôle prédominant de facteurs non locaux ou locaux. Cette transition peut généralement s'expliquer comme suit. Pendant les périodes sèches, les couches superficielles du sol sont relativement dépourvues d'eau de sorte que leur conductivité hydraulique est faible. Les éventuelles précipitations tombant sur ce sol ont donc tendance à être évapotranspirées avant qu'elles ne puissent être redistribuées latéralement. Même dans le cas où un front de saturation réussirait à se former dans les couches superficielles du sol, il ne persisterait pas longtemps, compte tenu du fort potentiel évaporatif du sol. Ainsi, seuls les contrôles locaux ont une influence notable sur la distribution de l'eau du sol (Grayson *et al.*, 1997). La situation est cependant tout autre lorsque les précipitations sont supérieures à l'évapotranspiration. Au fur et à mesure que le bassin versant devient humide, les zones de haute convergence, notamment les lignes de drainage, approchent de l'état de saturation maximale et un apport en eau minime est suffisant pour déclencher le ruissellement. La forte conductivité hydraulique du sol y favorise les mouvements latéraux de l'eau, et c'est ainsi que les patrons organisés ou connectés sont établis. La fin de cette période humide intervient lorsque le sol n'est plus saturé et que sa conductivité hydraulique diminue, empêchant ainsi l'écoulement latéral de dominer les flux verticaux (Grayson *et al.*, 1997).

Il est important de noter que certains environnements sont exclusivement dominés par l'un ou l'autre des états et qu'il n'y a jamais de transition de l'un à l'autre. C'est notamment le cas des régions arides pour lesquelles l'évapotranspiration excède toujours les précipitations, ou des régions très humides dont le potentiel évaporatif est toujours très faible. Ainsi, l'équilibre entre les précipitations et l'évapotranspiration détermine l'établissement de l'un ou l'autre des états préférentiels, tandis que la capacité du réservoir « sol » influence la rapidité avec laquelle la transition entre les deux états peut s'effectuer (Grayson *et al.*, 1997). Par ailleurs, l'hypothèse telle qu'initialement formulée suppose que les deux transitions, soit celle de l'écoulement latéral à l'écoulement vertical et celle de l'état humide à l'état sec, se font de façon synchrone. McNamara *et al.* (2005) affirment cependant qu'il est plus correct de considérer ces deux phénomènes comme asynchrones, en particulier lorsque l'on étudie des bassins versants affectés par la fonte nivale.

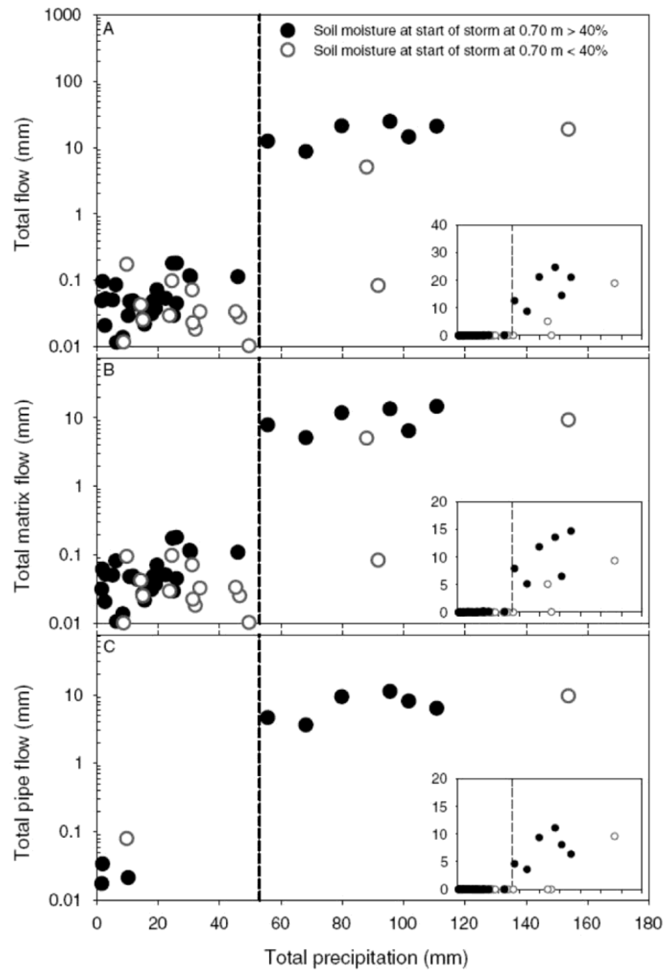


Figure 1.7 – Relation seuillée, établie sur une base événementielle, entre le volume total de précipitations et **(A)** le ruissellement total, **(B)** l'écoulement dans la matrice de sol, et **(C)** l'écoulement macroporeux recueillis au niveau d'un versant excavé dans le bassin de Panola (Géorgie, États-Unis). Les relations sont représentées selon une échelle semi-log et selon une échelle linéaire. La ligne pointillée illustre le seuil de 55 mm pour le volume total de précipitations (original de Tromp-Van Meerveld & McDonnell, 2006a).

L'hypothèse des états préférentiels est intéressante car elle permet aussi d'introduire le concept de seuil en hydrologie des bassins versants. En effet, selon Grayson *et al.* (1997), il existe une valeur critique d'humidité du sol au-delà de laquelle une proportion substantielle du bassin versant se comporte à l'unisson et génère du ruissellement de crue. Lorsque cette valeur critique est atteinte dans l'état humide, la distribution spatiale des aires saturées n'a plus vraiment d'importance puisqu'elles ont toutes une valeur de saturation supérieure à la valeur critique. La question des seuils hydrologiques est étroitement liée à celle de la relation non linéaire entre la production de ruissellement de crue et les apports en eau de pluie ou de fonte. Dans une étude exhaustive de 147 événements de pluie dans le bassin versant de Panola (Géorgie, États-Unis), une valeur seuil de 55 mm a été identifiée comme nécessaire pour qu'il y ait production d'un écoulement de crue de proche subsurface significatif (Figure 1.7). De plus, Tromp-Van Meerveld & McDonnell (2006a) ont effectué une recension de la littérature et ainsi découvert que ce type de relation seuillée n'était pas nouveau, bien qu'il n'ait pas toujours été explicité dans les publications (Tableau 1.2). Il s'agirait donc d'un phénomène plutôt répandu (Weiler *et al.*, 2005 ; Lehmann *et al.*, 2007), bien que l'on doive faire attention aux différences dans les valeurs seuil obtenues pour les divers bassins versants. Selon Lehmann *et al.* (2007), il est même possible d'affirmer qu'à l'échelle d'un versant, l'existence d'une valeur critique de pluie pour l'activation du ruissellement est une propriété émergente que l'on doit relier à l'établissement d'une connectivité spatiale entre les sources hypodermiques. C'est d'ailleurs l'idée qui est véhiculée par l'hypothèse du *fill and spill*.

Tableau 1.2 – Relations seuillées entre les précipitations et les principaux mécanismes d'écoulement de crue.

Région d'étude	Variable(s) dépendante(s)	Conditions d'humidité	Valeur seuil de précipitation	Références de l'étude
Plastic Lake, Canada	Écoulement de versant	Inconnues	8 mm	Peters *et al.*, 1995
	Débit du cours d'eau	Inconnues	17 mm	
Pennsylvanie, États-Unis	Écoulement macroporeux	Inconnues	10 à 20 mm	Guebert & Gardner, 2001
Japon	Écoulement hypodermique	Inconnues	20 mm	Tani, 1997
Maimai, Nouvelle-Zélande	Écoulement hypodermique	Inconnues	23 mm	Mosley, 1979
Nord-est des États-Unis	Écoulement hypodermique	Sèches	35 mm	Whipkey, 1965
		Humides	Indéfini	

L'hypothèse du *fill and spill* (Tromp-Van Meerveld & McDonnell, 2006b) se base sur un double mécanisme de saturation, dans les horizons de proche surface et à l'interface entre le sol et la roche-mère ou tout autre horizon imperméable, pour expliquer l'établissement de la connectivité hypodermique à l'échelle d'un versant. Cette double dynamique est attribuable à la présence de sols peu épais et de dépressions à l'interface entre le sol et le matériel parental. Ainsi, avant d'observer des patrons de saturation temporaires hypodermiques, il faut que les dépressions de l'interface sol-roche-mère soient remplies d'eau (Figure 1.8 A). Après cette étape (*fill*), le surplus d'eau se déverse (*spill*) le long de la topographie de subsurface, et c'est ainsi que la connectivité des sources hypodermiques est établie (Figure 1.8 B). Pour le bassin versant de Panola (Géorgie, États-Unis), cette connectivité n'est établie que suite à des apports pluvieux de plus de 55 mm, et l'écoulement hypodermique alors produit est 75 fois supérieur à celui que l'on aurait obtenu sans « remplissage et déversement » (Tromp-Van Meerveld & McDonnell, 2006b). L'hypothèse du *fill and spill* a également été évaluée dans un bassin versant du bouclier canadien (Spence & Woo, 2003) mais dans la perspective plus large des écoulements tant de surface qu'hypodermiques. L'étape de remplissage avant le déversement et l'établissement de patrons de saturation et de connectivité à grande échelle peut ainsi expliquer le délai de réponse de certains bassins versants par rapport au pic de précipitations.

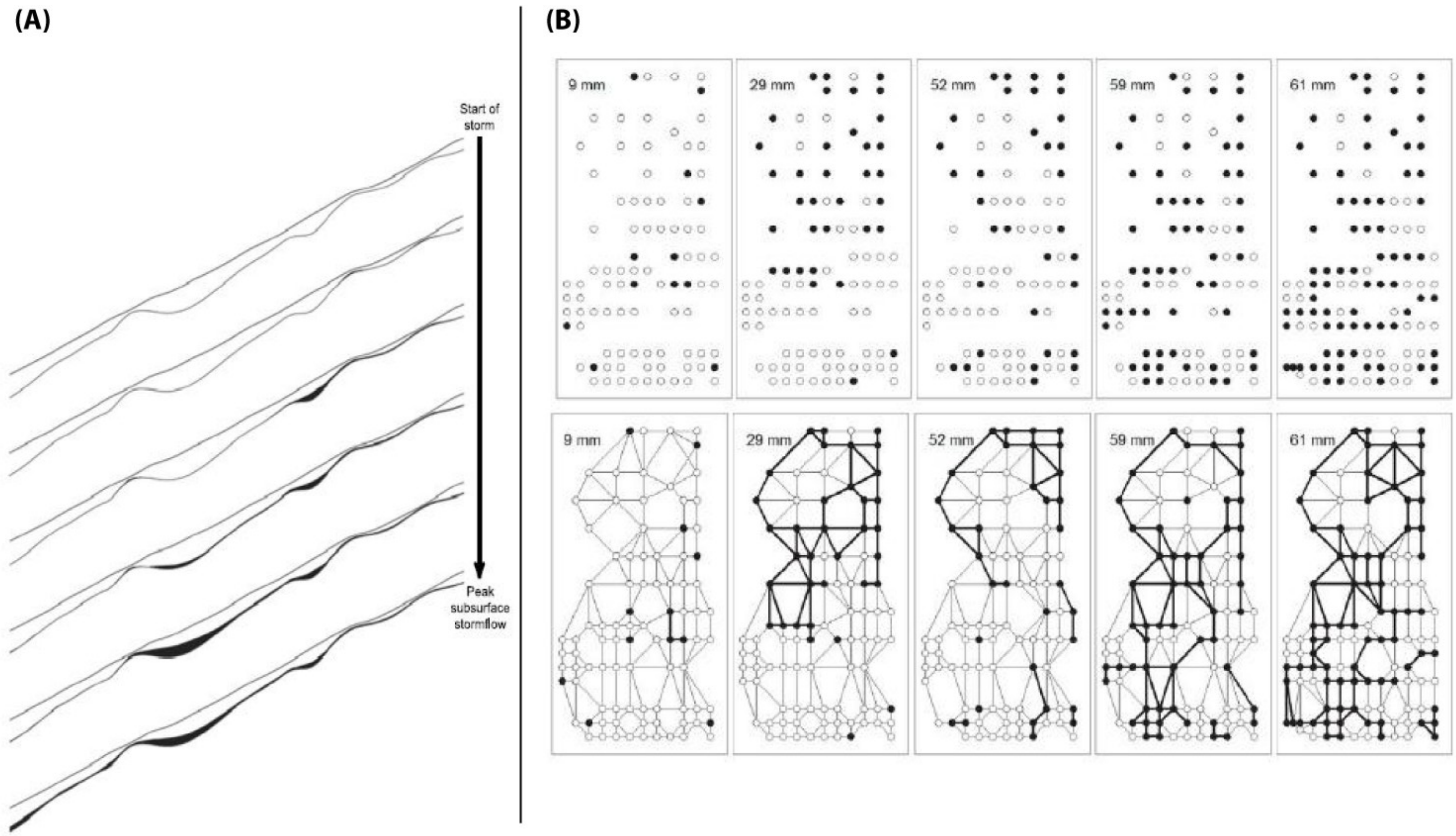


Figure 1.8 – **(A)** Illustration de l'hypothèse de '*fill and spill*'. Les zones en noir correspondent aux régions saturées (original de Tromp-Van Meerveld & McDonnell, 2006b) ; **(B)** Patrons de saturation temporaire hypodermique associés à des volumes de précipitations différents pour le bassin versant de Panola (Géorgie, États-Unis). Les sites de mesure représentés par des disques blancs sont secs, tandis que ceux représentés par des disques noirs sont humides ou saturés. Les lignes noires symbolisent la libre circulation de l'eau hypodermique entre les sites et constituent donc un patron de connectivité. La connectivité hypodermique est nettement accrue lorsque le seuil de 55 mm pour le volume de précipitations est dépassé (original de Lehmann *et al.*, 2007).

Autrement, en plus de la relation non linéaire entre la production de ruissellement de crue et les apports en eau, il est possible d'étudier celle entre la production de ruissellement de crue et les conditions d'humidité antécédentes. Pour un bassin versant de prairies en région tempérée (Tarrawarra, Australie), par exemple, une très petite augmentation du degré de saturation moyen du bassin provoque une très grande augmentation du coefficient de ruissellement (volume de ruissellement/volume de précipitations) (Figure 1.9 A) (Western & Grayson, 1998). Un comportement similaire a été observé dans un bassin forestier (James, 2005) (Figure 1.9 B). Ainsi, les effets de seuils et les comportements non linéaires des bassins versants constituent la base de la théorie hydrologique renouvelée. Ces nouvelles connaissances doivent maintenant être prises en compte à des fins de prédiction de la réponse hydrologique, que ce soit via l'utilisation de modèles ou via la réalisation de transferts d'échelles spatiales et temporelles.

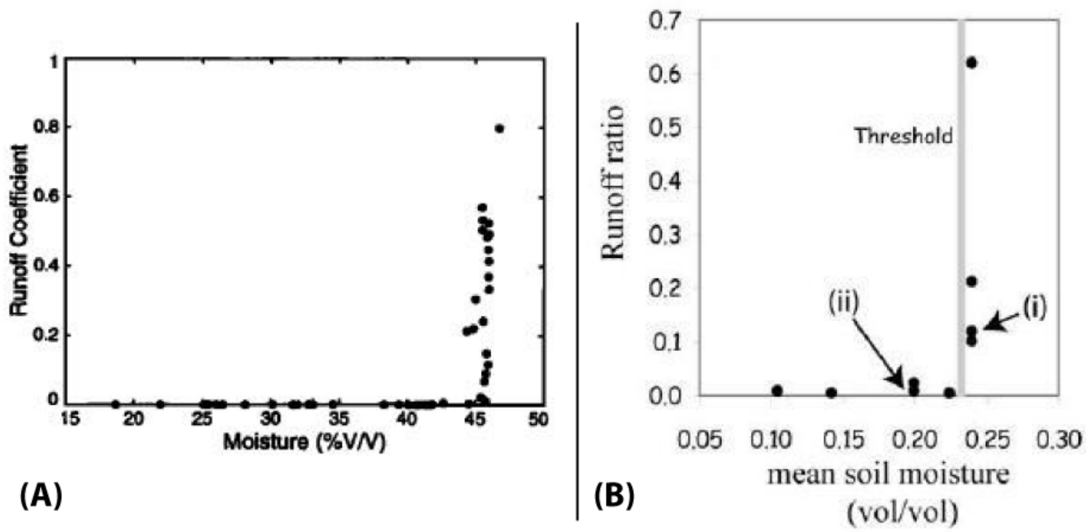


Figure 1.9 – Relation seuillée entre le coefficient de ruissellement et le contenu moyen en eau du sol pour **(A)** un bassin versant de prairies en climat tempéré sec (Tarrawarra, Australie) (original de Western & Grayson, 1998) ; et **(B)** un bassin versant forestier en climat tempéré humide (Mont-St-Hilaire, Québec, Canada) (original de James, 2005).

"*How far can we go in distributed hydrological modelling*?" (Beven, 2001, p. 1)

1.3 Postulats pour la prédiction de la réponse hydrologique

1.3.1 La modélisation

Étant donné la multiplicité et la complexité des processus hydrologiques exposés plus tôt, la représentation des bassins versants sous la forme de modèles est nécessairement une simplification de la réalité. Selon Perrin (2000), le développement d'un modèle repose sur la définition de trois éléments, soit 1) le système observé et ses limites spatiales et temporelles, 2) l'objectif de la modélisation, et 3) le compromis entre réalisme et précision. Les modèles hydrologiques les plus populaires ont pour objectif l'étude de la transformation de la pluie en débit. Les classifications de ces modèles sont cependant multiples : ils peuvent ainsi être déterministes ou stochastiques, globaux ou semi-distribués ou spatialisés, descriptifs ou explicatifs, empiriques ou conceptuels ou théoriques, boîte noire ou à réservoirs ou à base physique. Par ailleurs, ils peuvent être exécutés sur une base continue ou événementielle, selon des pas de temps variant de quelques minutes à plusieurs mois. Les modèles les plus adéquats, quand on s'intéresse aux processus hydrologiques, sont les modèles conceptuels, à réservoirs, spatialement distribués. L'adjectif « conceptuels » renvoie au fait que le cadre mathématique du modèle est simplifié à l'extrême et ne considère que les processus jugés pertinents par le modélisateur. Les réservoirs dont il est question représentent des sous-processus interconnectés et interdépendants lors de la transformation de la pluie en débit. Certaines équations permettent donc la distribution des apports en eau entre ces différents réservoirs, tandis qu'une fonction de routage ou de transfert permet d'acheminer l'eau jusqu'au cours d'eau. Enfin, les modèles spatialisés ou spatialement distribués tiennent compte, de manière explicite, de la variabilité spatiale des processus et/ou des données d'entrée. Ces modèles diffèrent surtout par la manière dont ils appréhendent l'espace, soit à base de mailles carrées ou de subdivisions basées sur les valeurs d'un indice de similarité (Refsgaard, 1997 ; Perrin, 2000 ; Durand *et al.*, 2002 ; Chahinian, 2004).

S'il est vrai qu'une grande majorité de bassins versants de par le monde sont sujets à des effets de seuils (e.g. Zehe *et al.*, 2007 ; Zehe & Sivapalan, 2009), alors il est nécessaire de s'assurer que les modèles hydrologiques utilisés à des fins de prédiction soient en mesure de simuler les dynamiques non linéaires qui conduisent à la contribution épisodique de certaines sources au débit du cours d'eau. Savenije (2009) soulignait, à juste titre, qu'un modèle hydrologique n'est pas un outil mais plutôt une hypothèse de travail puisque le choix d'un modèle laisse entendre que l'on s'est déjà fait une idée sur les mécanismes hydrologiques dominants au sein du bassin versant étudié. Dans le cadre de cette thèse, il a donc été choisi de s'intéresser uniquement aux modèles conceptuels qui tiennent compte, explicitement, de la dynamique des aires contributives variables, une dynamique qui constitue l'essence même de la connectivité hydrologique. C'est notamment le cas des modèles basés sur des indices de similarité topo-hydrologique.

D'un point de vue purement théorique, l'utilisation des indices de similarité topo-hydrologique devrait permettre d'estimer, de manière adéquate, le degré de connectivité d'un bassin versant. En effet, ils servent principalement à estimer la limite supérieure de la nappe d'eau perchée ; ils fournissent donc, indirectement, la distribution spatiale de l'humidité du sol et la localisation des aires saturées qui sont susceptibles d'être spatialement connectées au cours d'eau. Les indices de similarité topo-hydrologique les plus connus sont ceux établis par Beven & Kirkby (1979) et O'Loughlin (1981). Selon la formulation de Beven & Kirkby (1979), l'indice topographique λ_i est obtenu en faisant le ratio de l'aire contributive drainée à un point i (a_i) par l'angle local de pente mesuré à ce même point i ($\tan \beta_i$), soit deux propriétés physiques des bassins versants qui influencent grandement l'acheminement de l'écoulement de crue et donc la connectivité :

$$\lambda_i = \ln\left(\frac{a_i}{\tan\beta_i}\right) \tag{Éq. 1.1}$$

Les fonds de vallée ont des valeurs élevées d'indice topographique, en raison de leur gradient de pente faible et/ou de la grande aire contributive qui leur est associée, tandis que les hauts de versants ont de plus faibles valeurs d'indice topographique. Si l'indice topographique fut, à l'origine, développé pour être intégré à *TOPMODEL* (*TOPography-based MODEL*) (Beven & Kirkby, 1979), plusieurs autres modèles l'utilisent aujourd'hui pour identifier les zones les plus susceptibles de contribuer à l'écoulement de crue, et c'est notamment le cas de *RHESSys* (*Regional Hydro-Ecologic Simulation System*) (Tague & Band, 2001) et *DHSVM* (*Distributed Hydrology Soil Vegetation model*) (Wigmosta *et al.*, 1994). On suppose souvent que l'indice topographique est représentatif de la distribution spatiale du temps de résidence de l'eau dans la nappe perchée. En effet, les temps de résidence importants devraient être associés à des valeurs d'indice topographique élevées, puisque les zones de grande inertie hydrologique sont celles qui drainent de larges superficies et qui sont caractérisées par de faibles gradients de pente (Monteith *et al.*, 2006).

La question est maintenant de savoir si les modèles hydrologiques qui s'appuient sur le calcul d'un indice topographique sont à même de distinguer des états préférentiels et donc de simuler des réponses hydrologiques non linéaires. À cet égard, la version originale de *TOPMODEL* est reconnue pour offrir des performances mitigées dans plusieurs bassins, notamment pour des périodes où le degré de saturation des sols est faible (Piñol *et al.*, 1997 ; Shaman *et al.*, 2002 ; Stieglitz *et al.*, 2003). La simulation des périodes de transition entre des conditions sèches et des conditions plus humides est également difficile, et ce problème a été décrit comme « *the inappropriateness of TOPMODEL's conceptual basis to describe, meaningfully, hydrologically shallow, hilly situations where transient, perched groundwater flow plays substantial roles in controlling watershed hydrology* » (Walter *et* *al.*, 2002, p. 1). Cette lacune du modèle pourrait être attribuable à l'utilisation d'un indice topographique statique, plutôt que dynamique, pour prédire l'extension spatiale des aires contributives (Barling *et al.*, 1994). Stieglitz *et al.* (2003) mentionnent également que *TOPMODEL* ignore l'existence de l'écoulement de crue de proche subsurface, un écoulement pourtant crucial pour l'établissement de la connectivité hydrologique à l'échelle d'un versant. Il est bon de préciser que l'utilisation des indices de similarité topo-hydrologique va de pair avec l'acceptation de l'hypothèse de prédominance de l'écoulement latéral hypodermique. Ainsi, les modèles basés sur ces indices ne considèrent pas le ruissellement par excès d'infiltration à moins que des équations particulières ne soient développées en ce sens. Ces indices sont également basés sur une deuxième hypothèse, soit celle de l'existence d'un équilibre *steady-state* selon lequel le contenu en eau du sol en un point donné est influencé par la totalité de l'aire contributive définie par la topographie en amont de ce point. L'aire contributive serait donc invariante dans le temps (Durot, 1999). Cette hypothèse a cependant été nuancée par les travaux de Barling *et al.* (1994). L'indice développé par ces derniers a été qualifié de quasi-dynamique, car il varie dans le temps selon les caractéristiques de l'événement pluvieux et les propriétés du sol. L'indice quasi-dynamique semble ainsi plus performant que l'indice statique pour représenter la distribution spatio-temporelle de l'humidité du sol. Cependant, il considère lui aussi la seule influence de l'écoulement latéral hypodermique, une supposition réaliste en conditions humides mais peu probable en conditions sèches (Welsch *et al.*, 2001).

Par ailleurs, d'autres indices ont été développés en utilisant des paramètres autres que l'aire contributive. Les exemples de nouveaux paramètres mentionnés dans la littérature comprennent l'élévation au-dessus de la berge (*elevation above the stream bank*, variable notée E) (Crave & Gascuel-Odoux, 1996), ou le gradient de pente descendante (*downslope gradient*, variable notée DG, qui est le ratio de E par la distance la plus courte (D) menant au cours d'eau) (Merot *et al.*, 1995). Par ailleurs, Merot *et al.* (1995) ont révisé la formulation de l'indice topographique classique en utilisant une aire contributive multidirectionnelle (Quinn *et al.*, 1991) et en substituant *DG* à la pente. D'autres auteurs utilisent plutôt le degré de courbure, car il s'agit d'un bon indicateur de la convergence locale (Thompson *et al.*, 2001 ; Welsch *et al.*, 2001). Ainsi, les dépressions ont tendance à être plus humides que les zones planes car elles ont effectivement un degré de courbure supérieur (Moore *et al.*, 1991). L'utilisation du degré de courbure a cependant donné des résultats mitigés, en termes de corrélation avec la distribution spatiale de l'humidité du sol (Welsch *et al.*, 2001). Mentionnons ici que la qualité des modèles numériques de terrain, autant en termes de résolution que de précision, est cruciale pour dériver tous ces paramètres. En effet, il est avéré que les modèles numériques de terrain de faible résolution horizontale conduisent, systématiquement, à une surestimation des aires contributives (Quinn *et al.*, 1991 ; Zhang & Montgomery, 1994 ; Farajalla & Vieux, 1995 ; Brasington & Richards, 1998) et du paramètre *DG* (Chaplot *et al.*, 2000), et à une sous-estimation des pentes locales (Zhang & Montgomery, 1994 ; Thompson *et al.*, 2001). Autrement, on peut aussi tenir compte des propriétés intrinsèques du sol ; par exemple, la tendance qu'a un sol à se saturer peut être évaluée à l'aide de l'équation d'O'Loughlin (1986) :

$$\frac{Aq}{b} \geq TS \qquad \text{(Éq. 2)}$$

où A est l'aire contributive et q le flux d'eau qui se draine au niveau de la courbe de niveau b, T est la transmissivité locale du sol et S la pente. Cette équation exprime ainsi le fait que des conditions de saturation sont favorisées lorsque l'eau accumulée en un endroit excède la capacité du sol à la transmettre latéralement. Enfin, il est bon de noter que la plupart des indices topographiques supposent que tant les flux d'eau de surface que ceux hypodermiques sont dépendants de la topographie de surface. Cette hypothèse néglige cependant l'extrême variabilité des chemins d'écoulement hypodermique, qui sont influencés par des éléments tels que les transitions entre les horizons de sol, la présence de couches de moindre perméabilité ou l'interface entre le sol et la roche-mère. À ce propos, les travaux de Chaplot & Walter (2003) ont montré que la corrélation entre les valeurs mesurées de l'humidité du sol et l'indice topographique sont 43 % meilleures lorsque les calculs sont effectués sur la base de la topographie de subsurface. La question des seuils hydrologiques est également importante lorsqu'il s'agit d'évaluer notre capacité à prédire la réponse hydrologique. En effet, Zehe *et al.* (2005) ont montré que notre capacité à prédire le comportement hydrologique des bassins versants dépend des conditions d'humidité antécédentes. Ainsi, il est plus difficile de prédire la réponse hydrologique lorsqu'on se situe très près d'un seuil de transition entre deux états préférentiels distincts. Ces éléments sont donc importants à considérer dans la mesure où on souhaite reproduire fidèlement la dynamique des bassins versants pour toute une gamme de conditions hydro-météorologiques.

"*Process Complexity at Hillslope Scale, Process Simplicity at the Watershed Scale: Is There a Connection?*" (Sivapalan, 2003b, p. 1)

1.3.2 Les transferts d'échelle

Avant d'aborder la question des transferts d'échelle dans l'étude des processus hydrologiques, il est bon de se pencher sur le concept d'unicité. En effet, si tous les lieux concernés par une analyse spécifique ont des caractéristiques uniques, il est pertinent de se demander comment on peut généraliser des résultats en hydrologie (Beven *et al.*, 2001) ou, à tout le moins, élaborer des théories élégantes pour expliquer comment ils évoluent d'une échelle spatiale à l'autre. La question se pose tout autant d'un point de vue temporel (Blöschl, 2001) alors que certains processus n'entrent en jeu que dans certains créneaux climatiques spécifiques. D'un point de vue opérationnel, il semble que seule une mesure de débit ou de concentration d'un traceur dans un cours d'eau soit une mesure indépendante des dimensions d'espace et de temps, car elle intègre la variabilité qui est présente à petite échelle pour donner une bonne indication des processus effectifs à l'échelle de tout le bassin versant (Buttle, 1994 ; Kendall & Caldwell, 1998 ; Joerin, 2000 ; Beven *et al.*, 2001 ; Dahlgren, 2006). En effet, comme le mentionnent Beven *et al.* (2001), la plupart des mesures hydrologiques sont effectuées à des échelles ponctuelles ou sur de très petites surfaces en comparaison avec l'échelle naturelle des processus hydrologiques et leur variabilité spatio-temporelle. Ceci est le propre de l'unicité de lieu. Également, puisque les hydrologues ne disposent que de périodes et de moyens limités pour effectuer des mesures de terrain, l'unicité de temps est à considérer. Ainsi, les résultats obtenus tant en hydrologie expérimentale qu'en modélisation doivent être nuancés, de manière à tenir compte du paradoxe entre l'unicité de lieu et de temps et l'équifinalité des processus mesurés et des paramètres modélisés.

Tout comme la connectivité hydrologique, les concepts d'échelle et de transfert d'échelle ont de multiples interprétations. L'échelle, par exemple, fait référence à la dimension spatiale ou temporelle d'un phénomène. D'un point de vue opérationnel, on peut donc distinguer l'échelle d'un processus (i.e. celle à laquelle la variabilité naturelle s'exprime) de l'échelle de mesure (i.e. intervalle d'échantillonnage) (Kavvas, 1999 ; Western & Blöschl, 1999). La question des transferts d'échelle, notamment celle de l'extrapolation, est épineuse en hydrologie. Les processus hydrologiques se caractérisent souvent par une très grande hétérogénéité à petite échelle, en raison de mécanismes comme l'acheminement de l'eau du sol ou la recharge de la nappe phréatique, qui sont très complexes. Cette complexité, inhérente à la plupart des systèmes naturels, disparaît cependant aux échelles plus grandes avec l'apparition de propriétés émergentes (Sivapalan, 2003b ; Soulsby *et al.*, 2006 ; Tetzlaff *et al.*, 2007). Les études multi-échelles ont pour objectif de capter l'hétérogénéité spatiale (et éventuellement temporelle) des processus de genèse du ruissellement de crue. Les effets de la taille des bassins versants sur la réponse hydrologique sont importants, mais les études sur le sujet n'arrivent pas aux mêmes conclusions. Ainsi, dans les systèmes dominés par le ruissellement de surface hortonien, l'écoulement de crue hypodermique, le ruissellement sur surfaces saturées ou l'écoulement macroporeux, le temps de réponse et le débit maximal à l'exutoire diminuent avec la taille du bassin versant (Dunne, 1978 ; Jones, 1997) (Figure 1.10 A). Également, le coefficient de ruissellement est inversement proportionnel à la superficie du bassin (Jones, 1997) (Figure 1.10 B). Brown *et al.* (1999) arrivent cependant à la conclusion contraire. Plusieurs études ont aussi tenté d'établir un lien entre les apports en eau nouvelle et la taille du bassin versant et selon les régions étudiées, on obtient une corrélation positive (Brown *et al.*, 1999 ; Sueker *et al.*, 2000), négative (Pearce, 1990) ou nulle (Buttle, 1994) entre ces deux variables. Également, l'effet de la taille d'un bassin versant n'est pas à confondre avec celui de la dissection du paysage. Ainsi, les travaux de McGuire *et al.* (2005) ont démontré que le temps moyen de résidence de l'eau n'était pas corrélé à la taille des bassins versants mais plutôt à des indices morpho-topographiques comme la taille moyenne des sous-bassins, la pente moyenne, l'intégrale hypsométrique et la longueur des chemins d'écoulement (*flowpaths lengths*) tels que prédits par la topographie de surface et l'indice topographique de Beven & Kirkby (1979). Toutes ces études donnent donc à penser que si le transport de l'eau profonde ne répond pas à des facteurs de grande échelle spatiale, il est néanmoins régi par les formes structurelles internes des bassins versants (McGuire *et al.*, 2005).

La question d'échelle, tant spatiale que temporelle, d'étude de la connectivité hydrologique reste encore à résoudre. La question de l'échelle spatiale a cependant déjà été abordée par les biologistes dans leur étude du taux de dispersion des espèces et du degré de connectivité entre leurs divers habitats. Ainsi, selon Calabrese & Fagan (2004), deux aspects méritent d'être pris en considération. D'une part, il faut se demander à quelle échelle la connectivité devrait effectivement être définie. Ainsi, en biologie, bien que plusieurs publications aient porté sur le sujet (Tischendorf & Fahrig, 2000 ; Tischendorf, 2001), il semble qu'aucune d'entre elles n'aient pu affirmer que la définition de la connectivité devait être limitée à une échelle particulière, soit celle de la *patch* ou celle du paysage.

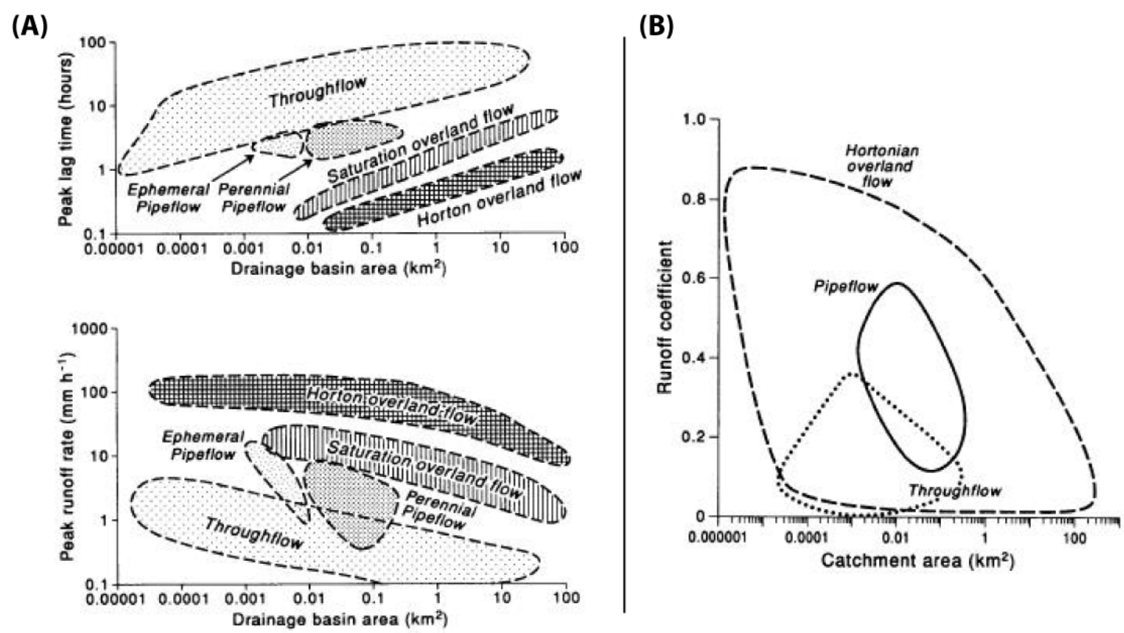


Figure 1.10 – Relations entre **(A)** les processus hydrologiques et la taille du bassin versant ; **(B)** le coefficient de ruissellement et la taille du bassin versant (originaux de Jones, 1997).

En hydrologie, cela reviendrait donc à évaluer la pertinence de définir la connectivité à l'échelle de la parcelle, du versant ou du bassin de drainage dans son ensemble. Par ailleurs, si l'on suppose que la connectivité change avec l'échelle spatiale, la question du choix de l'échelle appropriée pour un problème particulier se pose. Dans le cas d'une étude sur les habitats, Calabrese & Fagan (2004) affirment que c'est le taux de dispersion des espèces qui détermine l'échelle à laquelle l'étude doit être conduite. Ce taux de dispersion est cependant généralement méconnu en biologie, et on peut faire un parallèle entre ce taux de dispersion et la vitesse de transit de l'eau du sol en hydrologie. Dans un tel contexte, il est alors indispensable d'examiner la connectivité, de manière explicite, à plusieurs sous-échelles spatiales imbriquées, pour mieux évaluer la façon dont le phénomène évolue en fonction de la zone considérée.

"*Hydrological connectivity: Linking concepts with practical implications*"
(Lexartza-Artza & Wainwright, 2009, p. 1)

1.4 Objectifs de la recherche

La présente thèse se veut une contribution méthodologique importante qui pourrait guider la conduite de futures recherches en hydrologie des bassins versants. En effet, étant donné que seuls quelques bassins versants sont étudiés en détail de par le monde, la question du potentiel de généralisation des résultats est cruciale lorsqu'il s'agit d'élaborer des théories sur les processus hydrologiques. Plusieurs auteurs (e.g. Sivapalan, 2005 ; McDonnell *et al.*, 2007) ont souligné la nécessité de trouver un concept qui fasse le lien entre les processus locaux et globaux et qui transcende ainsi les différentes échelles tant spatiales que temporelles, et il semble que la connectivité hydrologique offre un fort potentiel pour relever ce défi. Dans la mesure où une définition et une mesure concrètes seraient trouvées, ce concept permettrait non seulement d'améliorer nos prédictions du comportement hydrologique mais également de considérer le fonctionnement émergent d'un bassin sans passer par l'étape intermédiaire des processus actifs à l'échelle des versants. L'adoption de ce concept ne peut toutefois pas se faire sans des bases solides, simplement parce que le concept est actuellement « à la mode ». Puisque le principal incubateur de la géographie physique et de l'hydrologie est le terrain, tout nouveau concept doit démontrer son utilité par la mesure. Le but ultime de la thèse est donc de clarifier la définition, les méthodes d'investigation et les utilités qui sont prêtées au concept de connectivité hydrologique.

Si l'adoption du concept de connectivité et son opérationnalisation dans les recherches hydrologiques sont problématiques, c'est notamment parce que :

- la connectivité est plus un concept qu'une quantité aisément mesurable ;
- on ne sait pas à quelle échelle spatiale cette connectivité doit être définie ni comment elle se comporte lorsqu'on effectue un changement d'échelle ;
- les conséquences de l'existence de conditions changeantes de connectivité sur la modélisation hydrologique des bassins versants restent à évaluer.

En conséquence, le développement de la thèse se fait en trois temps en réponse aux questions suivantes :

1) Quel cadre méthodologique adopter pour une étude sur la connectivité hydrologique ?

L'expression « cadre méthodologique » est ici utilisée au sens large et désigne surtout l'existence d'une définition concrète et le choix de variables hydrologiques cibles et de stratégies d'échantillonnage adéquates. Cet aspect fait l'objet du Chapitre 2 et sert de point de départ pour le choix du design expérimental de l'étude également décrit au Chapitre 2.

2) Comment évaluer le degré de connectivité hydrologique des bassins versants à partir de données de terrain ?

De multiples réponses sont apportées à cette question dans les Chapitres 3 à 5. Des approches de type « boite noire », « boite grise » et « boite blanche » sont notamment proposées de manière indépendante puis confrontées les unes ou autres. Ces trois approches sont testées sur un même bassin versant forestier de tête situé en milieu tempéré humide, soit l'Hermine (Laurentides, Québec), qui est décrit à la fin du Chapitre 2.

3) Dans quelle mesure nos connaissances sur la connectivité hydrologique doivent-elles conduire à la modification des postulats de modélisation hydrologique ?

Cette problématique est finalement brièvement abordée dans le Chapitre 6 sous la forme d'un essai, en alliant des idées issues de la littérature à l'intégration des divers résultats issus des Chapitres 3 à 5 de cette thèse.

Les objectifs spécifiques de la présente recherche s'inscrivent donc dans la perspective de combler des lacunes ou de développer des idées soulignées tout au long de ce chapitre. En effet, les promoteurs de la théorie hydrologique renouvelée insistent sur la nécessité d'étudier les propriétés émergentes des bassins versants plutôt que des mécanismes de genèse de l'écoulement très spécifiques à petite échelle, et c'est l'approche qui est privilégiée dans cette thèse centrée sur l'étude de la connectivité hydrologique. Premièrement, la question du cadre théorique doit être revisitée pour préciser la définition de la connectivité et circonscrire les mécanismes qui permettent son établissement. Deuxièmement, pour passer de la théorie à la pratique, des travaux de terrain doivent être réalisés afin d'estimer le degré de connectivité d'un bassin versant tant sur le plan qualitatif et quantitatif. Troisièmement, les données de terrain peuvent servir à élaborer un modèle perceptuel de l'établissement de la connectivité hydrologique pour ainsi modifier la structure des modèles hydrologiques actuels. Apporter des réponses aux trois questions de recherche précitées constitue donc un apport de connaissances significatif qui s'inscrit dans la théorie hydrologique renouvelée (Figure 1.11). La contribution de la thèse se veut donc d'abord méthodologique, dans le but que les techniques testées dans le cadre des approches de type « boite noire », « boite grise » et « boite blanche » soient éventuellement transférables à d'autres bassins versants que l'Hermine. L'application de ces différentes techniques permet néanmoins d'en apprendre plus sur le comportement particulier du petit bassin versant à l'étude, ce qui constitue aussi une contribution au savoir général sur la variabilité spatio-temporelle des processus hydrologiques.

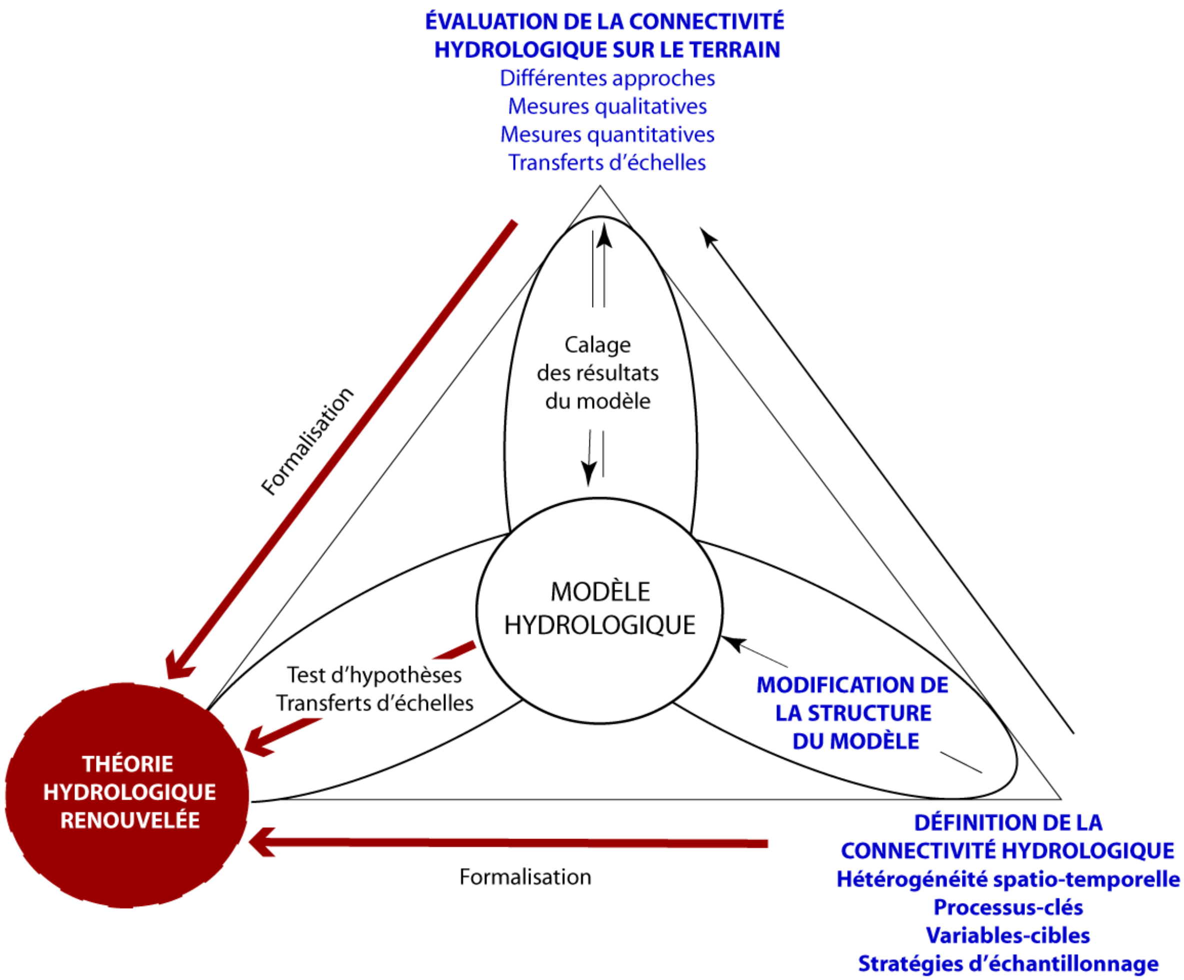


Figure 1.11 – Illustration des étapes du raisonnement devant guider la planification d'une recherche sur le concept de connectivité hydrologique. Les flèches rouges indiquent les étapes devant mener à des gains de connaissances significatifs pour la théorie hydrologique renouvelée. Les étapes indiquées en bleu font l'objet de la présente thèse.

CHAPITRE 2

CADRE MÉTHODOLOGIQUE POUR L'ÉTUDE DE LA CONNECTIVITÉ HYDROLOGIQUE

2.1 Contexte

La connectivité hydrologique est considérée comme un élément essentiel à la compréhension de la dynamique des bassins versants. Il n'y a cependant pas de consensus concernant la définition précise du concept ni la manière de mesurer la connectivité à partir de données de terrain. L'article scientifique reproduit dans la section 2.2 de ce chapitre vise donc à répondre à deux questions : i) quelles sont les variables à étudier, et ii) quel est le plan d'échantillonnage optimal pour capter les changements de connectivité hydrologique dans les bassins versants tempérés humides ? Étant donné que les études hydrologiques antérieures ne se sont jamais penchées sur le sujet sous cet angle particulier, apporter des réponses à ces questions est une étape essentielle avant de choisir et de présenter le *setup* expérimental utilisé pour la recherche doctorale.

2.2 Revisiting Hydrologic Sampling Strategies for an Accurate Assessment of Hydrologic Connectivity in Humid Temperate Systems[1]

[1] Ali, G. A. & A. G. Roy, 2009. 'Revisiting Hydrologic Sampling Strategies for an Accurate Assessment of Hydrologic Connectivity in Humid Temperate Systems', *Geography Compass* **3**(1): 350–374, doi: 10.1111/j.1749-8198.2008.00180.x.

2.2.1 Introduction

Hydrologists recently suggested a refined approach to catchment dynamics studies based on the examination of 'Patterns, Processes and Functions' (Sivapalan, 2005; Schröder, 2006; McDonnell *et al.*, 2007) (Figure 2.1). 'Patterns' are observations whose spatial/temporal structure is not inherited from a random process; 'processes' are interactions between different entities in a system; and the term 'function' embeds the mechanisms from which patterns and processes emanate (Sivapalan, 2005).

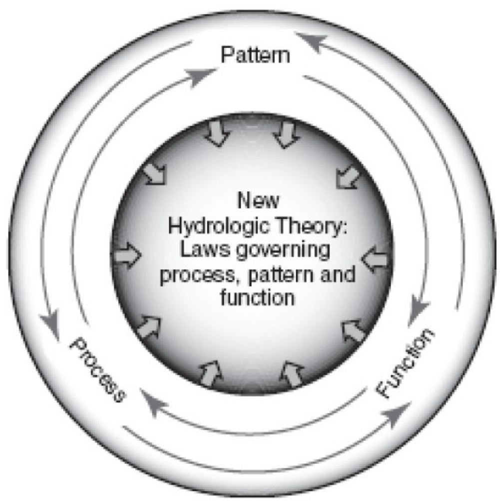


Figure 2.1 –Pattern, process and function feeding back on each other as drawn by Sivapalan (2005) to illustrate elements of a unified theory of hydrology at the catchment scale.

Hydrologists are therefore urged to look for catchments emergent properties, rather than over-focusing on small-scale heterogeneity (McDonnell *et al.*, 2007). The allusion to 'emergent properties' is not casual, as it refers to the arising of novel and coherent patterns from self-organizing processes. The unified theory of hydrology likewise alleges that the examination of catchment functional traits forces the apparent heterogeneity to collapse into a coherent and reproducible pattern (McDonnell *et al.*, 2007). Hydrologists are thus in a hunt for '*a mechanism in any such aggregation to whittle down unnecessary details, and to transfer dominant process control from the hillslope to the watershed scale*' (Sivapalan, 2003b, p. 1038).

A concept presently gaining attention and in accordance with the foregoing criteria is hydrologic connectivity. It relates to the functional connectedness between catchment elements (Pringle, 2003a; Ocampo *et al.*, 2006), for example flow paths (Amoros & Bornette, 2002) or variable source areas (Ambroise, 2004). It is an emergent process, since it occurs at the hillslope scale as a consequence of plot scale interactions. Connectivity appears to be crucial to our understanding of catchment behaviour (Pringle, 2003; Lane *et al.*, 2003; McDonnell *et al.*, 2007; Tetzlaff *et al.*, 2007), and yet few rigorous and unambiguous ways of assessing it from field observations were defined (Slaymaker, 2006; Bracken & Croke, 2007). The overall goal of this paper is to revisit some spatial sampling schemes to identify those especially suitable for the investigation of hydrologic connectivity. Field hydrologists face several questions about the kind of data needed and the "best" measurement sites for an inexpensive, reasonably accurate and time-effective sampling campaign aimed at capturing the connectedness in a watershed (Tarboton *et al.*, 1987; Freer *et al.*, 2002; Park & Van De Giesen, 2004). The scale at which direct field observations are made is also problematic (Klemeš, 1983) as detailed process observation is only practicable at the small scale while extrapolation at the catchment scale was proven misleading by several authors (Wheater *et al.*, 1993; Sivapalan, 2003b; Soulsby *et al.*, 2006 among others). Processes important at one scale may not necessarily be important at other scales (Sivapalan *et al.*, 2003a; Slaymaker, 2006) and this issue is particularly relevant to determine at which spatial scale should connectivity be defined. This stresses the importance of getting the processes right at the appropriate scale (Sidle, 2006).

This paper reviews the literature to examine the following questions: (1) what are the main variables to investigate to characterize hydrologic connectivity?, and (2) what is the optimal spatial sampling strategy for its measuring in humid temperate systems? State-of-the-art and operational perspectives related to connectivity are reviewed to formulate recommendations regarding the spatial and temporal sampling of the phenomenon. Following the identification of specific criteria, the effectiveness of various sampling strategies to meet the criteria is discussed. This effectiveness is first assessed qualitatively, and the criteria are later combined into an objective function whose optimized value leads to the optimal sampling schemes for the investigation of hydrologic connectivity.

2.2.2 Hydrologic Connectivity: State-of-the-Art and Operational Perspectives

a. Multiple Definitions for a Passe-Partout Concept

The growing popularity of the hydrologic connectivity concept is easily assessed with an inventory of the papers on this topic released since the year 2000 (Figure 2.2). Such an inventory reveals that over 100 papers were published during that period with an increasing rate of publication. Even though the connectivity concept was first taken up by ecologists (Amoros & Bornette, 2002; Pringle, 2003a), it is increasingly used in hydrology, mainly as a justification for the growing number of nonlinear catchment behaviors documented around the world. There is a lack of consensus among hydrologists on what connectivity is, how to identify and measure it, and how to relate it to existing research (Bracken & Croke, 2007). A thorough literature review enabled us to find four categories of definitions with increasing preciseness. Hydrologic connectivity can thus be defined from (1) components of the water cycle, (2) landscape features, (3) spatial patterns of hydrological properties, and (4) flow processes. Definitions are given in Table 2.1.

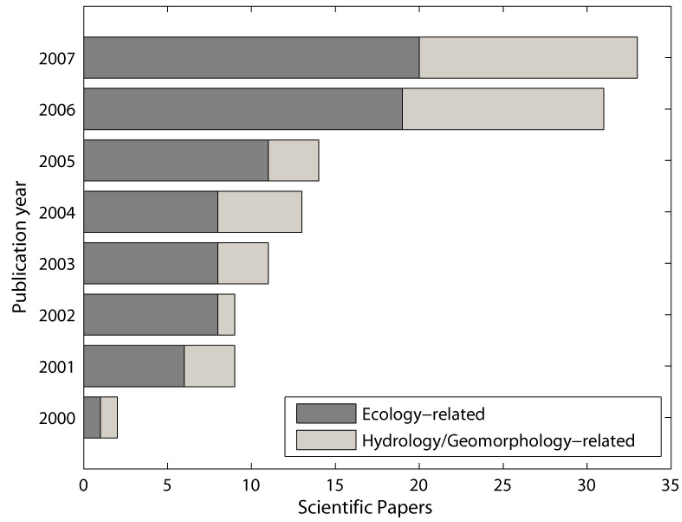


Figure 2.2 – Recent use of the "hydrologic connectivity" or "hydrological connectivity" concept in the published literature; articles with a mention of the term in the title, keywords or abstract during the 2000-2007 period.

- Firstly, the definition proposed by Pringle (2003a) is the most global and perhaps as a result imprecise as far as hydrological patterns, processes and functions are concerned. It basically describes the movement of water within the water cycle and is not explicit about how to identify and measure hydrologic connectivity.
- Secondly, some other definitions are more specific about the factors controlling hydrologic connectivity. The emphasis is usually put on the influence of topography that can either facilitate or impede flow movement within the catchment. These definitions are the most numerous yet they are not the most recent, as connectivity was first referred to by Brunsden & Thornes (1979) as coupling. This concept, relying on the identification of linkages and discontinuities in landscapes, was since elaborated by Brunsden (1993) and Harvey (2001, 2002). Their work provides us

with a terminology to characterize geomorphological systems as not coupled, coupled or decoupled. This terminology is in agreement with the range of connectivity types (no, full and partial connectivity) drafted by Croke *et al.* (2005).

- Thirdly, some definitions focus on spatial patterns of hydrological properties, especially soil moisture. Connectivity is present when we can identify significant spatial clusters of high soil moisture content. These definitions are better suited to derive accurate and objective methods for describing such patterns.
- Lastly, the most specific definitions directly refer to hydrological flow processes that allow a rapid, threshold-driven hydraulic connection between landscape units, for example subsurface flow or translatory (piston) flow acting above an impeding soil layer.

Justification for the above classification lies in the importance attached to the unambiguous reference in the definitions to (1) hydro-geomorphic processes and (2) scale issues. Indeed, the first two types of definitions in Table 2.1 associated with the watershed scale are in fact scale-independent, while the other two focus explicitly on landscape units, and more specifically on hillslopes. Definitions based on the water cycle and landscape features also make no assumption about the processes involved and the resulting patterns while others do. The proposed classification is in agreement with the categorization proposed by Ibrahim (2005), who clearly distinguished between "process connectivity" and "spatial connectivity". The first focuses on the process interaction that takes place between various geomorphic systems, while the second concentrates on the lines, points or areas along which geomorphic systems are connected. Both process and spatial connectivity can be assessed on the longitudinal, lateral, vertical, and temporal dimensions of catchments (Amoros & Bornette, 2002; Lane *et al.*, 2003), which adds to the overall fuzziness of the concept. Consequently, we could call hydrologic connectivity a *passe-partout* concept, as it is rarely used in the scientific literature with a clear definition at a specific scale or dimension.

Table 2.1 – Synthesis of hydrologic connectivity definitions.

WATER CYCLE	[..] An ecological context to refer to water-mediated transfer of matter, energy and/or organisms within or between elements of the hydrologic cycle (Pringle, 2003a)	WATERSHED scale
LANDSCAPE FEATURES	All the former and subsequent positions, and times, associated with the movement of water or sediment passing through a point in the landscape (Bracken & Croke, 2007)	WATERSHED scale
	Flows of matter and energy (water, nutrients, sediments, heat, etc.) between different landscape components (Tetzlaff *et al.*, 2007)	WATERSHED scale
	The extent to which water and matter that moves across the catchments can be stored within or exported out of the catchment (Lane *et al.*, 2004)	WATERSHED scale
	Physical linkage of sediment through the channel system, which is the transfer of sediment from one zone or location to another and the potential for a specific particle to move through the system (Hooke, 2003)	HILLSLOPE scale
	The physical coupling between discrete units of the landscape, notably, upland and riparian zones, and its implication for runoff generation and chemical transport (Stieglitz *et al.*, 2003)	HILLSLOPE scale
	The internal linkages between runoff and sediment generation in upper parts of catchments and the receiving waters. […] Two types of connectivity: direct connectivity via new channels or gullies, and diffuse connectivity as surface runoff reaches the stream network via overland flow pathways (Croke *et al.*, 2005)	HILLSLOPE scale
SPATIAL PATTERNS	Hydrologically relevant spatial patterns of properties (e.g. high permeability) or state variables (e.g. soil moisture) that facilitate flow and transport in a hydrologic system (e.g. an aquifer or watershed) (Western *et al.*, 2001)	WATERSHED and HILLSLOPE scale
	Spatially connected features which concentrate flow and reduce travel times (Knudby & Carrera, 2005)	WATERSHED and HILLSLOPE scale
FLOW PROCESSES	The condition by which disparate regions on a hillslope are linked via lateral subsurface water flow (Hornberger *et al.*, 1994; Creed & Band, 1998)	HILLSLOPE scale
	Connection, via the subsurface flow system, between the riparian (near-stream) zone and the upland zone (also known as hillslope) occurs when the water table at the upland-riparian zone interface is above the confining layer (Vidon & Hill, 2004; Ocampo *et al.*, 2006)	HILLSLOPE scale

b. The Multiplicity of Definitions: Opportune or Troublesome?

The lack of a consistent definition for hydrologic connectivity is often seen as a disadvantage since it limits its application (Bracken & Croke, 2007). Yet, this multiplicity of definitions reflects the complexity of the phenomenon and as such may be helpful as it points out key variables to investigate to fully capture the nature, extent and impact of connectivity. Starting from definitions based on landscape features, spatial patterns and flow processes, it is possible to identify several criteria that would guide sampling strategies.

Issues related to the sampling of 'terrain connectivity'. Terrain attributes are critical in describing connectivity. Surface features are particularly important for depicting hillslope-channel coupling as hillslopes may feed directly or not into streams (Harvey, 2001; Pringle, 2003a; Bracken & Croke, 2007). It is agreed that slope length greatly influences connectivity (Aryal *et al.*, 2003), but on longer slopes it is very likely that re-infiltration of surface runoff will occur before it actually reaches the foot slope (Lane *et al.*, 2003; Bracken & Croke, 2007). The role of surface micro-topography must also be examined for a better assessment of infiltration characteristics. Furthermore, it was recently shown that subsurface flows are strongly affected by subsurface features such as impervious soil horizons, saprolites or bedrock upper limits (Chaplot & Walter, 2003; Tromp-Van Meerveld & McDonnell, 2006b). Indeed, these flows occur when transient water tables form and induce lateral flow to the channel (Stieglitz *et al.*, 2003; Weiler *et al.*, 2005). This calls for an adequate sampling strategy aiming at building multiple depths digital models of a range of topographic attributes, at a spatial resolution that allows for an accurate representation of small-scale details regarding morphological units delineation.

Issues related to the sampling of 'soil moisture connectivity'. Examining multiple depths spatial patterns of soil moisture to investigate connectivity is the most popular and promising approach. Justification for such an approach lies in the preferential states hypothesis (Grayson *et al.*, 1997) and in the ease of the visualization procedure. The preferential states hypothesis suggests a catchment is characterized by at least two contrasted states. The dry state is when soil moisture patterns are disorganized because of the influence of local control factors (e.g. soil and vegetation characteristics, local slope) and the predominance of vertical soil water fluxes. On the contrary, the wet state is when soil moisture patterns are highly organized/connected because of the influence of nonlocal control factors (e.g. upslope contributing area) and lateral soil water fluxes. These patterns are particularly interesting as they bring into light the effects of different spatial controls on soil moisture depending on the chosen scale of observation (Western *et al.*, 2002). The data sampling must however be in accordance with the statistical approaches used for the description of spatial variability. The most commonly used techniques are geostatistics (Cressie, 1993; Goovaerts, 1997; Western *et al.*, 1998), connectivity statistics (Allard, 1994; Western *et al.*, 2001) and temporal stability analysis (Vachaud *et al.*, 1985; Grant *et al.*, 2004). Throughout this paper, our main focus is on geostatistical methods as they form the core of already released connectivity-related papers in hydrology. The accuracy of both geostatistics and connectivity statistics depends on relatively large datasets, as the quantity and spacing of data pairs is particularly important for estimating the correlation structure (continuity and connectivity) of spatial fields (Western *et al.*, 1998). Some authors recommended conducting extensive data surveys and refer to them as LOP ('lots-of-points') collections of pattern information (Grayson *et al.*, 2002; James, 2005). The best example of this is the series of field experiments conducted in the Tarrawarra catchment (Southern Victoria, Australia). These experiments based on data collected at 500 to 2000 sampling points required '*a major commitment of resources including 250 person days in the field, with a further 100 person days in the laboratory preparing for field trips and checking and collating data*' (Western & Grayson, 1998, p. 2765). Such a commitment of resources is difficult to replicate. In attempting to minimize sampling effort, some authors rather tested the estimation of semi-variograms with various sample sizes and spatial sampling intervals. Russo & Jury (1987a, b) found a 25 % or greater error in spatial correlation prediction when using less than 72 data pairs per lag bin, while Yates &

Warrick (2002) argued that using 30 data pairs per lag bin was enough for an accurate characterization of the semi-variance. Webster & Oliver (1992) also recommended at least 150 samples in order to estimate a stable semi-variogram. We assume that these recommendations could apply to the estimation of the integral connectivity scale, as it describes the average distance over which points are connected and it is similar to the integral correlation scale used in traditional geostatistics (Western *et al.*, 2001). As for temporal stability analysis, it describes the persistence of spatial patterns of soil water content over time, especially the degree of linear correlation between soil moisture values measured at consecutive times. Together with the fact that connectivity is intimately related to rainfall and antecedent moisture thresholds that trigger rapid hillslope outflows (James, 2005; Weiler *et al.*, 2005; Tromp-Van Meerveld & McDonnell, 2006a; Lehmann *et al.*, 2007), the use of this technique requires a sufficiently high-frequency temporal sampling scheme to capture a wide variety of catchment states.

Issues related to the sampling of 'flow processes connectivity'. For an effective characterization of flow processes involved in the establishment of connectivity, subsurface stormflow should also be measured. Several studies focusing on subsurface stormflow were conducted using trench excavations no longer than 20 m (Tromp-Van Meerveld & McDonnell, 2006a, b) or 60 m (Woods & Rowe, 1996). This technique cannot be deployed on the whole catchment area to fully capture the processes that trigger subsurface stormflow and their scaling properties. Another way to investigate subsurface stormflow is the study of active and maybe connected flow paths using the geochemical signature of stream and soil water (Weiler *et al.*, 2005). Sampling locations and number of soil lysimeters must therefore be selected with great care in order to monitor the flow processes adequately. Still, this approach yields an integrated view of the processes and does not always provide enough details.

Issues related to the sampling of 'dynamic connectivity'. Finally, the dynamic nature of connectivity has serious implications for sampling planning. 'Dynamic connectivity' refers to the fact that catchment internal linkages vary over different timescales due to the time-changing availability of surface/subsurface water. It is often assumed that the greater the soil moisture content, the higher the degree of connectivity (Fitzjohn *et al.*, 1998; Leibowitz & Vining, 2003). Recent studies challenged this view, stating that besides the magnitude of change in hydrologic conditions, frequency, duration, timing and rate of change are also important in the establishment, maintenance or disruption of connectivity (Bracken & Croke, 2007). This relates to the theory of 'active' versus 'contributing' areas and periods (Ambroise, 2004). Antecedent moisture conditions are crucial to evaluate dynamic connectivity (Bracken & Croke, 2007), since threshold exceedance dictates the initiation of several flow mechanisms (Lehmann *et al.*, 2007; Tromp-Van Meerveld & McDonnell, 2006a). However, this threshold-driven theory of catchment connectivity draws two stumbling blocks with respect to sampling, namely (1) a somehow distorted dichotomist view of connectivity which is either present or absent depending on whether we are above or below a unique threshold value; and (2) an absolute need for a sampling plan aiming at capturing an episodic, very short-lived catchment behavior near one unknown critical state. Rather than conceptualizing connectivity as a catchment property that either does or does not emerge, we argue that lateral, longitudinal and vertical catchment linkages should be thought of as a probability distribution over both time and space. This idea has already shown great potential towards a quantitative, deterministic assessment of connectivity in wetland hydrology. Leibowitz & Vining (2003) defined 'temporal connectivity' as '*any landscape connections that are impermanent, temporally discontinuous or sporadic*'. For wetlands, they suggested mapping the recurrence interval of different connectivities, given soil moisture databases of a fine-enough spatio-temporal resolution. Such an approach, even though time-consuming in terms of sampling, provides a more holistic view of catchment-scale connectivity. Besides, it is in accordance with the 'isolation-connectivity continuum' concept, which states that '*wetlands lie in a continuum of ecological flow control*' (Leibowitz, 2003). In hydrological terminology, this translates into a continuum of hydrologic states between completely isolated and connected saturated areas. Sampling of temporal connectivity should then take into account not only the presence and location of functional linkages but also their frequency and duration.

Table 2.2 – Recommendations for an appropriate sampling strategy aiming at hydrologic connectivity investigation.

VARIABLES TO INVESTIGATE	SPATIAL SAMPLING	TEMPORAL SAMPLING	SCALING (SPATIAL/TEMPORAL)
Surface topography Subsurface topography	Optimal sampling interval for the derivation of non spurious DEMs	None	Easily recognisable landscape features while DEM coarse-graining
Surface soil moisture patterns Subsurface soil moisture patterns	Adequate number and spacing of data pairs for geostatistical analysis	Frequency aimed at capturing various wet/dry preferential states	Preservation of spatial continuity/connectivity properties while up-scaling
Surface flow paths Subsurface flow paths	Hydrologically-significant locations for lysimeters installation	Frequency aimed at capturing thresholded outflow generation	Scale-invariant (time and space) precipitation and moisture thresholds for outflow generation

In conclusion, given the variables and scales involved, several considerations for the investigation of hydrologic connectivity need to be considered (Table 2.2). For the sake of brevity, only issues related to spatial sampling are dealt with in this paper. Nevertheless, we keep in mind that spatial sampling should be relatively easy to deploy with a high temporal frequency to ensure that neuralgic instants are not under-sampled. The next section is a review of several sampling schemes widely used in environmental science so as to discuss whether they are in accordance with our listed criteria.

2.2.3 Appropriate Spatial Sampling Scheme(s) for Hydrologic Connectivity

a. Sampling Criteria and Objective Function Methodology

While several sampling schemes are available for hydrologic purposes, they are rarely compared with respect to their effectiveness to meet specific research criteria. Focus is therefore put on a continuum of sampling strategies, hereafter listed from the less (i.e. random, systematic) to the more 'process-based' (i.e. stratified). Satisfaction to five specific sampling criteria is further assessed, as appropriate spatial sampling schemes for hydrologic connectivity should be (1) relatively easy and straightforward to implement, (2) suitable for the derivation of non spurious digital terrain models, (3) suitable for geostatistical analysis, (4) inclusive of hydrologically-significant locations, and (5) insensitive to spatial coarse-graining. These five criteria may be fully, partly or not satisfied depending on fine, intermediate or coarse data spacing (Table 2.3).

An objective function is further developed to translate the qualitative assessments of satisfaction into quantitative ones. For each sampling scheme, a satisfaction score SS_i to each sampling criterion i is attributed, namely 1 when the criterion is satisfied regardless of data spacing and 0 when it is not. Otherwise, intermediate scores ranging from 0 to 1 are attributed when the satisfaction of a criterion is dependent upon data resolution. The overall performance of a sampling scheme with respect to all criteria is finally assessed via an objective function SS_t that computes the sum of all five SS_i values.

Table 2.3 – Comparison of spatial sampling schemes that are listed from the less to the more "process-based"; ● means that the property or criterion is satisfied regardless of data spacing; ○ means that the property or criterion may be partly satisfied depending on data spacing; and *ø* means that the property or criterion cannot be satisfied.

	SAMPLING SCHEMES PROPERTIES						SAMPLING CRITERIA				
	Sampling unit		Sampling procedure			Sample size					
Sampling methods	Hillslope-based?	Catchment-based?	Systematic?	Random?	Stratified?	Reasonable?	Easy to implement?	Adequate for non spurious DEMS?	Adequate for geostatistical analysis?	Hydrologically-significant sampling locations?	Insensitive to coarse-graining?
Simple, random	○	○	ø	●	ø	○	●	ø	ø	ø	ø
Individual transects	○	○	●	●	ø	○	●	○	○	○	ø
Nested transects	○	○	●	●	ø	○	●	○	○	○	●
Grids	○	○	●	●	ø	○	●	○	○	○	ø
Cyclic sampling	○	○	●	ø	ø	○	ø	●	●	●	●
HRU-based	○	○	ø	ø	●	○	ø	ø	ø	●	●
Index-based	○	○	ø	ø	●	○	ø	ø	ø	●	○

Thus, the optimal sampling scheme for the investigation of connectivity must have an objective function value close to the maximum of 5.

b. Random versus systematic sampling schemes

Although not very popular in field hydrology, random sampling schemes lead to an unbiased sample ensuring that every possible measurement location has an equal chance of being selected (Holmes *et al.*, 2006). The relative unpopularity of random sampling is often justified by the fact that it ignores so-called "expert opinion", as no information about the study area intervenes in the sites selection process. This could result in rare properties being under-sampled while some others are over-sampled because of their greater spatial extent. Also, because of the uneven distribution of sampling locations and of the potential exclusion of critical points, random sampling does not comply with the requirements for digital elevation models derivation or geostatistical analyses, nor does it allow for the monitoring of hydrologically significant landscape units at multiple scales (Table 2.3). Contrary to the random approach, systematic sampling has two advantages in that it is easier to implement and it also ensures an even distribution of the sampling points over the hillslope or the catchment area. This is particularly important so as to satisfy geostatistical constraints, regardless of whether we work in one (transects) or two dimensions (grids).

Line transects are quite popular for intensive spatial investigation of hydrological variables. Either regular or random arrangements can be made on transects (Holwerda *et al.*, 2006). It is also possible to randomize their locations by selecting randomly their starting point or their orientation (Holmes *et al.*, 2006). The most common way to proceed in field hydrology, however, consists in locating transects on upland-to-lowland topographic sequences in order to capture the dynamic connection between contiguous landscape units. Transects, along with all systematic methods described further on, can lead to the construction of non-spurious digital elevation models given a fine enough spacing between individual sampling plots. In the same manner, all systematic sampling schemes allow the representation of hydrologically significant locations given that the measurements resolution is not too coarse for these features to go undetected (Table 2.3). Single and nested transects can serve geostatistical purposes (McBratney & Webster, 1983), but their use is problematic for the estimation of anisotropic semi-variograms as they do not permit the exploration of spatial variation in several directions. Nested transects are especially acknowledged for examining differences in processes and patterns across multiple scales (Holmes *et al.*, 2006), which makes them particularly suitable for hydrologic connectivity investigation.

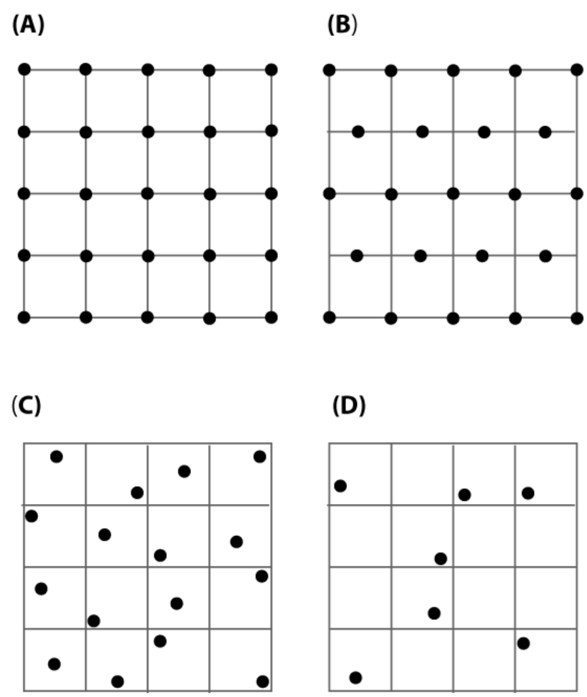


Figure 2.3 – Gridded sampling schemes. **(A)** Uniform; **(B)** Equilateral triangular; **(C)** Unaligned; and **(D)** Randomized.

As for grids, they can be considered as a series of parallel transects (Webster & Oliver, 2001) forming a network of sampling points. Several configurations are possible as the grid spacing may or may not be regular and of rectangular shape. In the same way as transects, the origin and spacing of grids can be selected randomly (Figure 2.3 D). Traditionally, grids are designed as uniform as shown in Figure 2.3 A, and using fine spacing intervals can potentially lead to a considerable number of sampling locations (e.g. Western & Grayson, 1998). This scheme, however, presents a drawback for geostatistical applications as reported by Conwell *et al.* (1997). Indeed, when using rectangular uniform grids, the number of data pairs is highly variable between the lag distance bins, thus leading to the computation of unstable semi-variograms. Otherwise, grids agree with most of the sampling criteria listed in Table 2.3. Other possible configurations are equilateral triangular grids (Figure 2.3 B) and unaligned grids (Figure 2.3 C) that offer similar advantages as uniform grids (Holmes *et al.*, 2006).

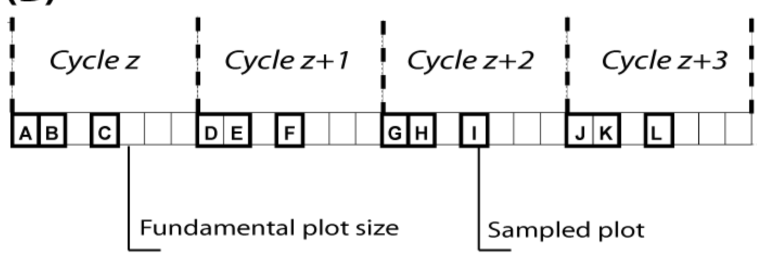
Lastly, cyclic sampling was recently adapted to spatial investigations in two dimensions and could thus be an alternative to traditional gridded strategies. Burrows *et al.* (2002) illustrated this type of sampling scheme with a 3/7 one-dimensional design (Figure 2.4 A, B), which means that only three plots in every seven are measured. The targeted three locations plots are spaced by a cycle that repeats itself, so that pairs of sampling points can be found within a distance equaling one, two, three, four, five, six or seven plot widths (Figure 2.4 B). Cyclic sampling provides an important benefit compared to uniform rectangular grids, as it is much less expensive in terms of the number of measurements required to capture the spatial variability, regardless of the scale considered. It is therefore insensitive to coarse-graining given a correct estimation of the cycle length. The drawback of this method is that it requires the determination of the approximate scale at which spatial patterns occur prior to installing measurement plots on the field. This issue is intimately related to the new avenue of characteristic scales (Grayson & Western, 1998; Blöschl, 2001; Skøien *et al.*, 2003; Thierfelder *et al.*, 2003). Cyclic sampling can be implemented in several dimensions, which allows researchers to compare it with either uniform or random sampling schemes to see how it complies with geostatistical requirements.

(A)

Cycle Definition	*Cycle Length (x)*	*Plots Sampled (n)*	*Sample Locations (0 to x-1)*
1/1	1	1	0
2/3	3	2	0, 1
3/7	7	3	0, 1, 3
4/13	13	4	0, 1, 3, 9
5/21	21	5	0, 1, 4, 14, 16
6/31	31	6	0, 1, 3, 8, 12, 18
7/37	37	7	0, 1, 6, 10, 17, 23, 35

Based on Clinger and Van Ness (1976)
A 3/7 cycle indicates that three plots in every seven are measured. The three plots are spaced such that pairs of plots can be found that are separated by one, two, three, four, five, six, and seven plot widths. The seven-plot cyclic pattern provides additional plot pairs separated by eight, nine, …, and so on plot widths.

(B)



Plot Distance	*Plot Pairs*	*Number of Pairs*
1	…, AB, DE, GH, JK, …	4
2	…, BC, EF, HI, KL, …	4
3	..., AC, DF, GI, JL	4
4	…, CD, FG, IJ, L…	4
5	…, CE, FH, IK, L…	4
6	…, BD, EG, HJ, K…	4
7* Cycle length	…, AD, BE, CF, DG, EH, FI, GJ, HK, IL, J…, K…, L…	12
8	…, AE, DH, GK, J…	4
9	…, BF, EI, HL, K…	4
…	…	…

Figure 2.4 – Cyclic sampling. **(A)** Selected sampling design patterns (modified from Burrows *et al.* (2002)); **(B)** Example of a one-dimensional 3/7 sampling design (modified from Burrows *et al.* (2002)).

Working on vegetation type patterns with 312 measurement plots, Burrows *et al.* (2002) found that cyclic sampling helped decreasing by 60 % the number of sampling locations needed to obtain stable semi-variograms. The cycle can also differ along the *x* and *y* dimensions, which is interesting in the case of directional phenomena that do not always occur on similar scales. Cyclic sampling should therefore be thoroughly investigated in order to fully assess its potential for hydrological patterns investigation.

c. Stratified sampling schemes

Selecting delineated spatial units that are assumed to be key in the description of catchments runoff processes can also improve the location of measurement points. The justification for such stratification rests in the fact that watersheds consist of various land units having characteristic responses regarding hydrological and geomorphological processes (Cammeraat, 2002). Key indicators should therefore be chosen to ensure that these response units are easy to differentiate from one another.

For instance, it was often suggested to break up the landscape using hydrological response units (HRUs). The theory of HRUs provides researchers with tools for doing an effective stratification of catchment landscapes. HRUs are '*distributed, heterogeneously structured entities having a common climate, land use and underlying pedological-topographical-geologic association controlling their hydrological dynamics*' (Flügel, 1995, p. 426). There exist many names in the literature for HRUs, e.g. grouped response units (Kouwen *et al.*, 1993), representative elementary areas (Woods *et al.*, 1995), hydrologically similar units (Karvonen *et al.*, 1999), hydrologically sensitive areas (Walter *et al.*, 2000), critical source areas (Agnew *et al.*, 2006) and hydrologically similar surfaces (Bull *et al.*, 2003). HRUs can be defined either at the plot, hillslope or catchment scale (Bull *et al.*, 2003). However, the "mosaic pattern" formed by HRUs is known to be scale independent

(Fitzjohn *et al.*, 1998), an interesting property for connectivity investigations. Factors used to define or delineate HRUs can be quite variable (Table 2.4) but they almost always include terrain attributes. When the aim is a thorough investigation of connectivity, this forces a pre-sampling of topographic information using either transects or grids, while the HRU-based stratification is only helpful in sampling soil moisture and soil water at a reduced number of homogeneous plots. The resulting hydrologically significant sampling locations do not, however, satisfy the geostatistical constraints (Table 2.3).

Table 2.4 – Variables used to delineate hydrological response units (HRUs and similar land units). (Adapted from Bull *et al.* (2003) and Devito *et al.* (2005)).

AUTHOR	YEAR	NUMBER OF VARIABLES	VARIABLES USED TO PREDICT HRUS
Flügel	1995	6	Rainfall distribution, slope, aspect, land use, unsaturated zone, bedrock zone.
Sharma *et al*.	1996	4	Soil, vegetation, slope, rainfall distribution.
Becker and Braun	1999	3	Evaporation, runoff, groundwater recharge.
Frankenberger *et al*.	1999	3	Soil, land use, elevation.
Karvonen *et al*.	1999	3	Soil, land use, slope.
Bull *et al*.	2003	3	Geology, land use, slope.
Devito *et al*.	2005	5	Climate, bedrock geology, surface geology, soil and vegetation, topography.

Another way to explicitly include "expert-knowledge" in the selection of sampling sites is by using index-based methods. Both in experimental and modeling studies, hydrologists suggested considering key landscape units separately, namely hillslopes and gullies, to better assess their degree of inter-connection (Grayson & Western, 2001; Uhlenbrook *et al.*, 2002). This issue is intimately linked to the partial area (Betson, 1964) or the variable source area (Hewlett & Hibbert, 1967) concepts. The most common way to illustrate variable source behaviors is to compute the topographic index λ_i:

$$\lambda_i = \ln(\frac{a_i}{\tan \beta_i}) \tag{2.1}$$

where a_i is the upslope-drained area to a point i, and tan β_i the local slope angle at that point (Beven & Kirkby, 1979). All points having the same topographic index saturate to the same extent and produce the same levels of runoff. Lowland areas tend toward higher topographic index values, due to low slope angle and/or large upslope area, while upland areas tend toward lower topographic index values. Using thresholded values of the topographic index distribution could thus be useful to delineate topographically and hydrologically similar regions for an improved stratified sampling scheme (Table 2.3). However, several authors underlined some problems with the topographic index, as the effective contributing area may vary over time (Barling *et al.*, 1994; Beven, 1997). A measure of hillslope effective length was proposed instead, that is the length of a hillslope beyond which an increase in length does not result in increased saturation or subsurface flow at its downstream end (Aryal *et al.*, 2003). Although the computation of hillslope effective length is quite extensive depending on rainfall characteristics, hillslope geometry and soil properties, it could be useful as a preliminary step to sampling design selection, to detect more or less large proportions of catchment area that hardly ever contribute to subsurface flow at the catchment outlet and are therefore needless for connectivity investigation. Lastly, topographic index computations are highly sensitive to DEM resolution (Zhang & Montgomery, 1994; Beven, 1997), which makes them problematic for the examination of connectivity across spatial scales.

d. Overall performance of individual methods and combinations of methods

An examination of Figure 2.5 reveals that the performance of random sampling, transects and grids is highly dependent upon data resolution while the performance of cyclic sampling, HRUs- and index-based methods is not. None of the reviewed sampling schemes but nested transects with a fine resolution agrees with all five listed criteria. This therefore calls for a combination of methods to meet all sampling criteria.

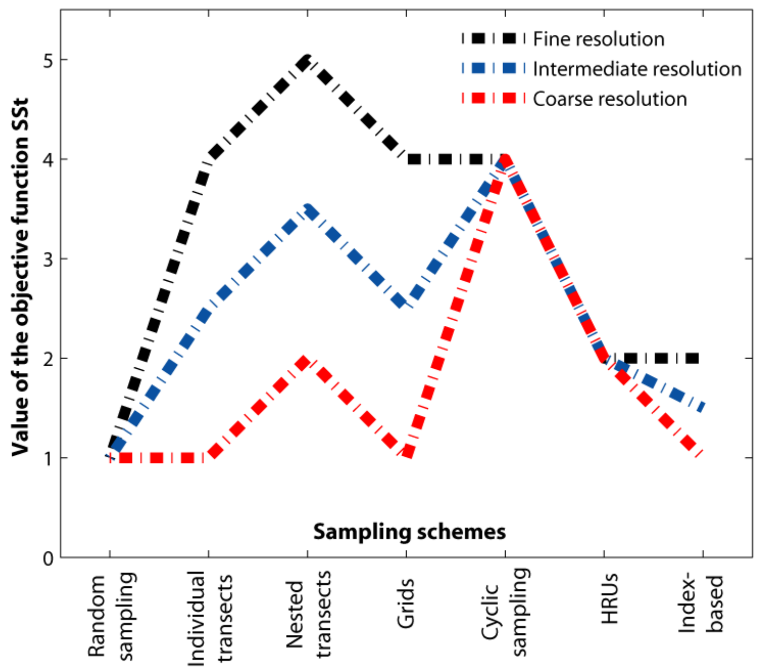


Figure 2.5 – Quantitative assessment of the overall performance of individual sampling schemes to five criteria: (1) easiness of implementation, (2) suitability for the derivation of non spurious digital terrain models, (3) suitability for geostatistical analysis, (4) inclusiveness of hydrologically-significant locations, and (5) insensitiveness to spatial coarse-graining. Values of the objective function SS_t are strongly dependent upon data resolution, here characterized as either fine, intermediate or coarse.

Several combinations of methods were tested so as to optimize the value of the SS_t objective function. Figure 2.6 reveals that the combination of two sampling schemes does not always improve the value of the objective function. Grids alone have overall performance scores of 4, 2.5 and 1 with fine, intermediate and coarse resolution respectively, and these scores are not increased when grids are combined with either individual transects or HRUs (Figure 2.6 A, B). On the other hand, the effectiveness of random sampling (score of 1 when used alone) is improved when it is used jointly with either grids or HRUs (Figure 2.6 C, D), but the optimal score of 5 cannot be reached.

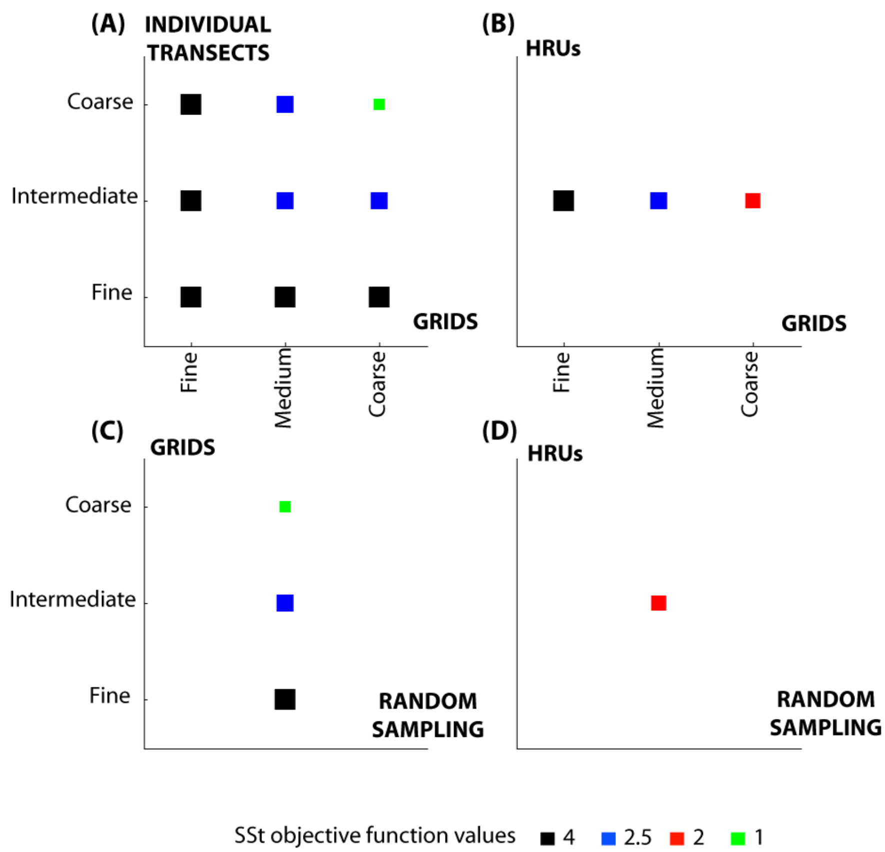


Figure 2.6 – Quantitative assessment of the overall performance of four combinations of sampling schemes to five criteria. **(A)** Grid and individual transects; **(B)** Grid and HRUS; **(C)** Random sampling and grid; **(D)** Random sampling and HRUs. Marker colors and sizes are proportional to the values of the objective function SS_t. The performance of some combinations is strongly dependent upon data resolution of each of the two sampling schemes. Data resolution is qualitatively characterized as either fine, intermediate or coarse.

The only strategy with a fairly good overall performance score regardless of data resolution is cyclic sampling. Otherwise, once a sampling strategy or a combination of sampling schemes is chosen, the optimal spacing must be defined to ensure a relatively "cheap" design that is (1) still in accordance with the five listed criteria, and (2) also resilient to scale and scaling issues. The qualitatively defined 'fine resolution' is the optimal spacing but its quantitative definition remains challenging.

e. Further challenges toward an optimal sampling strategy

The question 'at which scale should connectivity be defined?' has yet to be resolved. In the meantime, hydrologic sampling should be designed in such a way that the consequences of upscaling and downscaling are minimized. Process-based methods are the more likely to be insensitive to coarse-graining. This is attributable to the cycle definition for cyclic sampling (Burrows *et al.*, 2002), while landscape units appear as the solution to upscaling (Cammeraat, 2002) because their resulting pattern is scale-independent (Fitzjohn *et al.*, 1998). As suggested by Klemeš (1983), '*we cannot impose scale but have to search for those which exist and try to understand their relationships and patterns*'. This is particularly important when aiming at studying emergent processes like hydrologic connectivity. These scale issues must therefore be solved, especially for gridded and transect-based sampling designs. HRU- and index-based methods are very popular because they allow hydrologists to include some sort of "expert-knowledge" in the sampling process, but their inadequacy to comply with geostatistical constraints is problematic for hydrologic connectivity investigation. Lastly, as far as optimizing a sampling design is concerned, some authors suggested that it cannot be done unless two phases of sampling are undertaken (Legendre *et al.*, 1989; Holmes *et al.*, 2006). Webster & Oliver (2001) argued that stratified random (nested) sampling, doubled up with a systematic sampling, is the best approach when aiming at capturing the spatial variability of a phenomenon.

Landscape units can be delineated and random samples taken from these units; the systematic approach provides information on the whole studied area while small-scale variability is taken care of by the random approach. Grids or transects can also be twined with either HRUs- or index-based methods in order to satisfy most of the previously listed sampling criteria. We should however mention that while we advocate the advantages of two-stage sampling from a hydrological perspective, its implementation is statistically challenging. Indeed, the characteristics computed from the second-stage sample include some uncertainty induced by the first-stage sample. Sufficient knowledge on standard error correction methods is therefore required to ensure a fair level of (double) inferential accuracy.

2.2.4 Conclusion

We examined several definitions of connectivity published in recent years. Even though we strongly support the combined use of topography and soil moisture to assess the spatial extent of the phenomenon, we recognize that it is difficult to advocate a single definition of hydrologic connectivity. All definitions currently used may be necessary as a whole but none of them are individually sufficient to 'get the full picture', especially when it comes to the dynamic nature of connectivity. Hence, we built upon this work to provide a contextual definition that encompasses several descriptions. The proposed unified statement is that:

> Hydrologic connectivity is a continuum of hydrological states characterized by an increased contribution from lateral subsurface water flow that sporadically activates the topographic linkages between riparian and upland areas and thus gives rise to highly correlated spatial patterns of hydrologic state variables (e.g. soil moisture) at the hillslope and the catchment scales.

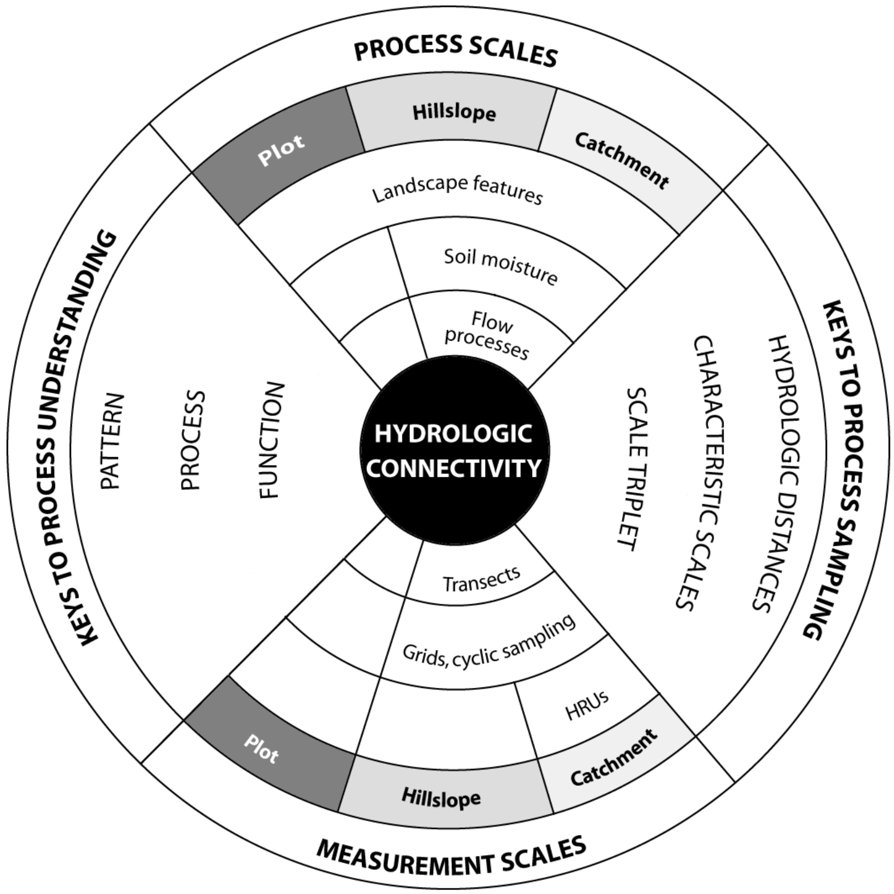


Figure 2.7 – Synthesis of variables and concepts involved in hydrologic connectivity definition and sampling.

We surely hope that this definition is a first step towards an agreement upon guiding principles for the investigation of connectivity. Such an agreement is urgent before a fuzzy concept becomes embedded in hydrological theory and is difficult to implement in hydrological practice. Furthermore, making the case for a viable concept also relies on the development of robust quantitative measures of connectivity. Our review on sampling strategies should help the discussion on this matter. In order to fully capture the extent of connectivity, the main characteristics to identify are landscape features, soil moisture patterns and subsurface flow pathways. While pattern, process and function are the keys to catchment response, further thinking is required to identify the keys to process understanding that would reconcile process and measurement scales (Figure 2.7). Such reconciliation will be within our reach once we develop methods to integrate characteristic scales into our sampling designs, or to replace Euclidean distances by hydrologic distances in our descriptions of point-to-point connectivity. It is impossible to put forward an ‘optimal’ sampling strategy for hydrologic connectivity investigation, optimality being evaluated solely from a hydrological standpoint. For the moment, the best way to ensure progress seems to involve two-stage sampling. Emergent processes like connectivity should be examined at a scale where all system components, active/inactive, connected/disconnected/unconnected, are represented. New ideas related to standard definitions and standard metrics are needed to build an unambiguous, connectivity-based theory of watershed hydrology.

2.3 Paragraphe de liaison “2-3”

La revue critique et commentée de la section 2.2 a permis d’établir un cadre méthodologique pour l’étude de la connectivité hydrologique. Il a notamment été argumenté que la combinaison de deux schémas d’échantillonnage, soit un systématique et un stratifié, était la plus adéquate pour étudier les processus spatialement distribués liés à la connectivité hydrologique en autant que l’espacement entre les sites de mesure ne soit pas trop grand. En conséquence, le design expérimental retenu pour la présente thèse consistait à la superposition d’une grille régulière (i.e. échantillonnage systématique) et de transects suivant des profils topographiques (i.e. échantillonnage stratifié). Ces éléments sont décrits dans la section 2.4.2.

Il a également été recommandé de tirer parti de la multiplicité des définitions de la connectivité qui existent dans la littérature. Ces définitions révèlent que trois types de données hydrologiques peuvent être utilisés pour évaluer, de manière directe ou indirecte, le degré de connectivité dans un bassin versant :

i) des données simples sur le cycle (bilan) en eau d’un bassin versant, soit des données de précipitations et de débits ;

ii) des données sur la composition chimique de l’eau du sol et de l’eau du cours d’eau ; et

iii) des données spatialement distribuées de la topographie de surface et de subsurface, de l’humidité du sol ou de la hauteur de nappe phréatique.

La question est maintenant de savoir si le choix de l’un ou l’autre de ces types de données conduit à des conclusions similaires sur le comportement d’un bassin versant ; le cas échéant, certaines définitions publiées dans la littérature pourraient être invalidées au profit d’autres. Par ailleurs, chacun de ces types de données est associé à des méthodes d’analyse et un niveau de détail spécifiques, de sorte que l’on se demande quelle serait l’approche permettant un gain maximal de connaissances. La discussion de la section 2.2 se termine aussi avec une proposition de définition unifiée de la connectivité hydrologique, définition selon laquelle la connectivité n'est pas une propriété dichotomique mais bien un continuum d'états préférentiels d'un bassin versant. Il s'agit de vérifier que les trois types de données hydrologiques identifiés permettent de capter ce continuum. L'analyse concurrente des trois types de données est donc suggérée à des fins de validation croisée, et c'est l'approche qui a été choisie pour le présent projet de recherche.

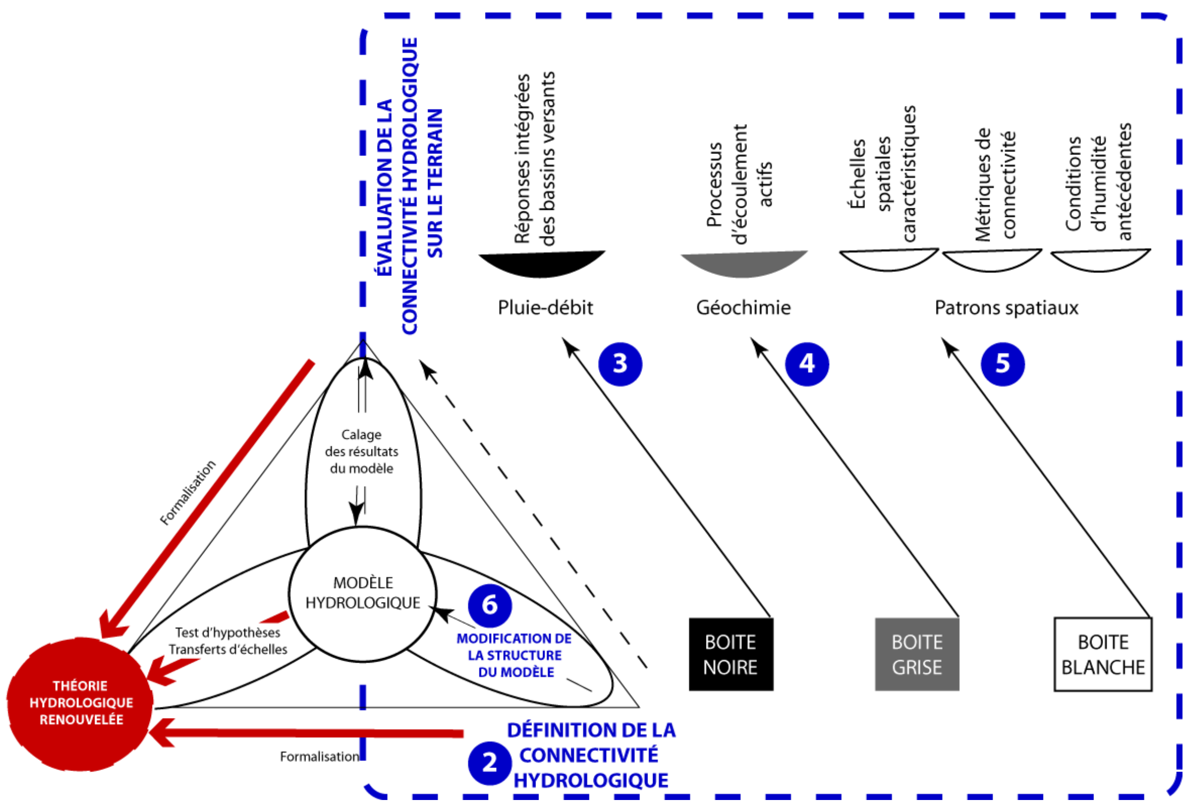


Figure 2.8 – Illustration détaillée des étapes du raisonnement devant guider la planification d'une recherche sur le concept de connectivité hydrologique. Le cadre bleu tireté délimite les étapes traitées dans la thèse. Les chiffres blancs dans les bulles bleues font référence aux chapitres de la présente thèse.

La Figure 2.8 illustre la structure de la thèse en fonction de la revue de la littérature effectuée au Chapitre 1 et du cadre méthodologique décrit à la section 2.2. Premièrement, pour ce qui est de l'exploitation des données de pluie et de débits uniquement, on se réfère à la théorie systémique en adoptant une approche de type « boite noire » (*black box*). Cette approche signifie que l'on évalue les changements de connectivité hydrologique sans étudier le fonctionnement interne du système (i.e. bassin versant) et en se servant uniquement des entrées (i.e. variables météorologiques) et des sorties (i.e. hydrogrammes de crue). Deuxièmement, des données géochimiques ponctuelles sont utilisées afin de représenter le fonctionnement interne du bassin versant. L'approche adoptée est alors de type « boite grise » (*grey box*), puisque l'on dispose d'un peu plus d'informations pour évaluer les changements de connectivité hydrologique. Troisièmement, des patrons spatiaux exhaustifs de la topographie de surface, la topographie de subsurface et l'humidité du sol sont analysés. Il s'agit là d'une approche de type « boite blanche » (*white box*) car on utilise des données spatialement détaillées reflétant l'état du bassin versant pour estimer la connectivité hydrologique. La disponibilité de données exhaustives d'humidité du sol est particulièrement intéressante puisqu'elle permet l'analyse des effets d'échelles, des mesures quantitatives de connectivité et des conditions d'humidité antécédentes (Figure 2.8). Les approches « boite noire », « boite grise » et « boite blanche » sont traitées séparément dans les Chapitres 3, 4 et 5 en utilisant un seul lieu d'expérimentation, soit le bassin versant de l'Hermine (voir section 2.4.1). Ces trois approches sont ensuite confrontées dans le Chapitre 6 et les gains de connaissances qu'elles apportent évalués dans la perspective d'une modification des modèles hydrologiques.

2.4 Méthodologie de la recherche

2.4.1 Site d'étude

L'Hermine a été choisie comme site « test » pour comparer les différentes approches d'évaluation de la connectivité hydrologique. Il s'agit d'un bassin versant de premier ordre situé dans la région des Laurentides, à environ 80 km au nord de Montréal, Québec (45º59' N, 74º01' W, altitude c. 400 m) (Figure 2.9 A). Le cours d'eau principal, qui s'écoule de manière éphémère d'est en ouest et s'assèche généralement durant la période estivale, draine une superficie d'environ 5,1 hectares. Les principales caractéristiques topographiques du bassin versant sont résumées dans la Figure 2.9. La particularité du bassin versant de l'Hermine est sa morphologie en forme de cuvette, avec une dénivelée maximale de 29 m entre le point le plus haut et l'exutoire. Le versant sud a aussi la particularité d'être plus long et d'avoir une pente moyenne plus élevée que le versant nord.

Des travaux de terrain précédemment réalisés à l'Hermine (Drouin, 1999) ont permis de récolter des données d'élévation en 640 points d'échantillonnage répartis sur tout le bassin versant. Ces données ont ensuite été interpolées pour obtenir un modèle numérique d'altitude dont la résolution horizontale est d'un mètre et la précision verticale de l'ordre du centimètre. L'algorithme d'interpolation utilisé pour ce faire, soit celui du voisinage simple naturel lissé, fut choisi en raison de sa meilleure performance en comparaison avec les algorithmes de krigeage, distance pondérée ou triangulation. En effet, Drouin (1999) a montré que la microtopographie du basin versant de l'Hermine ainsi que la grande quantité points d'échantillonnage posaient problème lors de l'interpolation. Les modèles numériques générés grâce à divers algorithmes présentaient des caractéristiques très différentes en ce qui avait trait au nombre de dépressions et à la distribution de fréquence des valeurs d'altitude et de pente. L'algorithme de voisinage naturel simple lissé permettait ainsi de minimiser l'écart entre les valeurs d'élévation réelles mesurées au niveau de 640 points et les valeurs interpolées à ces mêmes points. La distribution spatiale de l'indice topographique obtenue présentait également le moins d'artefacts ; cela permet d'affirmer que le modèle numérique d'altitude de l'Hermine peut-être utilisé à des fins de modélisation hydrologique avec TOPMODEL, par exemple.

Le modèle numérique d'altitude (Figure 2.9 B) et la carte des pentes (Figure 2.9 D) montrent bien la topographie de surface irrégulière du bassin. Les seules zones relativement planes (Figure 2.9 E) se cantonnent aux alentours du ruisseau, des rigoles, ou d'une zone plus humide située en amont du bassin versant, à la naissance du ruisseau. Ces zones sont aisément visibles sur la carte de distribution spatiale de l'indice topographique (Figure 2.9 G) puisque ce sont celles dont la propension à se saturer est la plus grande. Les sols sont des Podzols, d'une épaisseur maximale de 1 à 2 m, développés sur un till glaciaire. Ces sols sont répartis uniformément sur tout le bassin, mais ceux du versant orienté vers le sud se distinguent par des horizons organiques plus épais et une tendance à la gléyification.

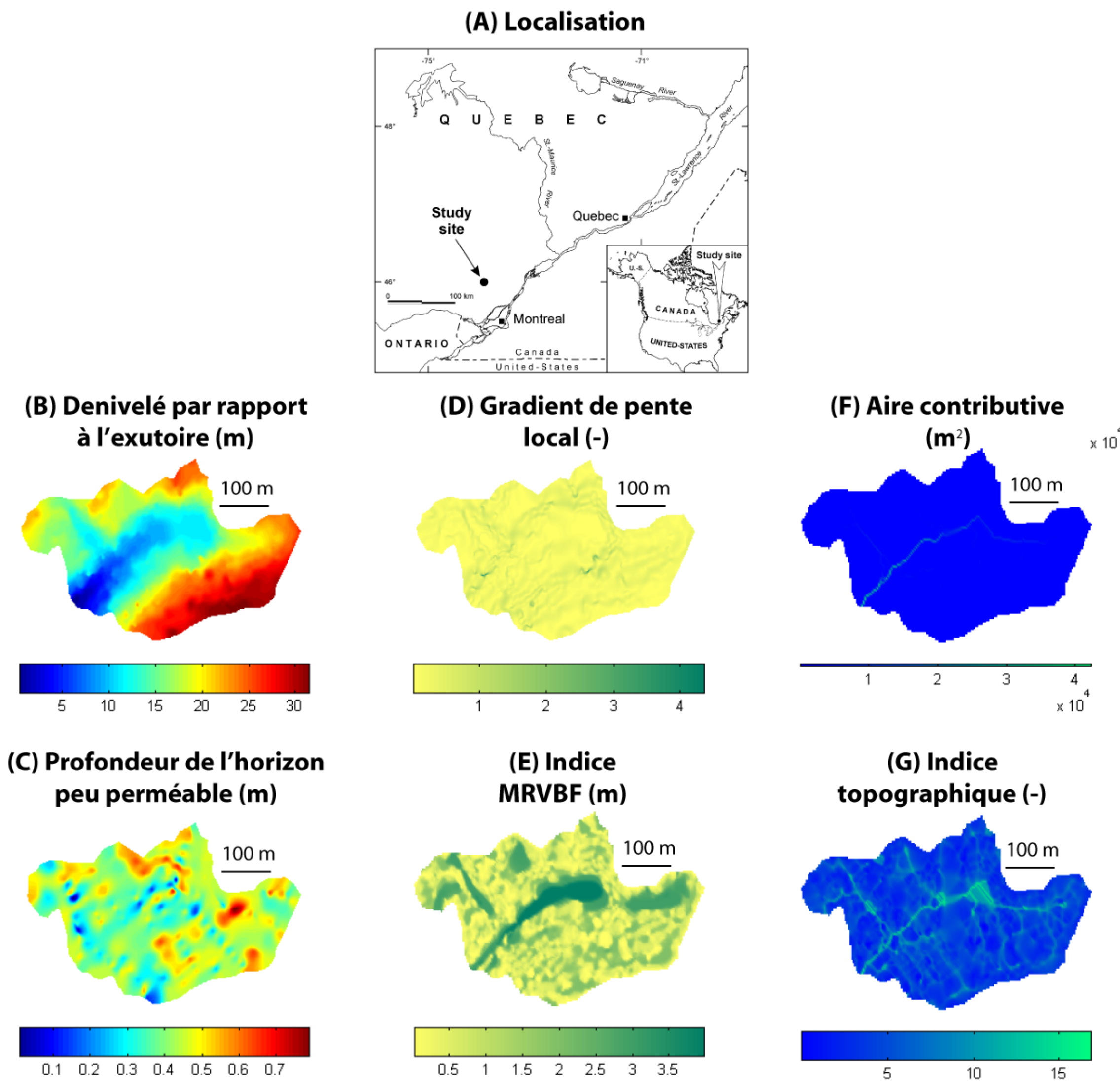


Figure 2.9 – Caractéristiques principales du bassin versant de l'Hermine. **(A)** Localisation ; **(B)** Dénivelée par rapport à l'exutoire ; **(C)** Profondeur de l'horizon peu perméable ; **(D)** Gradient de pente local ; **(E)** Indice MRVBF (*multi-resolution valley bottom flatness*) ; **(F)** Aire contributive ; **(G)** Indice topographique de Beven & Kirkby (1979). N.B. : Les cartes de pente et d'aire contributive ont été dérivées à l'aide d'un algorithme multidirectionnel de routage de l'écoulement. L'indice MRVBF prend des valeurs élevées lorsque le gradient de pente est très faible (zone plane).

Autrement, les sols du bassin se caractérisent par la présence d'un horizon cimenté, compact et quasi-imperméable mais discontinu, qui limite la pénétration des racines et ralentit l'infiltration de l'eau. Les travaux précédemment publiés sur l'Hermine suggèrent une profondeur de 75 cm pour l'horizon cimenté (Biron *et al.*, 1999 ; Courchesne *et al.*, 2001 ; Turgeon, 2004). De récents forages réalisés dans le bassin versant font plutôt croire à la présence d'éléments de toutes sortes qui limitent la pénétration de l'eau à des profondeurs supérieures à 50 cm (Figure 2.9 C). Ces éléments peuvent être des fragments de l'horizon cimenté discontinu, la roche en place ou plutôt de gros blocs de roche composant le till glaciaire et qui ont un impact sur les chemins d'écoulement préférentiels de l'eau dans le sol. Il est bon de mentionner que la carte présentée à la Figure 2.9 C a été obtenue en interpolant des valeurs moyennes de profondeur de l'horizon cimenté récoltées en 257 points répartis sur tout le bassin versant de l'Hermine. À chacun de ces 257 points d'échantillonnage, trois forages à la tarière ont été réalisé dans un rayon d'un mètre autour du point de manière à sonder l'épaisseur de sol « meuble » au-dessus de l'horizon cimenté. Les données ainsi mesurées ont ensuite été interpolées (résolution horizontale : 1 m) en utilisant, de nouveau, l'algorithme de voisinage naturel simple lissé. Effectuer trois sondages à la tarière en chaque site d'échantillonnage a ainsi permis d'écarter les données qui semblaient refléter la présence de petits blocs rocheux isolés plutôt que celle de l'horizon cimenté. Il est donc fortement probable que les données recueillies illustrent la réelle localisation de l'horizon cimenté dans le profil de sol, ou alors la présence de blocs de roche en place de plus de deux mètres de diamètre et qui, de fait, ont une influence sur les patrons d'écoulement hypodermique.

La microtopographie de surface du bassin versant est également complexe, en raison de la présence d'affleurements rocheux, de blocs et de troncs d'arbres au dessus des horizons organiques (Figure 2.10).

Figure 2.10 – Illustrations de la microtopographie de surface dans le bassin versant de l'Hermine. **(A)** Blocs de roche en place et troncs d'arbre à la surface du sol ; **(B)** Assèchement progressif du cours d'eau principal à la fin de la période de fonte printanière ; **(C)** Grande aire saturée en amont d'un gros bloc de roche en place ; **(D)** Rigole activée en cas de forte pluie pour drainer la crête d'un versant vers le cours d'eau principal ; **(E)** Zone saturée de manière quasi-permanente au pied d'un versant.

D’un point de vue climatique, le bassin versant de l’Hermine se situe en milieu tempéré humide. Les températures journalières maximales sont observées en juillet et atteignent +25°C en moyenne, tandis que les minima journaliers (–30°C) sont plutôt observés en janvier. Quant aux apports en eau, ils totalisent 1150 mm sur une base annuelle (± 136 mm). Les observations des 30 dernières années ont, par ailleurs, montré qu’environ 30 % des précipitations survenaient sous forme de neige, ce qui équivaut à près de 350 mm par année (Biron *et al.*, 1999).

La couverture intégralement forestière du sol a des conséquences importantes sur la saisonnalité du bilan hydrique du bassin. En effet, le peuplement végétal, âgé de 80 à 160 ans, est dominé à 78 % par l’érable à sucre (*Acer saccharum*), tandis que d’autres espèces (hêtre à grandes feuilles ou *Fagus grandifolia*, bouleau jaune ou *Betula alleghaniensis*, sapin baumier ou *Abies balsamea*, bouleau à papier ou *Betula papyrifera*, peuplier faux tremble ou *Populus tremuloides*, peuplier à grandes dents ou *Populus grandidentata*) occupent le reste de la canopée (Courchesne *et al.*, 2001 ; Turgeon, 2004). Les effets de l’évapotranspiration sont donc au minimum entre les mois d’octobre et d’avril et durant cette période, c’est le drainage gravitaire qui contrôle les changements de teneur en eau et de hauteur de la nappe phréatique dans le sol. Au contraire, pendant la période estivale, les effets combinés de l’interception par la canopée et de l’évapotranspiration diminuent la probabilité d’observer du ruissellement de crue de surface, sauf à la suite des épisodes pluvieux très intenses. Cet effet de saisonnalité se reflète dans les débits observés à l’exutoire (Figure 2.11). Les conditions prévalant dans le bassin versant de l’Hermine sont d’ailleurs propices à la genèse de ruissellement de surface par excès de saturation, comme en témoignent les variations de la hauteur de la nappe phréatique durant les 12 dernières années (entre 1 et 108 cm de profondeur, moyenne de 68 cm) (Biron *et al.*, 1999).

En résumé, le bassin versant de l’Hermine possède les caractéristiques particulières suivantes : i) des précipitations qui excèdent l’évapotranspiration la plupart du temps, ce qui permet la formation d'aires saturées et l'acheminement du ruissellement de crue depuis les versants jusqu'au cours d'eau, et ii) des sols avec un horizon de moindre perméabilité à quelques dizaines de centimètres de profondeur, qui favorise la formation de nappes perchées et l'écoulement latéral de proche subsurface. Si l'on se fie à Grayson & Western (2001), le bassin versant de l'Hermine est donc un cas intéressant pour l'application de modèles hydrologiques basés sur des indices de similarité topo-hydrologique.

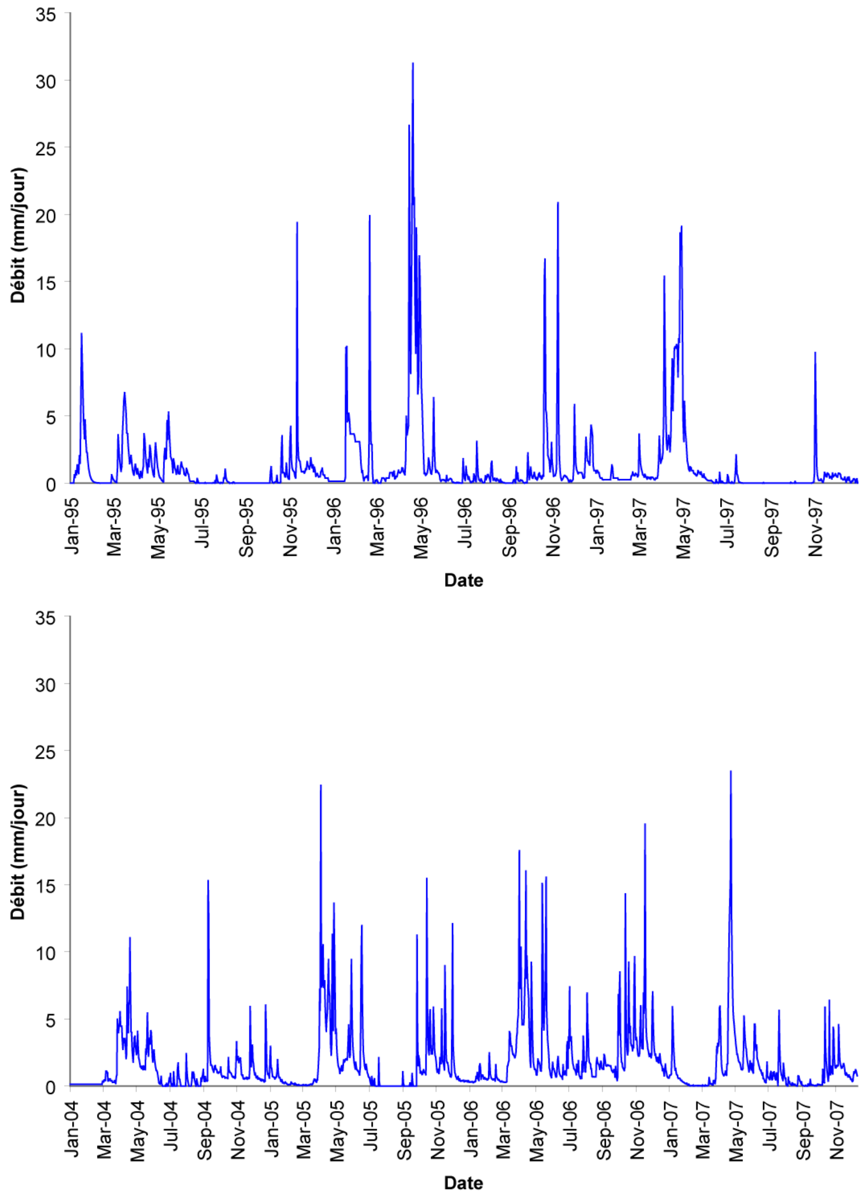


Figure 2.11 – Évolution du débit journalier enregistré à l'exutoire du bassin versant de l'Hermine pour les périodes 1995-1997 et 2004-2007.

2.4.2 Montage expérimental et données de terrain

Le bassin versant de l'Hermine est un site de recherche expérimentale où l'on retrouve plusieurs installations permanentes en fonction depuis 1993. Certaines données historiques fournies par ces installations, notamment les données géochimiques et les débits du cours d'eau, sont reprises dans le cadre de ce projet. Des instruments supplémentaires ont été utilisés afin de répondre aux objectifs de recherche énoncés plus tôt.

Figure 2.12 – Instrumentation dans le bassin versant de l'Hermine. **(A)** Station météorologique ; **(B)** Instrumentation des neuf parcelles ; **(C)** Système *TDR* utilisé sur les neuf parcelles ; **(D)** Échantillonneur d'eau automatique ; **(E)** Station de jaugeage ; **(F)** Système *TDT* ; **(G)** Système *FDR* (*AQUATERR*).

On suppose que les variables météorologiques d'intérêt, notamment la température de l'air et les précipitations, sont uniformes sur le bassin versant. Les données proviennent de la station météorologique de la Station de Biologie des Laurentides, gérée par l'Université de Montréal et située près d'un km au nord de l'Hermine (Figure 2.12 A). Les données utilisées ont été enregistrées à une fréquence de 15 minutes depuis 2003. Ces données sont utilisées dans les Chapitres 3, 4 et 5 de cette thèse.

Les données géochimiques constituent la majeure partie des données historiques pour l'Hermine. L'étude des caractéristiques de l'eau de pluie et de l'eau dans le sol est rendue possible par la présence de neuf parcelles instrumentées (Figure 2.13). Trois d'entre elles se situent en bas de pente à proximité du cours d'eau (parcelles 1, 2 et 3), trois en milieu de pente en tête de bassin versant (parcelles 4, 5 et 6) et trois en haut de pente (parcelles 7, 8 et 9). Les parcelles ont été ainsi positionnées pour tenir compte de la variabilité spatiale de la topographie, mais leur localisation géographique est également intéressante du point de vue de leur distance (et de leur possible connectivité) par rapport à l'exutoire du bassin versant.

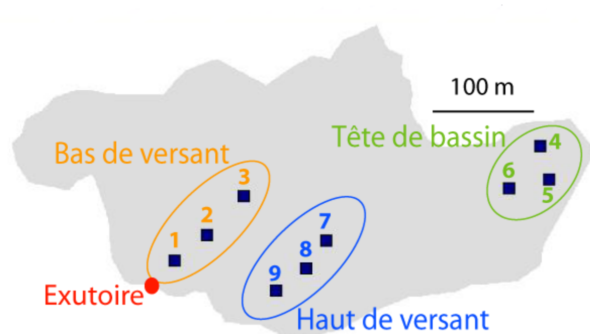


Figure 2.13 – Localisation des neuf parcelles instrumentées et de l'exutoire pour les études géochimiques dans le bassin versant de l'Hermine.

Chacune des parcelles est équipée d'un collecteur à pluviolessivat ou à neige et de deux lysimètres à 0 et 50 cm de profondeur dans le sol (Figure 2.12 B) de manière à prélever, respectivement, l'eau de pluie non interceptée par la canopée, la solution de sol des horizons organiques et celle des horizons minéraux. Par ailleurs, deux autres types de données géochimiques sont mesurés à l'Hermine. D'une part, les précipitations incidentes sont prélevées au niveau d'une tour dont le sommet se trouve au-dessus de la canopée. Cet échantillonnage, tout comme celui des parcelles, est effectué une fois par mois pendant l'hiver et deux fois par mois pendant la saison de croissance. D'autre part, l'eau du ruisseau est prélevée une fois par jour pendant la saison de croissance et une fois tous les deux jours (prélèvement composite) pendant l'hiver à l'aide d'un échantillonneur d'eau automatique (Figure 2.12 D). À quelques occasions, cependant, cette fréquence d'échantillonnage est augmentée afin de suivre l'évolution des concentrations d'éléments chimiques sur une base événementielle. Les propriétés et éléments chimiques mesurés sont notamment le pH, la conductivité électrique, les cations majeurs, les anions majeurs et le carbone organique dissous. Ces données sont disponibles pour les périodes 1994-1997 et 2000-2005.

Les procédures analytiques associées à la mesure des propriétés et éléments chimiques dans le bassin versant de l'Hermine sont résumées par Biron *et al.* (1999) et Turgeon (2004). Brièvement, les échantillons d'eau de pluie, de pluviolessivat, de solution de sol et d'eau du ruisseau sont récoltés dans des bouteilles de plastique préalablement lavées à l'acide puis conditionnées sur le terrain en utilisant une partie de l'échantillon visé. Dans un délai de moins de 24 heures après la collecte, une partie de l'eau recueillie est soumise à des analyses de pH et de conductivité électrique tandis que le reste est filtré en utilisant des membranes de polyéthylène (Millipore, 0,45µm) puis réfrigéré à 4°C. À partir des échantillons d'eau filtrés, les concentrations de nitrate (NO_3^-), d'ammonium (NH_4^+), de sulfate (SO_4^{2-}), de potassium (K^+), de chlore (Cl^-) et de sodium (Na^+) sont mesurées à l'aide d'un chromatographe ionique (Waters) tandis que les concentrations de calcium (Ca^{2+}) et de magnésium (Mg^{2+}) sont mesurées à l'aide d'un spectromètre à adsorption atomique (Perkin-Elmer). Quant aux concentrations de carbone organique dissous, elles ont été estimées de manière indirecte à partir d'équations de régression linéaire établies entre l'absorbance des échantillons et la quantité de carbone organique dissous donnée par un analyseur de carbone total (Shimadzu, Kyoto) (Turmel *et al.*, 2005). L'absorbance des échantillons d'eau a été mesurée par spectrophotométrie à une longueur d'onde de 254 nm avant d'appliquer les équations de régression linéaire dont la précision de est 0,01 mg/l et l'écart avec les concentrations réelles se situe entre 1 et 3 % (Biron *et al.*, 1999). Ces données sont notamment utilisées dans le Chapitre 4 de cette thèse.

Les données hydrométriques recueillies à l'Hermine sont de plusieurs natures et obéissent à des schémas d'échantillonnage différents. Une liste des variables échantillonnées est fournie ici. Premièrement, le débit du cours d'eau est mesuré en un seul endroit, soit à l'exutoire du bassin versant (Figure 2.12 E). Cette mesure, effectuée en volts grâce à un senseur à ultra-sons, est convertie en volume d'eau à une fréquence de 15 minutes. Un niveaumètre est également disponible et il permet essentiellement de combler les trous de données qui résulteraient d'un mauvais fonctionnement du senseur. Ces données sont disponibles depuis 2004 et sont utilisées dans les Chapitres 3, 4 et 5 de la thèse. Deuxièmement, deux variables hydrologiques sont mesurées dans les neuf parcelles décrites plus tôt. Tout d'abord, pour chacune des parcelles, un puits permet de mesurer la hauteur de la nappe phréatique (Figure 2.12 B). Ensuite, une sonde *TDR* (*Time Domain Reflectometry*) permet de mesurer la teneur en eau du sol (0 à 60 % pour la saturation) à environ 25 cm de profondeur (Figure 2.12 C). La fréquence d'échantillonnage de ces deux variables est la même que pour les données géochimiques des parcelles pour les périodes 1994-1997 et 2000-2005.

En dernier lieu, afin d'établir des patrons spatiaux d'humidité du sol à plusieurs profondeurs et à la grandeur du bassin versant, un réseau de 150 sites d'échantillonnage a été géoréférencé. Selon une fréquence variable, la teneur en eau du sol a été relevée à ces sites grâce à une sonde *AQUATERR* (0 à 100 % pour la saturation) basée sur la technologie

FDR (*Frequency Domain Reflectometry*) (Figure 2.12 G). Cette mesure s'est faite à quatre profondeurs différentes (5, 15, 30, 45 cm) et a été calibrée par rapport aux parcelles de manière à convertir les mesures d'humidité sur une échelle de 0 à 60 % plutôt que de 0 à 100 %. Il est bon de mentionner que la répartition spatiale des 150 sites vise à répondre à deux objectifs distincts tout en suivant l'une des recommandations énoncées à la section 2.2. D'une part, il s'agit d'étudier la relation entre la teneur en eau du sol, à différentes profondeurs, et les gradients topographiques mesurés selon l'axe Nord-Sud. Les sites d'échantillonnage sont donc, pour la plupart, positionnés sur des transects orientés dans cette direction (Figure 2.14 A). D'autre part, étant donné que l'analyse des patrons spatiaux avec les méthodes géostatistiques requiert une distribution quasi-uniforme des points, les sites d'échantillonnage ont été positionnés pour remplir une grille régulière de 121 cases (15 m x 15 m) couvrant tout le bassin versant (Figure 2.14 B).

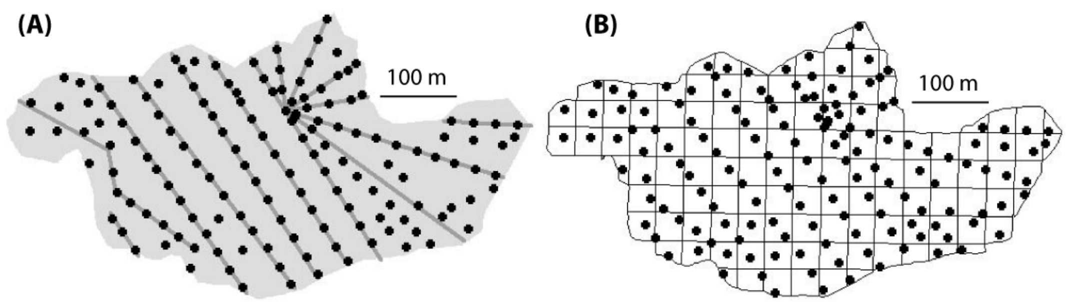


Figure 2.14 – Stratégies d'échantillonnage de l'humidité du sol dans le bassin versant de l'Hermine. **(A)** Transects orientés dans la direction Nord-Sud ; **(B)** Grille régulière.

Tableau 2.5 – Conditions hydro-météorologiques prévalant au moment des campagnes d'échantillonnage de l'humidité du sol dans le bassin versant de l'Hermine.

Date	AP_1	AP_2	AP_5	AP_7	AP_{10}	AP_{12}	AP_{14}
6/08/2007	0	0	4	4	36	36	36
13/08/2007	12	12	17	44	44	48	48
7/09/2007	8	8	8	8	8	22	44
14/09/2007	0	0	14	14	15	22	22
21/09/2007	0	0	0	18	22	32	32
28/09/2007	4	4	4	4	4	4	22
5/10/2007	0	0	0	6	10	10	10
12/10/2007	25	25	40	42	42	42	48
26/10/2007	0	0	15	43	43	43	67
2/11/2007	3	3	3	33	36	48	76
9/11/2007	0	0	17	17	20	20	50
20/05/2008	10	20	36	39	39	39	54
2/06/2008	2	21	27	29	29	49	61
17/06/2008	13	14	14	29	29	37	37
15/07/2008	2	3	19	43	43	54	59
21/07/2008	0	0	33	35	42	73	75

Date	DSP	DSP_{10}	DSP_{20}	DSP_{30}	PET	$MSMC$	CD_DISCH
6/08/2007	0	0	0	9	2.61	33.8	0.66
13/08/2007	0	1	7	16	2.58	23.3	0.22
7/09/2007	1	9	15	41	3.15	27.0	0.05
14/09/2007	0	3	22	48	2.19	29.0	0.07
21/09/2007	6	6	29	55	2.07	27.7	0.06
28/09/2007	0	13	36	62	1.73	27.9	0.10
5/10/2007	7	20	43	69	2.40	17.3	0.09
12/10/2007	0	0	1	76	1.49	39.6	5.87
26/10/2007	3	3	7	90	1.33	23.1	0.91
2/11/2007	1	6	6	6	1.23	21.5	1.52
9/11/2007	3	3	13	13	0.86	21.1	1.71
20/05/2008	0	2	22	141	1.87	34.4	1.80
2/06/2008	0	2	35	154	2.89	30.0	0.83
17/06/2008	0	1	50	169	2.37	32.2	0.52
15/07/2008	1	3	6	197	2.51	31.5	0.42
21/07/2008	0	0	3	203	2.44	35.2	0.78

AP_x : Cumulatif des précipitations (mm) tombées dans les x jours précédant l'échantillonnage

DSP : Nombre de jours écoulés depuis la dernière quantité de pluie enregistrée par le pluviomètre

DSP_x : Nombre de jours écoulés depuis la dernière pluie dont l'intensité excédait x mm/j

PET : Évapotranspiration potentielle (mm/j) calculée selon l'équation de Hargreaves (1975)

$MSMC$: Humidité (vol %) du sol moyenne pour tout le bassin versant

CD_DISCH : Débit journalier moyen mesuré à l'exutoire à la date d'échantillonnage

Seize campagnes de mesure de l'humidité du sol ont été réalisées à l'Hermine entre les mois d'août 2007 et de juillet 2008. Ce nombre de campagnes d'échantillonnage se compare favorablement aux treize réalisées dans le bassin versant tempéré sec de prairies de Tarrawarra en Australie (Western & Grayson, 1998) et aux neuf réalisées dans un bassin versant forestier tempéré humide du Mont St-Hilaire au Québec (James & Roulet, 2007). Étant donné que l'automne 2007 fut particulièrement sec tandis que l'été 2008 fut particulièrement humide, les seize campagnes de mesure réalisées à l'Hermine ont permis de capter un bon éventail de conditions hydro-météorologiques pouvant prévaloir dans le bassin versant (Tableau 2.5). Les variables illustrées dans le Tableau 2.5 sont souvent utilisées afin d'approximer les conditions d'humidité antécédentes dans un bassin versant, en l'occurrence l'Hermine, en l'absence de données spatialement détaillées sur le contenu en eau des sols. Ces variables montrent bien la variabilité des conditions associées à chacune des campagnes d'échantillonnage de l'humidité du sol dans le bassin versant de l'Hermine, non seulement en ce qui a trait au cumulatif mais aussi à la distribution temporelle des apports en eau. Ces changements météorologiques devraient se traduire en changements de degré de connectivité hydrologique à l'Hermine, et cette question fait l'objet de trois articles scientifiques reproduits dans cette thèse (Chapitre 5).

Les patrons spatiaux d'humidité du sol mesurés à chacune des 16 occasions dans le bassin versant de l'Hermine sont illustrés dans les Figures 2.15 à 2.30. Il est notamment intéressant d'observer un fort contraste entre les campagnes d'échantillonnage correspondant à des conditions sèches (e.g. 5 octobre 2007, 2 et 9 novembre 2007), humides (e.g. 12 octobre 2007, 15 et 21 juillet 2008) ou transitoires ou intermédiaires (6 août 2007, 20 mai et 2 juin 2008). Il est également important de noter qu'en période très humide, l'Hermine ne répond pas au modèle théorique selon lequel les zones proximales au cours d'eau et situées en bas de versant sont celles où le contenu en eau du sol est le plus élevé. En effet, les cartes des Figures 2.22 ou 2.30, par exemple, laissent entendre que les zones dont l'humidité volumétrique est la plus élevée se situent préférablement au niveau des rigoles intermittentes, de la zone humide à la naissance du ruisseau et de la portion nord du bassin versant de l'Hermine. Le ruisseau n'apparait pas comme une zone qui se sature de manière régulière, ce qui laisse supposer que la topographie de surface n'est pas le contrôle dominant sur la distribution spatiale de l'humidité du sol à l'Hermine. Par ailleurs, le contenu volumétrique en eau du sol est généralement beaucoup plus important à des profondeurs de 5 et 15 cm, en comparaison avec 30 et 45 cm. Ces différences entre les patrons spatiaux d'humidité du sol selon les profondeurs de sol et les dates d'échantillonnage font notamment l'objet du Chapitre 5 de cette thèse.

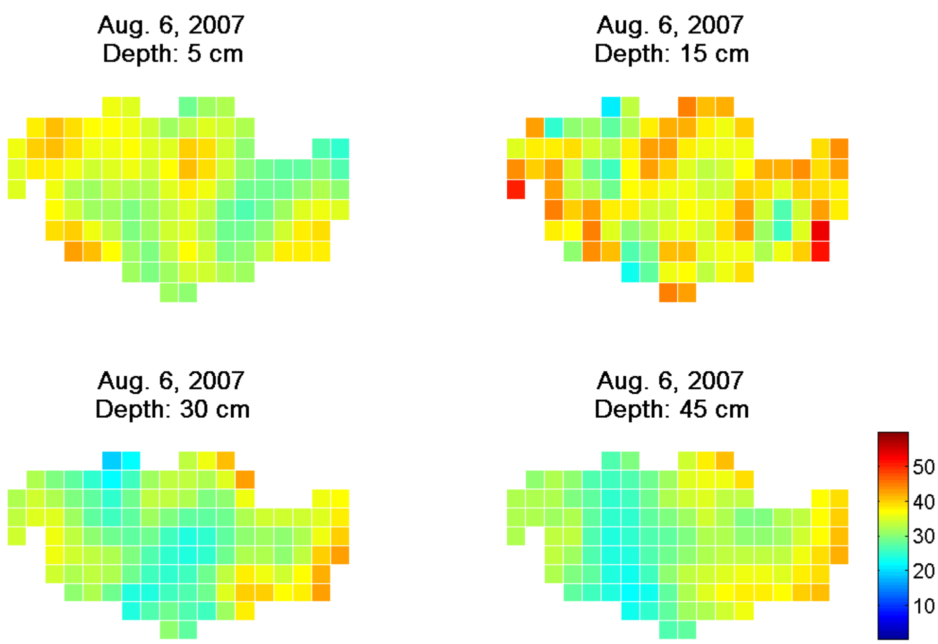


Figure 2.15 – Patrons d'humidité du sol mesurés à l'Hermine le 6 août 2007.

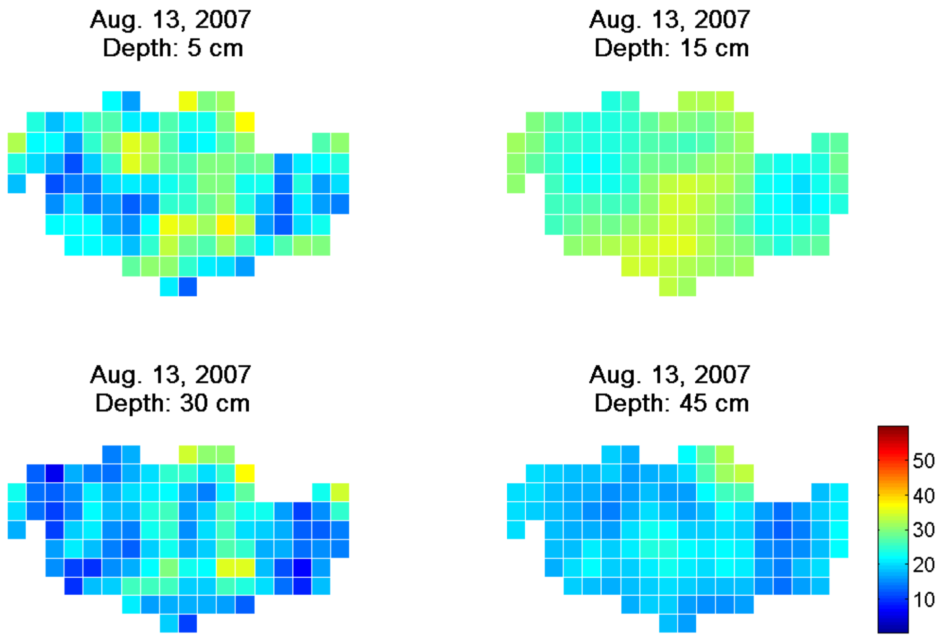


Figure 2.16 – Patrons d'humidité du sol mesurés à l'Hermine le 13 août 2007.

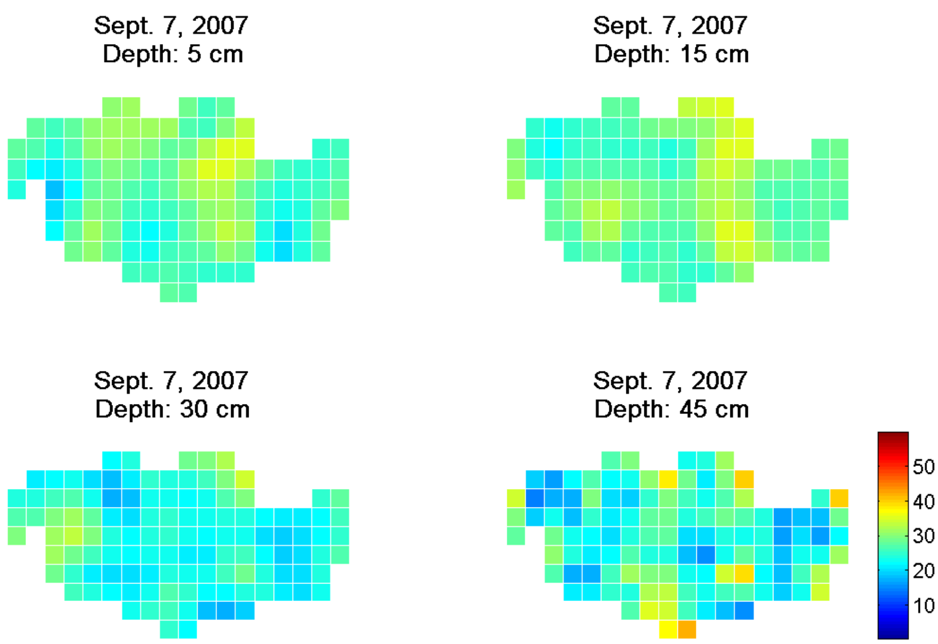


Figure 2.17 – Patrons d'humidité du sol mesurés à l'Hermine le 7 septembre 2007.

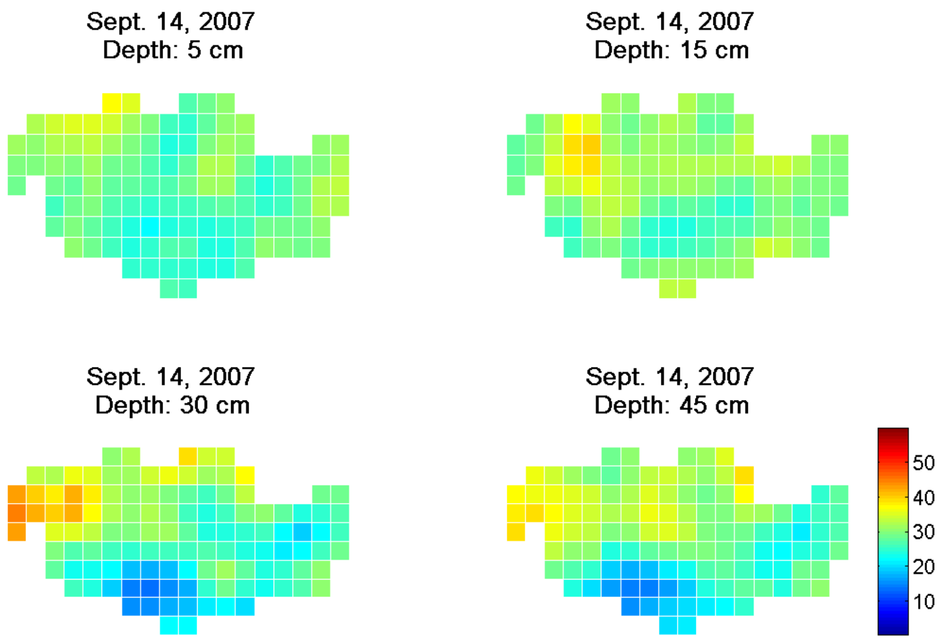


Figure 2.18 – Patrons d'humidité du sol mesurés à l'Hermine le 14 septembre 2007.

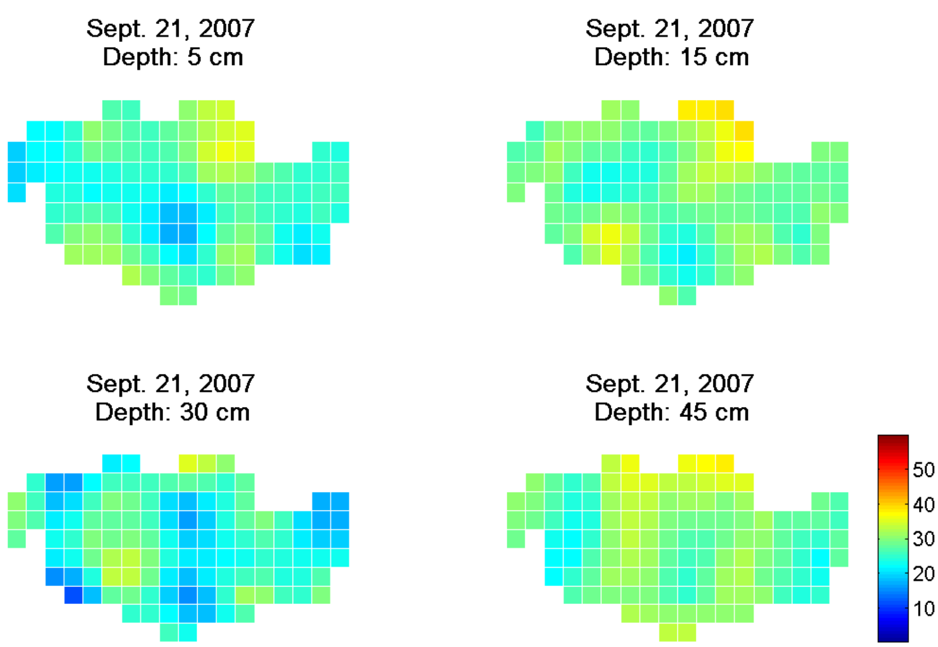


Figure 2.19 – Patrons d'humidité du sol mesurés à l'Hermine le 21 septembre 2007.

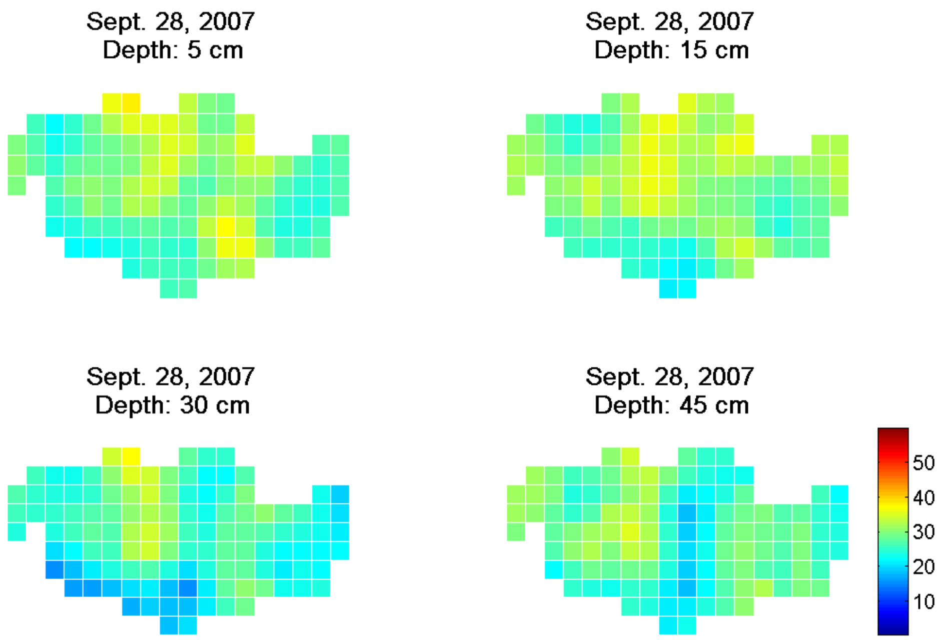


Figure 2.20 – Patrons d'humidité du sol mesurés à l'Hermine le 28 septembre 2007.

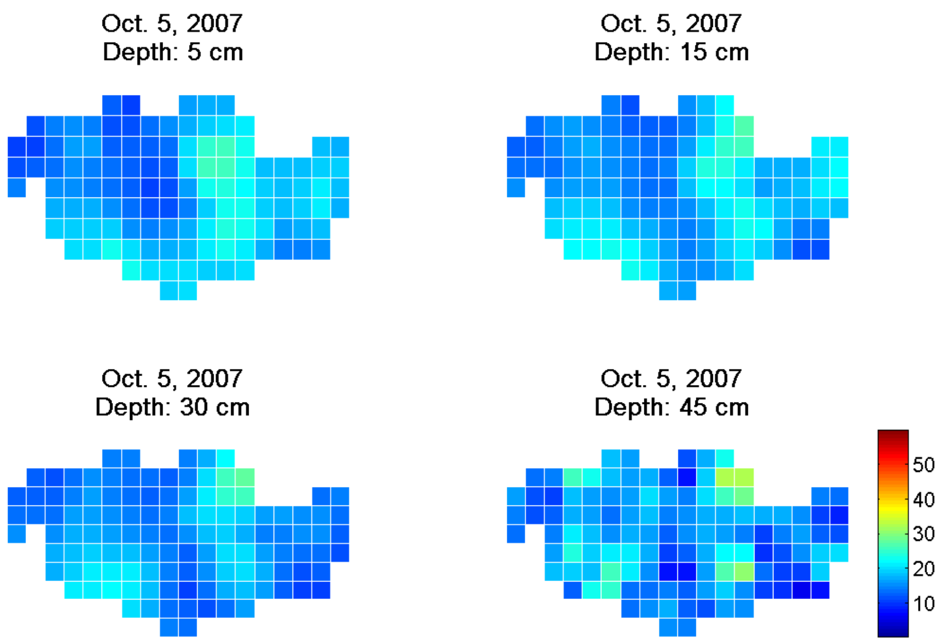


Figure 2.21 – Patrons d'humidité du sol mesurés à l'Hermine le 5 octobre 2007.

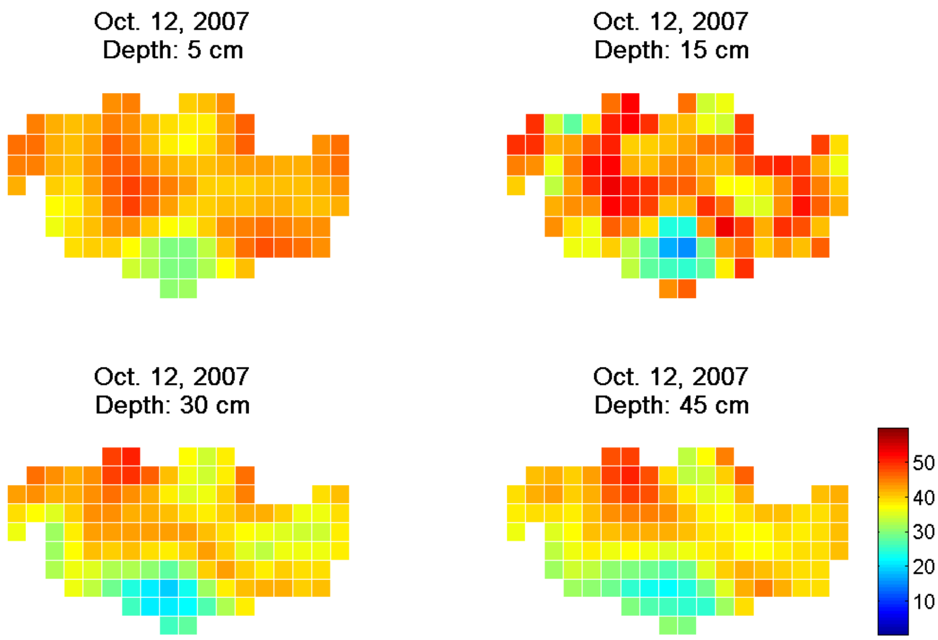


Figure 2.22 – Patrons d'humidité du sol mesurés à l'Hermine le 12 octobre 2007.

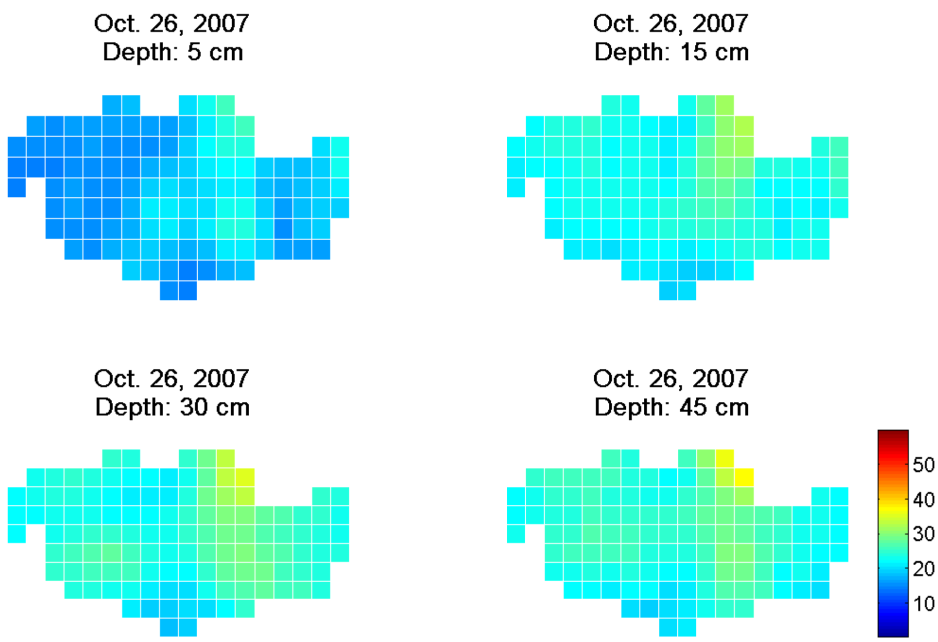


Figure 2.23 – Patrons d'humidité du sol mesurés à l'Hermine le 26 octobre 2007.

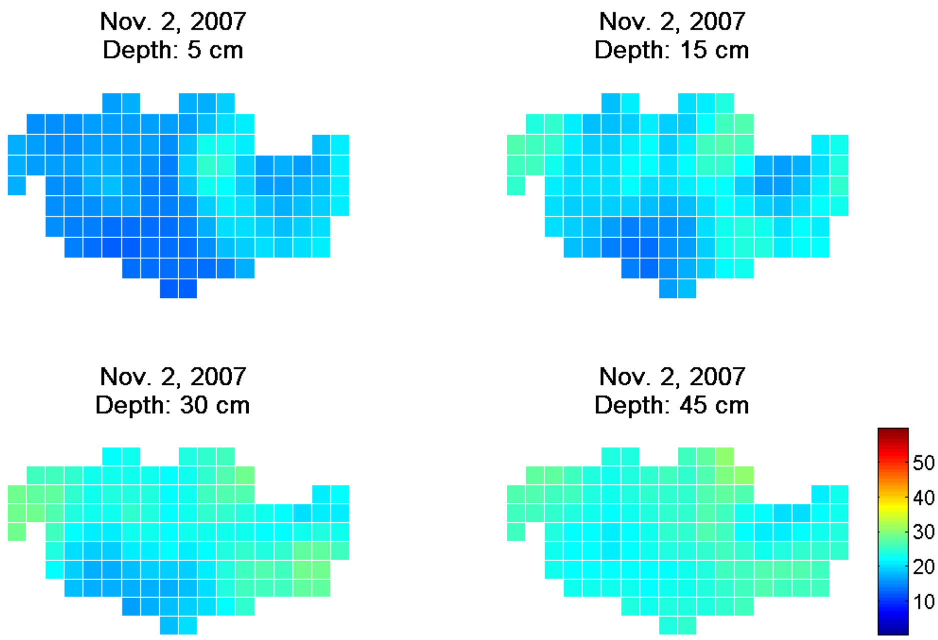


Figure 2.24 – Patrons d'humidité du sol mesurés à l'Hermine le 2 novembre 2007.

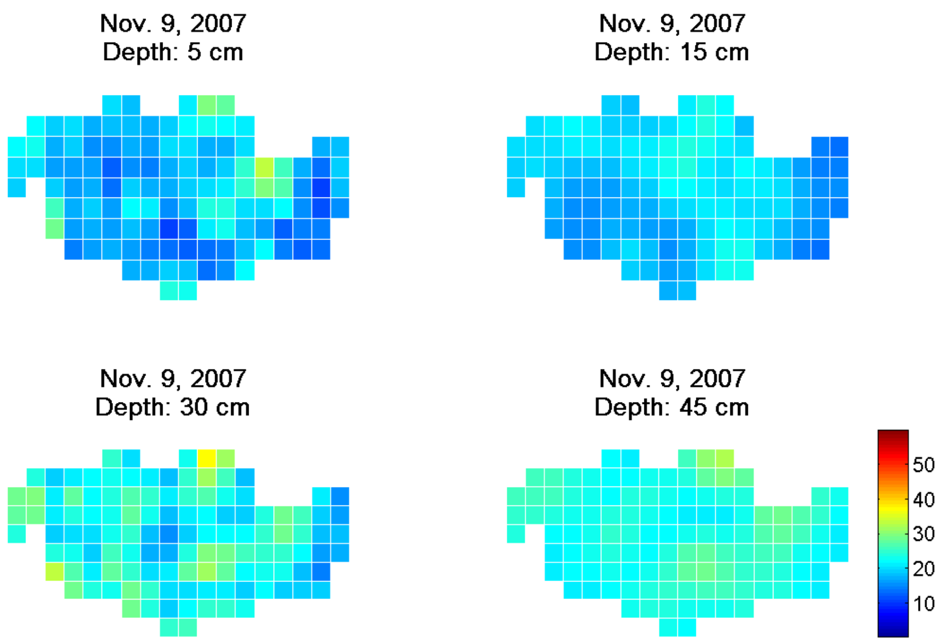


Figure 2.25 – Patrons d'humidité du sol mesurés à l'Hermine le 9 novembre 2007.

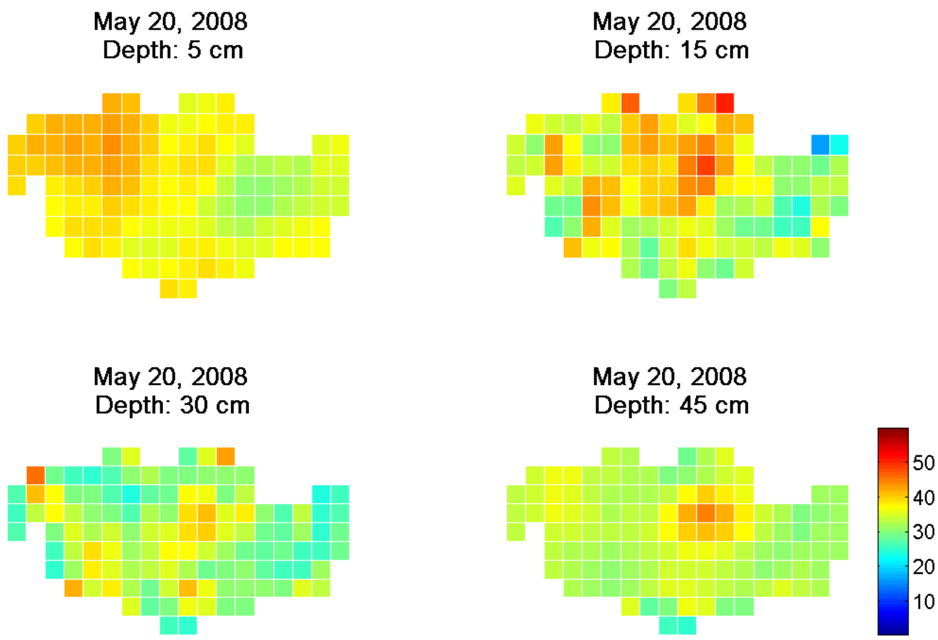


Figure 2.26 – Patrons d'humidité du sol mesurés à l'Hermine le 20 mai 2008.

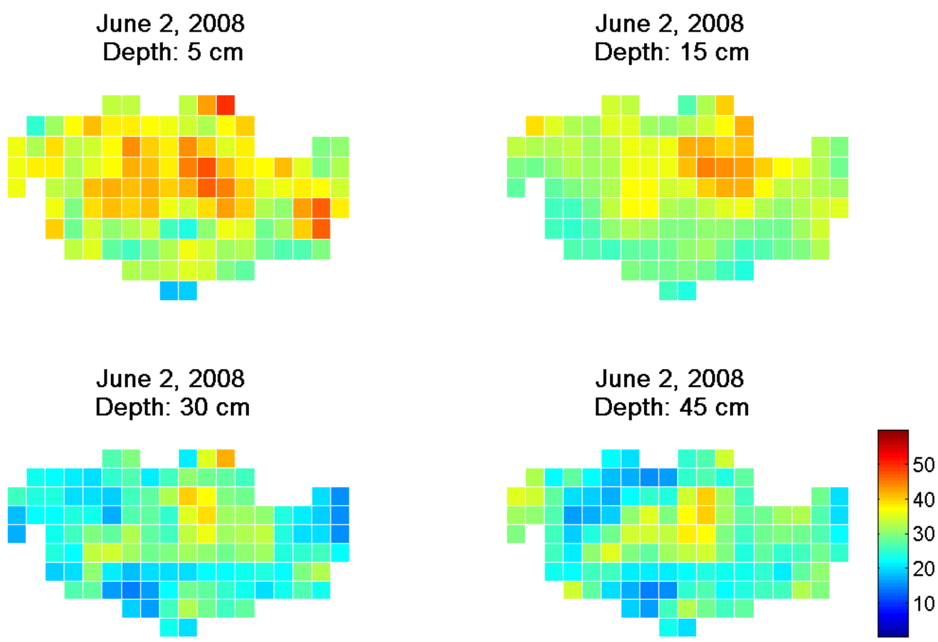


Figure 2.27 – Patrons d'humidité du sol mesurés à l'Hermine le 2 juin 2008.

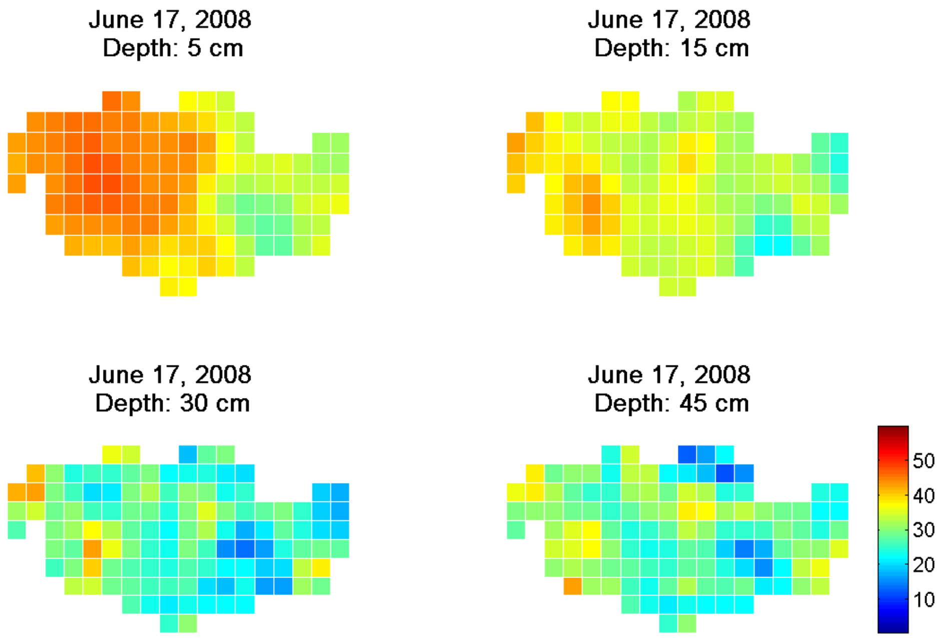


Figure 2.28 – Patrons d’humidité du sol mesurés à l’Hermine le 17 juin 2008.

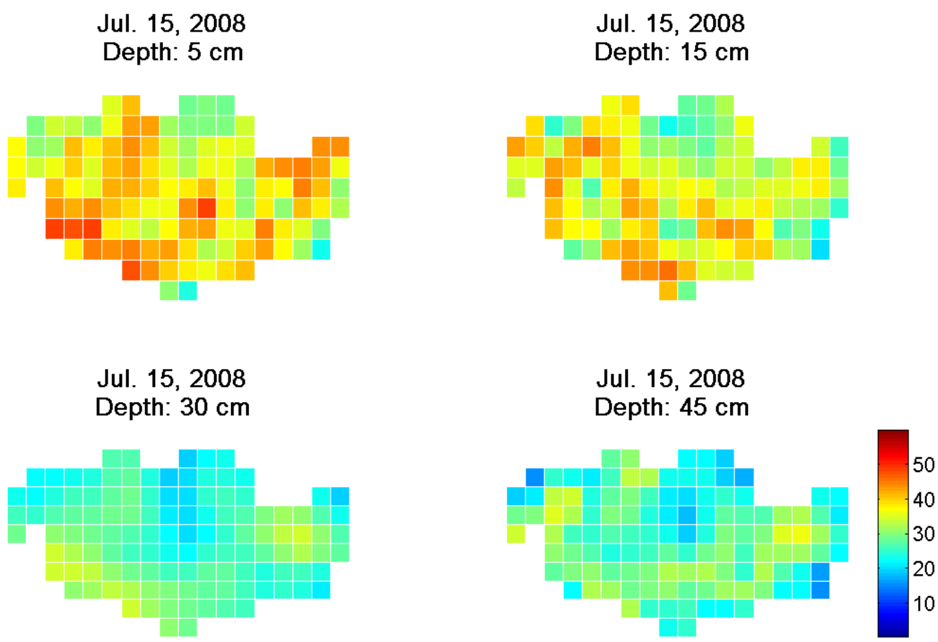


Figure 2.29 – Patrons d’humidité du sol mesurés à l’Hermine le 15 juillet 2008.

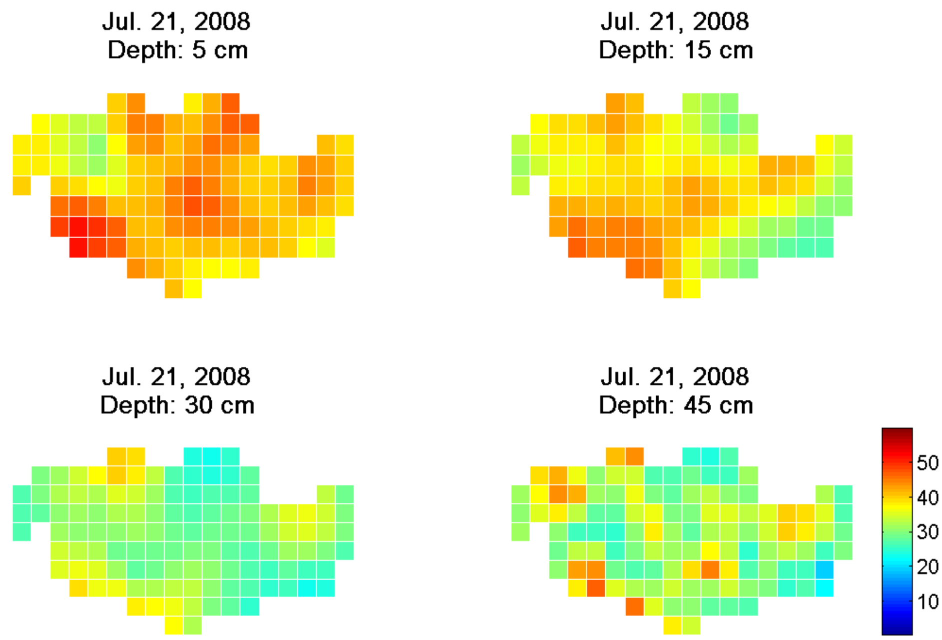


Figure 2.30 – Patrons d'humidité du sol mesurés à l'Hermine le 21 juillet 2008.

Les Chapitres 3, 4, 5 et 6 de cette thèse visent donc à évaluer différentes approches d'estimation des changements de connectivité hydrologique dans le bassin versant de l'Hermine. Pour ce faire, trois approches, de type « boite noire », « boite grise » et « boite blanche », sont mises de l'avant avant d'être confrontées les unes aux autres. Ces approches reposent non seulement sur des données de nature différente mais aussi sur des techniques d'analyse différentes. La contribution méthodologique de cette thèse consiste donc à évaluer le gain de connaissances relatives à la connectivité que l'on peut effectivement retirer de l'analyse de données hydrométriques globales (données de pluie et de débit) isolément (« boite noire », Chapitre 3) ou en combinaison avec des données géochimiques (« boite grise », Chapitre 4) ou des données hydrométriques spatialement distribuées (patrons d'humidité du sol, « boite blanche », Chapitre 5).

CHAPITRE 3

ÉTUDE DE LA CONNECTIVITÉ HYDROLOGIQUE SELON L'APPROCHE « BOITE NOIRE »

3.1 Contexte

Ce chapitre a pour but d'utiliser l'approche « boite noire » afin d'estimer les changements de connectivité hydrologique dans le bassin versant de l'Hermine. Pour ce faire, des données historiques de températures, de pluie et de débits recueillies dans le bassin versant de l'Hermine sont analysées. Le but premier de l'exercice est de déterminer dans quelle mesure des données aisément accessibles peuvent renseigner les hydrologues sur les comportements linéaires ou non linéaires et les effets de seuil dans un système hydrologique. L'article scientifique reproduit dans la section 3.2 décrit l'analyse statistique de 96 hydrogrammes de crue associés à 96 événements pluvieux dans le bassin versant de l'Hermine afin i) de contraster différents types de réponse hydrologique, ii) d'identifier les variables météorologiques qui influencent le plus ces types de réponse, et iii) de déterminer les valeurs « seuils » de variables météorologiques qui permettent l'activation ou la désactivation de chaque type de réponse. Les résultats de cette analyse statistique sont finalement discutés pour évaluer s'ils plaident en faveur de l'existence de conditions changeantes de connectivité hydrologique dans le bassin versant de l'Hermine.

3.2 Multivariate Analysis as a Tool to Infer Hydrologic Response Types and Controlling Variables in a Humid Temperate Catchment [2]

3.2.1 Introduction

Recent literature in catchment hydrology provides several examples of highly complex behaviors involving strong nonlinearities. Although these behaviors are not yet fully understood (McDonnell, 2003; Weiler *et al.*, 2005; McGrath *et al.*, 2007), it is agreed that the initiation of runoff production processes is critical; therefore the focus is especially upon precipitation and moisture thresholds above which the movement of soil water is favored to generate stormflow at the hillslope scale and streamflow at the catchment scale. Antecedent moisture conditions, which can be assessed through a wide variety of measures (e.g. antecedent precipitation indices), are thought to be major environmental controls on stormflow generation since they influence the activation of both catchment runoff sources and delivery flowpaths to the stream (Sivapalan, 1993). At the hillslope scale, the fill and spill hypothesis (Spence & Woo, 2003; Tromp-Van Meerveld & McDonnell, 2006b) was recently put forward to explain the critical initiation of lateral subsurface flow at the Panola Mountain research watershed for storms exceeding 55 mm in size (Tromp-Van Meerveld & McDonnell, 2006a, b). That mechanism is now thought to be responsible for thresholded hydrological responses in many landscapes as it induces the spatial connectedness of transient saturation patches at the soil-bedrock interface (Buttle *et al.*, 2004; Spence & Woo, 2006; Gomi *et al.*, 2008). At the catchment scale, relationships between the spatial arrangement of hydrological variables (i.e. the catchment internal state) and streamflow (i.e. the catchment integrated response) have been investigated. In particular, Grayson *et*

[2] Ali, G. A., A. G. Roy, M.-C. Turmel & F. Courchesne, 2010c. 'Multivariate analysis as a tool to infer hydrologic response types and controlling variables in a humid temperate catchment', *Hydrological Processes*, doi: 10.1002/hyp.7705.

al., 1995) found that the spatial organization of antecedent moisture had an effect on event hydrographs obtained from distributed hydrological models. Working in a semi-arid rangeland catchment, Western *et al.* (2001) distinguished between dry and wet conditions by classifying shallow soil moisture patterns as random or organized, computing integral connectivity scale lengths (Allard, 1994) for these patterns, and linking these connectivity metrics values to catchment discharges simulated by the Thales hydrological model (Grayson *et al.*, 1995). In a temperate humid forested catchment from the Canadian Shield, however, the distinction between dry and wet states was not perceptible in shallow soil moisture patterns, despite a significant nonlinear 'threshold' relationship between the runoff ratio and the catchment mean soil moisture content (James & Roulet, 2007). Ocampo *et al.* (2006) provided experimental evidence of a perfect match between the timing of the occurrence of connectivity between landscape units and event hydrographs parameters: riparian zones were said to control the catchment storm response while upland zones were considered as storage units influencing the base flow component of streamflow. Shuster *et al.* (2008) also found that the rate of streamflow recession was intimately linked to the extent of hydraulic connectivity between landscape units.

These examples are especially interesting as they highlight the ability of specific hydrograph parameters to reflect specific catchment internal processes. For that reason, the general aim of the present paper is to study several event hydrographs using a combination of multivariate statistical methods in order to characterize dominant catchment hydrologic response types. In this study, we define hydrologic response types in terms of low and high magnitude and slow and quick timing of runoff. Motivation for such an approach is twofold.

Firstly, it is recognized that existing data archives (e.g. streamflow records) have yet to be exploited to their full potential towards hydrological interpretation (Sivapalan *et al.*, 2003b). Therefore, hydrologists should aim to learn from observed data and especially from patterns behind the data (Sivapalan, 2003a; McDonnell *et al.*, 2007). As the current PUB initiative (Prediction in Ungauged Basins) calls for new data analytical approaches even while looking at old data (Sivapalan *et al.*, 2003b), we assess the benefits of multivariate analysis techniques for exploring and predicting types of hydrologic response. Multivariate methods involve the simultaneous statistical consideration of several measured properties of a system, rather than isolating and examining them individually. These methods enable researchers to explore the joint expression of these properties and to determine their influence on one another. Multivariate statistics are not usually aimed at replacing pure physical analysis. Nevertheless, they can prove to be useful as a preliminary investigation tool or to point out aspects which would not necessarily come out in a classical univariate approach. There are three main categories of multivariate analyses, namely clustering, statistical tests of hypotheses, and ordination (Legendre & Legendre, 1998). The vast majority of recent clustering applications in hydrology have to do with watershed classification (e.g. Laaha & Blöschl, 2006; Wagener *et al.*, 2007). As for ordination, it is a dimension reduction technique which allows the arrangement or 'ordering' of objects along gradients, thus facilitating the visualization of multivariate data sets (Legendre & Legendre, 1998). In most cases, hydrologists make use of unconstrained ordination methods to study the interrelationships between different solutes concentrations in stream water (e.g. Christophersen & Hooper, 1992). Constrained ordination, better known as canonical analysis, is further available to study how interrelationships between different properties respond to changes in controlling variables (Legendre & Legendre, 1998).

Secondly, we also argue that the statistical analysis of hydrologic response types used in this study can help inferring a catchment state-of-connectivity from a qualitative standpoint. Although several definitions of connectivity exist (e.g. Western *et al.*, 2001; Stieglitz *et al.*, 2003; Bracken & Croke, 2007), all intend to describe the ease with which stormwater moves through a landscape and contributes to streamflow. Measures of ‘dynamic connectivity’ usually involve collecting high-resolution soil moisture data, building complex hillslope and subsurface flow models and identifying threshold effects. Some authors (e.g. Western *et al.*, 2001; James & Roulet, 2007) have computed connectivity statistics based on LOP (‘lots-of-points’) collections of pattern information. Evidence of threshold relations in subsurface stormflow and connectivity through filling and spilling of bedrock depressions was also obtained given several years of intense hillslope monitoring (Tromp-Van Meerveld & McDonnell, 2006a, b), and later confirmed using a hillslope-scale hydrological model based on percolation theory (Lehmann *et al.*, 2007). Such commitments of field and modeling resources are, however, difficult to replicate at multiple locations. Thus, the statistical framework introduced in the present study is a less ‘resources-greedy’ approach relying on the potential to associate both meteorological and streamflow records with the state of watershed connectivity. We hypothesize that a catchment state-of-connectivity can be inferred from the analysis of storm hydrographs. This argument is based on the assumption that the timing and magnitude of peak runoff are controlled by the degree of hydrologic connectivity. In the idealized case of a linear response, highly connected systems should be characterized by short response times to precipitation, steeper rising hydrograph limbs, higher peak discharges and greater runoff coefficients than unconnected or partially connected systems. In the more likely case of nonlinear behaviors, however, the previous assumption may not be entirely valid. On the one hand, large precipitation amounts falling on a ‘dry’ catchment may result in little, if any, outflow. On the other hand, large precipitation amounts falling on a transitional state may produce a similar hydrograph to very small rainfall quantities falling on a ‘wet’ state, even though soil moisture patterns might exhibit greater spatial connectivity in the ’wet’ case. Studying event hydrographs in conjunction with meteorological surrogates for antecedent moisture conditions should therefore help us understand the variability of catchment responses associated with spatial connectivity, even though no actual quantitative measure of connectivity is available.

Hence, in this paper, we use both ordination (unconstrained and constrained) and clustering methods in an approach to characterize the behavior of a small, temperate humid, forested catchment from meteorological and hydrological records. Specifically, three objectives are addressed: (1) discriminate contrasting types of hydrologic responses, in terms of magnitude and timing of runoff, (2) identify the hydro-meteorological variables that explain best the differences in the types of hydrologic responses, and (3) detect breakpoints or thresholds in the hydro-meteorological variables that lead to a switch in hydrologic responses.

3.2.2 Methods

a. Study site

We examined the hydrological behavior of a 5.1 ha headwater forested catchment, the Hermine, located in the Laurentians about 80 km North of Montréal, Québec, Canada (45°59’ N, 74°01’ W, elevation c. 400 m) (Figure 3.1 A). The catchment has a relief of 31 m and is drained by an ephemeral stream (Figure 1 B). The maximum daily average temperatures are observed in July (+ 25°C) while daily minima (– 30°C) occur in January. The total annual precipitation averages 1150 mm (± 136 mm) for the last 30 years, of which about 30 % falls as snow (Biron *et al.*, 1999).

Soils are 1 to 2 m deep bouldery Podzols developed over a glacial till. They present a discontinuous confining layer at a depth of about 50 to 75 cm (Figure 3.1 C) that restricts root penetration, slows water infiltration and enhances the probability of rapid lateral subsurface flow. Transpiration is minimal between October and April, so that changes in soil moisture and water table in that period are mostly governed by downslope drainage movement. The interception capacity of the forest canopy, combined with high summer potential evapotranspiration, reduces the likelihood of surface runoff, except during heavy rainstorms or wet and cool summers. Water table depths measured at nine riparian, midslope and upslope 300 m² sampling plots in the catchment have also fluctuated between the soil surface and 108 cm below (mean value: 68 cm) for the last 12 years. Shallowness of the perched water table during wet periods indicates that lateral saturation excess flow can rapidly occur following a significant precipitation event in the Hermine catchment.

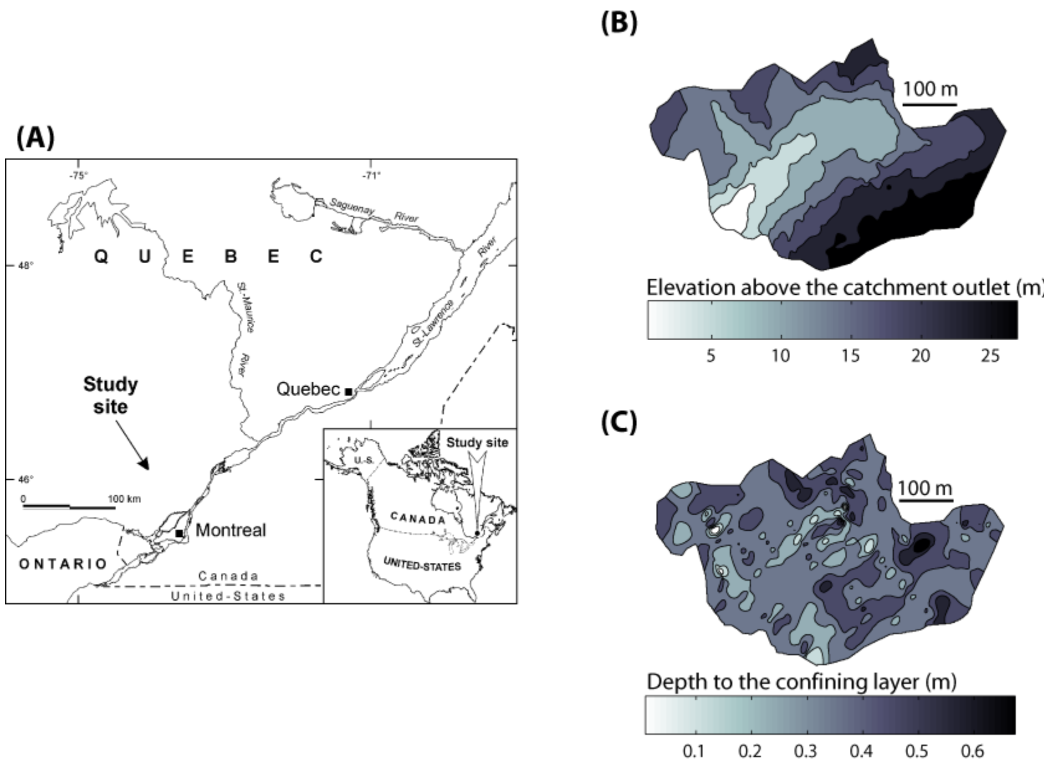


Figure 3.1 – (**A)** Location of the Hermine catchment; **(B)** Surface digital elevation model; **(C)** Depth to the confining soil layer. The raster grid is 2 m × 2 m.

b. Data pre-processing

In this study, we analyze a four-year long (2004-2007) record of rainfall and streamflow data collected at a frequency of 15 minutes. The time series was segmented into hydrological events. This segmentation was delicate since the definition of a hydrological event had to include all kinds of rainfall amounts and intensities resulting in more or less sharp changes in streamflow characteristics. Hence, we determined dry periods as periods of at least 48 hours during which no water input was recorded at the rain gauge. An event was then defined as starting as soon as rainfall intensity equaled or exceeded 1 mm/h after a dry period. The ending of an event was determined when streamflow decreased at or below the level of the preceding dry period. The overall procedure yielded 96 rainfall-induced events during three hydrologically active seasons, namely late spring (mid-May to mid-June), summer (mid-June to mid-September) and early fall (mid-September to mid-November). Variables associated with these events were then derived and incorporated into a database for multivariate analyses.

Table 3.1 – Characteristics of the rainfall-induced hydrological events (n = 96) selected for multivariate analyses.

		MIN.	MAX.	MEAN	STD. DEV.
RESPONSE VARIABLES					
Total event discharge (L)	TOTDIS	2.3	2542.4	442.7	617.1
Maximum event discharge (L/s)	MAXDIS	0.1	25.1	4.0	4.8
Runoff coefficient (-)	RC	0.0	2.8	0.3	0.4
Time to peak discharge (h)	PEAK	1.3	94.0	15.8	16.0
Time lag (h)	LAG	-1.3	71.5	11.6	13.6
EXPLANATORY VARIABLES					
10-day antecedent rainfall (mm)	AP10	0.0	116.0	29.1	22.2
Total event rainfall (mm)	TOTRAIN*	1.0	110.0	23.5	19.7
Maximum rain intensity (mm/h)	MAXRAIN*	4.0	136.0	14.8	16.4
Season	SEASON	1 = Late Spring	2 = Summer	3 = Early Fall	

* TOTRAIN and MAXRAIN are considered as storm characteristics (STORM)

Throughout this paper, data cases are events (n = 96), response variables or descriptors are common hydrograph features, and explanatory variables are selected hydro-meteorological variables (Table 3.1). With regards to the response variables, we assume that the time to peak (i.e. time from the beginning of the rising limb to the occurrence of peak discharge) and the time lag (i.e. time between the center of mass of the effective rainfall hyetograph and the center of mass of the direct runoff hydrograph) are good indicators of catchment runoff timing because flow-connected landscape units convey water to the stream faster than unconnected units. Lag times and times to peak are important hydrological variables because they are closely related to the time of concentration that is not a hydrograph parameter. Time to concentration is the delay required for water to travel from the most distant point hydraulically (in time) to the outlet. This variable is an indicator of connectivity as it is influenced by catchment slope, roughness and flow path length (Chow *et al.*, 1988). Total and maximum discharges and the runoff coefficient (i.e. runoff ratio, computed as depth of streamflow divided by depth of precipitation) signal the magnitude of stormwater inputs to the stream. The runoff ratio is especially important as it is known to depend on initial moisture conditions (Longobardi *et al.*, 2003). High values of the runoff coefficient may therefore reflect the exceptional contribution of new rainfall water as surface runoff in addition to the displacement of old water that was stored in the soil prior to an event in the catchment. Base time (i.e. duration of the direct runoff hydrograph) was also computed but not included in subsequent analyses as it was highly correlated to total discharge ($r = 0.75$, $p < 0.001$). A Box-Cox transformation to normality was performed on all response variables using the R Package (Macintosh version, P. Legendre, A. Vaudor). Descriptors were also centered on their means then scaled with respect to their standard deviations prior to multivariate analyses to give them equal importance in terms of variability. Explanatory variables characterize antecedent moisture conditions, storm characteristics and seasonal properties (Table 3.1). A

10-day antecedent precipitation value is used as a surrogate for antecedent moisture conditions (Noguchi *et al.*, 2001), while the season variable is used to assess the presence/absence of tree leaves that affect transpiration and interception and to contrast different rates of vegetation activity. Both total event rainfall and maximum rain intensity are considered as "storm characteristics" so as to compare the magnitude of the runoff response to the magnitude of rainwater inputs.

c. Principal component analysis (PCA)

Discriminating several types of hydrologic responses involves searching for combinations of response variables (i.e. hydrograph features) that explain best the intra-variability of the dataset. Principal component analysis (PCA) is particularly suitable for pattern detection as it transforms the original, interrelated response variables into a new set of variables, the principal components (PC). PCA consists in the eigenanalysis of the correlation or covariance matrix of the response variables, and the resulting PC axes are uncorrelated and ordered in terms of the proportion of explained variance in the original response variables (Legendre & Legendre, 1998). In our case, PCA produces a score matrix that provides information on the types of hydrologic responses present among the 96 rainfall-induced events, and a loading matrix that represents the influence each hydrograph feature bears on these types of hydrologic responses. Hence, the PCA reduced space is a classification space where hydrological events are located with respect to their main characteristics. Only the first two PC axes are retained in this paper, so that events are classified into four response types or quadrants defined by the first two PC axes. A PCA function was developed in the R environment (Comprehensive **R** Archive Network, http://cran.r-project.org/) for the purpose of this paper.

Results obtained from PCA can be shown using either a distance biplot or a correlation biplot. The distance biplot is useful for classification purposes, especially in this study as it illustrates the location of each individual event in the reduced space. In this kind of biplot, distances among objects (i.e. events) are approximations of their Euclidean distances in multidimensional space (Legendre & Legendre, 1998). The correlation biplot rather focuses on the response variables that led to the positioning of individual elements in the reduced space. The main features of the correlation biplot are: (1) the angles between descriptor-axes reflect their inter-correlations; (2) projecting a descriptor arrow at right angle on a PC axis shows its covariance with the PC axis. Each PC axis is therefore labeled according to the descriptors that mostly contribute to its formation (Legendre & Legendre, 1998). An equilibrium circle of descriptors is also drawn on the biplot to assess the contribution of each descriptor to the formation of the reduced space. Descriptors whose projected lengths reach or exceed the values of their respective equilibrium contributions are the most important to explain the structure of the reduced space. The angles between descriptor-axes and PC axes may also be used to study the contributions of the descriptors to the various PC axes (Legendre & Legendre, 1998).

d. Partitioning methods

Partitioning methods aim at determining the proportion of variance in dependent variables attributable to the influence of chosen independent, explanatory variables. In this paper, we hypothesize that the differences between the four PCA-derived response types (i.e. dependent variables) can be induced by several hydro-meteorological (independent) variables. We test this hypothesis using two different methods, variation partitioning and univariate classification tree modeling, as the former assumes a linear relationship between dependent and independent variables while the later rather models nonlinear, threshold-based relationships. In this paper, we intend to address the issue of linear versus nonlinear catchment responses by comparing the success or the failure of both partitioning methods.

Variation partitioning. Variation partitioning is used to further assess the relative influence of antecedent moisture conditions, storm characteristics and seasonal properties on observed types of hydrologic response. Variation partitioning is a widely used method that splits the variation of a response variable (or data table) among two or more sets of explanatory variables using a series of regressions (or canonical analyses) (Borcard *et al.*, 1992). In this study, it is used to discriminate the variation in PCA-derived response types that is (1) uniquely explained by antecedent moisture conditions, storm characteristics, or seasonal properties; (2) explained by the pairwise interactions between antecedent moisture conditions, storm characteristics and seasonal properties; (3) unexplained. Variation partitioning was achieved using functions from the *Vegan* package (Oksanen, 2004) in the R environment. Partial canonical analyses and permutation tests ($p < 0.05$; 1000 permutations applied) were conducted (see Legendre & Legendre, 1998, p. 608-612) so that we could only investigate variables that had a significant influence on hydrological response types.

Univariate classification tree modeling. The four PCA-derived response types were further analyzed so as to detect thresholds in the hydro-meteorological variables corresponding to switching conditions from one response type to another. For this purpose, the CART (classification and regression tree) method is used, as it is a non-parametric technique that does not assume any linear relationship between the establishment of each hydrologic response type and the hydro-meteorological variables. Its ultimate objective is to build a nested sequence of individual groups or subtrees that are as homogeneous as possible. Initially, all hydrological events, labeled from 1 to 4 depending on the PCA-derived response type they belong to, are put in the same group. A recursive search is then conducted to find the rule which splits the response types into the most two dissimilar subsets. In order to find the rule, all explanatory variables are scanned; the hydro-meteorological property whose breakpoint value minimizes the heterogeneity within each subset is chosen as the most important hydro-meteorological variable and its breakpoint value is retained as the threshold. After the initial split, each dissimilar subset is recursively split with the same method until each terminal node contains very few events (Breiman *et al.*, 1984). To be able to assess cascade-like processes, an explanatory variable could be used several times in the tree if it improved the predictive performance of the classification.

The optimal number of nodes in the tree is determined using a cross-validation procedure. This procedure is necessary to avoid an oversized, over-fitted tree with very few elements in each terminal node (Breiman *et al.*, 1984). Here, a 10-fold cross-validation is used, that consists of splitting the initial data set in 10 equally sized groups. As nine groups are used for calibration purposes and the final one for validation, several tree sizes are tested until the one with the smallest prediction error is found (Breiman *et al.*, 1984). The oversized classification tree is then pruned back to its optimal size as defined by cross-validation. Classification tree analysis was achieved using functions from the *Rpart* package (Therneau and Atkinson, 1997) in the R environment.

3.2.3 Results

a. Hydrological response types

Figure 3.2 A shows a correlation biplot in which the descriptor-axes (i.e. the transformed response variables) are drawn as arrows in the reduced space. The PCA of the hydrograph features of the 96 rainfall-driven events reveals that 84% of the variance is captured by the first two PC axes. PC axis 1 is associated with the total and maximum event discharges, the runoff coefficient and the time to peak while the time lag contributes to PC axis 2 (Table 3.2). These results seem to indicate that PC axis 1 is a gradient of runoff magnitude, because it is mainly influenced by the hydrograph features while PC axis 2 is rather a gradient of runoff timing. Response types in the Hermine catchment are highly variable along the magnitude axis rather than along the timing axis. Hence, hydrological events belonging to quadrants 1 to 4 in the PCA space can be partitioned into low/high magnitude and slow/quick timing response types (Figure 3.2 B).

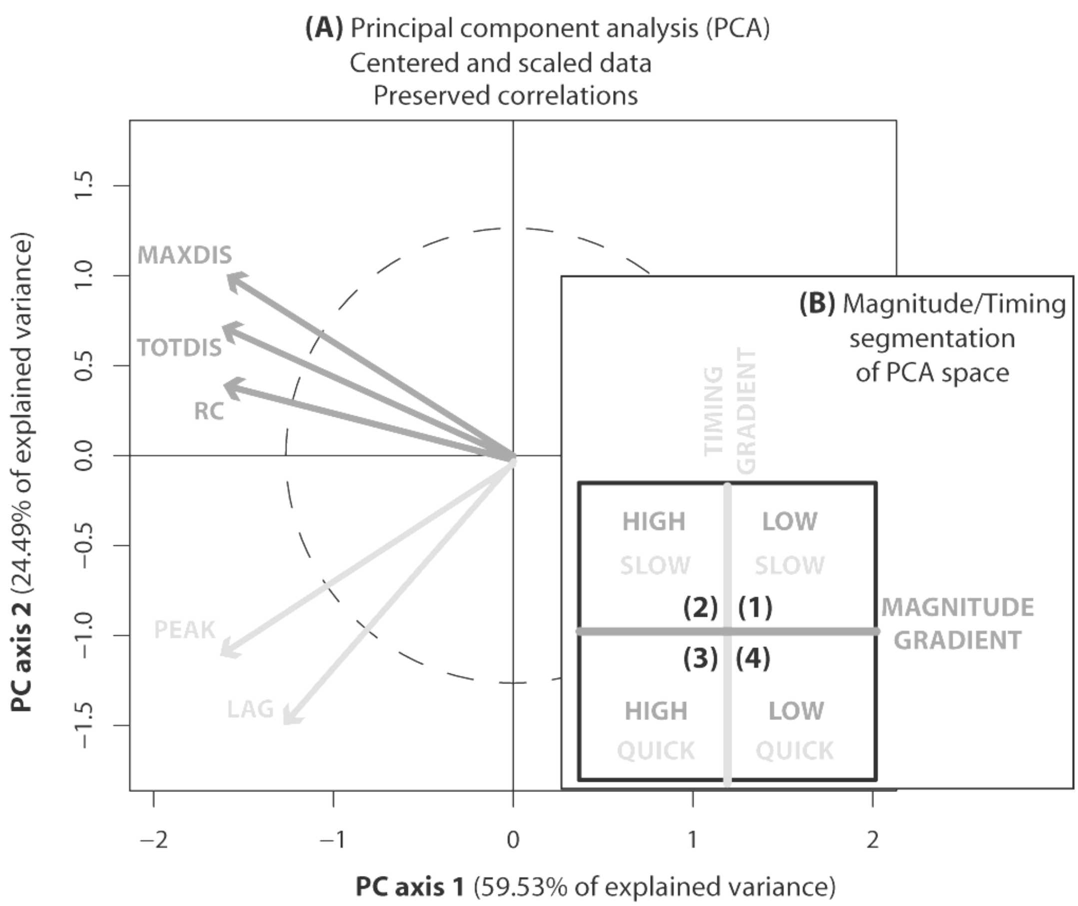


Figure 3.2 – **(A)** Principal component analysis (PCA) correlation biplot. Arrows illustrate descriptor-axes (i.e. response variables) while objects (i.e. events) are not shown. The dashed equilibrium circle of descriptors is drawn to assess the contribution of each descriptor to the formation of the reduced space. **(B)** Magnitude and timing segmentation of PCA space. Characterization of quadrants as illustrative of low/high magnitude and slow/quick timing runoff events is based upon orientation of descriptors arrows in the PCA space and correlation between descriptors and PC axes.

Table 3.2 – Correlations between descriptor-axes and principal component (PC) axes. The higher the absolute values of these correlations, the greater the contributions of the respective descriptor to the various PC axes.

	PC AXIS 1	PC AXIS 2
TOTDIS	-0.81	0.37
MAXDIS	-0.81	0.51
RC	-0.80	0.19
PEAK	-0.79	-0.52
LAG	-0.63	-0.72

Events positioning in the reduced space is further investigated with a distance biplot (Figure 3.3). In each quadrant, dots are generally well clustered with one another, meaning that there is some internal consistency between the events that are assumed to belong to the same response types. Typical hydrological events associated with each PCA quadrant are shown in Figure 3.3 in support to a magnitude/timing partitioning of events. Indeed, hydrographs associated with quadrants 1 and 4 illustrate low magnitude events with discharge values below 1.5 L/s. On the contrary, hydrographs associated with quadrants 2 and 3 show discharges exceeding 10 L/s for the Hermine catchment. On all hydrographs, the timing of peak flows is determined by both event rainfall and prior wetness conditions as portrayed by 10-day antecedent precipitation values. Events from quadrant 1 and 2 are classified as "slow timing" because the rising limb of the single-peak hydrographs is initiated almost at the end of the rain falling period (Figure 3.3). For "quick timing" events in quadrants 3 and 4, every single burst of rainfall yields an almost immediate response at the outlet, thus resulting in multiple-peak hydrographs. Continuous AP10 time series plotted on Figure 3.3 also show that the greater the antecedent precipitation values, the higher the peak discharges (e.g. sample event from quadrant 3). The location of several events near the (0,0) origin or adjacent to either PC axis 1 or 2 in the distance biplot is however telling of the difficulty in classifying each hydrological event in a unique PCA quadrant (Figure 3.3).

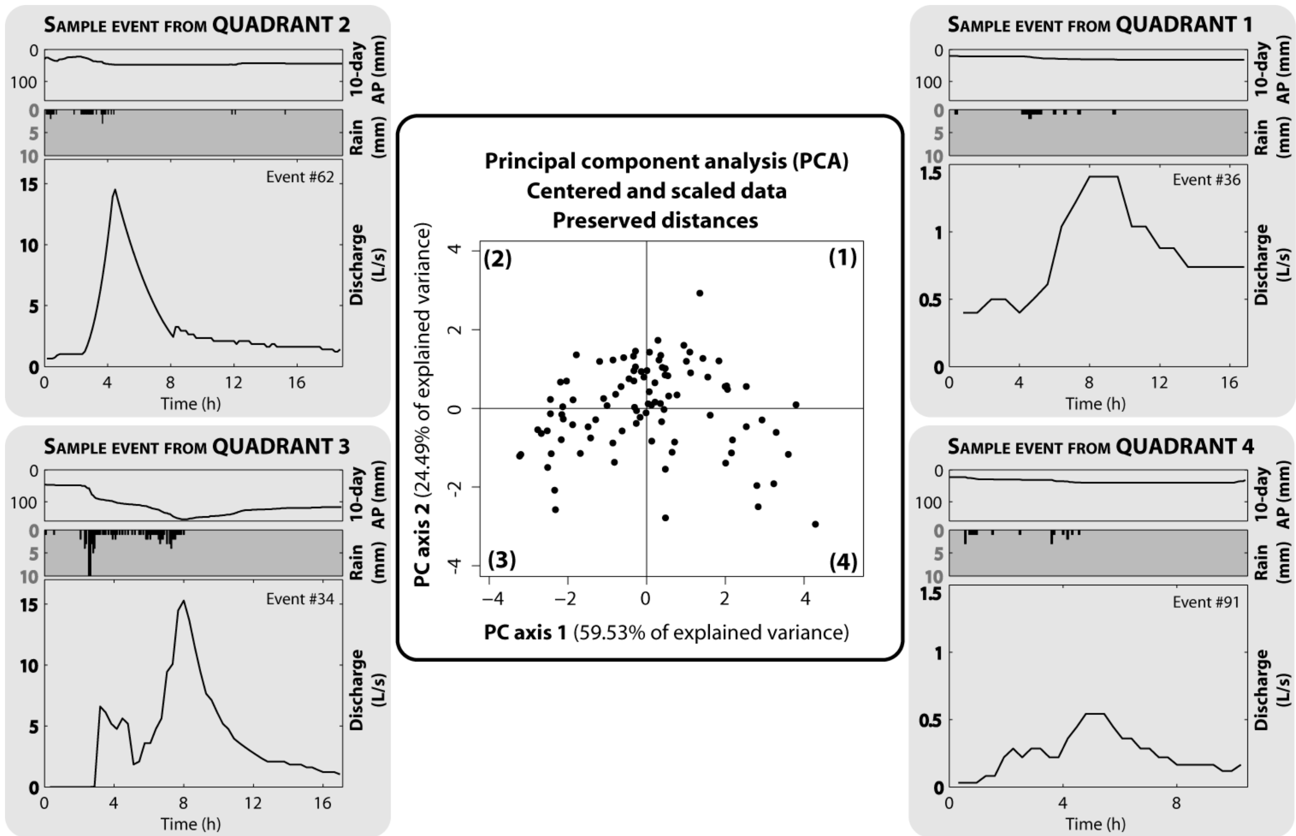


Figure 3.3 – Principal component analysis (PCA) distance biplot and sample hydrological events in the Hermine catchment. In the middle white panel, objects (i.e. events) are illustrated as dots in the four PCA quadrants while descriptor-axes (i.e. response variables) are not shown. In the corner grey-colored panels, typical hydrological events associated with each PCA quadrant are shown. For each sample event, hourly 10-day AP (antecedent precipitation, mm), rainfall (mm) and discharge at the catchment outlet (L/s) are drawn. Note that a single value of AP10 was used in all statistical analyses to characterize each storm event; continuous time series of AP10 are plotted here only to illustrate the temporal evolution of moisture conditions through the course of the events. Y-axes for the 10-day AP and rainfall plots are reversed.

b. Controlling variables

Variation partitioning results between low and high magnitude response types (PCA quadrants 1 and 4 versus 2 and 3) and between slow and quick timing response types (PCA quadrants 1 and 2 versus 3 and 4) are shown using Venn diagrams (Figure 3.4). Levels of variation among classified quadrants that are explained neither by antecedent moisture conditions nor by storm characteristics or seasonal properties are high (i.e. 51% for low/high magnitude events, 47% for slow/quick timing events).

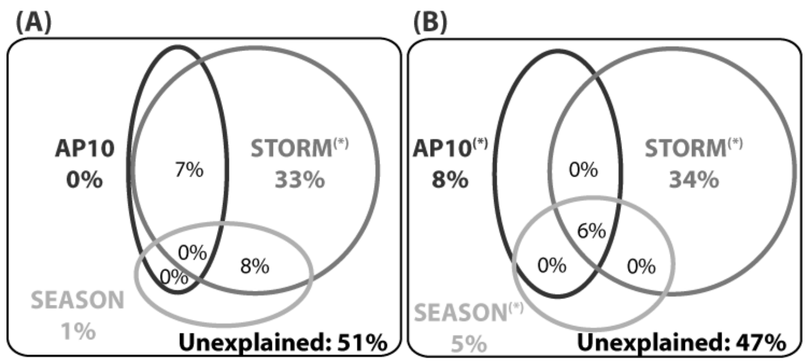


Figure 3.4 – Variation partitioning of event hydrograph features between three groups of explanatory variables: 10-day antecedent precipitation (AP10), storm characteristics (total event precipitation and maximum rain intensity, referred to as STORM) and seasonal properties (SEASON). Venn diagrams illustrate **(A)** Differences in controls on low versus high magnitude events, and **(B)** Differences in controls on **s**low versus quick timing events. In each case, the rectangle represents 100% of the variation in the events characteristics, while the intersection between two ellipses is the amount of variation explained by both explanatory variables associated with the two ellipses. Individual fractions of variance were tested for significance ($p < 0.05$) using permutation tests. Joint effects could not be tested for significance because they cannot be obtained directly by a canonical analysis. Significant fractions are flagged with an (*) on the Venn diagrams.

Storm characteristics explain most of the variation among event hydrograph features. The differences between low and high magnitude runoff events are best explained by storm characteristics alone, and by the joint effect of storm characteristics and antecedent moisture conditions (Figure 3.4 A). The same conclusion applies for the differences between slow and quick timing events, except that antecedent moisture conditions have a greater control on the establishment of quick timing events (Figure 3.4 B). The usefulness of seasonal influences in discriminating low from high magnitude response types is rather low, unless their joint effect with storm characteristics is considered (Figure 3.4 A). The individual effect of the SEASON variable is more significant as we differentiate slow timing from quick timing events (Figure 3.4 B).

c. Triggering thresholds

Cross-validation results are shown in Figure 3.5. They illustrate the different classification tree sizes that were tested before choosing an optimal one and pruning. A simple rule that can be used to choose an optimal tree is to identify the smallest cross-validation error, that is, the cross-validation relative error which is within one standard error of the minimum (Breiman *et al.*, 1984). Hence, in Figure 3.5, the solid line shows the cross-validation relative error for each tree size tested while the dashed line marks the cutoff, one standard error above the cross-validation error minimum. The 'best' tree is illustrated by the grey-filled circle as the smallest tree size under the cutoff.

The optimally-sized, pruned classification tree (9 nodes) is shown in Figure 3.6 and includes 10-day antecedent precipitation (AP10), total event rainfall (TOTRAIN) and maximum rainfall intensity (MAXRAIN) as explanatory variables. Each split is labeled with the decision variable, its threshold value that determines the split, and the distribution of observed runoff events according to their PCA quadrant classification. The vertical depth of each split is directly proportional to the variation explained by each split. The average misclassification rate of the model (i.e. the proportion of events belonging to response type 'x' but not classified as such after cross-validation) is 28.1%, but it is worth discriminating prediction errors with respect to each of the four PCA quadrants (Table 3.3).

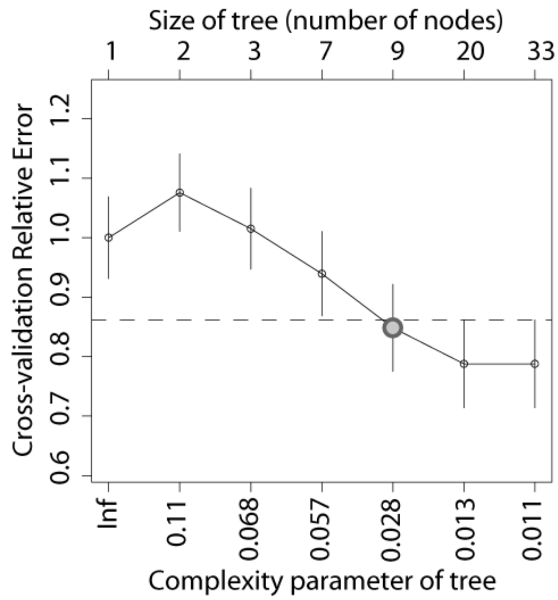


Figure 3.5 – Cross-validation relative error for the regression tree of PCA-derived response types. The horizontal dashed line is drawn 1 standard error (1-SE) above the minimum cross-validation relative error. Following a single 10-fold cross-validation and according to the 1-SE rule, the optimal size of tree (marked by the large grey-filled circle) is the leftmost value for which the mean lies below the horizontal line.

Table 3.3 – Assessment of prediction uncertainty of the classification tree. Misclassification rates are computed following 10-fold cross-validation.

	NUMBER OF EVENTS	NUMBER OF MISCLASSIFICATIONS	RATE OF MISCLASSIFICATION
All quadrants	96	27	28.1%
Quadrant 1	30	7	23.3%
Quadrant 2	22	13	59.1%
Quadrant 3	25	2	8.0%
Quadrant 4	19	5	26.3%

Misclassification is less frequent for events belonging to PCA quadrant 3 but events belonging to PCA quadrant 2 have a 60% chance of being misclassified. These results suggest that explanatory variables are mostly useful to differentiate low from high magnitude events, in comparison to slow versus quick timing events, in agreement with Figure 3.2. These results are also consistent with the distance biplot (Figure 3.3) on which the agglomeration of several events along the PC axes is observed. Given that several events are positioned at the limit between two (or more) response types in the PCA space, we see that their associated prediction error (i.e. misclassification rate) tends to be higher.

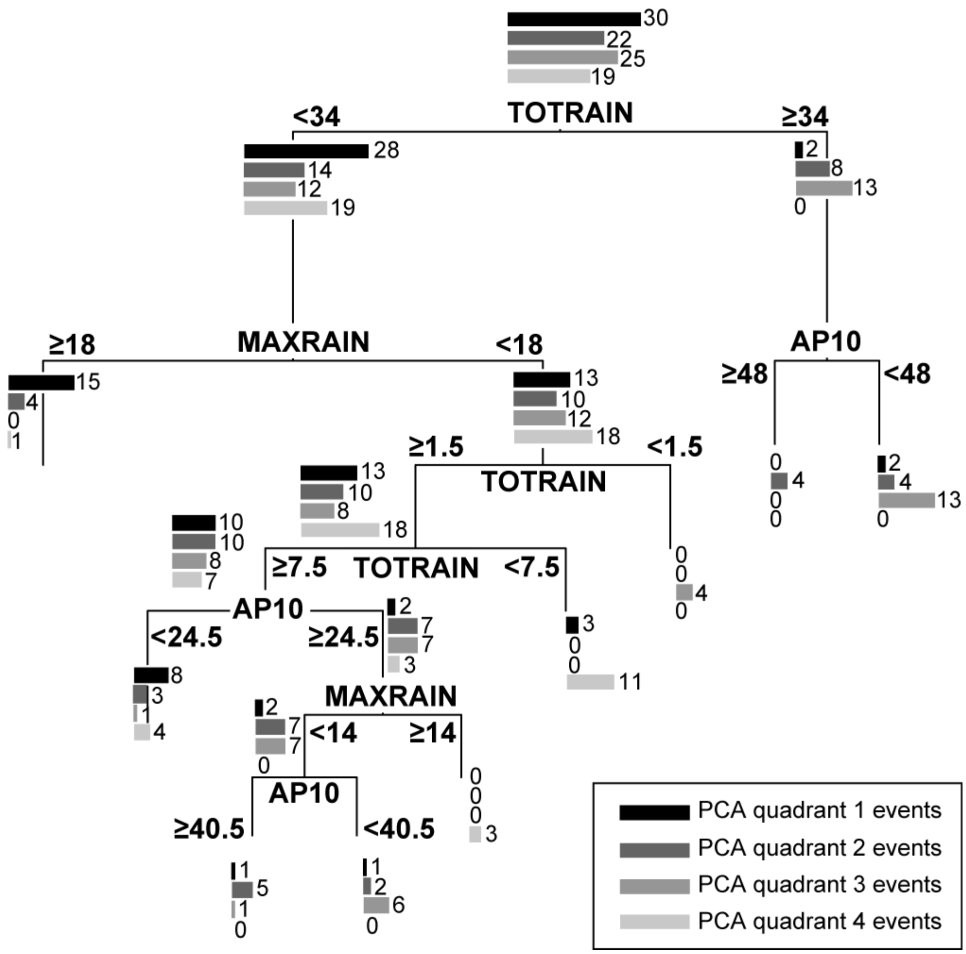


Figure 3.6 – Regression tree analysis of the four categories of runoff events (i.e. PCA quadrants). The explanatory variables retained after pruning the tree were 10-day antecedent precipitation (AP10, mm), total event rainfall (TOTRAIN, mm) and maximum rainfall intensity (MAXRAIN, mm/h). Each split is labeled with the decision variable, its threshold value that determines the split, and the distribution of observed runoff events according to their PCA quadrant classifications. The vertical depth of each split is directly proportional to the variation explained by each split.

Total event rainfall is the most important differentiation criterion between events from the four PCA quadrants (Figure 3.6). Low magnitude events associated with PCA quadrants 1 and 4 mostly occur when total event rainfall does not exceed 34 mm. However, events belonging to PCA quadrants 2 and 3 are almost as numerous regardless of whether total precipitation is above or below 34 mm. Maximum rain intensity comes as the second most important differentiation criterion. High magnitude events preferentially occur when total event rainfall and maximum rain intensity do not exceed 34 mm and 18 mm/h respectively. Prior wetness conditions represented by the 10-day antecedent precipitation values determine the preferential occurrence of high magnitude and/or quick timing events. When total event rainfall reaches or exceeds 34 mm, there are as many PCA quadrant 2 events below and above the 48 mm 10-day antecedent precipitation (AP10) threshold, while PCA quadrant 3 events occur only when AP10 is below 48 mm. When total event rainfall is below 34 mm, however, AP10 thresholds have a greater influence on the occurrence of events belonging to PCA quadrants 3 and 4 and associated with quick timing runoff. Interestingly, quick timing events are subjected to a threshold behavior in which a lower and an upper bound are involved. Events from PCA quadrants 3 and 4 are present when AP10 is below 24.5 mm, but they are more numerous when AP10 is between 24.5 and 40.5 mm. It is also worth mentioning that seasonal properties do not intervene at any level in the pruned classification tree (Figure 3.6) meaning that they only have a limited effect on runoff response types in comparison to storm characteristics and antecedent moisture conditions.

3.2.4 Discussion

a. On the magnitude-timing classification: relevance and theoretical basis

The combination of multivariate techniques used in this paper confirms that catchment-specific response types can be discriminated on the basis of storm hydrograph features. These features explain a significant amount of the variation among the Hermine catchment multiple runoff responses to rainfall inputs, although explanation is higher along PC axis 1 (Figure 3.2). The labeling of the first two PC axes as “runoff magnitude” and “runoff timing” can be translated into “temporal connectivity” and “spatial connectivity” gradients respectively. Indeed, several authors have advocated that hydrologic connectivity exerts a crucial control on the propagation of the ‘flood wave’ within a catchment, and hence it influences both the magnitude and timing of peak runoff (Branfireun & Roulet, 1998; Lane *et al.*, 2003). It is also possible that runoff magnitude is the result of catchment water balance and partitioning of flow between different flow paths (Lane *et al.*, 2003). Temporal or dynamic connectivity refers to the fact that catchment internal linkages vary over different timescales due to the time-changing availability of surface/subsurface water. This time-changing availability of water is reflected in most response variables contributing to PC axis 1, namely the total and maximum event discharges and the runoff coefficient. For a given rainfall amount, the higher the runoff coefficient, the more likely we will see the contribution of both new water and old subsurface water to the storm hydrograph (James & Roulet, 2009). On the other hand, timing effects are thought to dominate when prior conditions are wet enough for numerous catchment areas to produce runoff (Lane *et al.*, 2003). Response time often reflects the wetness of a watershed or a hillslope (Dingman, 1994; Carey & Woo, 2001). The time lag variable that influences PC axis 2 indicates the degree of catchment-scale spatial connectivity by signaling when active areas effectively might contribute to the direct runoff portion of the hydrograph. Hence, following the definitions of catchment runoff sources by McGlynn & McDonnell (2003), response variables contributing to PC axis 1 are indicative of the behavior of temporal sources (i.e. old versus new water) while response variables contributing to PC axis 2 are rather indicative of the contribution of spatial sources (e.g. catchment topographic units, saturated areas). Using a time and space discrimination of the PCA space has a strong theoretical basis, since plotting the temporal against the spatial dimension of events is indicative of hydrological flow routing velocity. Such discrimination is, however, at odds with the orthogonal property of the PC axes. Uncorrelated "time" and "space" labeled PC axes are not realistic given that the temporal and spatial dimensions are highly correlated in catchment hydrology. Labeling of the PC axes was also delicate as it was done according to response variables which preferentially contribute to their explained variance. In the PCA correlation diagram (Figure 3.2), the arrows describing the total and maximum event discharge and the runoff coefficient are very much clustered with each other and correlated with PC axis 1, which legitimizes our classification regarding the runoff magnitude gradient. However, correlations of the time to peak and time lag arrows with PC axes 1 and 2 are weaker (Table 3.2), which illustrates the difficulty in assigning them to the explanation of a unique principal component. While the PCA application in this study gives us some insights about the influence of temporal and spatial runoff sources on the establishment of catchment response types, it lacks information about spatial structures that greatly influence both the magnitude and timing of peak flows (Lane *et al.*, 2003).

b. On hydro-meteorological variables: necessary but not sufficient

The relationships between the values of the hydro-meteorological variables and the establishment of the four response types as identified by PCA are rather complex. For example, according to the variation partitioning results, antecedent moisture conditions have a very weak control on types of hydrologic responses (Figure 3.4). When considering the architecture of the classification tree, however, antecedent moisture conditions are very important to discriminate events from PCA quadrants 3 and 4 associated with quick runoff timing (Figure 3.6). Confronting variation partitioning and CART results is therefore interesting for hypothesis building and testing. The weak explanation power of antecedent moisture conditions according to variation partitioning results may indicate that either AP10 is not a good surrogate for antecedent moisture or that the relationship between the type of runoff response and antecedent moisture conditions is not linear as assumed by the constrained ordination technique. Yet, the influence of AP10 on PCA quadrants 3 and 4 events is clear at multiple stages in the hierarchy of the classification tree. This result provides some indirect evidence of hydrologic connectivity in the Hermine catchment, as it suggests that a relationship between the type of runoff response and antecedent moisture conditions can be found if assumed nonlinear and dependent upon specific meteorological thresholds.

The main contribution of this study is the identification of several hydrological threshold effects. These thresholds are valid at the catchment scale since they are derived from storm hydrograph parameters and cannot be applied to hillslope-based precipitation thresholds such as those obtained from trench flow studies (e.g. Whipkey, 1965; Mosley, 1979; Tromp-Van Meerveld & McDonnell, 2006a). Peters *et al.* (1995) showed that a rainfall threshold for hillslope flow (8 mm) was half the value of the rainfall threshold triggering stream response (17 mm) in a forested catchment from the Canadian Shield. More recently, James & Roulet (2007) also found a significant threshold-based relationship between the runoff ratio and the catchment mean soil moisture content used as a measure of antecedent conditions. While Tromp-Van Meerveld & McDonnell (2006a) evaluated the hillslope-scale precipitation threshold to be large (55 mm) both under dry and wet conditions at Panola (Georgia, USA), Tani (1997) rather observed a single hillslope-scale precipitation threshold to be dependent on antecedent moisture conditions in Japan. Our results suggest the inverse situation to that witnessed in Japan, since catchment-scale antecedent conditions thresholds (i.e. AP10 thresholds) are multiple and depend on amounts of total event rainfall (TOTRAIN). Further investigations should, therefore, be conducted in order to establish whether the reverse situation is site-specific or attributable to the scale of analysis (hillslope versus catchment).

The double threshold dynamics associated with antecedent moisture conditions and quick timing events, together with the high unexplained variation in the Venn diagrams, underlines the limits of this study with regards to inferring the governing properties of hydrologic response. While hydro-meteorological variables explain a substantial proportion of the variance in runoff response types, half of the variability remains unaccounted for and could be better understood with a comprehensive examination of catchment morphological features and their effects on the spatial distribution of stormflow. Very few studies have exposed double threshold dynamics similar to the one discussed in this paper. Yair & Raz-Yassif (2004) determined that the rainfall-runoff response of an arid catchment was dictated by two rainfall thresholds: a 'lower threshold' marking the minimum water input required for runoff generation to take place in high rainfall intensity conditions, and an 'upper threshold' representing the necessary water input in intermittent, low rainfall intensity conditions. The difference between the 'lower' and the 'upper' thresholds was found to increase with drainage area, as the storm concentration time needed for spatially-connected surface runoff to occur also increases with drainage area. At a much smaller scale, Leighton-Boyce *et al.* (2005) examined the moisture 'transition zone' concept which states that two separate soil moisture critical thresholds exist and have an impact on stormflow routing: one threshold below which repellency dominates and one above which wet conditions dominate. Modeling studies also make use of a double threshold dynamic in conceptual models, given that field capacity is a 'lower threshold' for soil storage and saturation excess overland flow results from an 'upper' soil storage threshold (e.g. Kusumastuti *et al.*, 2007). Given the very different experimental set-up that we used here and the lack of comparison basis with the previously mentioned studies, we can only hypothesize that our double threshold dynamics is the result of simultaneous triggering conditions for dominant hydrological processes in the Hermine catchment. Given TOTRAIN > 34 mm, when AP10 is larger than 24.5 mm, it is reasonable to presume that the spatial connectivity of source areas is enhanced due to a widespread influence of rapid shallow lateral subsurface flow on the steep hillslopes of the catchment, thus explaining the increasing number of quick timing events in PCA quadrant 3 and in PCA quadrant 4 to a lesser extent. The fact that runoff events associated with AP10 below the 40.5 mm threshold are significantly faster than those associated with AP10 above the 40.5 mm threshold may be attributed to maximum rainfall intensity which is inferior to 14 mm/h in the later case. As antecedent conditions are high, several active humid areas may be present throughout the catchment, however small rainfall intensity may not be sufficient for widespread connectivity to take place between humid areas over the longest hillslopes or between valley side slopes and the stream channel. The unusual occurrence of quick timing events in dryer conditions (e.g. when AP10 is below 24.5 mm) may reflect the presence of conditions conducive to soil hydrophobicity. This phenomenon has been proposed as an explanation for this type of events in the Hermine catchment by Biron *et al.* (1999). It is known to occur following long dry periods in forested catchments because of the water-repellent behavior of organic materials in surface organic horizons and of the dehydrated organic matter coatings present on soil particles in the upper mineral soil horizons (Wilson *et al.*, 1990; Burcar *et al.*, 1994; Doerr *et al.*, 1996). By limiting infiltration, the hydrophobic effect favors surface runoff over unsaturated near-stream zones even more rapidly than under more hydrophilic conditions.

c. On prediction uncertainty: reliability of inferential hypotheses

The current application of the CART method enabled us to detect breakpoints or thresholds in the hydro-meteorological variables that lead to a switch between response types. The relatively high misclassification rates following cross-validation highlight the complexity of the catchment response. Events in PCA quadrant 3 labeled as "high magnitude" and "quick timing" runoff responses are forecasted with the most accuracy because they are associated with the most extreme values of hydro-meteorological variables. This is encouraging given that prediction usually aims not at transitional but rather at large events. This is also interesting from a methodological standpoint, as our characterization of the variability of hydrologic responses is only based on simple integrated measures derived from easily available data. The misclassification rate of events with low magnitude and slow timing characteristics could however be lowered, and the current value of 23.3% really illustrates how difficult it is to decide upon a lower threshold to label the less significant events in terms of runoff response.

In order to fully address these uncertainty issues, some further analyses (that could not be conducted in this study due to the small number of sampled events) would have been required. For instance, issues related to prediction uncertainty could be addressed in the context of poorly gauged catchments, as one may ask how much hydrological event data is needed in order to determine the appropriate threshold values and therefore predict future catchment behaviors when data are missing. CART prediction models have an optimal complexity that is only dependent upon the dataset, and it is intuitive that the larger the dataset, the more robust the model. Instead of using a 10-fold cross-validation procedure, several "test" and "independent validation" datasets of various sizes could be examined in order to choose the optimal number of nodes and the rules for the classification tree. The proposed multi-stage multivariate analysis of storm hydrographs could also be twined with a regionalization method so as to evaluate what the robustness of the classification thresholds is when we move from the headwater scale to the drainage basin scale. Typically, regionalization is the transfer of hydrological information (e.g. model or hydrograph parameters), without any calibration needed, from gauged sites to rather poorly gauged or ungauged sites where data is short in time, scarce in space or nonexistent (Blöschl & Sivapalan, 1995; Tung, 1997; Wagener & Wheater, 2006). One of the most widely used regionalization approaches is regression analysis, as it attempts to identify the 'structure' of a model that describes the functional relationship between the studied or modeled hydrological parameters and catchment characteristics (Tung, 1997). In the context of poorly gauged catchment, a regionalization approach should be based on easily available information such as physical catchment descriptors (Kokkonen *et al.*, 2003). The use of hydrologic regionalization with our multivariate approach could, therefore, prove useful in evaluating the (spatial) generalization potential of the site-specific response types and their associated triggering thresholds.

3.2.5 Conclusion

The proposed combination of multivariate techniques was helpful to identify dominant runoff response types but also to detect switches and thresholds in controlling variables that trigger the establishment of these runoff response types within a humid temperate forested catchment. Response types were discriminated into low versus high magnitude events, and into slow versus quick timing events. While no seasonal influence on hydrologic responses was found, runoff magnitude appears to be mainly controlled by storm characteristics whereas runoff timing is impacted by the joint effect of storm characteristics and initial conditions as portrayed by 10-day antecedent precipitation. These observations support recent work in catchment hydrology and recent definitions of catchment-wide connectivity which state that the availability of water to be routed to the stream depends not only on the magnitude of change in hydrologic conditions but also on the timing and rate of change (Bracken & Croke, 2007). Even though they are site-specific, our results show that it is possible to characterize a wide range of catchment response types based on simple hydrological measures and to associate them with realistic hydrological processes in space and time. The CART method is a very promising technique in such a context, as it is an easy-to-use, visual-friendly technique that works from the bottom upwards, thus extracting important and key information from a dataset without prior knowledge or assumption about the shape of the governing relationships. The proposed multi-stage multivariate analysis of storm hydrographs therefore appears as a useful complement to complex process-based models, an alternative that would become even more robust as issues related to prediction uncertainty, sample size and spatial scales are resolved.

3.3 Paragraphe de liaison "3-4"

L'étude relatée dans la section 3.2 représente une double contribution à la théorie hydrologique renouvelée. D'un point de vue technique, trois méthodes d'analyse statistique rarement utilisées dans le domaine ont pu être présentées. Il a été démontré que leur utilisation combinée plutôt qu'isolée pouvait être bénéfique afin de tester des hypothèses sur le comportement hydrologique d'un petit bassin versant forestier tempéré humide. Il a aussi été démontré qu'en se basant uniquement sur les caractéristiques des hyétogrammes et des hydrogrammes de crue, il était possible de classer les réponses hydrologiques en fonction de leur magnitude (faible ou grande) et de leur *timing* (lent ou rapide). Le comportement non linéaire du bassin versant de l'Hermine a été mis en évidence puisque la présence de l'un ou l'autre des types de réponses hydrologiques est régie par le dépassement de valeurs seuils de précipitations et de conditions d'humidité antécédentes.

La présence d'effets de seuil et de comportement non linéaires laisse croire à des changements de connectivité hydrologique dans le bassin versant. En conséquence, on peut affirmer que l'approche « boite noire » est une manière indirecte d'estimer la connectivité hydrologique, et elle a l'avantage de ne se baser que sur des données hydro-météorologiques aisément accessibles et sur des méthodes statistiques faciles à mettre en application. Cependant si les résultats obtenus dans ce chapitre vont dans le sens de l'existence de conditions changeantes de connectivité, on ne sait pas quelles sont les unités morphologiques (spatiales) du bassin versant de l'Hermine qui influencent le plus ces changements. Les types de réponses hydrologiques définis à partir de la magnitude et du *timing* des débits mesurés à l'exutoire ne laissent aucun doute quant à l'importance du nombre d'aires contributives à l'écoulement et de leur localisation par rapport au cours d'eau. Des informations précises sur ces aires contributives ne peuvent cependant pas être obtenues simplement par l'analyse des hyétogrammes et des hydrogrammes de crue.

Dans le but de remédier à ce problème, le Chapitre 4 utilise une approche « boite grise » afin d'estimer la connectivité hydrologique dans le bassin versant de l'Hermine. Contrairement à l'approche « boite noire », l'approche « boite grise » considère un faible niveau de discrétisation spatiale afin d'en apprendre plus sur la localisation et la contribution respective des sources de ruissellement au débit du cours d'eau. Une analyse de la variabilité spatio-temporelle des sources de ruissellement est donc effectuée dans le but de mieux circonscrire les mécanismes qui sous-tendent l'établissement de la connectivité hydrologique à l'échelle du bassin versant.

CHAPITRE 4

ÉTUDE DE LA CONNECTIVITÉ HYDROLOGIQUE SELON L'APPROCHE « BOITE GRISE »

4.1 Contexte

Cette partie de la recherche découle du principe que la nature de la connexion hydrologique entre les versants et le cours d'eau peut être évaluée en identifiant les sources spatio-temporelles du ruissellement. On adopte ainsi une approche de type « boite grise » puisque l'on se sert de données locales sur le fonctionnement interne du bassin versant de l'Hermine pour évaluer les changements de connectivité. L'article scientifique reproduit à la section 4.2 cherche à déterminer i) combien de sources contribuent à l'alimentation du débit du cours d'eau, ii) quelles sont leurs contributions relatives, et iii) à quelle moment la contribution de ces sources est-elle activée ? À cette fin, des données géochimiques historiques collectées à l'exutoire du ruisseau de l'Hermine et dans les trois groupes de parcelles expérimentales (i.e. bas de versant, haut de versant, tête de bassin) sont utilisées. Chaque groupe de parcelles est considéré comme une source spatio-temporelle potentielle, et il s'agit de comparer la composition chimique de l'eau des différents compartiments (i.e. pluviolessivat, horizons organiques, horizons minéraux et nappe phréatique profonde) à celle de l'eau du ruisseau. Dans la foulée du Chapitre 3, on cherche ainsi à approfondir nos connaissances sur les mécanismes qui sous-tendent l'établissement de la connectivité hydrologique dans le bassin versant de l'Hermine.

4.2 Source-to-Stream Connectivity Assessment through End-member Mixing Analysis [3]

4.2.1 Introduction

The establishment, maintenance and disruption of catchment-wide hydrologic connectivity have been associated with critical runoff production processes and precipitation or moisture thresholds above which stormflow generation is favored (Weiler *et al.*, 2005; Tromp-Van Meerveld & McDonnell, 2006a; James & Roulet, 2007; Lehmann *et al.*, 2007). Dimensions and controlling variables of connectivity are, however, multiple, thus leaving the door open for a large number of definitions, interpretations and approaches of the concept. Following the work of Bracken & Croke (2007), a recent review of the literature led to a classification of hydrologic connectivity definitions into four categories of increasing preciseness (Ali & Roy, 2009). The definitions classified as the "most specific" directly refer to flow processes that allow a rapid, threshold-driven hydraulic connection between landscape units, and they suggest the necessity to investigate processes like subsurface flow or translatory (piston) flow acting above an impeding soil layer.

In order to look into subsurface stormflow, several studies have been conducted using trench excavations (Dunne & Black, 1970a, b; Woods & Rowe, 1996; Tromp-Van Meerveld & McDonnell, 2006a, b), but this technique is not widely used because it generates hydraulic artifacts and since it cannot be deployed over the whole catchment area in order to fully capture triggering processes and their scaling properties. An alternate way to investigate subsurface stormflow is the study of active and maybe connected flow sources using the geochemical signature of stream and soil waters (Bazemore *et al.*, 1994;

[3] Ali, G. A., A. G. Roy, M.-C. Turmel & F. Courchesne, 2010b. 'Source-to-Stream Connectivity Assessment through End-member Mixing Analysis', *Journal of Hydrology*.

Weiler *et al.*, 2005). Indeed, the conditions encountered by water originating from different catchment sources while *en route* to the stream control biogeochemical transformations that ultimately determine stream water chemistry (Bishop *et al.*, 1990; Mulholland *et al.*, 1990; Bonell, 1993; Jenkins *et al.*, 1994; Brown *et al.*, 1999; Hill *et al.*, 2000; McClain *et al.*, 2003). As a result, mixing models relying on natural tracers (i.e. chemical elements) have been shown to be effective for stormflow generation hypotheses testing; they assume that stream water is a mixture of discrete "source" solutions that have extreme solutes concentrations in comparison to streamflow (Christophersen *et al.*, 1990; Christophersen & Hooper, 1992). Traditional end-member mixing analysis (EMMA) models, based on principal component analysis (PCA), were first introduced in the 90s and require not only knowledge of the stream chemistry but also the explicit identification of potential end-members (i.e. streamflow sources) (Christophersen *et al.*, 1990; Christophersen & Hooper, 1992). Hooper diagnostic tools for mixing models of stream chemistry were formally defined a decade later (Hooper, 2003), thus providing a more general mathematical formulation in which eigenvector and residual analyses of observed stream water chemistry are performed to estimate the appropriate number of contributing end-members. End-members sampled in the field are then screened for their ability to fit into the mixing space, i.e. the multidimensional space obtained from the PCA of observed stream water chemistry (Hooper, 2003; James & Roulet, 2006).

Mixing models are especially useful as they allow inferring and quantifying the relative contributions of different sources to streamflow by using small-scale, internal catchment measurements (e.g. groundwater and soil water chemistry) to explain the integrated, large-scale response at the catchment outlet (Genereux & Hooper, 1998; Hooper, 2001, 2003; James & Roulet, 2006). However, one challenge associated with mixing models is the large spatial and temporal variability of stormwater flow paths. Active flow paths and contributing water sources to streamflow depend on the interaction between rainfall intensity and amount (Dunne, 1978), antecedent catchment conditions (Elsenbeer *et al.*, 1994), soil depth (Ross *et al.*, 1994) and surface or bedrock topography (Brammer & McDonnell, 1996; Brown *et al.*, 1999). These catchment properties are also thought to control hydrologic connectivity, making it difficult to build a simple conceptual model of catchment hydrological behavior. A thorough literature review by Brown *et al.* (1999) reveals that most studies conducted in temperate forested catchments have focused on streamflow generation processes that take place when prior catchment conditions are wet and soil moisture deficits are low, or in high rainfall areas. Meanwhile, mechanisms that control soil water and groundwater routing to the stream when catchment antecedent conditions are dry or transitional are much less investigated and understood. When the aim is to get some insight into variable contributing areas and periods in a specific catchment, event-based geochemical data associated with a wide range of hydro-meteorological conditions are required. When such data are unavailable, another approach that consists in breaking down a multiyear stream chemistry dataset into multiple sub-datasets associated with different hydro-meteorological conditions should be privileged as it can reveal temporal changes in the nature and/or the number of contributing streamflow sources. Mixing models rely on the premise that the geochemical signatures of end-members are time-invariant (Hooper, 2001; James & Roulet, 2006). They assume that only the presence and the mixing of end-members in streamflow vary with time, and such an approach is consistent with hydrologic connectivity definitions that usually imply an increased contribution of stormflow from source areas, both quantitatively (number of contributing areas) and volumetrically (importance of individual contributions).

Following a recommendation of Liu *et al.* (2008), we use a combination of Hooper diagnostic tools and end-member mixing analysis in a headwater, temperate humid, forested catchment. Liu *et al.* (2008) argued that such a combination of methods reinforces the assumptions of mixing models and enhances their results, especially if chemical data are limited. In this paper, a 11-year stream chemistry dataset has been broken into 64 different hydrologic scenarios in order to test for the variability of controlling end-members across a range of hydrologic conditions. Sub-datasets were discriminated from one another with respect to stream discharge at the catchment outlet, and as a function of 2-day or 7-day antecedent precipitation values. Cumulative precipitation values were used as surrogates for catchment antecedent conditions over the short- and the medium-term. Justification for the chosen hydrologic scenarios lies in the fact that strong nonlinearities and threshold-like dynamics affect headwater catchments, a phenomenon that has been observed at the study site (Ali & Roy, 2010c). Examining such a complex internal catchment dynamics from the point of view of stream chemistry is the main contribution of this paper. The objectives of the study are to:

(1) assess the number of streamflow sources needed to explain the Hermine catchment dynamics under several dozens of different hydrologic scenarios;

(2) examine how the relative contributions from some sources (11 potential) vary with each hydrologic scenario in order to assess catchment connectivity from a spatial (horizontal or vertical) perspective; and

(3) estimate scenario-dependent relative contributions of discrete sources to streamflow to characterize catchment connectivity from a volumetric standpoint.

4.2.2 Data Collection

a. Field Site

We examined the hydrological behavior of a 5.1 ha headwater forested catchment, the Hermine, located at the Station de Biologie des Laurentides (SBL) of the Université de

Montréal. It is situated on the Canadian Shield, in the Lower Laurentians about 80 km north of Montréal, Québec, Canada (45°59’ N, 74°01’ W, elevation c. 400 m) (Figure 4.1 (A)).

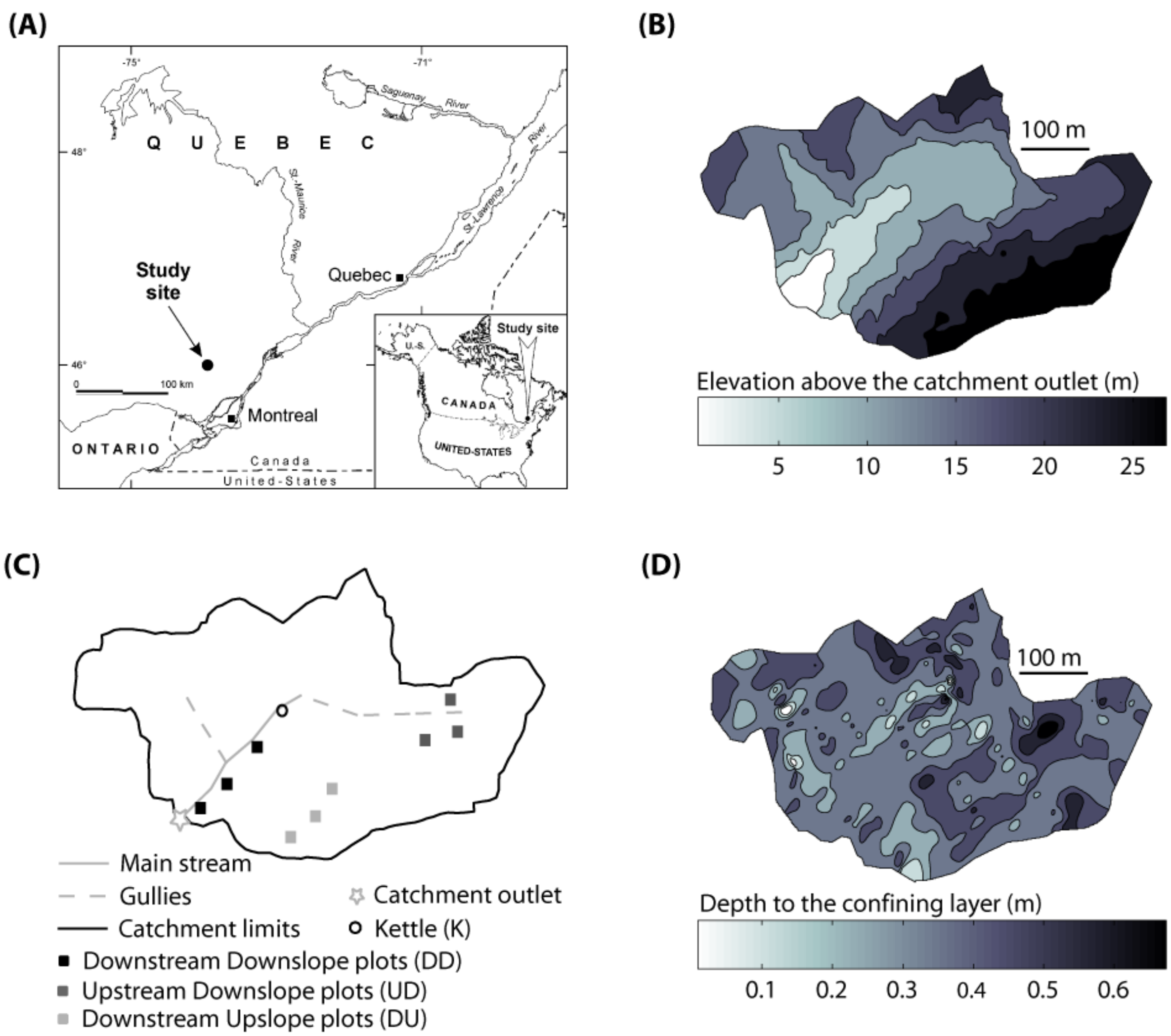


Figure 4.1. **(A)** Location of the Hermine catchment; **(B)** Surface digital elevation model; **(C)** Location of the sampling sites; and **(D)** Depth to refusal in soil. The raster grid is 2 m by 2 m in panels **(B)** and **(D)**.

The Hermine has a difference in elevation of 31 m between the outlet and the highest point in the catchment. Figure 4.1 (B)) and is drained by an ephemeral stream that runs east to west (Figure 4.1 (C)). The maximum daily average temperatures are observed in July (+ 25°C) while daily minima (– 30°C) occur in January. The total annual precipitation averages 1150 mm (± 136 mm) for the last 30 years, of which about 30 % falls as snow (Biron *et al.*, 1999).

Soils are developed over a relatively thin sedimentary cover composed of a glacial till. The bedrock is an igneous and impervious feldspar-rich Precambrian anorthosite of the Morin series. Till mineralogy is rather heterogeneous. Soils are mostly classified as 1 to 2 m deep sandy orthic, gleyed humo-ferric or ferro-humic Podzols (Turmel *et al.*, 2005); they present a discontinuous, compact and impervious layer at a depth of about 50 to 75 cm (Figure 4.1 (D)) that restricts root penetration, slows water infiltration and enhances the probability of rapid lateral subsurface flow. The canopy of the Hermine is dominated by sugar maple (*Acer saccharum* Marsh., 78% of total basal area), American beech (*Fagus grandifolia* Ehrn., 9%) and yellow birch (*Betula alleghaniensis* Britton, 6%) with the accompanying species balsam fir (*Abies balsamea* (L.) Mill.), white birch (*Betula papyrifera* Marsh.), trembling aspen (*Populus tremuloides* Michx.) and large-toothed aspen (*Populus grandidentata* Michx.) (Courchesne *et al.*, 2001). Floristic composition is not uniform throughout the catchment, as pioneer species (e.g. trembling and large-tooth aspen, white birch) tend to concentrate in upslope areas while non-pioneer species (e.g. sugar maple, yellow birch) rather cluster in downslope areas. Transpiration is minimal between October and April, so that changes in soil moisture and water table height during that period are mostly governed by downslope drainage movement. The interception capacity of the forest canopy and the high infiltration potential of soils, combined with high summer evapotranspiration, reduce the likelihood of surface runoff except during heavy rainstorms or spring snowmelt. From 1 m deep wells at nine downstream downslope (DD), upstream downslope (UD) and downstream upslope (DU) 300 m² sampling plots in the catchment (Figure 4.1 (C)), we estimated the mean water table depth at 68 cm for the last 12 years;

however, strong seasonal variations have been observed. The shallowness of the perched water table during wet periods indicates that transient lateral saturation excess flow can rapidly occur following a significant precipitation event in the Hermine catchment.

b. Field Sampling and Laboratory Analyses

The Hermine catchment is the subject of an ongoing long-term monitoring program initiated in 1993 and aimed at examining elemental cycling, hydrology and forest growth at several spatial and temporal scales. Since the beginning of the project, streamflow has been measured continuously at a 90° V-notch weir, thus providing us with mean daily discharge values. Daily rainfall totals are also obtained from a weather station at the Station de Biologie des Laurentides situated just 1 km north from the Hermine catchment. Comparisons between these data and the amount of rain collected fortnightly during the growing season and monthly during the dormant season in open samplers located within the watershed showed a close agreement (regression slope: 1.08, r = 0.98) (Biron *et al.*, 1999).

For the purposes of EMMA, we used stream water and soil water chemical data for the 1994-2005 period, except for 1998 when the project was interrupted. Stream water samples were collected daily at the weir using an automatic water sampler. However, all stream water data was not kept as we discarded samples associated with the winter and the snowmelt periods and samples for which an entire suite of 11 chemical characteristics could not be measured. As a result, our complete stream water chemical database (n = 1384) was made of 31% late spring (i.e. non snow-dominated) samples, 21% summer and 47% fall samples. Potential end-members were sampled at nine 300 m² experimental plots distributed in three zones: downstream downslope (DD), upstream downslope (UD) or downstream upslope (DU) (Figure 4.1 (C)). These zones illustrate the range of forest canopy conditions and elevations in the catchment. Downstream downslope plots are proximal to the main stream channel, while upstream downslope sites are situated near an intermittent gully that we know to be active in periods of heavy rainfall, and we assume all experimental plots to be representative of the spatial variability in the watershed.

Table 4.1. Description of 11 potential end-members independently sampled in the Hermine catchment. Percentages refer to the proportion of samples collected during late spring (no snowmelt), summer and fall.

Potential end-member	**n**	**Abbreviated name**	**Remarks**
Baseflow	178	B	Source or mixture of sources feeding the stream under very low flow conditions (less than 1 mm per day)
Kettle	23	K	Deep groundwater 48% late spring, 30% summer, 22% fall samples
Downstream Downslope[a]			
Throughfall[b]	204	DD-T	16% late spring, 58% summer, 26% fall samples
Organic[c]	187	DD-O	21% late spring, 56% summer, 23% fall samples
Mineral[d]	93	DD-M	43% late spring, 29% summer, 28% fall samples
Upstream Downslope[a]			
Throughfall[b]	223	UD-T	16% late spring, 57% summer, 27% fall samples
Organic[c]	137	UD-O	17% late spring, 56% summer, 27% fall samples
Mineral[d]	94	UD-M	46% late spring, 28% summer, 26% fall samples
Downstream Upslope[a]			
Throughfall[b]	163	DU-T	16% late spring, 56% summer, 28% fall samples
Organic[c]	130	DU-O	25% late spring, 49% summer, 26% fall samples
Mineral[d]	72	DU-M	53% late spring, 25% summer, 22% fall samples

[a] "Downstream Downslope", "Upstream Downslope" and Downstream Upslope" refer to experimental sampling plots locations. See Figure 4.1 (C)
[b] "Throughfall" water is used as a surrogate for surface runoff
[c] "Organic" designates soil solution from organic FH horizons under the forest floor
[d] "Mineral" represents soil solution at 50 cm in the mineral B horizon

Each of these experimental plots are equipped with a throughfall collector, a snow collector and two zero-tension lysimeters installed at 0 cm (under the LFH horizons, at the interface between the organic and mineral soil horizons) and 50 cm (under the rooting zone in the B-horizon). All zones and compartments were sampled both during the growing (15

May to 15 November, weekly) and the dormant (15 November to 15 May, monthly) seasons. However in this study, we only considered samples associated with the growing and more "hydrologically active" season. Also, similarly to what was done for stream water data, soil water samples for which a whole suite of 11 chemical characteristics could not be measured were discarded. This resulted into most throughfall and organic soil water samples to be associated with the summer and the fall seasons, while mineral soil water samples were almost equally distributed between late spring, on the one hand, and summer and fall on the other hand (Table 4.1). Occasionally, deep groundwater was sampled from a well located in a small depression (referred to as kettle or *K*) in the catchment (Figure 4.1 (C)). As for the potential baseflow end-member (also referred to as *B*), it was assumed to have the same chemical signature as streamflow under very low flow conditions (discharge < 1 mm/d). In total, 11 potential end-members or streamflow sources were considered in this paper (Table 4.1).

All stream water and soil water solutions were sampled in acid-washed plastic bottles. 24 hours after we went and collected the samples, each unfiltered stream or soil water sample was analyzed for pH and electrical conductivity (EC) using appropriate meters. The rest of the sample was passed through a 0.45 µm polycarbonate membrane (Millipore) filter and refrigerated at 4°C. Analyses performed on filtered solutions included nitrate (NO_3^-), ammonium (NH_4^+), sulfate (SO_4^{2-}), potassium (K^+), chloride (Cl^-) and sodium (Na^+) concentrations by ion chromatography (HPLC, Waters Milford, Massachussetts, USA), while calcium (Ca^{2+}) and magnesium (Mg^{2+}) concentrations were measured by atomic absorption spectrometry (Lambda 1, Perkin Elmer, Oak Brook, Illinois, USA). Dissolved organic carbon (DOC) was measured using a carbon analyzer (TOC analyzer, Shimadzu, Kyoto, Japan) on 5% of the samples. For the remaining unfiltered solution, DOC concentrations were estimated using a series of linear relations between absorbance at 254 nm and DOC (Turmel *et al.*, 2005). The precision of this method is 0.01 mg/l and the bias in the comparison with true values is between 1 and 3% (Biron *et al.*, 1999).

4.2.3 Analytical Methods

a. Tracer Selection and Hydrologic Scenarios

From the whole stream water dataset, the selection of solutes as tracers was achieved based on three criteria: (i) ability to distinguish between end-members, (ii) time-invariant concentrations in end-members, and (iii) consistency with the conservative mixing hypothesis. Regarding the first criterion, for each solute, nonparametric Kruskal-Wallis tests were performed to evaluate if concentrations were significantly different ($p < 0.05$) among at least one pair of potential end-members. Boxplots were also drawn to illustrate the differences in the chemical fingerprints of independently measured potential end-members. While “stable” or “time-invariant” end-members are often assumed in mixing analyses, this is hardly true for all solutes in catchments exhibiting strong seasonality. In our study, this assumption had to be verified before we could suggest that streamflow always consists in the mixing of the same end-members but in time-variable proportions. Hence, following Hooper (2001) and James & Roulet (2006), solutes retained for our mixing analyses had to exhibit a temporal variability in the potential end-members that was less than or in the same range as their temporal variability in streamflow. Temporal variability was assessed through the coefficient of variation (CV) of individual solutes in streamflow and in each of the independently sampled potential sources. To assess the solutes’ satisfaction to the last criterion, bivariate solute plots were drawn and examined for linear trends. Even though linear trends in these plots do not confirm conservative mixing, they are consistent with its core principle (Hooper, 2003; James & Roulet, 2006).

Hooper's diagnostic tools were especially devised to determine the appropriate number of end-members and conservative tracers for EMMA while using only streamflow chemistry. They rely on the physical and mathematical distinction between mixing and equilibrium chemistry (Hooper, 2003; Liu et al., 2008). Equilibrium reactions among solutes of different charges are proven dependent on high-order polynomial processes. Conversely, conservative mixing does not account for geochemical weathering and chemical interactions within each end-member reservoir and does not involve any ionic exchanges after source waters from different hydrologic units have reached the stream. Hence, it is considered as a linear process (Liu et al., 2008). We therefore discriminated non collinear ($r^2 < 0.2$, $p > 0.05$), weakly collinear ($0.2 \leq r^2 \leq 0.5$, $p < 0.05$) and linear ($r^2 > 0.5$, $p < 0.01$) solute pairs so as to complete our tracer selection.

In order to investigate the direct effects of antecedent wetness and stream discharge on mixing models results, four levels of discharge (*DIS_1*, *DIS_2*, *DIS_3* and *DIS_4*), of 2-day antecedent precipitation (*AP2_1*, *AP2_2*, *AP2_3* and *AP2_4*) and of 7-day antecedent precipitation (*AP7_1*, *AP7_2*, *AP7_3* and *AP7_4*) were defined (Table 4.2). The numerical thresholds differentiating the four levels for the three variables were decided upon based on a trade-off between the catchment response types observed in the field and the statistical distribution of the variables. *AP2* and *AP7* were chosen as surrogates for antecedent moisture conditions because they have distinct influences on the hydrology of the Hermine catchment. As for the thresholds between levels 1 and 2, levels 2 and 3, and levels 3 and 4, they correspond to the 10^{th}, 50^{th} and 90^{th} percentiles of the discharge, 2-day and 7-day antecedent precipitation datasets. In addition to using the whole stream water chemical dataset to perform EMMA, the four levels of discharge, 2-day and 7-day antecedent precipitation were also considered individually (n = 12) or in combinations (n = 64) so as to form hydrologic scenarios. For example, *DIS_1* refers to all samples collected at low flow regardless of prior wetness conditions, while the combination of *DIS_4*, *AP2_4* and *AP7_1* refers to samples collected when discharges were high and when short-term antecedent conditions were high but medium-term antecedent conditions were low. A possible total of 77 hydrologic scenarios could be studied (n = 1 + 12 + 64), however 13 combinations of scenarios were associated with no data (i.e. no hydrologic events), especially when it came to the highest discharge scenarios that had to be coupled with low antecedent conditions. Hence, this paper was articulated around 64 mixing spaces obtained from stream water chemical datasets of various sizes (5 ≤ water samples ≤ 1384).

Table 4.2. Conditions associated with the definition of hydrologic scenarios for the segmentation of the historical stream water chemical dataset prior to mixing analyses. Conditions illustrate different ranges of stream discharge (*DIS_X*) at the catchment outlet, and 2-day and 7-day antecedent precipitation values (*AP2_X* or *AP7_X*). Cumulative precipitation values are used as surrogates for catchment antecedent conditions over the short- and the medium-term.

INDIVIDUAL CONDITIONS				
mm/d	***DIS_1***	***DIS_2***	***DIS_3***	***DIS_4***
	Discharge < 0.4	0.4 < Discharge < 0.9	0.9 < Discharge < 4	Discharge > 4
mm	***AP2_1***	***AP2_2***	***AP2_3***	***AP2_4***
	2-day AP < 2	2 < *2-day AP* < 6	6 < *2-day AP* < 15	*2-day AP* > 15
mm	***AP7_1***	***AP7_2***	***AP7_3***	***AP7_4***
	7-day AP < 15	15 < *7-day AP* < 25	25 < *7-day AP* < 40	*7-day AP* > 40
HYDROLOGIC SCENARIOS (HS)				
Individual conditions or combinations of conditions Total : 77 hydrologic scenarios (for 13 of them, n = 0)				
SCENARIOS MOST REFERRED TO IN THIS PAPER				
HS 1	All samples	Whole stream water chemical dataset (n = 1384)		
HS 14	DIS_1 & AP2_1 & AP7_1	The driest and assumed "least connected" scenario (n = 134)		
HS 35	DIS_2 & AP2_2 & AP7_2	Dry to intermediate conditions (n = 13)		
HS 56	DIS_3 & AP2_3 & AP7_3	Intermediate to wet conditions (n = 28)		
HS 77	DIS_4 & AP2_4 & AP7_4	The wettest and assumed "most connected" scenario (n = 52)		

b. Stream Water Chemistry and Mixing Models

In an attempt to characterize stream water chemistry across scenarios, diagrams were constructed following the method of Piper (1944). Piper diagrams are made of two triangular plots (one for cations and one for anions) and a quadrilateral plot. All plots were generated using concentrations of the major cationic and anionic species expressed in units of meq/l. The trilinear plot of cations and anions illustrate the abundance of each solute (for cations: Ca, Mg and Na+K; for anions: Cl, SO_4 and HCO_3+NO_3) as a fraction of their sum. Alkalinity (ALK) is often used as a surrogate for bicarbonate (James & Roulet, 2006), but alkalinity titration was not performed on stream water samples from the Hermine catchment. Alkalinity was therefore estimated by assuming the electrical neutrality of the samples and balancing the appropriate charges (ALK = 2*[Ca] + 2*[Mg] + [Na] + [K] – [Cl] – 2*[SO_4] – [NO_3]). The two triangular plots are combined to form a quadrilateral graph in which the axes represent Ca+Mg and Cl+SO_4 as a fraction of total major cations and anions, respectively. The obtained patterns can, then, be examined to classify a given catchment into a groundwater facies (e.g. calcium-magnesium, bicarbonate, sodium-bicarbonate, etc.). Piper diagrams are especially useful in comparing stream water chemistries associated with different sites or flow conditions.

For the generation of each mixing space (or U-space) corresponding to each hydrologic scenario, we applied the diagnostic tools of Hooper (2003) and end-member mixing analysis with the following steps:

i. The stream water geochemical data (n samples × p solutes) were standardized by centering them about their means and dividing them by their respective standard deviations. That operation, yielding a correlation matrix, ensured that solutes with the greatest variability do not have more influence on the model at the expense of those with lesser variation.

ii. Eigenvector analysis (i.e. PCA) was performed on the correlation matrix to determine the dimensionality or the rank of the dataset. Indeed, for a mixing model based on a correlation matrix, (at least) one more end-member than the rank is needed to explain the stream water mixture. In searching for the number of eigenvectors (i.e. principal components) to retain, the rule of 1 was applied. This rule states that each additional eigenvector retained should explain at least 1/(number of solutes) of variance in the stream chemistry (Hooper, 2003; James & Roulet, 2006).

iii. Residual analysis was achieved to confirm the dimensionality of the mixing space. For each stream water sample, a residual value is obtained by subtracting its original value from its orthogonal projection in the mixing space. A "good" mixing space should be characterized by a random pattern of residuals plotted against the concentration of the original sample (Hooper, 2003). Structure or curvature in such a plot would rather indicate a lack of fit in the mixing space, possibly due to variable end-member concentrations or nonconservative tracers. Given that the residuals are in units of concentration, they were also evaluated in light of analytical precision; patterns in residuals were said to be unstructured (i.e. random) only when their average value was smaller than or similar in value to the solutes analytical precision (Hooper, 2003; James & Roulet, 2006) (Table 4.3). Additional eigenvectors were therefore retained until a random pattern in the residuals-concentrations plot is observed (Hooper, 2003).

Table 4.3. Tracer selection criteria and results for the Hermine catchment. The symbol "√√" means that the solute totally satisfies the criterion, while "√" means that the solute only partially satisfies the criterion. For each solute, the analytical error is expressed as a percentage of its average concentration in stream water.

Solutes	Distinct end-members signatures	Time-stable end-members	Assumed conservative behavior	Used for EMMA	Analytical error (%)
EC	√	√√	√√	Yes	8
H	√√	√√		No	5
Na	√	√		No	5
NH_4	√√	√√		No	20
K	√	√√		No	15
Ca	√	√	√√	Yes	2.5
Mg	√	√	√√	Yes	2.5
Cl	√	√√		No	8
NO_3	√	√√	√√	Yes	8
SO_4	√	√	√√	Yes	5
DOC	√√	√		No	5

iv. The fit between observed stream water chemistry concentrations and their orthogonal projections was evaluated using the relative bias (RB) and the relative root-mean-square error (RRMSE) for each solute j :

$$\mathrm{RB} = \frac{\sum_{i=1}^{n}(\hat{x}_{ij} - x_{ij})}{\bar{x}_j} \tag{4.1}$$

$$\mathrm{RRMSE} = \frac{\sqrt{\sum_{i=1}^{n}(\hat{x}_{ij} - x_{ij})^2}}{n \cdot \bar{x}_j} \tag{4.2}$$

where n is the number of samples in the stream water geochemical dataset, $\bar{x}_j$ is the mean concentration of solute j, x_{ij} is the observed concentration of solute j in sample i, and $\hat{x}_{ij}$ is its orthogonal projection in the mixing space (Hooper, 2003). These two measures of error were scaled by the mean concentration of each solute to make them dimensionless. For a scenario studied in a mixing space defined by its own eigenvectors, RB can be noted as $RB_{at\ scenario}$ and is always zero while the RRMSE can be noted as $RRMSE_{at\ scenario}$ and indicates how "noisy" the data cloud is in the reference mixing space (the greater the $RRMSE_{at\ scenario}$, the lesser the ability of the reference mixing model to explain the variability in stream water chemistry). The relative bias and root-mean-square error measures were particularly useful so as to assess the general predictive power of each of the 64 mixing spaces. Four scenarios (HS 14, HS 35, HS 56 and HS77) associated with dry, transitional and wet conditions were, in turn, considered as the "reference scenario" while the 63 others were "test scenarios". Projecting the "test scenarios" into the "reference scenario" and computing the two measures of error was therefore indicative of the ability of the reference mixing space to predict the chemistry of stream water samples that did not contribute to its formation. Positive projected biases ($RB_{in\ reference} > 0$) indicated that the reference model overestimated solute concentrations from the "test scenarios", while negative biases ($RB_{in\ reference} < 0$) rather suggested an underestimation of these concentrations. As for projected RRMSE values ($RRMSE_{in\ reference}$), they were indicative of how much poorer or better the fit of the projected data was in the "reference U-space", in comparison to the case when they were projected in the mixing space defined by their own eigenvectors.

c. End-member Selection and Relative Contributions

After the number of end-members required for each mixing space was defined, we examined 11 potential contributing sources independently sampled in the field (see Table 4.1) to assess their ability to explain the chemical composition of stream water. For each hydrologic scenario, measured end-member concentrations were standardized by subtracting the means and dividing by the standard deviation of the stream observations. They were then projected into each mixing space by multiplying the standardized values by the matrix of retained eigenvectors. The criteria chosen after the work of James & Roulet (2006) for selecting a set of potential end-members were as follows:

i. distinct solute concentrations;
ii. lower temporal variability than observed stream chemistry;
iii. bounding of stream chemistry in U-space; and
iv. less than a 15% difference between observed values and their orthogonal projections in the current scenario mixing space.

The satisfaction to these criteria, fully described in the next section, ensured that the selected end-members fitted in the mixing space and could be used to improve our conceptual understanding of water movements in the Hermine catchment.

For the determination of relative proportions of stream runoff derived from retained end-members, mass balance calculations were performed. In the case where two end-members were needed, the proportion of each potential source in stream water was obtained by solving the linear system formed by equations (4.3) and (4.4):

$$RC_1 + RC_2 = 1 \tag{4.3}$$

$$RC_1 \cdot U1\_EM_1 + RC_2 \cdot U1\_EM_2 = U1\_S \tag{4.4}$$

where RC_1 and RC_2 are the relative contributions of end-members 1 and 2, and $U1\_EM_1$, $U1\_EM_2$ and $U1\_S$ are, respectively, the concentrations of the two end-members (EM) and the stream (S) projected onto the first principal component (U1). Similar linear systems were used to compute relative contributions when three (see equations (4.5)-(4.7)) or four (see equations (4.8)-(4.11)) end-members were retained:

$$RC_1 + RC_2 + RC_3 = 1 \quad (4.5)$$

$$RC_1 \cdot U1\_EM_1 + RC_2 \cdot U1\_EM_2 + RC_3 \cdot U1\_EM_3 = U1\_S \quad (4.6)$$

$$RC_1 \cdot U2\_EM_1 + RC_2 \cdot U2\_EM_2 + RC_3 \cdot U2\_EM_3 = U2\_S \quad (4.7)$$

$$RC_1 + RC_2 + RC_3 + RC_4 = 1 \quad (4.8)$$

$$RC_1 \cdot U1\_EM_1 + RC_2 \cdot U1\_EM_2 + RC_3 \cdot U1\_EM_3 + RC_4 \cdot U1\_EM_4 = U1\_S \quad (4.9)$$

$$RC_1 \cdot U2\_EM_1 + RC_2 \cdot U2\_EM_2 + RC_3 \cdot U2\_EM_3 + RC_4 \cdot U2\_EM_4 = U2\_S \quad (4.10)$$

$$RC_1 \cdot U3\_EM_1 + RC_2 \cdot U3\_EM_2 + RC_3 \cdot U3\_EM_3 + RC_4 \cdot U3\_EM_4 = U3\_S \quad (4.11)$$

In some cases, stream observations happened to lie outside the mixing domain defined by the selected end-members, hence resulting in negative fractions of relative contributions (Liu *et al.*, 2004). This has been attributed to various sources of errors, such as time-variable end-members concentrations, unsampled end-members and tracers in disagreement with the conservative mixing hypothesis (Chaves *et al.*, 2008). When this problem usually arises, negative fractions are forced to zero and other contributions are assumed to be a mixture of the remaining end-members only (Liu *et al.*, 2004). In this paper, however, we only used stream observations enclosed in each scenario-dependent mixing domain for mass balance computations. As for the uncertainty of the results concerning end-members relative contributions, it was assessed using standard deviation and coefficient of variation values computed among the samples associated with each scenario.

4.2.4 Results

a. Stream Water Chemistry and Tracer Selection

From the Piper diagram (Figure 4.2) drawn to characterize the Hermine catchment, we observe that stream water samples are mostly located in the upper diamond of the quadrilateral plot, thus indicating a dominant calcium-magnesium-sulfate facies.

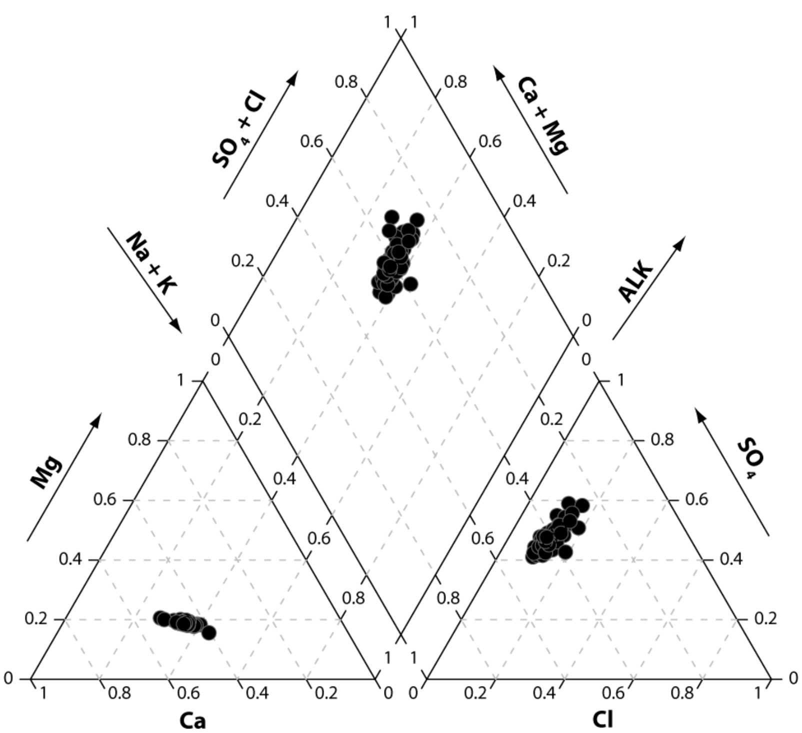


Figure 4.2. Piper diagram of stream water chemistry in the Hermine catchment. Each circle represents mean values for each hydrologic scenario.

Very slight differences arise as we compare the positioning of the filled circles associated with each scenario; this suggests that the variability of the stream water mixture across hydro-meteorological conditions is most likely controlled by time-variable proportional source contributions rather than dramatic changes in the nature of the end-members.

Almost all of the eleven solutes analyzed in the Hermine catchment had the potential to help us distinguish between end-members (Figure 4.3, Table 4.3). Cl^- is the least effective species for that purpose, even though it underlines the importance of throughfall water in feeding the catchment with chloride. K^+ is only useful when it comes to differentiating the baseflow (B) and the kettle (K) end-members. As for NH_4^+ and NO_3^-, they originate from all throughfall end-members (DD-T, UD-T and DU-T) and from downstream downslope and upstream downslope organic soil layers (DD-O and UD-O). EC is at an intermediate level in organic soil water at the downstream downslope and upstream downslope sites but reaches its highest values in downstream upslope organic soil horizons. DOC is also mostly present in near-surface, acidic soil layers, especially in the downstream upslope position. The B and the K end-members are the second-highest sources of Ca^{2+} and Mg^{2+} in the catchment behind organic soil horizons, while throughfall end-members are a potential lower bound to Ca^{2+} concentrations in stream water. Cations concentrations in K are usually depleted in comparison to B, whereas anions concentrations in K are slightly higher than those in B, except for NO_3^-. The B, K and mineral soil end-members (DD-M, UD-M and DU-M) show the highest concentrations of SO_4^{2-}, which is coherent with the mechanism of sulfate adsorption on iron oxides in the B horizon. The differences in geochemical signatures between potential end-members occur on a vertical (throughfall versus organic versus mineral water) rather than on a lateral (downstream versus upstream) scale, except for the downstream upslope organic soils that are markedly different from their counterparts in downslope positions (downstream and upstream, Figure 4.3), probably due to differences in floristic composition between the sites. Differences in vegetation cover are responsible for the spatial variability of litter composition and organic soil water chemistry in the Hermine catchment. The geochemical fingerprint of mineral soil water is consistent across all sites, which also confirms that spatial variability in soil water chemistry mainly affects the very shallow portion of the soil profile.

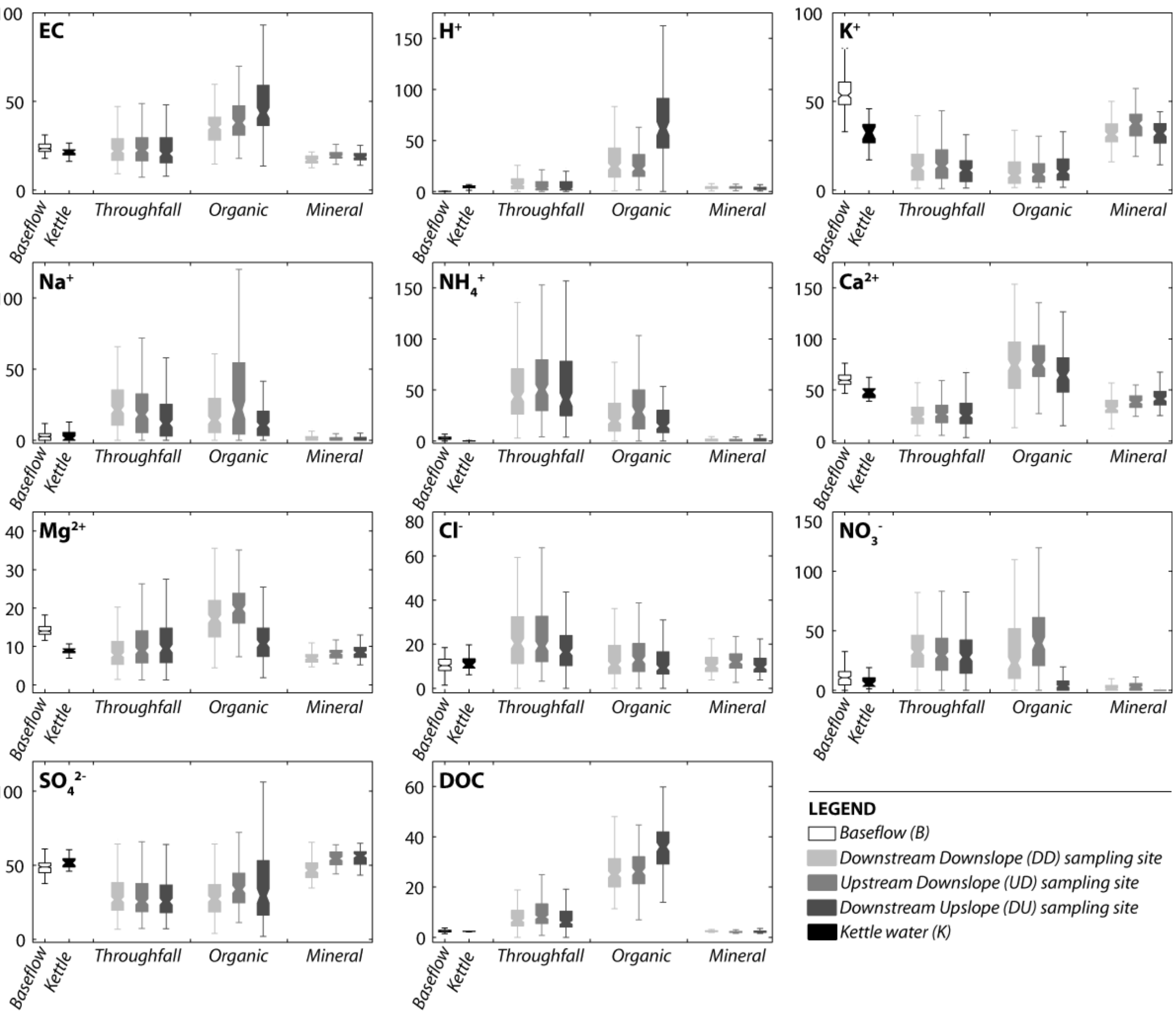


Figure 4.3. Box-and-whisker plots illustrating the chemical signatures of potential end-members independently sampled in the Hermine catchment. Each box has lines at the lower quartile, median, and upper quartile values, while the whiskers extend from each end of the box to show the extent of the rest of the data (minimum and maximum values). Outliers are not shown, but notches are drawn to provide a robust estimate of the uncertainty about the medians for box-to-box comparison. Ions are in units of µM/L, electrical conductivity (EC) is in units of µS/cm, and DOC is in units of mg/L.

Table 4.4. Coefficient of variation (CV) for individual solutes in stream water and in each of the independently sampled potential end-members.

Solutes	EC	H	Na	NH_4	K	Ca	Mg	Cl	NO_3	SO_4	DOC
Stream water	0.31	1.41	0.24	1.93	1.13	0.20	0.18	0.66	0.82	0.15	0.51
B	0.16	0.50	0.19	2.12	1.12	0.18	0.15	0.43	0.96	0.22	0.42
K	0.20	0.32	0.48	2.82	3.73	0.11	0.09	0.55	0.80	0.24	0.40
DD-T	0.45	1.16	0.99	1.05	0.73	0.58	0.69	0.86	0.72	0.52	0.93
UD-T	0.45	1.44	0.91	1.00	0.72	0.52	0.62	0.71	0.80	0.51	0.83
DU-T	0.53	1.48	1.04	1.05	0.97	0.63	0.91	0.77	0.83	0.54	1.13
DD-O	0.31	0.71	0.87	1.67	0.97	0.47	0.41	0.88	1.15	0.51	0.34
UD-O	0.33	0.61	0.86	1.17	0.93	0.33	0.37	0.87	0.83	0.44	0.32
DU-O	0.42	0.62	0.84	1.47	2.35	0.52	0.53	1.05	1.66	0.76	0.33
DD-M	0.14	0.42	0.32	1.54	1.51	0.26	0.24	0.62	1.45	0.14	1.85
UD-M	0.16	0.42	0.22	1.59	1.32	0.20	0.19	0.49	1.49	0.12	0.22
DU-M	0.14	0.61	0.34	1.54	3.58	0.24	0.27	0.57	3.15	0.11	0.81

Time-invariance of solutes concentrations in end-members was also assessed using temporal coefficients of variation (Table 4.4). H^+ is the only solute whose variation in all end-members concentration is always less pronounced than or similar to its variability in stream water. As for the other solutes, time-invariance (variability less or equal to the stream) can only be assumed for specific end-members. For instance, Ca^{2+} and Mg^{2+} concentrations can be qualified as temporally stable in B, K and mineral soil end-members, which happens to be where these two solutes are mostly present and useful to differentiate between potential sources. The assumption of EC as a time-stable tracer is reasonable for all potential end-members but the throughfall (DD-T, UD-T and DU-T) and downstream upslope organic soil waters (DU-O). NO_3^- can be considered as time-invariant in the throughfall, B and K but not for the soil water for almost all sites. SO_4^{2-} can be assumed time-stable in B, K and mineral soil horizons where it is mostly present. Tracers' satisfaction to the time-invariance criterion is summarized in Table 4.3.

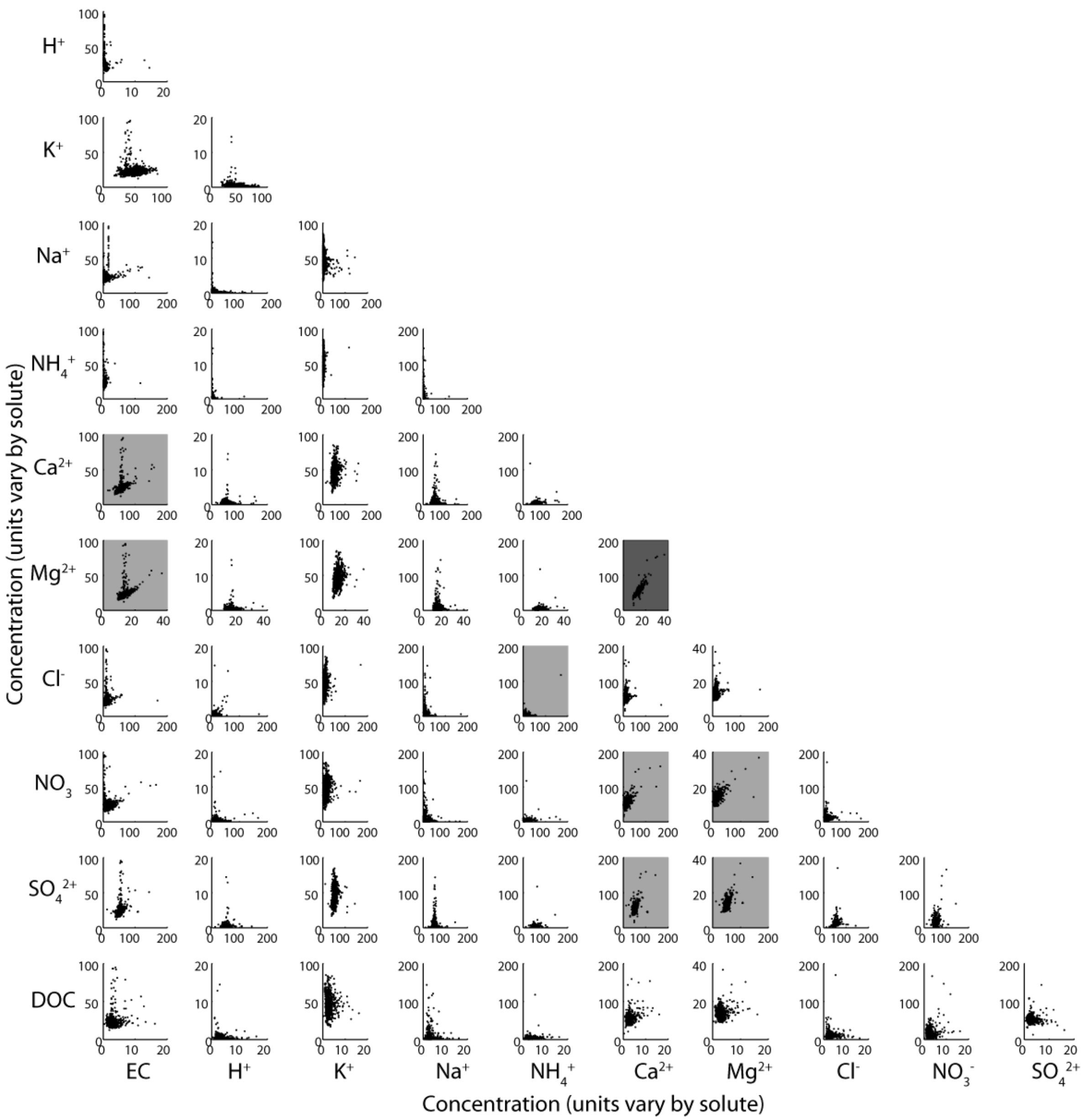


Figure 4.4. Bivariate solute plots of stream water chemistry in the Hermine catchment. White, light grey and dark grey panels indicate no significant, weak and strong linear trends, respectively. Ions are in units of μM/L, electrical conductivity (EC) is in units of μS/cm, and DOC is in units of mg/L.

Lastly, weak and strong linear trends in the bivariate solute plots were examined (Figure 4.4) to complete our tracer selection. On the one hand, even though they discriminate potential end-members, several solutes (e.g. DOC, H^+) could not be retained as they show no evidence of a possible linear stream mixing process. On the other hand, two biologically active species (SO_4^{2-} and NO_3^-) were kept for further analyses because they are involved in two weakly linear trends with two other solutes, and because there is some precedence for assuming conservative mixing with such tracers in a event-based (or scenario-based) context (Brown *et al.*, 1999; James, 2005). Consequently, we included EC, Ca^{2+}, Mg^{2+}, NO_3^- and SO_4^{2-} as tracers in our mixing analyses (Table 4.3).

b. Stream Water Chemistry and Mixing Space Dimensionality across Scenarios

For each stream water geochemical dataset (or sub-dataset) associated with each hydrologic scenario (HS), an independent mixing space dimensionality analysis was performed. Given that the PCA model included five solutes, the rule of one was applied so that eigenvectors explaining 20% of variance would be retained. At that point, 56 scenarios out of 64 were associated with a rank 1 mixing space, while the remaining (n = 8) rather resulted in rank 2 mixing spaces. Rank 1 mixing spaces explained between 69 and 99% of the variability in stream water geochemistry, while rank 2 mixing spaces had a proportion of explained variance ranging from 78 to 98%.

We examined the residuals for each solute in light of analytical error to complete our dimensionality analysis. Given the presence of structure or patterns in the residuals, the number of eigenvectors to retain had to be increased for a majority of scenarios. Two end-members (rank 1 mixing space) were needed to explain the stream water chemistry in 13 scenarios, while 49 other scenarios were associated with a rank 2 mixing space. In two exceptional cases, a rank 3 mixing (i.e. 4 end-members) was even required to explain most of the variance in stream water chemistry. The retention of additional eigenvectors following residual analysis had a beneficial effect on the effectiveness of the mixing models; proportions of explained variance were between 82 and 99%, 85 and 99% and 91 and 98% for rank 1, rank 2 and rank 3 mixing spaces respectively. The residual analyses performed across a range of hydro-meteorological conditions (e.g. scenarios) therefore suggest that most of the time, the stream water geochemical signature arises from the mixture of three catchment sources. Rank 1 mixing spaces are associated either with the lowest discharges scenarios, or with medium to high discharges occurring in relatively dry short-term conditions (low *AP2* scenarios). As for the two exceptional cases with a rank 3 mixing space, they are difficult to explain since they are associated with low to medium discharges, low to medium 2-day antecedent precipitation values and very high 7-day antecedent precipitation values. These exceptional cases of high *AP7* and low discharge might be representative of late hydrograph recession periods.

Scenario-specific stream water samples were first projected in the U-space defined by their own eigenvectors (“at-scenario” approach), hence bias values were null. $RRMSE_{at\ scenario}$ values are rather low, ranging from 0 to 14%, thus indicating that scenario-specific mixing models are robust and unbiased predictors of stream solutes concentrations. Ca^{2+}, Mg^{2+} and SO_4^{2-} are the species with the smallest values of $RRMSE_{at\ scenario}$ (< 3.5%), while the highest errors are encountered with EC and NO_3^- (11.8 and 13.5%, respectively). For Ca^{2+} and Mg^{2+}, $RRMSE_{at\ scenario}$ values are the greatest when discharges are high and when short-term (2-day) and medium-term (7-day) antecedent conditions are wet ($r_{Spearman} > 0.67$, $p < 0.05$). For NO_3^- and SO_4^{2-}, $RRMSE_{at\ scenario}$ are positively correlated with 2-day and 7-day antecedent precipitation ($0.4 < r_{Spearman} < 0.8$, $p < 0.05$). As for EC, $RRMSE_{at\ scenario}$ are positively correlated with stream discharge ($r_{Spearman} = 0.56$, $p < 0.05$) but negatively correlated with surrogates for antecedent conditions ($r_{Spearman} = -0.40$, $p < 0.05$).

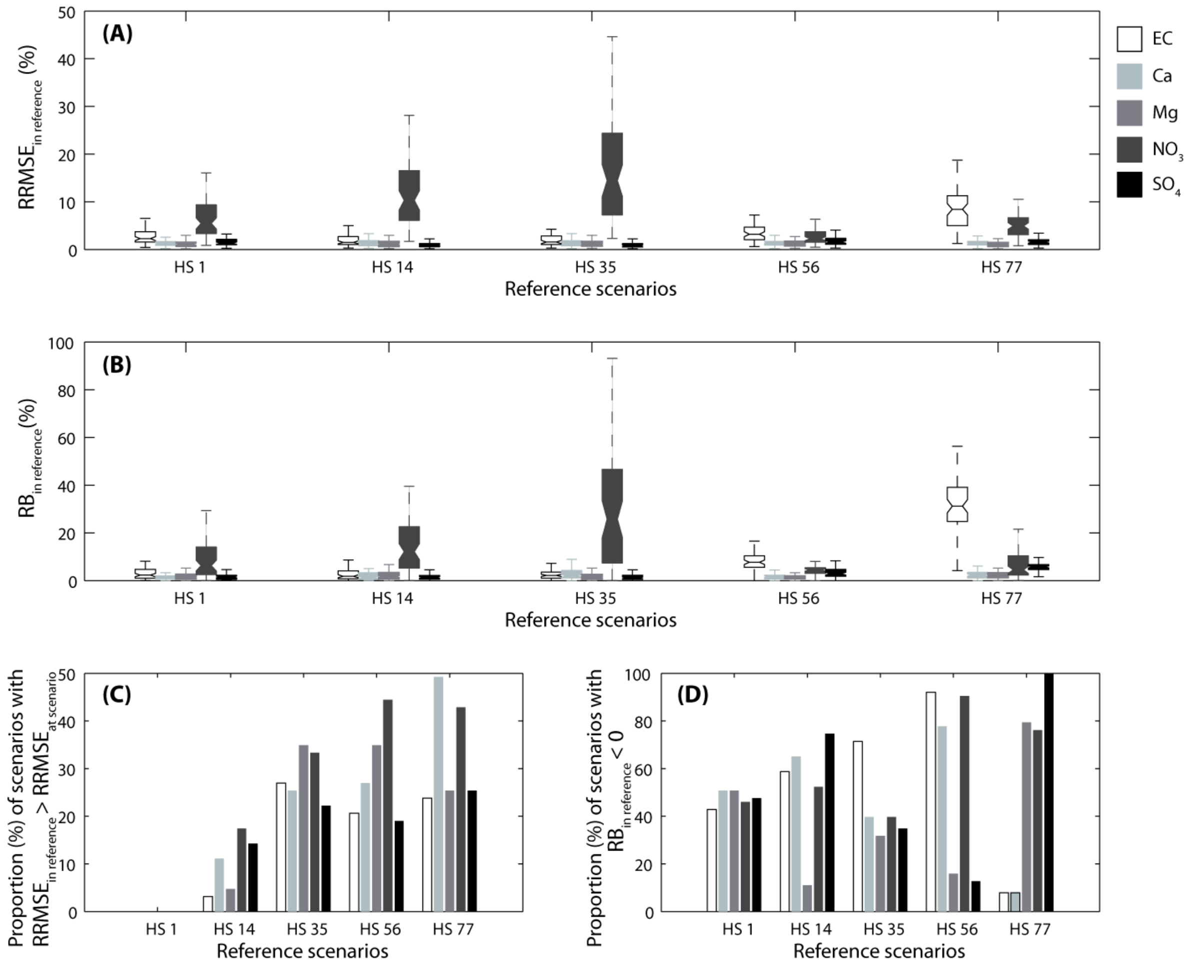


Figure 4.5. Summary of **(A)** $RRMSE_{in\ reference}$ values; and **(B)** $RB_{in\ reference}$ values associated with hydrologic scenarios when projected into "reference mixing spaces". **(C)** Proportion of "test scenarios" with $RRMSE_{in\ reference} > RRMSE_{at\ scenario}$. **(D)** Proportion of "test scenarios" with $RB_{in\ reference} < 0$.

Figure 4.5 illustrates to what extent four "reference" scenarios can predict the stream chemistry observed under different "test scenarios". Despite the fact that stream chemistries were examined in mixing spaces not defined by their own eigenvectors, $RRMSE_{in\ reference}$ associated with Ca^{2+}, Mg^{2+} and SO_4^{2-} remain very low (< 7%, see Figure 4.5 (A)). On the contrary, $RRMSE_{in\ reference}$ values often exceed 15% for EC when stream chemistries are projected into the high discharges, wet prior conditions the HS 77 reference mixing space. $RRMSE_{in\ reference}$ values for NO_3^- are the greatest, especially when the reference scenarios involve dry to transitional conditions and low to intermediate flows (e.g. HS 14 and HS 35). Regardless of the scenario used as a reference, $RB_{in\ reference}$ is important for NO_3^- and, to a lesser extent, EC (Figure 4.5 (B)). HS 56 used as a reference appears to be the mixing space with the largest predictive power as projected stream samples exhibit the lowest values of $RB_{in\ reference}$. HS 35 is the worst mixing space to predict projected NO_3^- concentrations, whereas HS 77 is the least effective in predicting projected EC concentrations.

When using HS 77 as a reference scenario, 25 to 50% of the projected scenarios present a better fit ($RRMSE_{in\ reference} > RRMSE_{at\ scenario}$), in comparison to when they are projected onto the mixing space defined by their own stream chemistry (Figure 4.5 (C)). This is particularly true for Ca^{2+} and NO_3^-, as the proportion of projected scenarios with a better fit increases to 50 and 40% respectively. When using scenarios HS 35 or HS 56 as a reference, the proportion of projected scenarios with a better fit is also in the range of 20 to 40%. When HS 14 is used as a reference, however, $RRMSE_{in\ reference}$ values are usually worse than $RRMSE_{at\ scenario}$ values, especially for EC and Mg^{2+}. HS 77 is associated with a large over-prediction of EC and Ca^{2+} and an under-prediction of the three other solutes (Figure 4.5 (D)).

c. Nature of End-Members and Relative Contributions across Scenarios

Figure 4.6 illustrates some examples of mixing spaces or U-spaces. They are associated with five different hydrologic scenarios and they include both stream water and end-member data projected into a reference system derived from eigenanalysis and defined by orthogonal principal axes (i.e. U1 and U2). Dimensionality results revealed that three end-members are generally needed to explain the Hermine catchment stream chemistry. The nature of these end-members varies among the considered hydrologic scenarios.

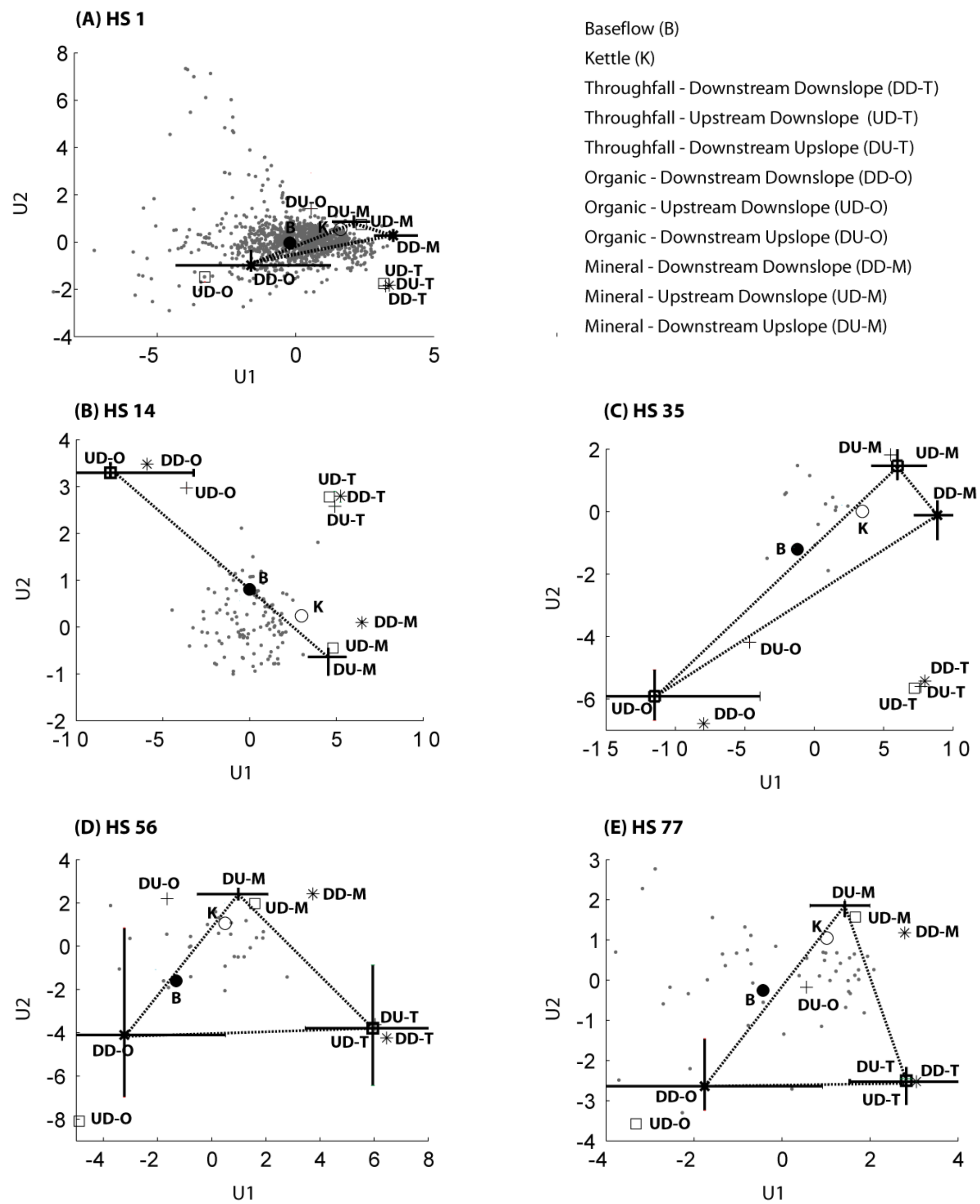


Figure 4.6. U-space mixing diagrams associated with five different hydrologic scenarios (HS). Refer to Table 4.2 for the description of each scenario. Stream samples are illustrated as small grey dots while dotted black lines are used to draw the bounding triangles. Error bars depict the interquartile range only for end- members at the apices of the bounding triangles.

With a few exceptions, baseflow (B) is not a viable end-member as it fails to bound the stream water mixing cloud in the U-spaces. The B component lies on the line joining upstream downslope organic soil water and downstream upslope mineral soil water in all mixing spaces (see example in Figure 4.6 (B)), hence suggesting that baseflow (e.g. stream water at low flow) is the mixture of these two sources. The kettle end-member has the second-best fit in each mixing space (average percentage difference of less than 8% for EC, Ca^{2+} and SO_4^{2-}; 30% for Mg^{2+} and NO_3^-) but it also fails to bound stream chemistry. Throughfall end-members (DD-T, UD-T and DU-T) exhibit the worst fit in all mixing spaces, except when discharges are high and medium-term (7-day) antecedent precipitation values are important. Percentage differences for these end-members markedly exceed 15%, especially for EC, NO_3^- and SO_4^{2-} (average percentage errors per solute atop 100%). Regardless of the mixing space considered, UD-T is the potential source among all throughfall end-members that has the best percentage differences and reasonably fits “high discharges and wet conditions” scenarios (e.g. HS 73, combining *DIS_4*, *AP2_3* and *AP7_4* conditions; HS 76, combining *DIS_4*, *AP2_4* and *AP7_3*; or HS 77, combining *DIS_4*, *AP2_4* and *AP7_4*). It is, however, worth mentioning that the percentage differences associated with DD-T and DU-T are less than 3% higher than those of UD-T (see the superimposition of symbols in Figure 4.6). This suggests that throughfall end-member could even be considered as “spatially invariant”. Organic soil end-members have a good fit in most mixing spaces, especially in the two downslope positions (downstream and upstream). Organic soil water from the downstream upslope area has the largest percentage differences, which suggest that it is less likely to contribute to the stream water mixtures associated with the majority of hydrologic scenarios. NO_3^- is the solute for which the greatest percentage differences are encountered, thus indicating that all mixing spaces fail to model accurately its concentrations. As for mineral soil end-members, they usually fit in all mixing spaces provided that they are located in downstream positions (downslope or upslope).

For most scenarios, many stream water samples projected in the U-space fall outside the mixing domain defined by the end-members (i.e. bounding triangle defined by three sources, see Figures 4.6 (A), (C), (D) and (E)). When examining the whole historical data set (HS 1), the chemical signatures that better fit in the mixing space are those of the organic and mineral soil layers in the downstream downslope zone and the mineral layer from downstream upslope experimental plots (Figure 4.6 (A)). For low discharges and dry antecedent conditions, streamflow appears as a the mixture of upstream downslope organic soil layer and downstream upslope mineral soil layers, which may represent a more or less diluted version of baseflow (Figure 4.6 (B)). In the opposite situation, for high discharges and wet prior conditions (Figure 4.6 (E)), contributing sources to streamflow are upstream downslope throughfall, organic soil layers from the downstream downslope area and mineral soil layers from downstream upslope locations. As for scenarios associated with intermediate levels of discharges (i.e. conditions *DIS_2* and *DIS_3*), they correspond to a mixing model that is similar to the one associated with HS 1 and involves a mixture of downstream downslope soil water (organic and mineral) and upslope mineral soil water. In almost all rank 2 mixing spaces, a more or less large number of stream observations fall outside the bounding triangle and therefore they were not considered in mass balance computations.

Mass balance calculations allowed us to further compare the stream water mixtures in mixing spaces. Proportional contributions were examined while keeping in mind that they are not weighted by scenario-specific mean discharge values. As illustrated in Figure 4.7, the differences observed along a continuum of discharge conditions (HS 2, HS 3, HS 4 and HS 5) did not affect the nature of the end-members but rather their relative contributions to streamflow. Pie diagrams in Figure 4.7 suggest that the higher the discharges, the greater the contribution from mineral soil water originating from downstream downslope sites in the Hermine catchment. The two other major sources are then organic soil water from upstream downslope sites and mineral soil water from downstream upslope areas.

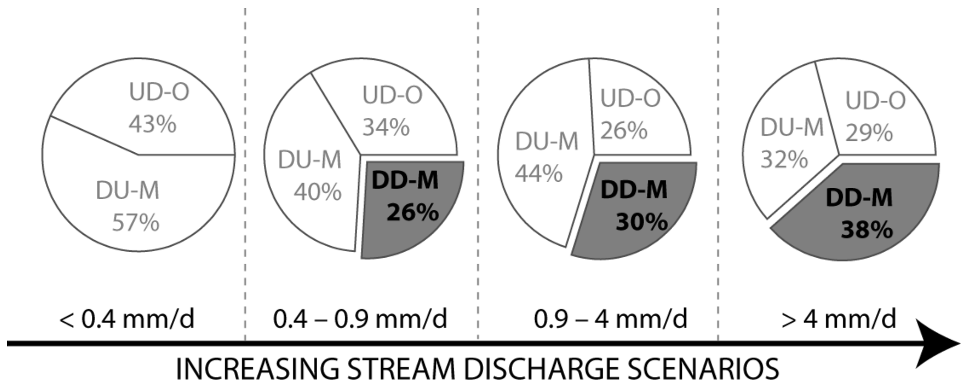


Figure 4.7. Relative contributions of end-members to streamflow for selected hydrologic scenarios of increasing discharge levels (refer to Table 4.1 for end-members abbreviated names).

Discharge scenarios were further discriminated with respect to 7-day antecedent precipitation, so that the relative end-member contributions from selected hydrologic scenarios could be confronted (Figure 4.8). The influence of 7-day antecedent precipitation on the temporal variability of end-member relative contributions to streamflow is greater than that of 2-day antecedent precipitation. At medium-low discharges (i.e. *DIS_2*) and dry conditions, the contribution from downstream upslope mineral soil water is greater than that of upstream downslope organic soil water. Although counter-intuitive, that result is confirmed by water table depths measured at the nine experimental plots (Figure 4.9); comparison of HS 14 and HS 30 reveals an enhanced contribution from upslope sources associated with the *DIS_2* level, in spite of *AP2_1* and *AP7_1* conditions.

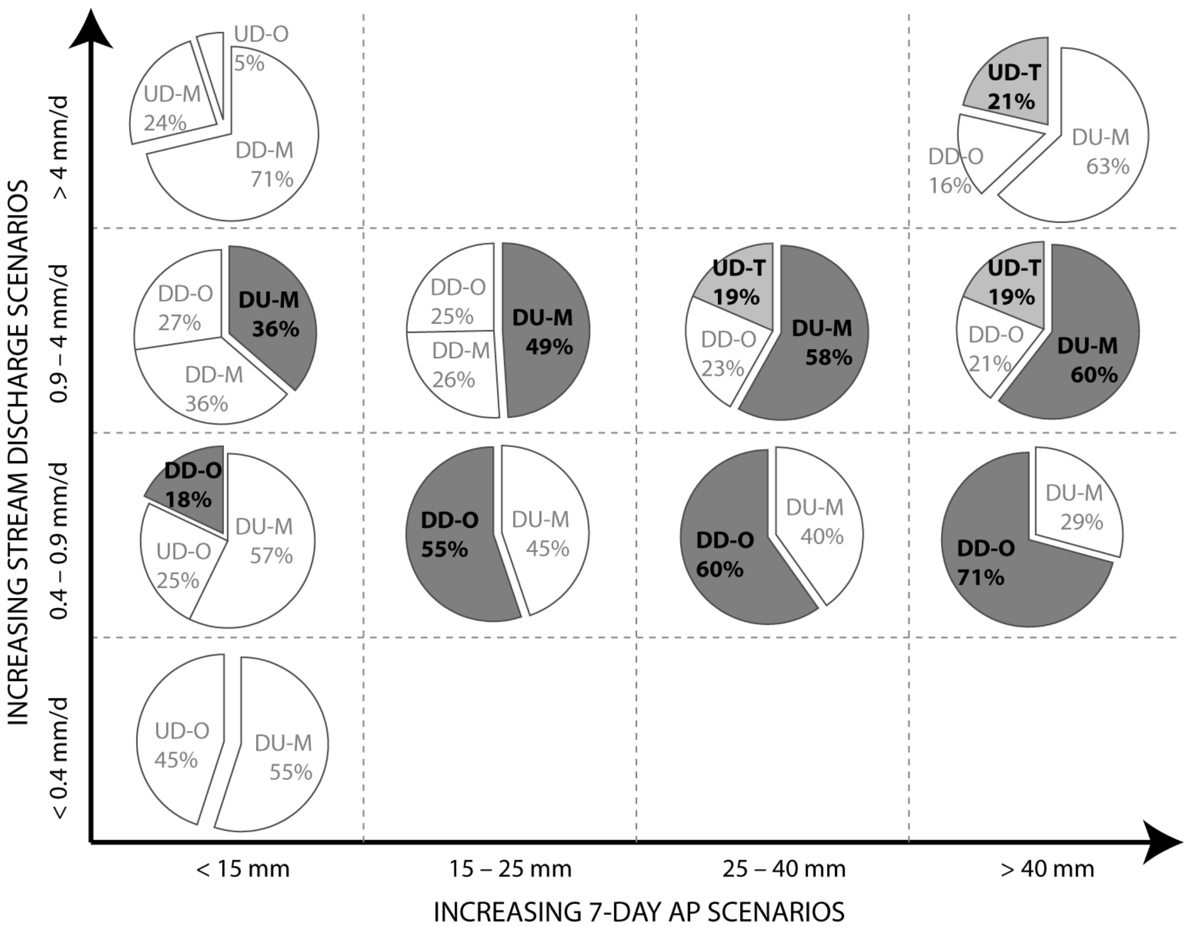


Figure 4.8. Relative contributions of end-members to streamflow (see Table 4.1 for abbreviated names) for selected hydrologic scenarios of varying discharge levels and 7-day antecedent precipitation (AP) amounts. 2-day AP values are medium high (*AP2_3* conditions).

That contribution was even bigger at high discharges and wet conditions was even larger (Figure 4.9), as most of the stream water originates from downstream upslope mineral soil layers, in addition to upstream downslope throughfall water and downstream downslope organic soil water (Figure 4.8). When discharges are high but prior conditions are dry, streamflow is mainly fed by mineral soil water. For medium-low discharges (i.e. condition *DIS_2*), we observe that as 7-day antecedent precipitation increases, the relative contribution of downstream downslope organic soil water also rises from 18 to 55, 60 and 71%.

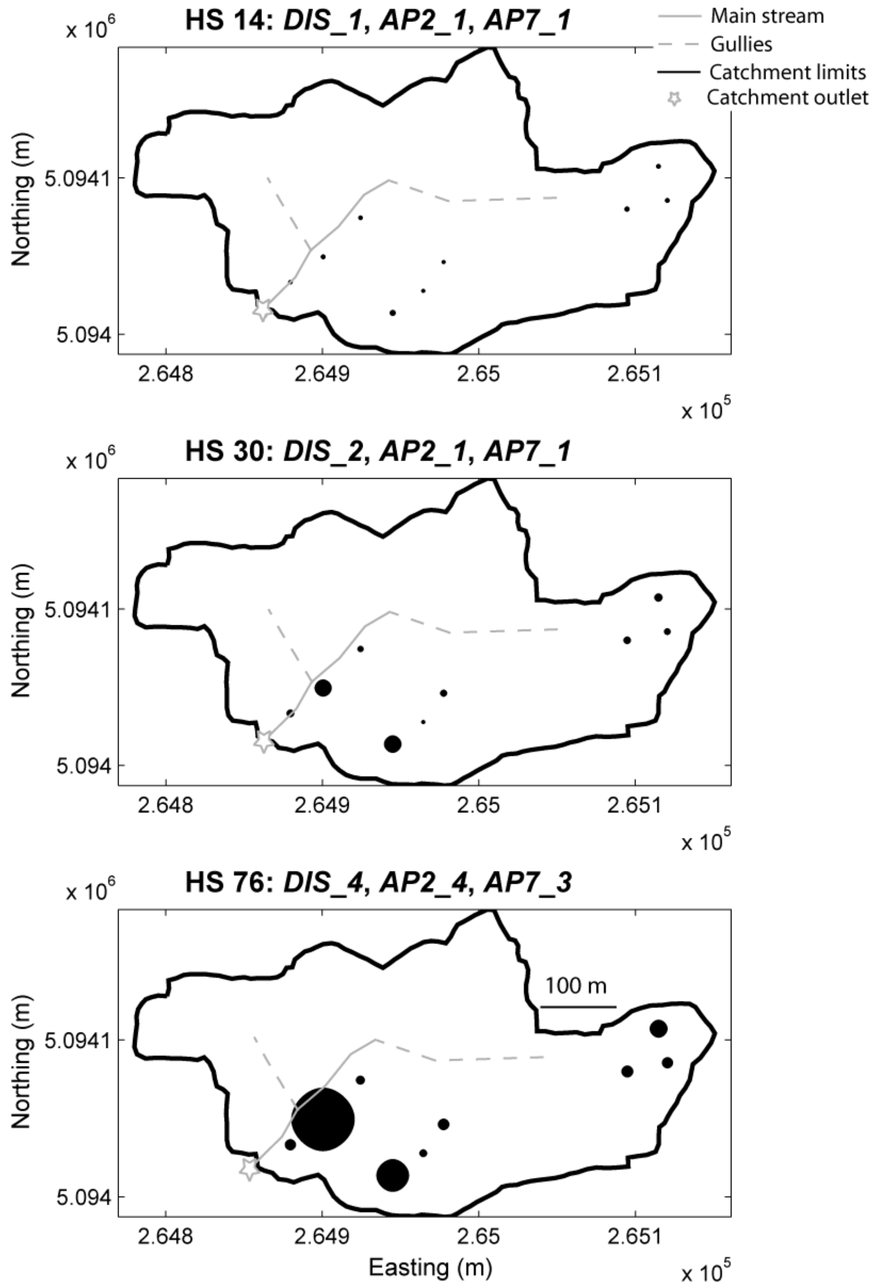


Figure 4.9. Schematic representation of average water table depths associated with three contrasted hydrologic scenarios. The bigger the filled circles, the closer the water table to the soil surface.

For medium-high discharges (i.e. condition *DIS_3*), however, we notice that as 7-day antecedent precipitation increases, it is rather the contribution of downstream upslope mineral soil water that goes up from 36 through 60%. Lastly, only for the largest discharge levels (condition *DIS_4*) and the wettest antecedent conditions (*AP7_3* and *AP7_4*) do we observe a contribution from throughfall water, which can be seen as a surrogate for saturation overland flow (Figure 4.8).

4.2.5 Discussion

a. Validity of Mixing Models Assumptions

By breaking down a multiyear stream chemistry data set prior to mixing analysis and mass balance computations, we were able to examine the changing nature of controlling end-members across a range of conditions. Even though stream water geochemical sub-datasets had various sizes among the scenarios (5 ≤ water samples ≤ 1384), it is unclear whether additional samples to each scenario would have yielded different results. Indeed, EMMA uses correlations between chosen tracers rather than absolute concentrations of chemical species. In that sense, although ionic concentrations are expected to vary among the seasons, it is assumed that correlation coefficients between the tracers will not be modified significantly with the addition of stream water samples (Liu et al., 2008). The same reasoning applies to soil water samples in spite of their unequal distribution among the growing and the dormant seasons (Table 4.1). The scenario-based approach can be seen as a way to investigate the effects of a changing state of connectivity within a catchment, since both the presence and proportional contribution of selected end-members reflect the potential activation of stormflow sources and pathways in some parts of the catchment. This is only valid if we assume that the geochemical signature of end-members is time-invariant, and that only the relative abundance of water from a given end-member in streamflow varies with time. Such an assumption can be challenged by the complex spatial and temporal heterogeneity to which a catchment is subjected (James & Roulet, 2006). In our particular case, some potential end-members projected in U-space display large error bars, and their variability contradicts the assumption of time-invariance. This can be attributed to the fact that a different tracer selection procedure was not carried on for each hydrologic scenario; a single selection was based on the whole stream water chemical dataset and then applied to all scenarios. The adoption of a single tracer selection was, however, necessary to have a uniform basis for the comparison of end-members and proportional contributions among scenarios. Time-invariance was rarely observed with throughfall end-members, and this may be explained by strong seasonal variations (plant growth and senescence) or variability in atmospheric inputs. Since the selected hydrologic scenarios were based on small scale hydrological changes (discharge, 2-day and 7-day antecedent precipitation) rather than seasonal changes, throughfall end-members were not closely examined with regards to time-invariant tracer concentrations. At the end of our analysis, it appeared that throughfall seldom fitted into streamflow mixing spaces, which supports the field observations that saturation excess overland flow hardly ever occurs in our forested catchment except under very high moisture conditions (i.e. extreme hydrologic scenarios). In generating the scenario-specific mixing spaces, structure was generally encountered in the residuals, hence residual analysis was needed to increase the ranks previously obtained by the rule of one method. This also challenges some of the mixing models assumptions, as tracers may seem to mix conservatively in the stream under some circumstances but not in some other cases (Hooper, 2003). Figure 4.5 shows that the mean RRMSE values of NO_3^- are much higher than those of EC, Ca^{2+}, Mg^{2+} and SO_4^{2-}, and that may indicate that nitrate does not behave conservatively in the Hermine catchment. We did run all computational steps for the 64 scenarios while excluding NO_3^- and considering only four tracers (EC, Ca^{2+}, Mg^{2+} and SO_4^{2-}, data not shown). It has caused the dimensionality of the mixing space to be reduced or increased by one rank for seven scenarios, all of them involving *AP2_1* conditions. The main problem with these computations based on four solutes resides in the identification of probable streamflow sources for each hydrologic scenario. With EMMA conducted with five solutes (EC, Ca^{2+}, Mg^{2+}, NO_3^- and SO_4^{2-}), very few “potential end-members” fitted in each mixing space (percentage difference less than 15%), thus making it easy to select two, three or four sources that bounded the mixing cloud and could be tagged as probable end-members. Such was not the case when EMMA was conducted with only four solutes (NO_3^- removed) as the fit of almost all end-members was improved in the mixing spaces. We were then left with multiple potential end-members bounding the mixing space (even B and K when conditions *AP2_4*, *AP7_3* and *AP7_4* were present), and the choice of only two, three or four among them was highly subjective. Hence, for pragmatic reasons, we decided to keep NO3- in the analysis because it satisfied our three data-based criteria for tracer selection (e.g. linear trend, ability to distinguish between streamflow sources, and time invariance), even though we cannot confirm its conservative behavior in the Hermine catchment.

b. Hydrologic Interpretations in Light of Catchment Connectivity

Hydrological interpretations made from our scenario-dependent mixing diagrams must be considered cautiously. Especially when it comes to rank 2 mixing spaces, a more or less large number of stream water samples lie outside of the bounding triangles (see examples in Figure 4.6), which may be attributable to insufficient information about other potential end-members than the 11 tested in this paper. When the Hermine long-term monitoring project was launched in 1993, it was then assumed that both the northern and southern hillslopes of the catchment behaved similarly as their appearance and properties would suggest. This explains the installation of lysimeters on the southern hillslope only. Recent work in the catchment involving spatially detailed soil moisture patterns has shown that (i) saturation does not occur symmetrically from the valley bottom upwards, and (ii) the northern slope intermittent gully acts as a significant contributing zone in very wet conditions. None of the 11 potential streamflow sources evaluated in this paper can capture the asymmetric dynamics, and therefore the EMMA exercise can only lead to a partial process understanding. We must, however, stress that the ultimate goal of the paper was not to find all streamflow sources in the Hermine catchment but rather to examine how the relative contributions from some sources (11 potential) varied across times. That allowed us to "estimate" the degree of catchment-scale connectivity, or at least the degree of connectivity between the southern instrumented slope and the outlet in the Hermine. The methodological approach is still sound since we consistently lacked the same field information about potential end-members for all scenarios.

We hypothesized that along a continuum of hydro-meteorological conditions, we should observe an increased contribution of stormflow from source areas, both quantitatively (number of contributing areas) and volumetrically (importance of individual contributions). Confirming this hypothesis would have given us some insights on the establishment of connectivity. Mixing space dimensionality hardly varied among the 64 hydrologic scenarios examined in this paper. Rank 1 mixing spaces set apart from the others, as they were mainly associated with low discharge and low antecedent precipitation, hence low connectivity scenarios. However, rank 2 mixing spaces were the most numerous and related to both transitional and wet catchment conditions, thus making it difficult to interpret increasing connectivity states on the sole basis of the number of contributing sources. It is worth mentioning that prior to the study presented here, end-member mixing analyses were performed on the same 11-year dataset broken down into a significantly lower number of scenarios (n = 12, then n = 27; data not shown). We then observed very few differences among the scenarios concerning the nature and the relative contributions of end-members but a better information gain was noticed with n = 27, and therefore the number of scenarios was increased for the purpose of this paper.

Indirect evidence of contrasting states of connectivity can be drawn from relative end-member contributions to streamflow. In a catchment saturation model working from the valley bottom upwards, we would have expected waters originating from downstream downslope areas to be the first to contribute to streamflow as catchment wetness increases, followed by downstream upslope and upstream downslope sources. However, in the Hermine catchment, downstream upslope mineral soil water contributes to streamflow in a wide range of wetness conditions, though in varying proportions. This result is difficult to conceptualize from a hydrological standpoint. The presence of downstream upslope mineral soil water as a contributing source in almost all hydrologic scenarios hints towards an uninterrupted subsurface flow wave from the top of the hillslopes to the catchment outlet; the absolute magnitude of that hypothetical flow process cannot be explained from EMMA results, unless they are associated with scenario-averaged water table depths (Figure 4.9). It also means that specific near-surface flow paths do not consistently come across much of the downstream downslope zone, but then our study comes short of identifying a non-shallow contributing source that would ensure the spatial connectivity of upslope mineral water to the stream. The increasing involvement of downstream downslope organic soil water suggests that under transitional or wetting-up conditions, the shallow portion of downstream downslope soils is responsible for the hillslope-stream coupling instead of acting as a buffer to stormflow. As for the contribution of throughfall water in the wettest conditions, it reflects the rare occurrences of saturation overland flow in the Hermine catchment.

Mixing analysis results can, however, be evaluated in light of the "horizon of last contact" hypothesis which states that the chemistry of the water reaching the stream is regulated by the characteristics of the soil horizon last encountered (O'Brien & Hendershot, 1993). Even though that hypothesis was put forward following the analysis of event-based chemical data in the Hermine catchment, we rely on it to say that deep groundwater and downslope (organic and mineral) soil water should control the chemical composition of stream water, regardless of the hydro-meteorological conditions. When more intense storm events generate surface runoff in the Hermine catchment, the presence of throughfall water originating from upstream downslope areas (see Figures 4.1, 4.6(E)) is consistent with the near-stream "horizon of last contact" hypothesis and with an enhanced upstream-downstream linkage given intermittent gullies connected to the stream channel. As far as the routing of downstream upslope mineral soil water is concerned, it is thought to be controlled by features such as subsurface boulders, the soil/impervious layer interface or other soil interfaces marked by a sharp downward decrease in hydraulic conductivity. As primary hydrologic flow paths within a catchment (Chaplot & Walter, 2003; Tromp-Van Meerveld & McDonnell, 2006b), these features are, in fact, diverse forms of the "horizon of last contact" even if they are not necessarily proximal to the stream. Findings of contributing sources that are not adjacent to the stream may also be attributed to the residence time factor, as mixing analysis does not consider the time needed to mix and move the water from an end-member or a geographic source to the catchment outlet. This issue was particularly stressed by McDonnell (2003) and Katsuyama *et al.* (2009) who stated that the questions of geographic sources (i.e. the origin of stream water), time sources (i.e. the moment when catchment water reaches the stream) and flow paths (i.e. the hydrologic route water takes to the stream) should be resolved simultaneously. Event water resulting from a stormflow wave will move rapidly throughout the catchment and have a short contact time with either soil or bedrock along its route (Mulholland *et al.*, 1990); hence it will "preserve" the chemical fingerprint acquired from its initial source. On the contrary, water moving in slower hydrologic flow paths is more likely to undergo various kinds of biogeochemical transformation (e.g. adsorption, oxidation, reduction, dissolution, cation exchange) (Katsuyama *et al.*, 2009). This would imply that mean residence time in the Hermine catchment is relatively short, at least for shallow soil water above the impervious layer. When discharges belong to categories *DIS_1* and *DIS_2*, our results suggest that most of the water fed to the stream originates from the downstream downslope zone or, at least, has resided long enough in the downstream downslope compartment for its original geochemical signature to be transformed (see Figure 4.8). For scenarios associated with the *DIS_3* and *DIS_4* conditions, the relative contribution of downstream upslope mineral soil water increases, which could signify that it travels by a quicker flow path without much change of its chemical composition.

The major drawback of the scenario-based approach is that we cannot assume a temporal sequence of water inputs to the stream from different sources. For example, in Figure 4.8, the presence of the DD-M component in *AP2_2* and *DIS_3* conditions and its "sudden" disappearance in *AP2_3* and *DIS_3* are puzzling. This is attributable to the fact that even though our hydrologic scenarios were built to represent a continuum of hydro-meteorological conditions, they cannot be interpreted in the logic of a storm hydrograph rising limb that is sequentially fed by several streamflow sources.

c. Predictive Power of a Single Mixing Model Across Times

In an effort to identify a single mixing space acting as a predictive model of internal catchment connectivity, we tested the ability of four mixing spaces to predict the stream water chemistries associated with all other scenarios. The performance of the "reference scenarios" with regard to predicting the "test scenarios" was highly dependent on the solute considered. For instance, the use of the wettest, highest discharge scenario (e.g. HS 77) as a reference resulted in high $RRMSE_{in\ reference}$ values for two out of five tracers (EC and NO_3^-, refer to section 4.2), yet more than 20% of "test scenarios" chemistries presented a better fit than when projected in their own mixing spaces (Figure 4.5(C)). It is plausible that the wettest, highest discharges scenario yields the most connected mixing model. This conceptual model potentially reflects not only the major hydrologically significant components of the catchment system but also the major functional links between them. It should thus be able to model least connected, drier and lower flow conditions that involve fewer components and links. However, the weak performance of HS 77 in modeling “test scenarios” concentrations of EC and NO_3^- did not allow us to choose that “reference scenario” as the best predictive model of stream water chemistry across times. On the contrary, HS 56, associated with *DIS_3*, *AP2_3* and *AP7_3* conditions (see Table 4.2), had the lowest projected biases and RRMSE values for all five solutes (see Figure 4.5). Consequently, it appeared to be the most suitable model to predict stream water chemistries associated with various hydro-meteorological conditions in the Hermine catchment. HS 56 yielded a rank 2 mixing space and involved downstream downslope organic soil water and downstream upslope mineral soil water end-members as most transitional scenarios, in addition to a throughfall end-member (Figure 4.6(D)) that we know, from field observations, to contribute to streamflow only under exceptionally wet conditions.

4.2.6 Conclusion

Streamflow sources across various hydrologic conditions were characterized in a 5.1 ha temperate humid forested catchment. Examining the temporal persistence of streamflow sources was only possible given the assumption that their geochemical signature is time-invariant and that only their presence and mixing in streamflow vary with time. Prior to our analyses, multiyear daily stream chemistry data were broken down into several hydrologic scenarios reflecting different conditions with respect to stream discharge and antecedent catchment wetness. Mixing space dimensionality did not vary significantly among the tested hydrologic scenarios, as three end-members were generally required to account for most of the variance in stream geochemistry. Differences were however significant in the ability of the tested end-members to fit in mixing spaces, and in the relative contributions of geographic sources to streamflow across times. The results obtained make up indirect evidence of a time-variable state of connectivity in the Hermine catchment. Partial conclusions could be drawn about geographic storm flow sources, even though our approach was not fully spatially distributed. The main contribution of this study lies in the computed, scenario-specific relative contributions to streamflow and the demonstration of their dependence on medium-term prior wetness conditions, which pleads in favor of connectivity. Also, from a methodological point of view, our results suggest a cautious evaluation of the predictive power of one single mixing space with regards to the nature of streamflow sources across hydrologic conditions.

4.3 Paragraphe de liaison "4-5"

L'originalité de l'article reproduit dans la section 4.2 réside dans son utilisation non traditionnelle du traçage environnemental et des modèles de mélange géochimiques. En effet, l'application de la méthode *EMMA* (*end-member mixing analysis*) à plusieurs sous-ensembles de données reflétant des scénarios hydrologiques différents a permis d'en apprendre plus sur la variabilité spatio-temporelle de l'écoulement dans le bassin versant de l'Hermine. L'hypothèse selon laquelle les débits élevés mesurés à l'exutoire seraient attribuables à une plus grande diversité de sources contributives n'a pu être confirmée. Toutefois, il a été démontré que les forts débits étaient associés à une contribution accrue de certaines sources. Cette idée d'un écoulement renforcé est à mettre en parallèle avec un fort degré de connectivité hydrologique entre la source concernée et le cours d'eau, d'autant plus que la force de ce lien hydraulique supposé dépend des conditions d'humidité antécédentes.

Contrairement à ce qui avait été affirmé à la fin du Chapitre 3 à l'issue de l'analyse statistique avec l'approche « boite noire », l'approche de type « boite grise » permet d'apprécier les unités morphologiques (parcelles expérimentales) du bassin versant de l'Hermine qui influencent le plus les changements de connectivité hydrologique. Cette appréciation est cependant partielle étant donné l'utilisation de données très locales sur des sources de ruissellement dont la représentativité à l'échelle du bassin versant tout entier est méconnue. Le faible niveau de discrétisation spatiale utilisé avec cette approche ne permet pas non plus d'estimer les chemins d'écoulement empruntés par le ruissellement de crue depuis chacune des sources jusqu'à l'exutoire. Ainsi, si l'approche « boite noire » a démontré l'existence d'un comportement non linéaire pour le bassin versant de l'Hermine et si l'approche « boite grise » a confirmé ce comportement en soulignant le caractère épisodique de la contribution accrue de certaines sources, les détails « mécaniques » de l'interaction entre les sources et le cours d'eau restent obscurs et ne peuvent que faire l'objet d'hypothèses et de suppositions.

Le recours à des patrons spatiaux détaillés de variables topographiques et hydrologiques permet au contraire de visualiser directement les interactions entre les différentes unités de versant et le cours d'eau dans un bassin versant. C'est la voie qui est préconisée dans le Chapitre 5, alors que l'approche de type « boite blanche » considère un fort niveau de discrétisation spatiale afin de préciser la localisation des aires actives et potentiellement contributives au débit du cours d'eau de l'Hermine. L'étude exhaustive de patrons spatiaux d'humidité du sol est donc réalisée dans le but d'appréhender la connectivité hydrologique sous trois angles différents, soit i) les échelles spatiales caractéristiques de la variabilité des processus hydrologiques dans le bassin versant de l'Hermine, ii) la mesure quantitative des propriétés émergentes, et iii) l'évaluation des conditions d'humidité antécédentes.

CHAPITRE 5

ÉTUDE DE LA CONNECTIVITÉ HYDROLOGIQUE SELON L'APPROCHE « BOITE BLANCHE »

5.1 Contexte

L'approche mise de l'avant dans ce chapitre est de type « boite blanche » puisque que l'on étudie des patrons spatiaux de la topographie de surface et de subsurface et de l'humidité du sol afin de les relier à des processus de genèse de l'écoulement et ainsi tirer des conclusions sur le rôle spécifique de la connectivité hydrologique. La mesure répétée dans le temps de patrons spatiaux du contenu en eau des sols permet de constituer des jeux de données exhaustifs très prisés en hydrologie pour l'étude des processus d'écoulement actifs (e.g. Grayson *et al.*, 1997 ; Western *et al.*, 1998, 2001 ; Tromp-Van Meerveld & McDonnell, 2006b ; James & Roulet, 2007 ; Lehmann *et al.*, 2007). Il est donc naturel de penser que le recours à de tels patrons spatiaux puisse livrer des informations cruciales sur les mécanismes d'établissement, de maintien et de rupture de la connectivité hydrologique. Dans cette optique, les données d'humidité du sol mesurées dans le bassin versant de l'Hermine entre 2007 et 2008 selon un double schéma d'échantillonnage systématique et stratifié à quatre profondeurs de sol et en 16 occasions différentes (voir section 2.4.2) sont analysées en rapport avec les conditions hydro-météorologiques prévalant au moment de la mesure. Trois articles scientifiques sont reproduits dans les sections 5.2, 5.3 et 5.4. Dans la section 5.2, les échelles spatiales caractéristiques de la variabilité des processus hydrologiques à l'Hermine sont identifiées. Il s'agit d'un exercice important afin de déterminer quelle superficie critique du bassin versant doit être saturée avant qu'un débit significatif ne soit observé à l'exutoire, débit significatif qui reflète l'existence d'une connectivité hydrologique accrue. Dans la section 5.3, la question de la mesure quantitative d'une propriété émergente telle que la connectivité est abordée alors qu'une panoplie de métriques spatiales sont testées dans le but de capturer les changements dans les patrons spatiaux d'humidité du sol. La capacité des métriques à transcender les échelles spatiales et leur transférabilité à d'autres bassins versants est également évaluée. Enfin dans la section 5.4, différentes méthodes d'évaluation des conditions d'humidité antécédentes sont examinées puisqu'elles celles-ci sont un élément-clé dans notre compréhension des mécanismes qui contrôlent les changements de connectivité hydrologique. Au-delà d'une contribution méthodologique significative, il est attendu que la mise en commun des résultats de ces trois articles permettra de mieux circonscrire le « pourquoi » et le « comment » des sources de ruissellement qui contribuent le plus à la réponse hydrologique observée à l'exutoire du bassin versant de l'Hermine.

5.2 Spatial Relationships between Soil Moisture Patterns and Topographic Variables at Multiple Scales in a Humid Temperate Forested Catchment[4]

5.2.1 Introduction

Soil moisture is a critical hydrological state variable since its spatiotemporal variation indicates the presence of 'active' or 'contributing' areas and periods (Ambroise, 2004). It is often used to determine if a catchment is characterized as being in a dry or wet state. Throughout this paper, the phrases 'dry state' and 'wet state' do not refer to evaporation dynamics but rather to the spatial organization of soil moisture. The dry state is when moisture patterns are disorganized because of the influence of local catchment attributes (e.g. soil and vegetation characteristics, terrain slope) and the predominance of vertical soil water fluxes (Grayson *et al.*, 1997). The wet state occurs when moisture patterns are highly organized/connected due to the influence of nonlocal factors (e.g. upslope contributing area) and the predominance of lateral soil water fluxes (Grayson *et al.*, 1997). These states stress the effects of various topographic controls on soil moisture (Western *et al.*, 2002). The reference to local and nonlocal control factors implies that the issue of spatial scale must be carefully considered while investigating hydrological processes. Here, 'scale' refers to the spatial size of a phenomenon while 'scaling' refers to the transfer of information between scales. Scale and scaling issues are critical in complex hydrological systems since catchment dynamics is the result of intertwined processes that are hierarchically structured. Processes occurring at a broad scale may be the result of other processes interacting at finer scales, yet the emergent behavior is not the exact sum of the

[4] Ali, G. A., A. G. Roy & P. Legendre, 2010a. 'Spatial Relationships between Soil Moisture Patterns and Topographic Variables at Multiple Scales in a Humid Temperate Forested Catchment', *Water Resources Research*.

parts (Sivapalan & Young, 2005). It is therefore crucial to identify the controlling variables and to assess if their relative influence on emergent soil moisture patterns depends on the chosen scale of observation.

One challenge concerns the choice of the most appropriate mathematical approach to discriminate and better understand scale-dependent hydrological mechanisms. Schulz *et al.* (2006, p. 1) called for the use of techniques aiming at providing new mathematical description and quantification of structure and pattern building processes at different scales. To achieve such description and quantification, one can either work with single-scale methods repeatedly at different scales, or use alternative methods that contain multiple-scale components in their mathematical formulation (Wu *et al.*, 2000). That is notably the case for semi-variance analysis (e.g. Western *et al.*, 1999; Skøien *et al.*, 2003; Western *et al.*, 2004), wavelet analysis (e.g. Redding *et al.*, 2003), spectral analysis (e.g. Cassel *et al.*, 2000) and fractal analysis (e.g. Kumar, 1999; Green & Erskine, 2004). Klemeš (1983, p. 1) stated ‘we cannot impose scale but have to search for those which exist and try to understand their relationships and patterns’. It implies that natural variables have their own distinctive range of spatial scales that characterize their behavior. Characteristic scales are the successive levels in a hierarchy that are associated with scale breaks and are thus easily differentiable (Wu & Li, 2006). These scales can be derived from a semi-variogram analysis of spatial patterns (Skøien *et al.*, 2003) or from Fourier analyses and harmonic regressions (Blöschl, 2001). Quantification of spatial structure can also be obtained through trend surface analysis which models spatial gradients with polynomial regressions (Legendre & Legendre, 1998). A major drawback of these methods is that they only allow for the very-broad-scale spatial variation to be modeled while finer spatial features remain undetected. This issue may however be resolved if examined in the framework of Moran’s eigenvector maps (MEM).

MEM are a recent family of spatial analysis techniques gaining popularity in ecology and fluid dynamics (Borcard *et al.*, 2004; Brind'Amour *et al.*, 2005; Dray *et al.*, 2006; Griffith & Peres-Neto, 2006; Bellier *et al.*, 2007; Lacey *et al.*, 2007; Roy *et al.*, 2009) but still unused in hydrology. It includes spatial-filtering methods (e.g. dbMEM: distance-based Moran's eigenvector maps; PCNM: principal coordinates of neighbor matrices) which rely on the diagonalization of a spatial connectivity matrix. The eigenvectors computed from the spatial connectivity matrix represent the decomposition of the Moran coefficient of spatial autocorrelation into all mutually orthogonal and linearly uncorrelated map patterns (Griffith & Peres-Neto, 2006). There is precedence in using the Moran coefficient in catchment hydrology. In a study of 10 catchments with different terrain characteristics and climatic regimes, Cai & Wang (2006) notably found a critical extent area of 1 km² over which the spatial autocorrelation of the topographic index becomes weak and static. These results refer to the representative elementary area (REA) concept (Woods *et al.*, 1995) and show the existence of threshold scales. Cai & Wang (2006) also detected a range of digital elevation model resolutions within which spatial autocorrelation was invariant. These findings underline the effect of sampling designs and data accuracy on our ability to capture scale-dependent processes. At first, the PCNM method was developed to dissect 1-D or 2-D spatial patterns across the whole range of scales perceptible within a given data set (Borcard & Legendre, 2002). It achieves a spectral decomposition of the sampling space to describe the dominant spatial scales to which a given variable can potentially respond. The PCNM method therefore allows one to identify the fraction of the total variation in a dependent variable that is spatially structured (Lacey *et al*., 2007). It was later found that PCNM are a particular case of dbMEM in the MEM framework ($\mathrm{PCNM} \subset \mathrm{dbMEM} \subset \mathrm{MEM}$), the difference between dbMEM and PCNM residing in their approximation of the Moran coefficient of spatial autocorrelation (Dray *et al.*, 2006). Regardless of whether dbMEM or PCNM are computed, the eigenvectors extracted from the spatial connectivity matrix are similar; they can be used as explanatory variables in multiple regression analysis to study the spatial structure of a single variable, or in multivariate constrained ordination methods (e.g. canonical redundancy analysis) to study multiple variables at once. The MEM framework therefore enables us to link dominant spatial scales of the response variable(s) (e.g. soil moisture) to the spatial patterns of environmental variables (e.g. topography). It is not aimed at depicting pairwise relationships (e.g. connectivity) between point locations but rather at modeling the correlation structure present at each scale and linking this structure to the spatial heterogeneity of environmental factors. Identifying characteristic scales through the application of the dbMEM procedure would substantially enhance our understanding of hydrological processes and of their scaling properties.

Here, we introduce the MEM framework as a new, promising ensemble of spatial statistical techniques for hydrology. For illustration purposes, we applied the dbMEM method to investigate the spatial scale-dependency of soil moisture content in a headwater temperate humid forested catchment. There are few studies, if any, that have used multivariate statistics to describe the spatial dependency of soil moisture and to quantify the effects of topographic controls on this variable. This study addresses three questions regarding soil moisture content and scale:

(1) What are the characteristic spatial scales of shallow soil moisture?

(2) Is there a strong relationship between soil moisture patterns and topographic variables at these scales?

(3) Which hydro-meteorological variables influence soil moisture scales and topographic controls in a significant way?

This paper demonstrates that the dbMEM procedure provides some insightful, quantitative answers to these questions for a specific catchment.

5.2.2 Field Measurements

a. Study Site

This study was done within a 5.1 ha headwater temperate humid forested catchment, the Hermine, located in the Lower Laurentians natural province about 80 km north of Montréal, Québec, Canada (45°59’ N, 74°01’ W, elevation c. 400 m) (Figure 5.1 A). An intermittent first-order stream flows east to west in the valley of the catchment, which has an elongated open book-like shape. Relief is moderate, with a maximum elevation change of 31 m from the lowest valley location to the highest point in the catchment. The forest floor has a complex micro-topography, partially due to fallen tree trunks and boulders at the soil surface. The total annual precipitation to the watershed averages 1150 mm (± 136 mm) over the last 30 years, of which about 30% falls as snow (Biron *et al.*, 1999).

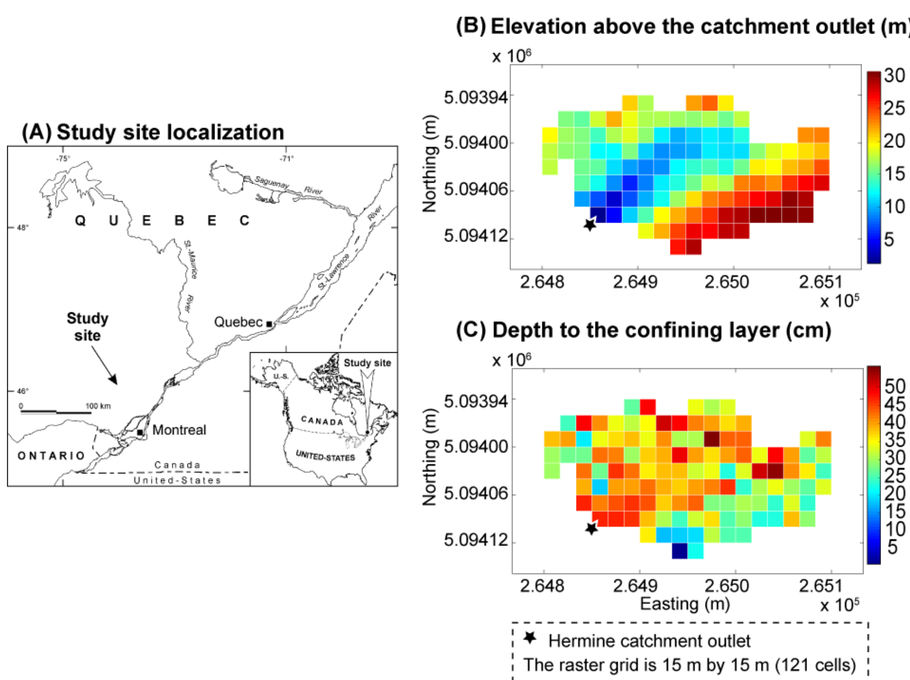


Figure 5.1 – **(A)** Location of the Hermine catchment, **(B)** Surface digital elevation model (DEM), **(C)** Depth to the confining soil layer.

Soils are 1 to 2 m deep bouldery Podzols developed over a glacial till. The occurrence of rapid lateral shallow subsurface flow and the formation of humid source areas are highly frequent at the Hermine given a confining soil layer at a depth of 50 to 75 cm that restricts root penetration and slows water infiltration. Data from wells installed at nine riparian, midslope and upslope 300 m² sampling plots in the catchment and monitored over the last 12 years confirm that the perched water table fluctuates between 1 and 108 cm below the soil surface (mean value: 68 cm). The occurrence of perched water tables is however sporadic during summer seasons, and surface runoff hardly ever happens due to interception of the forest canopy, uptake from the trees and high potential evapotranspiration. Between October and April, transpiration is minimal so that changes in soil moisture and water table during that period are mostly governed by snow-related processes and downslope drainage.

b. Soil Moisture Monitoring

Volumetric moisture content in the top 5, 15, 30 and 45 cm of the soil profile was measured in the Hermine catchment using a 15 by 15 m sampling grid, for a total of 121 cells. Measurements were taken using a portable 30-inch long rod equipped with a capacitance-based probe (AQUATERR Instruments & Automation). Sixteen surveys were collected between August 2007 and July 2008 to capture patterns associated with various antecedent conditions and hydrologic responses at the catchment outlet. Figure 5.2 shows examples of soil moisture patterns. Table 5.1 provides a list of hydro-meteorological variables that were used in this study to illustrate antecedent conditions and hydrologic responses, while Table 5.2 contains the specific values of selected hydro-meteorological characteristics for the 16 soil moisture surveys. These variables were meant to help us assess the hydro-meteorological dependence of the soil moisture patterns and their scaling properties.

Table 5.1 – Hydro-meteorological variables used as surrogates for antecedent conditions and hydrologic responses in the Hermine catchment.

	Variable	Description
Surrogates for antecedent conditions	**MSMC (%)**	Catchment mean soil moisture content
	PET (mm/d)	Potential evapotranspiration (Hargreaves, 1975) on the day of the survey
	Rainfall (mm)	Rainfall on the day of the survey
	AP2 (mm)	Cumulative precipitation from the 2 days before the survey; indicative of short-term antecedent conditions
	AP5, AP7	Cumulative precipitation from the 5 and 7 days before the survey; indicative of medium-term antecedent conditions
	AP12, AP14	Cumulative precipitation from the 12 and 14 days before the survey; indicative of long-term antecedent conditions
	DSP (d)	Days since precipitation Number of days since the last recording at the rain gage
	DSP5mm (d) **DSP10mm (d)** **DSP20mm (d)** **DSP30mm (d)**	Number of days since the last rainfall intensity exceeding 5, 10, 20 and 30 mm/d
	PD_Discharge (mm/d)	Catchment discharge on the day preceding the survey
Surrogates for hydrologic response	**CD_Discharge (mm/d)**	Catchment discharge on the day of the survey
	DA1_Discharge (mm/d)	Catchment discharge on the day following the survey
	DA2_Discharge (mm/d) **DA3_Discharge (mm/d)** **DA4_Discharge (mm/d)** **DA5_Discharge (mm/d)** **DA6_Discharge (mm/d)** **DA7_Discharge (mm/d)**	Catchment discharge in the 2, 3, 4, 5, 6 and 7 days following the survey

Table 5.2 – Value of selected hydro-meteorological variables associated with the 16 soil moisture surveys in the Hermine catchment.

Survey Date	MSMC (%)	AP7 (mm)	AP14 (mm)	PD_Discharge (mm/d)	CD_Discharge (mm/d)	DA1_Discharge (mm/d)
6 August 2007	33.8	4	36	0.0066	0.6619	0.2721
13 August 2007	23.3	44	48	0.0766	0.2224	0.0677
7 September 2007	27.0	8	44	0.0376	0.0486	0.0172
14 September 2007	29.0	14	22	0.0486	0.0667	0.4960
21 September 2007	27.7	18	32	0.0769	0.0649	0.0462
28 September 2007	27.9	4	22	0.0306	0.0980	0.1354
5 October 2007	17.3	6	10	0.0881	0.0881	0.0881
12 October 2007	39.6	42	48	0.2483	5.8726	3.0560
26 October 2007	23.1	43	67	1.0059	0.9087	4.3714
2 November 2007	21.5	33	76	1.3622	1.5208	1.4634
9 November 2007	21.1	17	50	2.0025	1.7077	1.4937
20 May 2008	34.4	39	54	0.9484	1.7975	1.0892
2 June 2008	30.0	29	61	0.8787	0.8288	0.8288
17 June 2008	32.2	29	37	0.5245	0.5241	0.4877
15 July 2008	31.5	43	59	0.5325	0.4193	0.3667
21 July 2008	35.2	35	75	0.9026	0.7835	1.4204

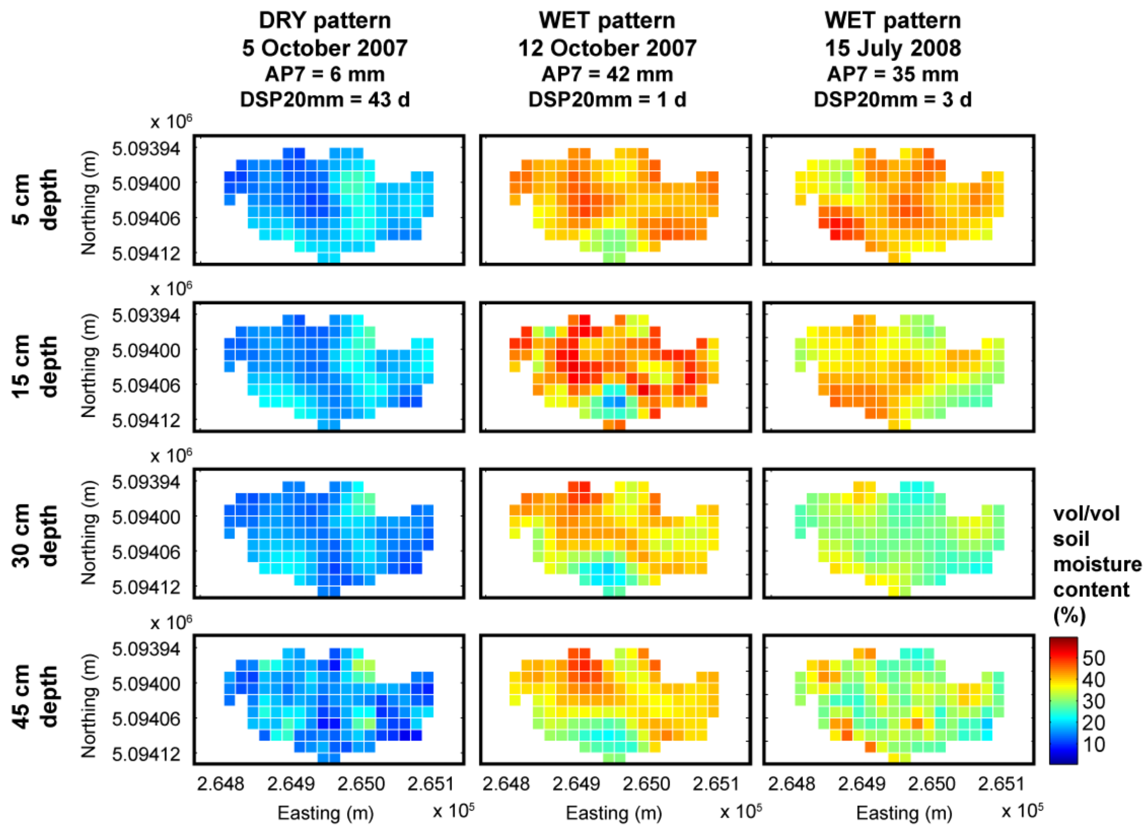


Figure 5.2 – Sample soil moisture maps obtained after three contrasted surveys in the Hermine catchment

c. Topographic Variables

A surface digital elevation model (DEM) of the Hermine catchment (horizontal resolution: 1 m) was obtained by interpolating 640 elevation points collected in the field (Drouin, 1999) with a smooth simple natural neighbor (SNN) algorithm (see Sibson, 1981 for details on the interpolation method). Bilinear re-sampling was used to convert the interpolated data into a 15 m resolution surface DEM (Figure 5.1 B) so that soil moisture data and elevation data were at the same scale of observation. Depth to the confining layer was measured on 257 points using a small hand auger that was forced vertically through the soil profile to refusal. For each sampling location, three auger to refusal measurements were made in a 1 m radius and checked for consistency to discard data associated with individual rocks rather than the impermeable layer. The data were interpolated at a 15 m resolution, thus giving a map (Figure 5.1 C) having the same resolution as the surface DEM and the soil moisture surveys results.

For each sampling square, elevation above the catchment outlet and depth to the confining layer were extracted. From the surface DEM, terrain slope, upslope contributing area and the topographic index (Beven & Kirkby, 1979) were also computed for each sampling square using the D8 (O'Callaghan & Mark, 1984) and the D∞ (Tarboton, 1997) algorithms. These topographic variables were then put in two groups to illustrate possible local and nonlocal controls on soil moisture patterns. Terrain slope and depth to the confining soil layer were considered as local influences (hereafter called *LOCAL variables* or *controls*), while elevation above the catchment outlet, upslope contributing area and the topographic index were assumed to represent nonlocal influences (hereafter called *NONLOCAL variables* or *controls*). To account for potential nonlinear topographic controls on soil moisture, the quadratic and cubic functions of each topographic variable were also included in the *LOCAL* and *NONLOCAL* groups of variables. The *LOCAL* and *NONLOCAL* groups of variables were meant to be used as explanatory matrices in subsequent regression analyses.

5.2.3 Analytical Methods

The MEM framework stands apart from traditional spatial analysis methods such as geostatistics. Geostatistical methods aim to explain how variance and covariance depend on the distance between observations. They model spatial structure by fitting a variogram function to an empirical variogram, assuming that the variable under study can be represented by a second-order stationary spatial process (Bellier *et al*., 2007). Geostatistics are therefore referred to as a model-based approach. Moran's eigenvector maps rather appear as a non-parametric method as they do not presume any form of spatial structure. Specifically, the dbMEM method is a spatial filtering technique (Blanchet *et al*., 2008) proceeding in two major stages: (1) the definition of a set of spatial proxy variables; this is done by means of a spatial connectivity matrix indicating the strength of the **potential** interaction between spatial units; and (2) the selection of the most important spatial proxy variables to explain the spatial structure of the variable under study. The definition of a spatial connectivity matrix only relies on the geographic coordinates of the sampling sites, hence the reference to a design-based approach. Regression or canonical analyses are later performed to associate the variable under study to a subset of spatial proxy variables. Specific analytical steps related to stages 1 and 2 of the dbMEM method are described in sections 3.1 and 3.2 respectively and in Figure 5.3.

a. dbMEM Generation

The steps involved in the generation of dbMEM are illustrated in Figure 5.3 and summarized below:

(1) Starting from the $x - y$ coordinates of the sampling grid locations, a Euclidean distance matrix D is calculated to store all possible distances d_{ij} between sampling locations i and j ($D = [d_{ij}]$).

(2) A spatial connectivity function called W is constructed by truncating D at a threshold distance (or truncation distance) d_t as follows (Borcard & Legendre, 2002; Dray *et al.*, 2006; Griffith & Peres-Neto, 2006):

$$W = (w_{ij}) = \begin{cases} 4 \times d_t & \text{if } d_{ij} > d_t \\ d_{ij} & \text{if } d_{ij} \leq d_t \end{cases} \quad (5.1)$$

Matrix W is therefore a truncated matrix in which not all sites are connected. Each non-null weight w_{ij} indicates the possible connection between sites i and j, and the actual value of w_{ij} illustrates the strength of the potential interaction between the two spatial units i and j (Dray *et al.*, 2006). The threshold distance d_t is estimated by computing a minimum spanning tree on D. d_t is either equal to or larger than the length of the longest link in the minimum spanning tree; that length represents the shortest distance required to maintain the graph of all locations connected (Borcard *et al.*, 2004; Lacey *et al.*, 2007).

(3) Given that n is the number of sampling locations, I is an $n \times n$ identity matrix, **1** is an $n \times 1$ vector of ones, and t represents matrix transpose, the eigenvectors (dbMEM) of the centered connectivity matrix (Eq. 5.2) are computed:

$$\Omega = (I-\mathbf{11}^t/n)W(I-\mathbf{11}^t/n) \quad (5.2)$$

Each eigenvector has a specific value for each sampling point, thus allowing the transition from the original location data to eigenvector maps (see bubble maps in Figure 5.3). Black and white circles in the bubble maps illustrate possible autocorrelation patterns to which the variable under study (e.g. soil moisture) may or may not correspond. Matrix W is non-Euclidean because not all connections among sampling sites are considered after truncation. Thus, the dbMEM procedure yields both positive and negative eigenvalues. According to Griffith & Peres-Neto (2006), W is also a term appearing in the numerator of the Moran coefficient of spatial autocorrelation. Hence, eigenvectors obtained from Ω represent the decomposition of the Moran coefficient into mutually orthogonal and linearly uncorrelated map patterns. The Moran coefficient (MC) associated with each eigenvector v can be estimated as follows:

$$MC(v) = \frac{n}{\mathbf{1}^t W \mathbf{1}} v^t W v \tag{5.3}$$

Values of MC are in the range $\left[(n/\mathbf{1}^t W\mathbf{1})\lambda_{min}, (n/\mathbf{1}^t W\mathbf{1})\lambda_{max}\right]$, given that λ_{min} and λ_{max} are the extreme eigenvalues of Ω (Dray *et al.*, 2006). As a result, dbMEM corresponding to small absolute eigenvalues represent fine scales and patchy spatial patterns in which spatial autocorrelation is low and spatial structures are difficult to discern. On the contrary, dbMEM corresponding to large absolute eigenvalues represent large or coarse scales of variability and are very suitable to define spatial structures (see bubble maps in Figure 5.3). Also, dbMEM paired with positive eigenvalues depict a positive spatial association; whereas dbMEM paired with negative eigenvalues depict a negative spatial association (Griffith & Peres-Neto, 2006). dbMEM are able to model a wide range of spatial features from planes, saddles and parabolas representing bumps or troughs to random auto-correlated variables (Borcard & Legendre, 2002; Dray *et al.*, 2006). All obtained eigenvectors are orthogonal to one another (i.e. their scalar product is null), with the consequence that their explained variation is additive. They represent nested spatial scales. These dbMEM (also called spatial eigenfunctions or spatial base functions) are spatial predictors/filters that can be used as explanatory variables in any classical statistical analysis.

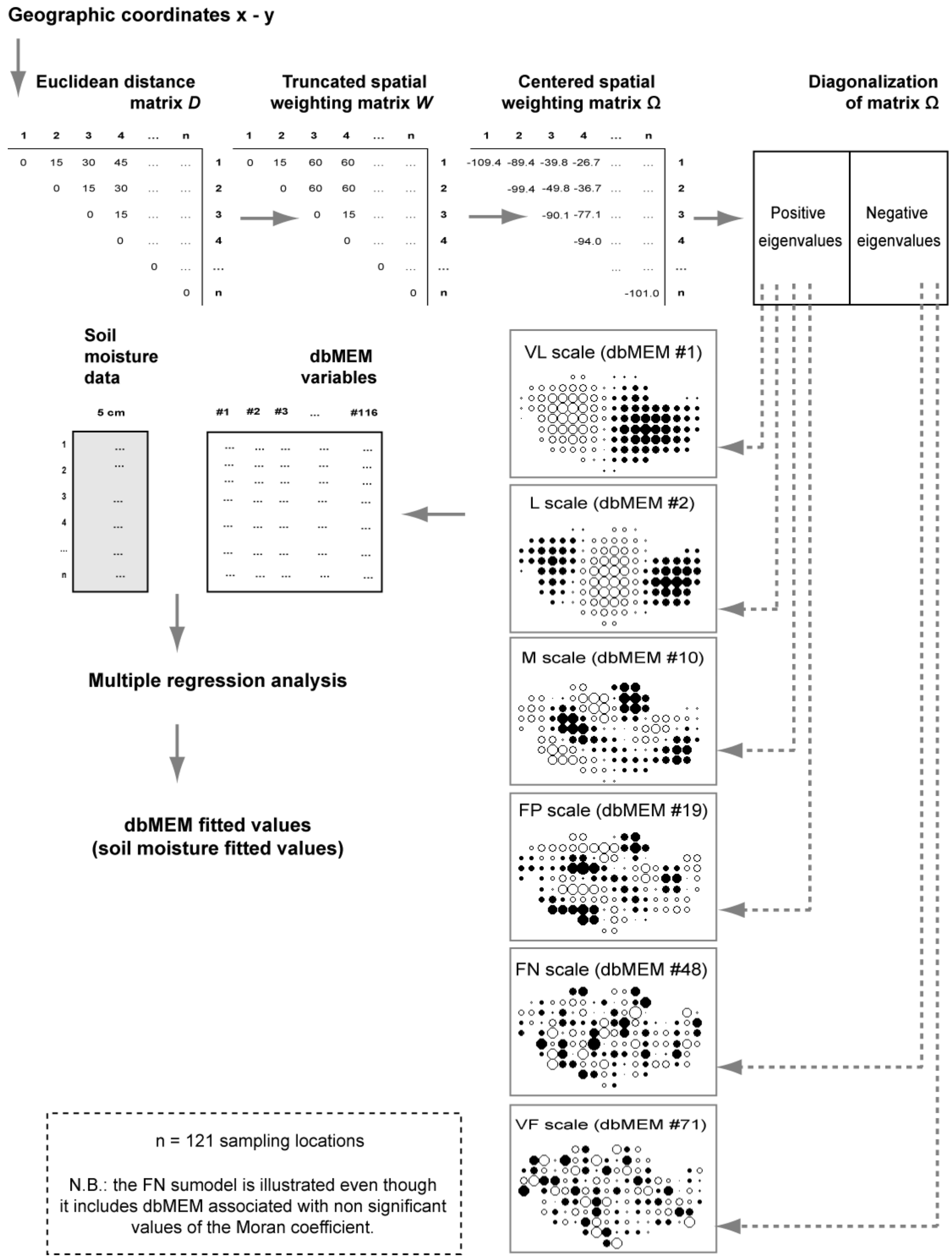


Figure 5.3 – Methodology for developing dbMEM variables and obtaining ‘soil moisture fitted values’ (‘dbMEM fitted values’). B: broad; VL: very large; L: large; M: meso; FP: fine positive; FN: fine negative; VF: very fine.

For regularly-spaced points, dbMEM are similar to a series of sine waves of decreasing periods (Borcard & Legendre, 2002). However, the dbMEM method does not only apply to periodic spatial processes, as the flexible combination of sine waves can model nonlinear features of any shape (Borcard *et al.*, 2004). dbMEM analysis does optimally when uniform sampling grids are used but it still does well with points having irregularly spaced x and y coordinates (Borcard & Legendre, 2002; Lacey *et al.*, 2007). The largest detectable scale corresponds to the dbMEM variable with the largest period, which is dictated by the distance between the furthest sampling locations (Lacey *et al.*, 2007). The technique cannot detect scales smaller than the threshold distance d_t (Borcard *et al.*, 2004).

b. Characterization of Relevant Spatial Scales

Spatial eigenfunctions obtained from dbMEM analysis form a global model which can explain a certain amount of the soil moisture patterns' spatial variation. This global model can be decomposed into individual dbMEM submodels, or into nested submodels each containing several eigenfunctions, to unravel the hierarchical levels at which processes may be the most important. The selection of the number of submodels and their associated scales is subjective and is generally decided upon consideration of the research objectives and the similarity between the periods of the significant eigenfunctions (Lacey *et al.*, 2007).

Here, we chose to study each of the 64 soil moisture patterns $(16 \text{ dates} \times 4 \text{ depths})$ individually, rather than considering all four depths from each survey in a multivariate framework. In doing so, we investigated whether surface or subsurface patterns of hydrologic properties should be used to predict our catchment response. This choice is particularly crucial in humid temperate systems that are thought to be dominated by subsurface stormflow (Weiler *et al.*, 2005). Hence it is important to study the scales at which bedrock-induced and confining layer-induced saturated areas occur at different levels in the soil column (Tromp-Van Meerveld & McDonnell, 2006b). Besides, nonparametric Kruskal-Wallis tests showed that our soil moisture patterns were significantly different ($p < 0.05$) among both survey dates and studied depths, thus calling for an individual analysis. A regression analysis was therefore run with each moisture pattern as the response variable and each spatial dbMEM submodel, in turn, as the explanatory variable. We took advantage of the orthogonal property of the spatial eigenfunctions, which implies that the variations explained by the various dbMEM submodels are additive. The contribution of each dbMEM submodel to the explanation of each moisture pattern was quantified using the coefficient of determination or *R*-square (R^2). We examined a global dbMEM model that was decomposed into six distinct and additive spatial submodels: very large (VL), large (L), meso (M), fine positive (FP), fine negative (FN) and very fine (VF) as in:

$$R^2_{global} = R^2_{VL} + R^2_{L} + R^2_{M} + R^2_{FP} + R^2_{FN} + R^2_{VF} \quad (5.4)$$

The higher the value of R^2, the higher the explained spatial variation in soil moisture at a particular scale. While the VL, L, M and FP scales represent positive spatial autocorrelation, the FN and VF scales rather represent negative spatial association. The adjusted *R*-square, R^2_α, was used in addition to the 'unadjusted' one. Unlike R^2, R^2_α has the advantage of allowing the comparison of regression equations involving different numbers of objects and explanatory variables, and its value increases only if a new explanatory variable improves the model more than would be expected by chance. R^2_α can take negative values in case of a low ratio of observations to regressors, thus suggesting the absence of link between the variables that are being tested. Equation 5.4, however, does not hold when R^2_α is used (Lacey *et al.*, 2007). The global spatial model (containing all dbMEM) and each of the six submodels were tested for significance ($p < 0.05$) using 999

Monte Carlo unrestricted permutations. Multiple regressions yielded 'fitted soil moisture values' (hereafter called 'dbMEM fitted values') that were kept for further analysis.

c. Data Detrending

Borcard *et al.* (2004) suggested checking the response data (e.g. soil moisture patterns) for linear trends before dbMEM analysis. Such trends indicate the presence of a spatial structure at a scale broader than the sampling extent. The use of undetrended and of nonstationary data is not problematical for dbMEM analysis except that it compromises the modeling of fine scale spatial features. In such cases, half of the available dbMEM variables would be used only to model the broad scale trend while finer scale features could go undetected. Each soil moisture pattern was therefore detrended by removing its spatial linear gradient. This was achieved by multiple regressions involving only the x and y coordinates as explanatory variables and soil moisture data for each survey, in turn, as response variable. The linear gradient removed from each pattern was then considered as a seventh spatial predictor, the broad (B) scale, in addition to the dbMEM associated with the VL, L, M, FP, FN and VF scales. As the B scale is not a dbMEM-derived model, however, it does not share the additive property that the VL, L, M, FP, FN and VF scales have. Multiple regressions yielded 'fitted soil moisture values' (hereafter called 'trend fitted values') that are used for further analysis.

d. Scale-Dependent Relationships between Moisture Patterns and Topographic Variables

Lastly, we linked the spatial structure in soil moisture patterns to the influence of topographic variables. This was achieved by using the 'trend fitted values' or the 'dbMEM fitted values' of each submodel as response variable and the topographic (explanatory) variables in variation partitioning analyses. In this common method, one partitions the variation of a response variable [or data table] among two or more sets of explanatory variables using a series of regressions [or canonical analyses]. The adjusted *R*-squares of the analyses are combined to compute the amount of variation explained uniquely by each explanatory table and also jointly by two tables. The rather simple algebra is described in Borcard *et al.* (1992) and Legendre & Legendre (1998). In our case, variation partitioning helped discriminating four fractions of variation, namely the variation in soil moisture at each scale (i.e. B, VL, L, M, FP, FN or VF) that is (1) uniquely explained by *LOCAL controls* (fraction [a]); (2) uniquely explained by *NONLOCAL controls* (fraction [c]), (3) explained by the joint effect of *LOCAL* and *NONLOCAL controls* (fraction [b]), and (4) unexplained by any of the topographic variables included in our analysis (fraction [d]). The contribution of each group of topographic variables to the explanation of soil moisture structure at each scale was quantified using R_{α}^{2} and illustrated using Venn diagrams. Individual fractions of variance were tested for significance ($p < 0.05$) using permutation tests. Joint effects could not be tested for significance because they cannot be obtained directly by a canonical analysis. Following variation partitioning, we kept the 'fitted site scores' (hereafter called 'fractions fitted site scores') associated with fractions [a+b+c], [a] and [c]. These 'fractions fitted site scores' would be used to map the strength of the spatial control that each topographic variable bears on soil moisture at each scale.

All statistical analyses were done using the spacemakeR package (Dray *et al.*, 2006), the Vegan package (Oksanen, 2004) and some custom-made functions in the R environment (R Development Core Team, 2009).

5.2.4 Results

a. Characteristic Scales of Soil Moisture

Data detrending and dbMEM analysis enabled us to quantify characteristic spatial scales of soil moisture in the Hermine catchment. Preliminary multiple regressions of soil moisture patterns on the x and y coordinates revealed significant ($p < 0.05$) linear spatial gradients. They correspond to the B scale structure that explained between 1 and 72% of the soil moisture spatial variation (Figure 5.4). We assume that this B scale represents the variation occurring at a scale larger than 1.4 ha, since 1.4 ha is the area corresponding to the VL scale (see below). In general, the B scale soil moisture explained variation was the largest at a depth of 5 cm.

For dbMEM analysis, matrix W was created using $d_t = 15\ m$. Diagonalization of matrix Ω yielded 116 dbMEM, 58 of which had positive eigenvalues. The progression from large to fine scale was observed with the obtained spatial eigenfunctions: the first dbMEM illustrate very large scale features while the last ones characterize very fine scale features (see bubble maps in Figure 5.3). Regardless of the survey date and measurement depth, the global dbMEM model explained a large proportion of the variation in soil moisture: $0.82 \leq R^2 \leq 0.99$ ($0.21 \leq R_{\alpha}^2 \leq 0.96$). Spatial base functions associated with positive eigenvalues accounted for most of the variation in soil moisture ($0.74 \leq R^2 \leq 0.98$; $0.57 \leq R_{\alpha}^2 \leq 0.96$) whereas base functions associated with negative eigenvalues explained 15% or less of the variation in soil moisture.

dbMEM were grouped into six spatial submodels, based on the size of the patches in the bubble plots (see examples in Figure 5.3) and on eigenvectors associated with values of the Moran coefficient (MC) significantly different from 0 ($p < 0.05$):

- **VL** (dbMEM #1): $0.85 \leq \text{Patches area (ha)} \leq 1.4$; $\text{MC} = 1.05$;
- **L** (dbMEM #2 to #9): $0.54 \leq \text{Patches area (ha)} \leq 0.85$; $0.83 \leq \text{MC} \leq 1.02$;
- **M** (dbMEM #10 to #18): $0.50 \leq \text{Patches area (ha)} \leq 0.54$; $0.60 \leq \text{MC} \leq 0.78$;
- **FP** (dbMEM #19 to #47): $0.22 \leq \text{Patches area (ha)} \leq 0.50$; $0.13 \leq \text{MC} \leq 0.58$;
- **FN**: no dbMEM were associated with significant values of MC;
- **VF** (dbMEM #71 to #116): $0.02 \leq \text{Patches area (ha)} \leq 0.10$; $-1.09 \leq \text{MC} \leq -0.15$.

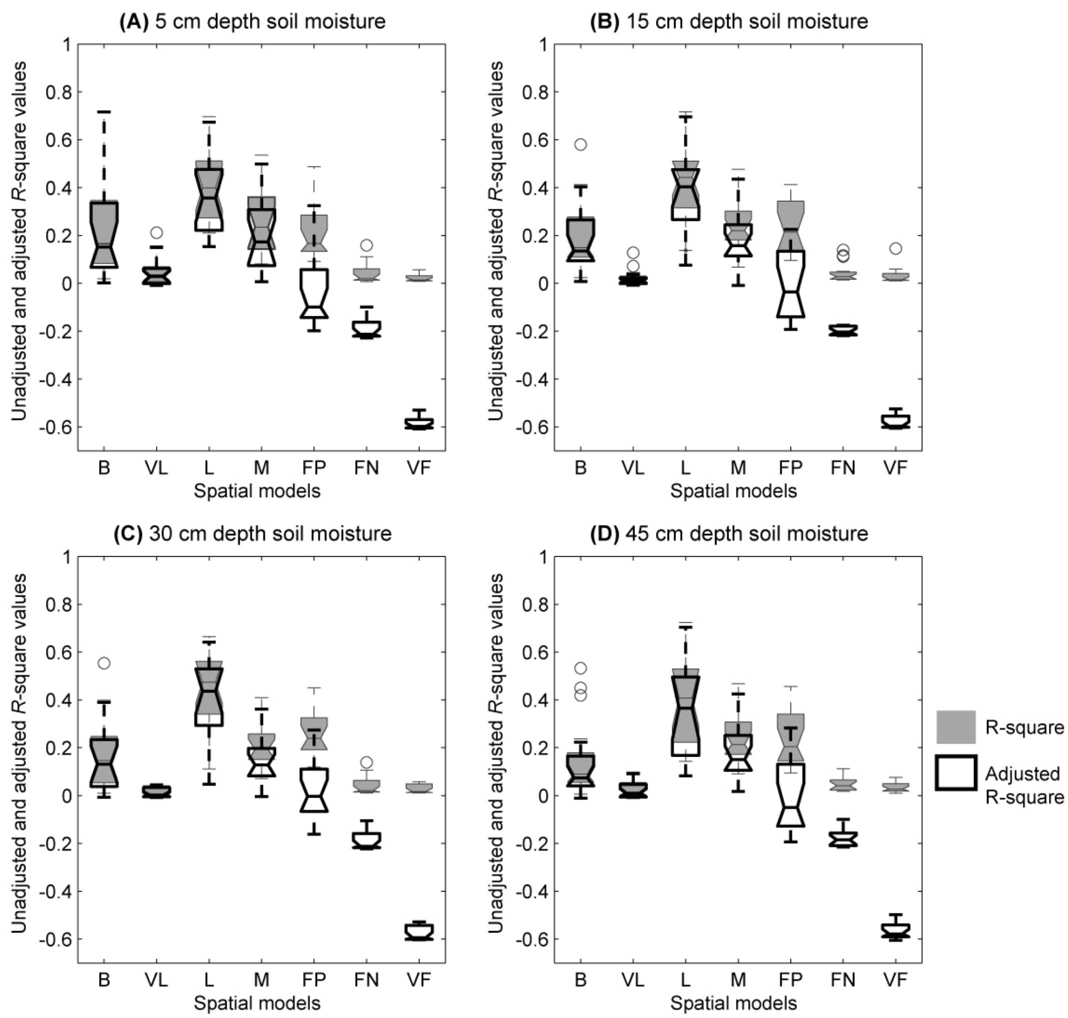


Figure 5.4 – Summary of scale-dependent soil moisture explained variance for the trend and dbMEM submodels. Circles represent statistical outliers. Notches show the 95% confidence interval in the median for box-to-box comparison. B: broad; VL: very large; L: large; M: meso; FP: fine positive; FN: fine negative; VF: very fine.

The global variation in detrended soil moisture was unequally partitioned between the dbMEM-derived characteristic spatial scales as illustrated in Figure 5.4. Variation mostly occurred at the L scale ($0.05 \leq R^2_\alpha \leq 0.70$) while the VF scale explained no variation in soil moisture patterns at any date nor any depths. The M, FP and VL scales explained an intermediate portion of the variation in soil moisture at all depths (M: $-0.01 \leq R^2_\alpha \leq 0.50$; FP: $-0.20 \leq R^2_\alpha \leq 0.32$; VL: $-0.01 \leq R^2_\alpha \leq 0.20$). For all dbMEM-derived spatial models, the average values of explained soil moisture spatial variation hardly varied among sampling depths (Figure 5.4).

b. Scale-dependent Influence of Topographic Variables on Soil Moisture

Figure 5.5 illustrates the strength of the scale-dependent relationships between soil moisture patterns and topographic variables. Variation partitioning following the computations of spatial gradients and dbMEM showed the presence of linear correlations between the structure of soil moisture at different characteristic spatial scales and topography, which also varies at these scales. At the B scale, topography was responsible for the spatial organization of soil moisture in a proportion of 21 to 53%. This was mainly attributable to *NONLOCAL variables* ($0.13 \leq R^2_\alpha \leq 0.46$), while *LOCAL controls* explained much smaller proportions of soil moisture spatial variance ($0.01 \leq R^2_\alpha \leq 0.13$). Topography had a lesser influence on the spatial organization of soil moisture at the dbMEM-derived scales. *NONLOCAL controls* generally explained most of the soil moisture spatial structure at the VL and L scales while topographic controls were the weakest at the M, FP and VF scales.

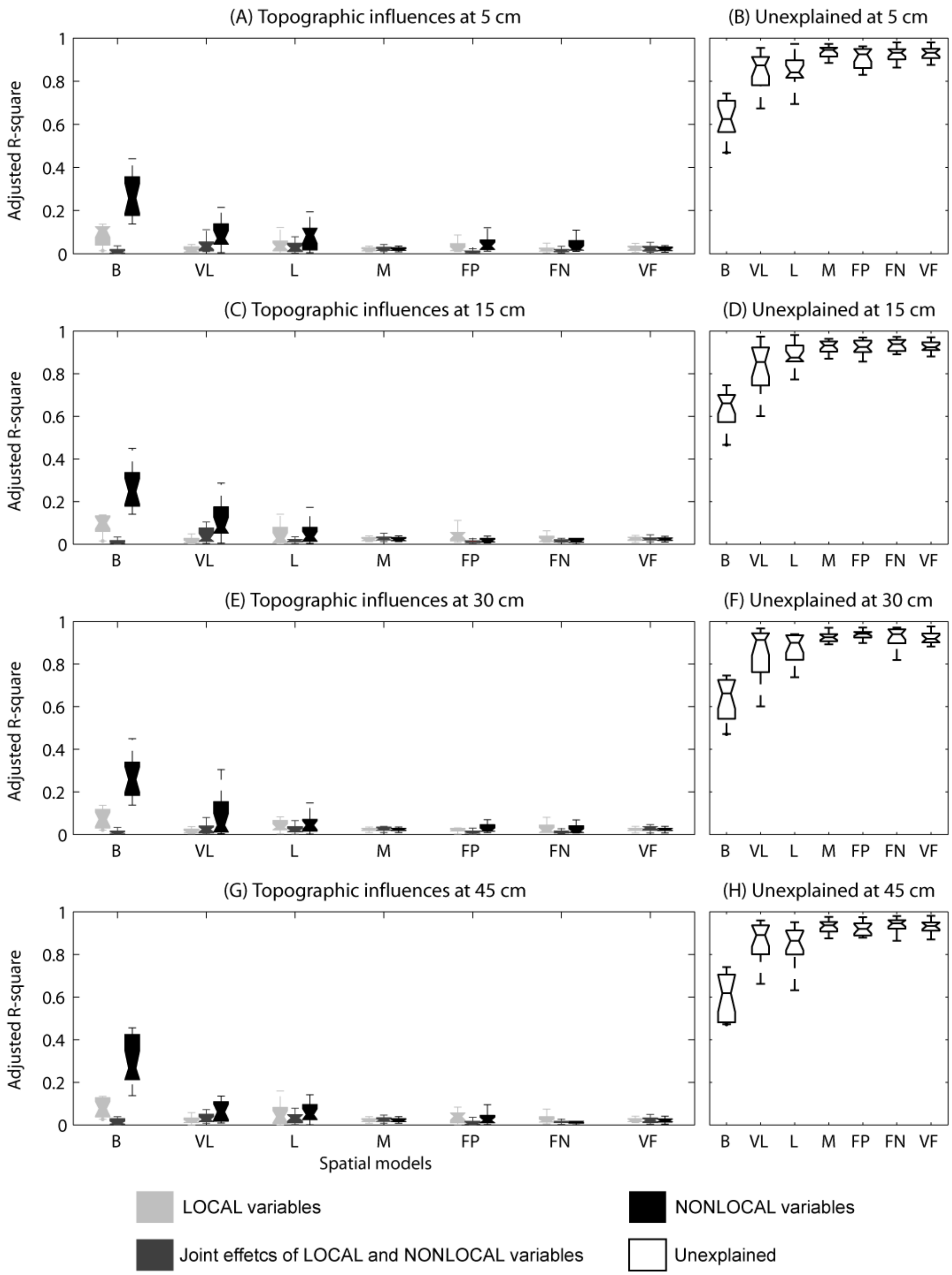


Figure 5.5 – Summary of scale-dependent topographic controls on soil moisture. Notches show the 95% confidence interval in the median for box-to-box comparison. B: broad; VL: very large; L: large; M: meso; FP: fine positive; FN: fine negative; VF: very fine.

Table 5.3 – Spearman correlation coefficients between the presence of spatial structure in soil moisture at each scale (i.e. adjusted R-square) and the magnitude of selected hydro-meteorological variables. B: broad; VL: very large; L: large; M: meso; FP: fine positive; FN: fine negative; VF: very fine. See descriptions of hydro-meteorological variables in Table 5.1.

		B	**VL**	**L**	**M**	**FP**	**FN**	**VF**
PET	5 cm							
	15 cm							
	30 cm							
	45 cm							
AP2	5 cm							
	15 cm							
	30 cm							
	45 cm							
AP5	5 cm			-0.51				
	15 cm							
	30 cm							
	45 cm							
AP7	5 cm							0.52
	15 cm							
	30 cm							
	45 cm							
AP12	5 cm							0.64
	15 cm							
	30 cm							
	45 cm							
AP14	5 cm							0.64
	15 cm							
	30 cm		0.63					
	45 cm		0.65					
DSP5mm	5 cm		0.51					
	15 cm							
	30 cm							
	45 cm							
DSP10mm	5 cm							
	15 cm							
	30 cm							
	45 cm							
DSP20mm	5 cm							
	15 cm							
	30 cm							
	45 cm							
DSP30mm	5 cm							
	15 cm	0.61	-0.76					
	30 cm							
	45 cm					0.54	0.64	0.59
PD_Discharge	5 cm		0.49					
	15 cm							
	30 cm		0.67					
	45 cm		0.61					

Table 5.4 – Spearman correlation coefficients between the presence of significant topographic controls on soil moisture at each scale (i.e. adjusted R-square values associated with fractions [a], [c] and [d] in variation partitioning) and the magnitude of selected hydro-meteorological variables. See descriptions of hydro-meteorological variables in Table 5.1.

			B	**VL**	**L**	**M**	**FP**	**FN**	**VF**
Fraction [a]	**AP14**	5 cm							
		15 cm							
		30 cm	0.59						
		45 cm	0.61						0.61
	DSP30mm	5 cm							
		15 cm							
		30 cm							
		45 cm						-0.51	
	PD_Discharge	5 cm							
		15 cm							
		30 cm							
		45 cm	0.64				0.70		0.85
Fraction [c]	**AP14**	5 cm		0.65					
		15 cm							
		30 cm	-0.65			0.52			
		45 cm	-0.60					0.58	
	DSP30mm	5 cm							0.64
		15 cm					0.52		0.74
		30 cm		0.54					0.55
		45 cm		0.49					
	PD_Discharge	5 cm		0.74					
		15 cm							
		30 cm	-0.49						
		45 cm	-0.52		0.52			0.53	0.58
Fraction [d]	**AP14**	5 cm							
		15 cm							
		30 cm	0.59						
		45 cm	0.56					-0.63	-0.54
	DSP30mm	5 cm							-0.59
		15 cm							
		30 cm							-0.57
		45 cm							
	PD_Discharge	5 cm		-0.62					
		15 cm							
		30 cm		-0.49					
		45 cm			-0.61			-0.61	-0.69

For all dbMEM-derived scales, a large fraction of the variation in soil moisture ($0.60 \leq R_{\alpha}^{2} \leq 0.99$) could not be explained by any of the studied topographic variables, especially at the finest levels.

c. Temporal Dependency of Preferential Scales and Topographic Controls

We found that the spatial scales at which soil moisture content is structured, as well as the explanatory potential of topographic controls, vary along gradients of antecedent conditions. Spearman correlation coefficients were computed between trend and dbMEM-related R_{α}^{2} values and surrogate variables for antecedent conditions. Some significant correlations were found when variables such as *AP5*, *AP7*, *AP12*, *AP14*, *DSP5mm*, *DSP30mm* and *PD_Discharge* were used (Table 5.3; also see Table 5.1 for variables definitions). The presence of B scale spatial structure at the 15 cm depth was positively linked to *DSP30mm* ($r_{Spearman} = 0.61$, $p < 0.05$), which suggests that broad scale patterns at that depth are not observed immediately after a significant storm event. On the contrary, VL scale soil moisture spatial structure at that same depth was negatively linked to *DSP30mm* ($r_{Spearman} = -0.76$, $p < 0.05$), which seems to indicate that coherent 1.4 ha wide patterns settle in soon after significant rainfall inputs in the Hermine catchment. Soil moisture explained spatial variance at the L, M and FP scales was not significantly linked to most of the surrogate variables for antecedent conditions (Table 5.3).

The most consistent correlations were obtained between VL scale-related R_{α}^{2} values at all depths but 15 cm and discharges monitored at the catchment outlet on each survey date and in the following days ($0.49 \leq r_{Spearman} \leq 0.79$, $p < 0.05$, see Figure 5.6). Some significant correlations were obtained between the magnitude of topographic influences on soil moisture (i.e. variation partitioning fractions) and *AP14*, *DSP30mm* and *PD_Discharge* (Table 5.4). For example, it appeared that the wetter the prior conditions, the larger the effects of *NONLOCAL controls* on VL scale soil moisture at 5 cm (see positive correlations between fraction [c] and *AP14* and *PD_Discharge* in Table 5.4). At depths of 30 cm and 45 cm, however, *NONLOCAL controls* at the VL scale were important when antecedent conditions were dry (see positive correlations between fraction [c] and *DSP30mm* in Table 5.4).

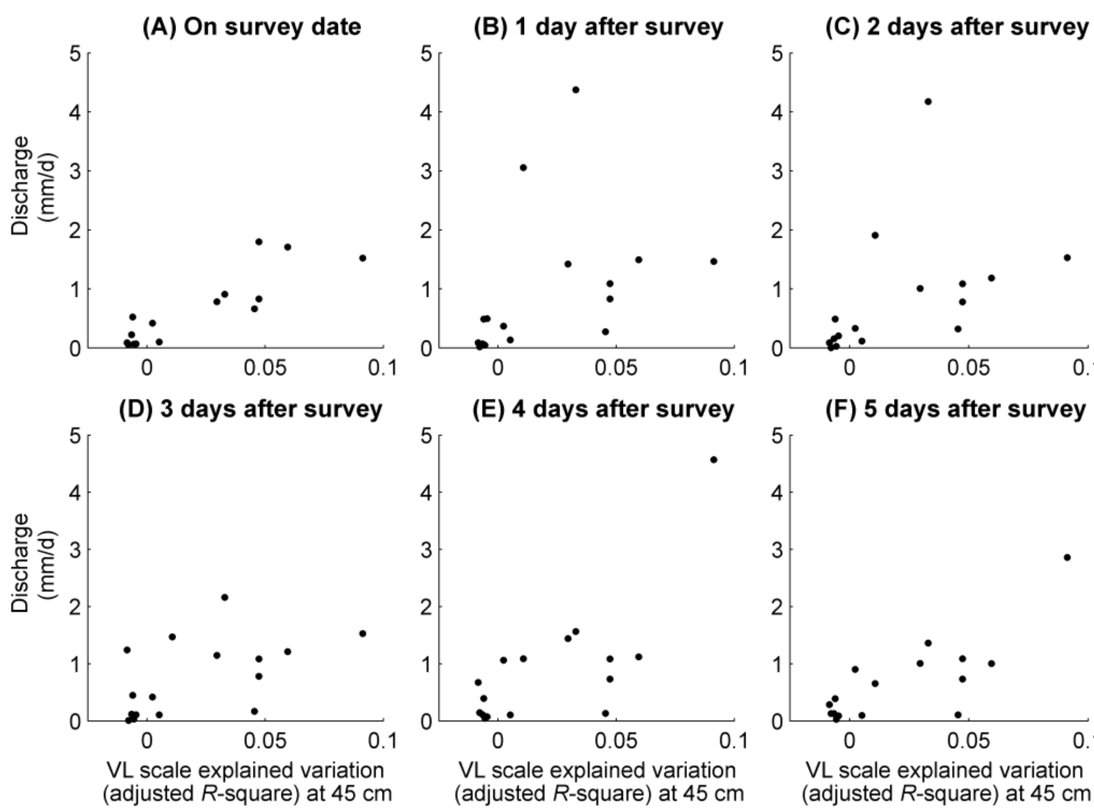


Figure 5.6 – Relationships between the presence of VL scale structure (adjusted R-square) in soil moisture at 45 cm and discharge values measured at the catchment outlet ($0.51 \leq R^2 \leq 0.79$).

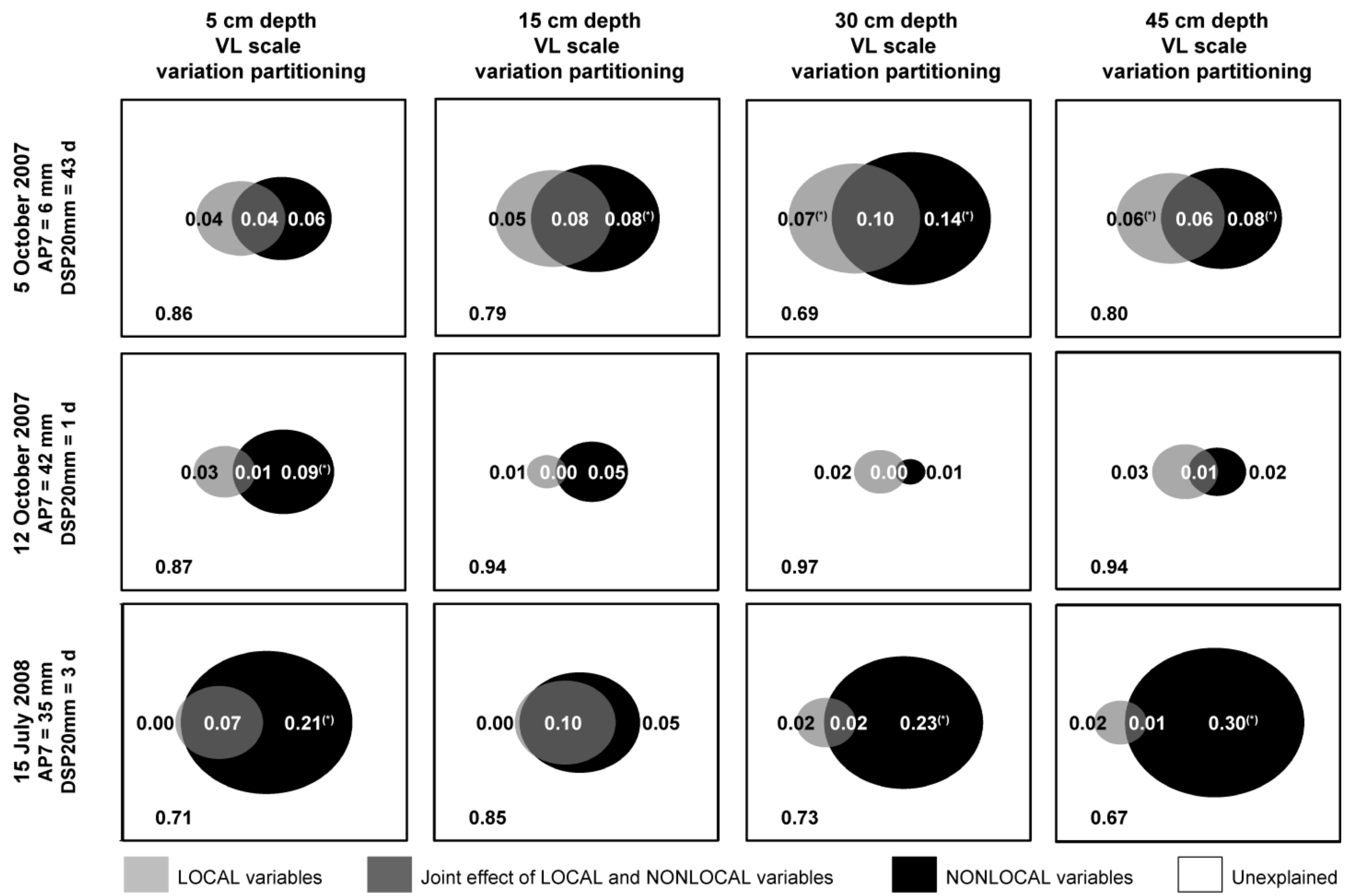


Figure 5.7 – Relative importance of VL scale topographic influences on soil moisture for three contrasted surveys. Significant variation partitioning fractions are flagged with an (*) on the Venn diagrams.

The effects of *LOCAL* and *NONLOCAL controls* on VL scale soil moisture were compared between three contrasted surveys (Figure 5.7). The 5 October 2007 survey took place at the end of a dry spell, while the 12 October 2007 and 15 July 2008 surveys yielded the wettest patterns in our dataset (*AP7* > 30 mm). The main difference between the two wet surveys was the number of days elapsed since the last significant storm event (*DSP20mm* value of 1 day versus 3 days). For the driest survey, the proportion of VL scale soil moisture spatial variance explained by topography ranged from 14 to 31% depending on the depth considered. That proportion of explained spatial variance was almost equally distributed between fractions [a], [b] and [c], except at a depth of 30 cm. Similarly, on 12 October 2007, effects of *LOCAL* and *NONLOCAL controls* (fractions [a] and [c]) had the same order of magnitude, while joint effects were null. Unlike on 15 July 2008, as the influence of *NONLOCAL controls* on VL scale soil moisture was markedly higher than that of *LOCAL controls*. Vegan diagrams shown in Figure 5.7 hence suggest that the influence of one meteorological variable alone cannot explain the magnitude of topographic influences on soil moisture spatial variation at a given scale. The influence of nonlocal control factors on soil moisture spatial variation at the three largest scales (B, VL and L) was dependent not only on rainfall amounts (e.g. *AP7*) but also on the way the water inputs were distributed in time (e.g. *DSP20mm*). VL scale fraction [a] at all depths was the lowest on 12 October 2007 and 15 July 2008, thus hinting that *LOCAL controls* at that scale are the most significant when prior conditions are dry (e.g. 5 October 2007). Maps of the 'fractions fitted site scores' were drawn to visualize the regions where topographic control on 45 cm soil moisture was the most important at a given scale (Figure 5.8). Red areas correspond to regions where topographic influences are the most important, whereas blue-colored areas correspond to regions where there is a lack of or a weak topographic control. These maps clearly show that topographic influences on the B scale soil moisture are more important than those on the VL scale soil moisture (see fraction [a+b+c] maps in Figure

5.8). For the VL scale fraction [a] map associated with the 5 October 2007 survey, the sites subjected to the strongest *LOCAL controls* are very few; they correspond to the locations of large boulders and bare outcrops visually identified in the Hermine catchment. The VL scale *NONLOCAL controls* on 15 July 2008 are more 'widespread' and located on the moderately steep hillslopes rather than in the bottom valley area (see fraction [c] maps in Figure 5.8).

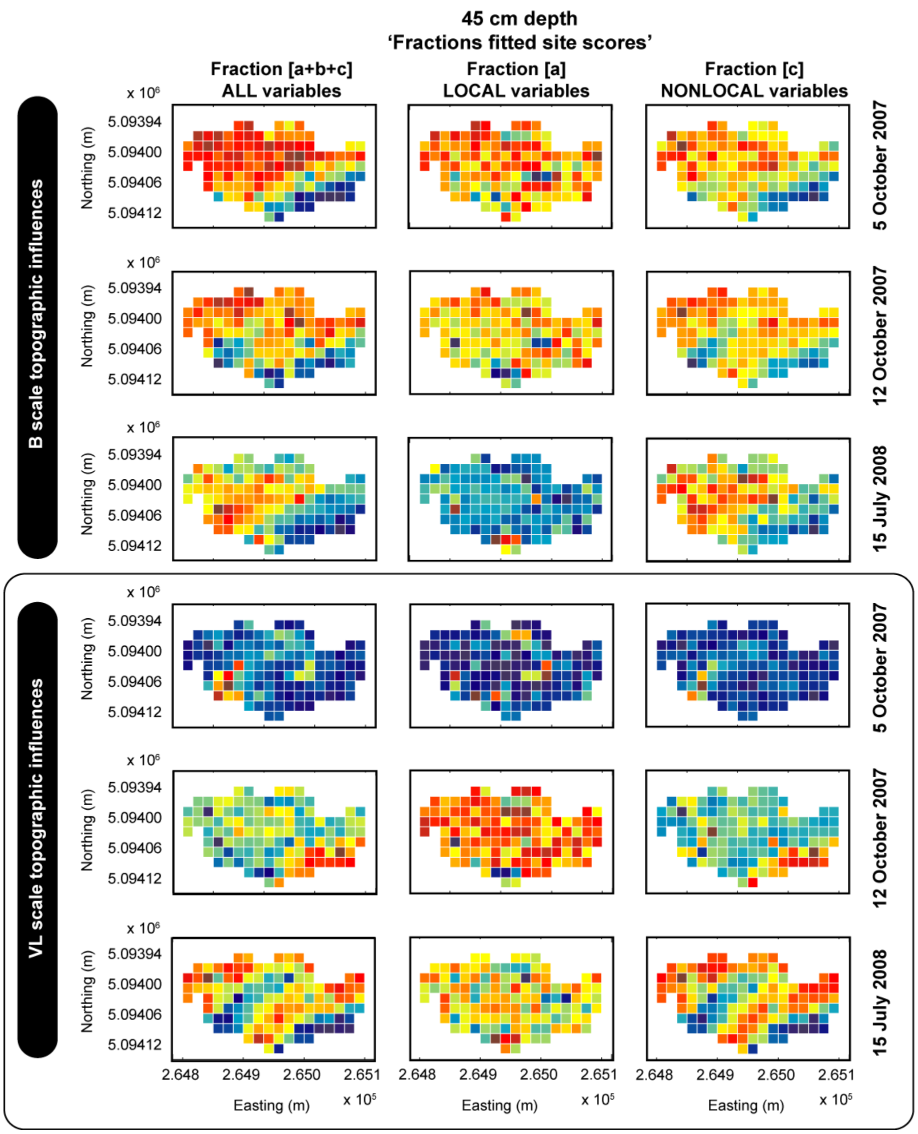


Figure 5.8 – Sample maps of the 'fitted site scores' for three fractions of the variation. Arbitrary units are not shown. Each map/date has its own color scale: orange and red areas show sites that are subjected to the strongest topographic controls on that specific date.

5.2.5 Discussion

a. Scale-Dependent Soil Moisture Variation and Topographic Influences

The global dbMEM model explained a large proportion of the spatial variation in soil moisture at all depths. This is partly attributable to a dense, regular sampling scheme over a fairly small catchment. The explicit quantification of characteristic scales is particularly interesting in the context of a headwater catchment to distinguish the so-called 'small scale' and 'large scale' over a 5.1 ha region. Values of R^2 and R_α^2 (Figure 5.4) allowed a precise assessment of the hydrological relevance of the scale-dependent critical source areas. Even though we considered a nested spatial framework, it appears that hydrologically relevant processes that produce coherent soil moisture patterns occur at a specific sensitive scale (VL, patches of 0.85 to 1.4 ha) and are not perceptible at the smaller scales (L and M, in particular). This is in accordance with the common assumption in complex systems theory that the emergent behavior is not the exact sum or the linear extrapolation of its parts. We expected, however, the F and VF dbMEM submodels (less than 0.22 ha) to explain a larger portion of the soil moisture spatial variation given the complex micro-topography of the catchment forest floor that may disrupt spatial soil moisture patterns. It is possible that the sampling resolution of 15 m was too coarse to capture such fine-scale variability in soil moisture.

The influence of *NONLOCAL variables* on soil moisture was significantly larger at the two largest scales (B and VL) than at the four smallest ones (L, M, FP and VF). This result is puzzling in the context of a headwater catchment, as it either means that topographic controls should primarily be studied at a scale of 1.4 ha or more, or that the two largest scales, especially the B scale, only describe the main hydrological flow gradient across the catchment, i.e. the main stream channel. The latter hypothesis is the most realistic since the main flow direction, namely the stream channel in the valley, is the catchment major spatial linear gradient that is not reflected in the detrended soil moisture data used for dbMEM analysis. To avoid such a 'bias', one could use undetrended topographic variables to explain the B scale soil moisture patterns, while detrended topographic variables would be used to explain the detrended moisture patterns at the dbMEM-derived spatial scales. The explanation for *LOCAL controls* having an effect only at the three largest scales may be of statistical nature rather than hydrological. Several studies have noted that fine-scale patterns identified by dbMEM analysis are often not explained by the available explanatory variables (Borcard *et al.*, 2004; Bellier *et al.*, 2007). It is also possible that fine-scale features might be influenced by fine-scale topographic variables that are yet to be measured. There was a significant fraction of soil moisture spatial variation at all depths that was not explained by any of the tested topographic variables. Non-topographic yet influential factors like soil texture or hydraulic conductivity could be important variables worth considering in variation partitioning.

b. Temporal Dependency of Soil Moisture Structure and Topographic Influences

Given the relatively small soil moisture data set used in this study (16 surveys × 4 depths), it is difficult to build a robust conceptual model of the Hermine catchment behavior across spatial scales and time. However, some of the strongest correlations obtained enable us to say that the B and VL scales were the most responsive to surrogate variables for antecedent conditions. Correlations between next-day catchment discharge and VL scale soil moisture structure (Figure 5.6) suggest that 'critical' source areas should preferably be investigated at the level of 0.85 to 1.4 ha patches. This is plausible given that source areas are usually well delineated in space and located on the lower hillslopes and in the bottom of the valley at the Hermine. It was also observed that the importance of *NONLOCAL controls* for soil moisture spatial variation at the three largest scales (B, VL and L) was dependent not only on rainfall amounts (e.g. *AP7*) but also on the way the water inputs were distributed in time (e.g. *DSP20mm*, see Figure 5.7). That observation can be opposed to time-invariant topography-derived upslope contributing areas or wetness indices that are often used in predictive or modeling studies when soil moisture data are missing (Beven & Kirkby, 1979; Barling *et al.*, 1994; Sorensen *et al.*, 2006). Our results indicate that not only real patterns of critical source areas but also the topographic influences they are subjected to are dynamic and highly dependent on antecedent conditions.

c. Spatial Filtering Methods and Characteristic Scales: an Improvement or a Burden?

The principal advantage of dbMEM analysis is that it enabled us to partition soil moisture structure over a range of nested characteristic spatial scales, and to identify some crucial relations with controlling variables. Conclusions and hypotheses about the Hermine catchment soil moisture dynamics can be drawn for all scales but the finest, especially those modeling negative spatial association. The major drawback of the method is the subjective visual identification of the dbMEM submodels. No other technique but the combination of nested variogram analysis and filter kriging is able to provide as precise estimates of the spatial variation of a variable across so many different scales as the dbMEM method. Bellier *et al.* (2007) presented an ecological application where they compared PCNM analysis and geostatistical estimation. The combination of nested variograms and filter kriging is not problem-free, notably as far as the identification of fine-scale structure is concerned. Bellier *et al.* (2007) therefore concluded that 'for a more objective identification of the relevant scales, both methods need further developments'.

One of the main differences between geostatistics and dbMEM analysis is philosophical, as one may choose to go for a classical design-based approach (i.e. dbMEM approach) rather than for a probabilistic, model-based approach (i.e. geostatistical) (Bellier *et al.*, 2007). Spatial filtering methods present another advantage for hydrology as recent developments have led to the use of asymmetric eigenvector maps (AEM) (Blanchet *et al.*, 2008). AEM are an extension of the MEM framework for directional processes (Griffith & Peres-Neto, 2006; Blanchet *et al.*, 2008; Mahecha & Schmidtlein, 2008); they could help us solve the question: at which spatial scale should hydrologic connectivity be defined? Hence, we foresee interesting applications of AEM in hydrological studies where detailed spatial data about drainage networks or subsurface storm flow paths are available.

5.2.6 Conclusion

Our objective was to test the effectiveness of a fairly new method to detect characteristic spatial scales in a small temperate humid forested catchment. Through an application to soil moisture data, we have shown that dbMEM analysis is a powerful tool for depicting the spatial structure of hydrological state variables. The global dbMEM model explained 21 to 96% (adjusted R-square) of the variation in the detrended soil moisture data apportioned into significant decreasing fractions from the very large scale (0.85 – 1.4 ha) to the very fine scale (0.02 – 0.10 ha). The role of catchment topography was also quantified, as the effects of topographic controls, both local and nonlocal, on soil moisture spatial organization were important at the large scale (0.54 – 0.85 ha) and above. Also, soil moisture broad linear gradients (> 1.4 ha) and very large scale spatial patterns were strongly dependent on previous storm properties (antecedent rainfall and days elapsed since the storm). Very large scale soil moisture patterns, in particular, were a good predictor of the catchment hydrologic response. The dbMEM method therefore allowed us to investigate the issue of spatial scale quantitatively rather than qualitatively. Apart from some issues related to spatial structure and effective spatial controls at the fine-scale, the combination of dbMEM analysis and variation partitioning was valuable to extract the spatiotemporal relationships between dynamic soil moisture content, static topographic variables and temporally-variable hydro-meteorological conditions. The potential of this method should therefore be exploited to test scale-dependent relationships between any hydrologic variable and any environmental variable sampled according to any design in both humid and arid regions. The fact that the dbMEM-derived characteristic spatial scales are nested fits well in the course of recent catchment hydrological studies (e.g. Cammeraat, 2002; Skøien *et al.*, 2003; Soulsby *et al.*, 2006; Didszun & Uhlenbrook, 2008). Similarly, future work at the Hermine or in similar environments should involve searching for scale-dependent runoff generation processes that are responsible for scale-dependent soil moisture patterns, topographic controls and temporal influences on catchment outflows.

5.3 Shopping for Hydrologically Representative Connectivity Metrics in a Humid Temperate Forested Catchment [5]

5.3.1 Introduction

Connectivity is an important concept towards building a refined theory of watershed hydrology. It relates to the functional connectedness between catchment elements (Pringle, 2003; Ocampo *et al.*, 2006) but its evaluation is complex since '*connectivity comes in multiple flavours*' (Calabrese & Fagan, 2004). Reviewing the hydrological literature led to a classification of hydrologic connectivity definitions in four categories with different levels of detail (Ali & Roy, 2009). Three main perspectives are worth studying as we look at either *terrain connectivity*, *soil moisture connectivity* or *flow processes connectivity*. They are not contradictory since changes in soil moisture patterns result from a shift in dominant subsurface flow processes that activate topographic linkages. There is, however, a great need for field data-tested connectivity metrics, especially if connectivity is to serve as an indicator of catchment macrostate in predictive studies. While connectivity is increasingly recognized as qualitatively important, limited efforts have been devoted to characterizing it quantitatively in hydrology and hydrogeology (Knudby & Carrera, 2005). This is particularly obvious when we compare the scarce quantitative measures of connectivity in hydrological papers (Western *et al.*, 1998; Western *et al.*, 2001; Bracken & Croke, 2007) to the multiple 'comparison-shopper's guides to connectivity metrics' published in spatial ecology (Tischendorf & Fahrig, 2000a, b; Moilanen & Nieminen, 2002; Calabrese & Fagan, 2004). The multiple definitions of hydrologic connectivity point out key variables (e.g. surface and subsurface topography, characteristics of soil moisture

[5] Ali, G. A. & A. G. Roy, in review/en revision a. 'Shopping for Hydrologically Representative Connectivity Metrics in a Humid Temperate Forested Catchment', *Water Resources Research*.

patterns) that should be incorporated in a connectivity metric (Ali & Roy, 2009). Hence, an adequate metric should be highly sensitive to wet and dry catchment macrostates since hydrologic connectivity is intimately related to rainfall and antecedent moisture thresholds that trigger rapid hillslope outflow (James, 2005; Weiler *et al.*, 2005; Tromp-Van Meerveld & McDonnell, 2006a; Lehmann *et al.*, 2007; Zehe *et al.*, 2007). The rationale behind connectivity metrics is to capture features in spatial patterns such as high-conductivity preferred flow paths or interconnected saturated source areas that might have an important influence on a catchment hydrological behavior (Western *et al.*, 2001; Knudby & Carrera, 2005). Hence, if connectivity is to serve as an effective diagnostic classification tool of hydrological behavior, it is important to identify or define metrics that are strongly correlated not only with catchment-scale antecedent conditions but also with the hydrological response at the catchment outlet. Such metrics are also of importance for hydrological modeling as they could be fine tuned in order to account for flow connectivity (i.e. flow rate increase induced by preferential flow paths) or transport connectivity (i.e. existence of fast paths allowing early solute arrival) (Knudby & Carrera, 2005). The objective of this paper is therefore to test and analyze a large selection of connectivity metrics in order to provide an appropriate assessment of the continuum of catchment macrostates in a humid temperate forested system. We are especially concerned with discussing the metrics ability not only to discriminate between patterns but also to relate to hydro-meteorological factors and to the catchment integrated hydrological response at the outlet.

5.3.2 Background

A growing body of articles supports the combined use of topography and shallow soil moisture patterns towards building connectivity metrics (e.g. Western *et al.*, 1998;

Western *et al.*, 2001; James & Roulet, 2007). Justification for such an approach lies in the availability of the data, the ease of the visualization procedure and the preferential states hypothesis (Grayson *et al.*, 1997). Soil moisture-based measures of hydrologic connectivity are mostly of a statistical nature and are meant to capture the time-variable spatial organization of the patterns that we visually observe (Grayson & Blöschl, 2000). Knudby & Carrera (2005) have valued the use of the bivariate entropy integral scale, as entropy measures disorder in contrast to connectivity that rather implies order. Otherwise, the core of published connectivity-related papers in hydrology mainly focuses on geostatistics and percolation theory to assess continuity (i.e. smoothness) and connectivity (i.e. presence of interconnected paths) in the patterns (Western *et al.*, 2001). In geostatistics, the semivariogram describes the variance between two points as a function of their separation distance (Cressie, 1993; Goovaerts, 1997); its range illustrates the maximum distance over which spatial correlation affects the target variable. Connectivity statistics (Allard, 1994) rather consider the probability that distant 'wet' locations are connected by any arbitrary continuous path of other 'wet' locations. Hence, the integral connectivity scale length (ICSL) can be computed as the average distance over which 'wet' locations are indeed connected. Furthermore, a topographic ICSL can be calculated instead of an omnidirectional ICSL to restrict the evaluation of connectivity to the two directions of steepest descent as indicated by slope (Western *et al.*, 2001). Traditional variograms are estimated on actual values while indicator variograms and connectivity statistics capture high and low values of the target variable (Journel, 1983). Indicator values indicate whether the actual value of a variable is above (indicator value = 1) or below (indicator value = 0) a particular threshold. The issue regarding the choice of the threshold must therefore be resolved (James & Roulet, 2007). For connectivity assessments, the threshold is usually a given percentile of the univariate distribution of soil moisture at a given depth under the surface for each survey. Hence, it is a depth-controlled, time-variable threshold. We claim that two alternative types of thresholds could be used. First, when multiple depths soil moisture patterns are available, one could compute a catchment-wide, time-variable threshold, namely a given percentile of the multivariate distribution of soil moisture (all depths confounded) for each survey. Second, the use of a time-invariant threshold, for example 40% volumetric soil moisture, could be considered. In the latter case, an indicator value of 1 signals a wet location. When percentiles are used, however, an indicator value of 1 simply means that a location is wetter than a certain proportion of the monitored locations. Addressing the threshold issue is therefore crucial as it relates to how we evaluate changes in the patterns and how we appreciate the critical nature of the establishment, persistence and disruption of connectivity.

The usefulness of geostatistics and connectivity statistics in quantifying hydrologic connectivity has already been assessed in various environments. For instance, traditional variograms were said to only represent spatial continuity and not being able to distinguish between patterns with and without connectivity (Western *et al.*, 2001). A similar conclusion was reached regarding indicator geostatistics in the Australian temperate rangeland catchment of Tarrawarra (Western *et al.*, 1998). Computed from volumetric soil moisture in the top 20-30 cm of the soil profile, connectivity statistics distinguished between connected and disconnected patterns at Tarrawarra (Western *et al.*, 2001) but not in the temperate humid forested system of Mont-St-Hilaire. James & Roulet (2007) attributed the latter result to the differences in climate settings between temperate and temperate humid catchments and to the fact that forested catchments exhibit larger variability in soil hydrologic properties than rangelands. We rather argue here that climate might act as an indirect control while contrasted runoff processes explain the differences between Tarrawarra and Mont-St-Hilaire. Indeed, the hydrological response at Tarrawarra is known to be dominated by saturation excess overland flow (Western *et al.*, 2001) while the response at Mont-St-Hilaire is thought to be controlled by perched water tables and shallow subsurface stormflow above a low-permability layer of fragipan within 30-50 cm of the soil surface (James & Roulet, 2007). At Tarrawarra, strong correlations were obtained between the nature of the visually inspected patterns (i.e. random, transitional or connected) and topographic ICSLs (Western *et al.*, 2001), as well as between the mean catchment soil moisture content and topographic ICSLs (Table 5.5). These results support the idea that the greater the soil moisture content, the higher the degree of hydrologic connectivity. Furthermore, simulations of the Thales hydrological model at Tarrawarra showed that connectivity scale lengths were strongly correlated to peak and total discharge, and that connected patterns induced runoff earlier than random patterns. No such conclusion was reached for the Mont-St-Hilaire system where the variability of the computed ICSLs among individual surveys was considerably lower than for the Tarrawarra catchment (Table 5.5). In fact, recent findings by James & Roulet (2007) only give partial support to the preferential states hypothesis in humid temperate forested catchments. Dry and wet states were easily identified with a change of flow regime as the wet state distinguished itself by an increased micro-scale shallow subsurface flow connection to the stream channel. This shift in catchment behavior was however not perceptible in the soil moisture patterns. It is therefore fair to expect hydrologically representative connectivity metrics to be able to differentiate between surface and subsurface processes, or between vertical and lateral soil water fluxes.

Table 5.5. Hydrological representativeness of the connectivity metrics computed for the Tarrawarra catchment (rangelands, Australia) and the Lk catchment (forested, Mont-St-Hilaire, Canada). Coefficient of variation values and Spearman correlation coefficients were computed based on data in Western *et al.* (1998, 2001) and James (2005).

Temporal change (coefficient of variation) in connectivity metrics values			
Tarrawarra catchment		Lk catchment	
Integral correlation scale	18	North-South variogram range	6
75th percentile indicator correlation length	14	East-West variogram range	14
50th percentile topographic ICSL	29	50th percentile topographic ICSL	8
75th percentile topographic ICSL	61	75th percentile topographic ICSL	20
90th percentile topographic ICSL	71	90th percentile topographic ICSL	78
Relationship (Spearman correlation coefficient) between connectivity metrics values and mean catchment soil moisture content			
Tarrawarra catchment		Lk catchment	
75th percentile indicator correlation length	0.15	North-South variogram range	-0.45
50th percentile topographic ICSL	0.76	East-West variogram range	0.79
75th percentile topographic ICSL	0.56	50th percentile topographic ICSL	0.28
90th percentile topographic ICSL	0.73	75th percentile topographic ICSL	0.54
75th percentile indicator correlation length	0.63	90th percentile topographic ICSL	-0.47

The conflicting results obtained from previous hydrologic connectivity investigations at the catchment scale raise several challenges towards improving connectivity metrics. Hence, several critical questions, such as the following, remain:

- Given that the transition from connected to unconnected hydrologic macrostates is assumed to rely on a shift in dominance of vertical rather than lateral water fluxes, should an appropriate connectivity metric be evaluated in three rather than in two dimensions?

- Regarding the pre-processing of soil moisture data, which approach should be used for indicator patterns derivation? The issue of the threshold must be investigated.
- In case of a two-dimensional connectivity metric, should surface or subsurface soil moisture patterns be used? This choice is particularly crucial in humid systems where both saturation excess overland flow and subsurface stormflow can occur. It is then important to capture the location and interconnections of bedrock and soil confining layer-induced saturated areas.
- Should a connectivity metric integrate topographic information? Metrics are characterized as either omnidirectional or directional depending on whether topography is considered explicitly in the computations. Both surface and subsurface topography could be involved in such computations.
- Should the source-to-stream connection be taken into account? Connectivity metrics may simply characterize the inter-connectivity of catchment source areas or they could be refined to include the episodic linkages between the network of source areas and the catchment outlet.
- Should the metric be linear or areal? Linear measures express the distances over which connected features are encountered, while areal measures are strongly related to the concept of variable source areas (Betson, 1964; Hewlett & Hibbert, 1967).
- Lastly, should hydrologic rather than Euclidean distances be used for linear directional metrics? It may seem reasonable to represent surface hydrological processes using the Euclidean distance because any two sites can be connected

due to a relatively free-flowing, multi-directional storm runoff on the soil surface. When it comes to subsurface runoff, however, it is better to use a hydrologic distance measure which ensures that distances are only measured along the course of preferential subsurface flow paths (i.e. flow lengths obtained from digital elevation model (DEM) analysis). Using hydrologic rather than Euclidean distances may therefore result in longer routing paths.

Some of these options regarding the computation of hydrologic connectivity metrics have never been tested nor compared within a single research project. The specific objective of this paper is therefore to provide answers to the previously mentioned critical questions by comparing a large selection of connectivity metrics. In the same way that Calabrese and Fagan fed the discussion among ecologists with their 'comparison-shopper's guide to connectivity metrics' (2004), we here wish to 'shop' for the best possible connectivity metrics to be applied in catchment hydrology.

5.5.3 Methods

a. Study Site

This study was conducted in a 5.1 ha, V-shaped though elongated, headwater forested catchment, the Hermine, located in the Lower Laurentians natural province about 80 km north of Montréal, Québec, Canada (45°59' N, 74°01' W, elevation c. 400 m) (Figure 5.9 (A)). The catchment has a relief of 31 m and is drained by an ephemeral stream flowing east to west. The total annual precipitation to the watershed averages 1150 mm (± 136 mm) over the last 30 years, of which about 30% falls as snow (Biron *et al.*, 1999).

Soils are 1 to 2 m deep bouldery Podzols with a confining layer at a depth of 50 to 75 cm that restricts root penetration, slows water infiltration and thus enhances the probability of rapid lateral shallow subsurface flow with the formation of humid surface source areas. The distribution of thick organic horizons does not follow the broad morphological structure of the catchment as hydrophilic regions are mostly present on the south-facing, steeper hillslopes. Also, the forest floor has a complex surface micro-topography due to fallen tree trunks and boulders at the soil surface.

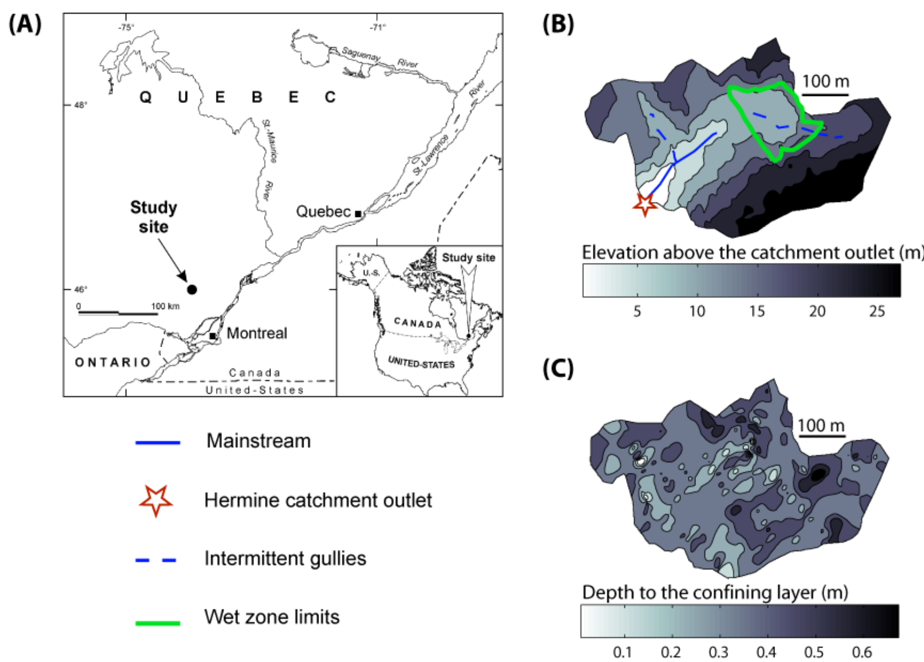


Figure 5.9. (A) Location of the Hermine catchment; (B) Surface digital elevation model (DEM); (C) Depth to the confining soil layer. The raster grid is 2 m by 2 m.

Forest canopy (mean age: 85 yr, mean basal area: 28 m^2 ha^{-1}) is dominated by sugar maple (78% of total basal area) (Turgeon, 2004; Courchesne *et al.*, 2005). As a result, transpiration is minimal between October and April so that changes in soil moisture and water table in that period are mostly governed by downslope drainage. The interception capacity of the forest canopy, combined with high summer potential evapotranspiration, greatly reduces the likelihood of surface runoff except during heavy rainstorms or wet and cool summers.

b. Field Measurements and Data Pre-processing

A surface digital elevation model (DEM) of the Hermine catchment (horizontal resolution: 1 m) was obtained by interpolating 640 elevation points collected in the field (Drouin, 1999) with a smooth simple natural neighbor (SNN) algorithm. Bilinear re-sampling was used to convert the interpolated data into a 2 m resolution surface DEM (Figure 5.9 (B)). Additionally, depth to the confining layer was measured at 257 points using a small hand auger that was forced vertically through the soil profile to refusal. For each sampling location, three auger refusal measurements were made in a 1 m radius and checked for consistency to discard data associated with individual rocks rather than the impermeable layer. The obtained data were then interpolated at a 2 m resolution, thus giving a subsurface DEM (Figure 5.9 (C)).

Volumetric moisture content in the top 5, 15, 30 and 45 cm of the soil profile was measured in the Hermine catchment along a 15 by 15 m sampling grid. Multiple depth measurements were made using a portable 30-inch long rod equipped with a capacitance-based probe (AQUATERR Instruments & Automation) that was pushed into the ground to the desirable depth. A total of 16 individual, one-day long surveys were collected between August 2007 and July 2008 to capture contrasted moisture patterns. Multiple surrogate measure for antecedent conditions and catchment response were used in this study; their abbreviated names and survey-related values are listed in Table 5.6.

To enable the computation of connectivity metrics, each of the 64 soil moisture maps (16 surveys x 4 depths) was transformed into 15 indicator maps using 15 different thresholds. Hereafter, original patterns will be referred to as *cont.* for continuous data, while indicator patterns will be referred to as '*dp*', '*cp*' or '*sm*'. Let $\theta_{5cm,\ t}$ be the set of soil moisture values measured at the 5 cm depth on survey *t*. $\theta_{15cm,\ t}$, $\theta_{30cm,\ t}$ and $\theta_{45cm,\ t}$ are the sets of soil moisture values collected on survey *t* at the depths of 15, 30 and 45 cm respectively, while $\theta_{catchment,\ t} = \{\theta_{5cm,\ t}\ ;\ \theta_{15cm,\ t}\ ;\ \theta_{30cm,\ t}\ ;\ \theta_{45cm,\ t}\}$. $\theta_{5cm,\ t}$, $\theta_{15cm,\ t}$, $\theta_{30cm,\ t}$ and $\theta_{45cm,\ t}$ are hereafter called "depth-specific" or "univariate" soil moisture distributions while $\theta_{catchment,\ t}$ are "catchment-wide" or "multivariate" soil moisture distributions. '*dp*' represents depth-specific percentiles: indicator patterns were computed using the 10th, 25th, 50th, 75th and 90th percentiles of $\theta_{5cm,\ t}$, $\theta_{15cm,\ t}$, $\theta_{30cm,\ t}$ or $\theta_{45cm,\ t}$ as thresholds. '*cp*' rather represents catchment-wide percentiles: indicator patterns were obtained using 10th, 25th, 50th, 75th and 90th percentiles of $\theta_{catchment,\ t}$ as thresholds. As for '*sm*', it refers to the use of constant soil moisture contents (i.e. 10%, 20%, 30%, 40% and 50%) as thresholds to derive the indicator patterns.

Table 5.6. Hydro-meteorological characteristics of the 16 soil moisture surveys in the Hermine catchment.

Date of survey	Antecedent conditions									Hydrological response		
	PET (mm d^{-1})	DSP (d)	AP1 (mm)	AP2 (mm)	AP5 (mm)	AP7 (mm)	AP12 (mm)	AP14 (mm)	PD_Discharge (mm d^{-1})	CD_Discharge (mm d^{-1})	DA1_Discharge (mm d^{-1})	MSMC (% vol)
Aug. 6, 2007	2.61	0	0	0	4	4	36	36	0.01	0.66	0.27	33.8
Aug. 13, 2007	2.58	1	12	12	17	44	48	48	0.08	0.22	0.07	23.3
Sept. 7, 2007	3.15	1	8	8	8	8	22	44	0.04	0.05	0.02	27.0
Sept. 14, 2007	2.19	0	0	0	14	14	22	22	0.05	0.07	0.50	29.0
Sept. 21, 2007	2.07	6	0	0	0	18	32	32	0.08	0.06	0.05	27.7
Sept. 28, 2007	1.73	0	4	4	4	4	4	22	0.03	0.10	0.14	27.9
Oct. 5, 2007	2.40	7	0	0	0	6	10	10	0.09	0.09	0.09	17.3
Oct. 12, 2007	1.49	0	25	25	40	42	42	48	0.25	5.87	3.06	39.6
Oct. 26, 2007	1.33	3	0	0	15	43	43	67	1.01	0.91	4.37	23.1
Nov. 2, 2007	1.23	6	3	3	3	33	48	76	1.36	1.52	1.46	21.5
Nov. 9, 2007	0.86	3	0	0	17	17	20	50	2.00	1.71	1.49	21.1
May 20, 2008	1.87	1	10	20	36	39	39	54	0.95	1.80	1.09	34.4
June 2, 2008	2.89	0	2	21	27	29	49	61	0.88	0.83	0.83	30.0
June 17, 2008	2.37	1	13	14	14	29	37	37	0.52	0.52	0.49	32.2
July 15, 2008	2.51	3	2	3	19	43	54	59	0.53	0.42	0.37	31.5
July 21, 2008	2.44	0	0	0	33	35	73	75	0.90	0.78	1.42	35.2

Notes

PET: Mean daily potential evapotranspiration computed after the temperature-based Hargreaves formula (Hargreaves, 1975)
DSP: Number of days since the last precipitation (rainfall intensity exceeding 5 mm d^{-1})
AP1, AP2, AP5, AP7, AP12, AP14: Cumulative precipitation from 1, 2, 5, 7, 12 and 14 days before the survey
PD_Discharge: Catchment discharge on the day preceding the survey
CD_Discharge and DA1_Discharge: Catchment discharges on the day of the survey and the day after
MSMC: Catchment mean soil moisture content (volumetric, on a 0-60% scale)

Table 5.7. Soil moisture-based connectivity metrics tested for the Hermine catchment.

Abbreviated name	2D	3D	Cont.	Ind.	Description (suitable for the present study)	Similar metrics commonly used in…
ENTROPY	√		√	√	Spatial entropy	Information theory Ecology, geography
SATAREA	√	√		√	Saturated area or volume of soil	Ecology, hydrology
SATCLUST	√	√		√	Number of isolated clusters of saturated areas or volumes	Ecology
EFFCAREA	√			√	Effective contributing area, i.e. saturated areas contributing (topographically) to the response at the catchment outlet	Hydrology
RANGE_OM	√		√	√	Range of fitted omnidirectional variograms	
RANGE_NS	√		√	√	Range of fitted variograms computed in the north-south direction (hillslopes orientation, gullies drainage in the Hermine catchment)	Geography, hydrology, earth sciences in general
RANGE_EW	√		√	√	Range of fitted variograms computed in the east-west direction ('valley' width effects, intermittent stream drainage in the Hermine catchment)	
OMNI	√	√		√	Omnidirectional ICSL based on Euclidean distances between sampling locations	Geology, hydrology
TOPO	√	√		√	Multidirectional ICSL based on surface macro-topography and Euclidean distances; all downslope directions (not only the two steepest) are considered	Hydrology
SUBTOPO	√	√		√	Multidirectional ICSL based on subsurface macro-topography and Euclidean distances	***
OMNI_STS	√	√		√	Source-to-stream omnidirectional ICSL: connected saturated paths must lead to the catchment outlet; based on Euclidean distances between sampling locations and the catchment outlet	***
TOPO_STS	√	√		√	Adaptation of OMNI_STS with the consideration of surface macro-topography	***
SUBTOPO_STS	√	√		√	Adaptation of OMNI_STS with the consideration of subsurface macro-topography	***
TOPO_HD	√			√	Same as TOPO with the use of hydrologic rather than Euclidean distances	***
SUBTOPO_HD	√			√	Same as SUBTOPO with the use of hydrologic rather than Euclidean distances	***
TOPO_HD_STS	√			√	Same as TOPO_STS with the use of hydrologic rather than Euclidean distances	***
SUBTOPO_HD_STS	√			√	Same as SUBTOPO_STS with the use of hydrologic rather than Euclidean distances	***

Cont.: Metric computed based on original (continuous) soil moisture data ; Ind.: Metric computed based on 'thresholded' (indicator) soil moisture data
***: Metric introduced/modified and tested in this paper

Thresholds for indicator patterns derivation
dp10, dp25, dp50, dp75, dp90: depth-specific percentiles (i.e. 10^{th}, 25^{th}, 50^{th}, 75^{th} and 90^{th}) of univariate soil moisture distributions
cp10, cp25, cp50, cp75, cp90: catchment-wide percentiles (i.e. 10^{th}, 25^{th}, 50^{th}, 75^{th} and 90^{th}) of multivariate (all depths confounded) soil moisture distributions
sm10, sm20, sm30, sm40, sm50: constant soil moisture contents (i.e. 10%, 20%, 30%, 40% and 50%)

c. Connectivity Metrics Computations

The connectivity metrics computed in this paper and their abbreviated names used throughout the text are listed in Table 5.7. Four areal metrics were tested, namely the 2D pattern entropy (ENTROPY), the number of isolated saturated clusters (SATCLUST), the catchment saturated area or volume (SATAREA) and the effective contributing area (EFFCAREA). Both ENTROPY and SATCLUST are an illustration of the spatial extent and the 'randomness' of saturation at the catchment scale. EFFCAREA restricts the evaluation of the catchment saturated area to the locations that are topographically connected to the outlet.

Linear metrics involved 2D variogram ranges and 2D and 3D integral connectivity scale lengths (ICSLs). Isotropic (RANGE_OM) and anisotropic (RANGE_NS and RANGE_EW) experimental variograms were computed. Given the orientation and the shape of the Hermine catchment, the north-south direction is representative of hillslope and gully drainage into the intermittent stream flowing east to west. Either exponential or hole-effect ('wave') semivariogram models were fitted to the experimental variograms to derive the ranges. Omnidirectional ICSLs (OMNI) were evaluated similarly to Western *et al.* (2001) and James & Roulet (2007) but topographic ICSLs computations were refined to weigh connectivity according to multidirectional flow apportionment among all downslope nearest neighbors. Topographic ICSLs were estimated using either the surface or the subsurface DEM. Source-to-stream (STS) ICSLs were only different from their non-STS counterparts in that they only considered connected saturated paths leading to the catchment outlet. As for HD topographic ICSLs, they relied on hydrologic distances (i.e. flow lengths derived from DEM analysis) rather than Euclidean distances to identify saturated connected locations. Even though we have some evidence of an asymmetric distribution of organic soil horizons in the Hermine catchment that probably affects source areas spatial connectivity, we did not include any soil property in the computed metrics as the data available was not as spatially detailed as the soil moisture sampling scheme.

d. Analytical Methods

Soil moisture maps and statistical distributions at different thresholds were visually checked for changes in the organization of spatial patterns. Connectivity metrics were then confronted in their ability to reflect the changes visually observed in the patterns. This was done by computing the coefficient of variation of each metric among the surveys as an indication of temporal change.

Spearman rank correlation coefficients (r_s) were used to assess the relationship between the values of the connectivity metrics and both the catchment mean soil moisture content (MSMC) and catchment discharges. Both short-term (0 to 2 days after survey) and medium-term (3 to 7 days after survey) catchment discharges were tested as no assumption was made about the catchment response rate.

The dependence of the connectivity metrics values upon meteorological factors was investigated using three-way variation partitioning. This method allows one to partition the variation of a response variable [or data table] among two or more sets of explanatory variables using a series of regressions [or canonical analyses]. The adjusted R-squares of the analyses are combined to compute the amount of variation explained uniquely by each explanatory table and also jointly by two tables (Borcard *et al.*, 1992). The variability in the values of the connectivity metrics was explained with regards to the individual effect or the joint effect of (i) current rainfall (on the day of the survey), (ii) potential evapotranspiration (PET) computed after the temperature-based Hargreaves formula (Hargreaves, 1975), and

(iii) antecedent precipitation from the 1, 2, 5, 7, 12 and 14 previous days (AP1, AP2, AP5, AP7, AP12 and AP14).

Lastly, metrics were classified according to their ability to satisfy three criteria. Hydrologically representative metrics were defined as the ones being (1) variable in time and sensitive to varying conditions, (2) dependent upon meteorological factors, and (3) correlated with either short- or medium-term catchment discharges. A satisfaction score (value of 1 to 3) to each of the three criteria was calculated for each metric at each threshold as shown in Table 5.8. An objective function, representing the overall performance of each metric at each threshold, was computed by summing the three satisfaction scores. The 'perfect' metric was expected to have an objective function value of 9. For the sake of brevity in this paper, emphasis was put on metrics with an objective function value of 8 or better.

Table 5.8. Scores to be attributed to each connectivity metric given the satisfaction to three criteria. Assessment of hydrologically representative metrics is based on the value of an objective function that is the sum of individual satisfaction scores.

Qualitative Criterion	Quantitative Criterion	Score = 1	Score = 2	Score = 3
Temporal variability	X1 = Temporal coefficient of variation	X1 < 50%	50% ≤ X1 < 100%	X1 ≥ 100%
Dependence upon meteorological factors	X2 = *R-square* from three-way variation partitioning	X2 < 0.5	0.5 ≤ X2 < 0.7	X2 ≥ 0.7
Influence on short- or medium-term catchment discharges	X3 = Spearman rank correlation between connectivity metric and discharge	X3 < 0.5	0.5 ≤ X3 < 0.7	X3 ≥ 0.7
OBJECTIVE FUNCTION = Score(X1) + Score(X2) + Score(X3)				

5.3.4 Results

a. Discharges and Change in Soil Moisture Patterns Organization

Half of the 16 surveys were associated with observable outflow (discharge > 0.6 mm d^{-1}) at the catchment outlet (Table 5.6). MSMC was positively correlated with rainfall inputs on the days of the surveys ($r_{spearman}$ = 0.76, 99% significance level) and with AP5 ($r_{spearman}$ = 0.59, 95% significance level) and negatively correlated with the number of days elapsed since the last rainfall event (DSP, $r_{spearman}$ = -0.73, 99% significance level). Discharges on surveying days were also positively correlated to AP5 ($r_{spearman}$ = 0.62, 95% significance level) and AP14 ($r_{spearman}$ = 0.65, 99% significance level) while negatively correlated with PET and DSP. Correlations between CD_Discharge and AP1 were small when all surveys were considered but very strong ($r_{spearman}$ = 0.9, 99% significance level) when only surveys associated with discharges greater than 0.6 mm d^{-1} were included in the computations. MSMC was not a good predictor of CD_Discharge unless the effects of seasonality as portrayed by PET were considered. Discharges associated with high PET showed a threshold-like change with MSMC (Figure 5.10), and 30% volumetric soil moisture appeared to be the tipping point above which a significant catchment response was observed. The three surveys associated with low PET values required smaller mean soil moisture contents (20-25%) for important discharges to occur. These observations suggest that there exists a switch in behavior in the Hermine catchment. Given the extensive canopy cover subjected to leaf senescence, it is however not a 'straightforward' switch as it is governed by antecedent conditions both at the seasonal and the sub-seasonal scales. Changes in soil moisture patterns, especially in terms of connectivity, were therefore expected to reflect this multiple states dynamics.

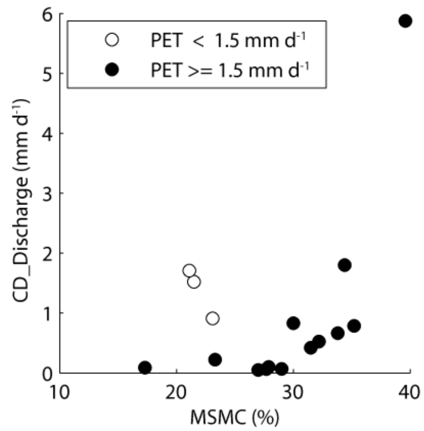


Figure 5.10. Relationship between CD_Discharge and MSMC as a function of PET for the 16 soil moisture surveys in the Hermine catchment. Refer to Table 5.6 for the meaning of acronyms.

Nonparametric Kruskal-Wallis tests showed that soil moisture patterns were significantly different (95% significance level) among both survey dates and studied depths. The visual evaluation of soil moisture spatial organization was also markedly different depending on the chosen threshold for indicator patterns derivation. As an example, the spatial patterns of 15 perspectives on soil moisture based on various thresholds are shown in Figure 5.11 for a 'dry' and a 'wet' pattern. Differences in the saturated pixels indicated by the *dp10*, *dp25* and *dp50* patterns between the two dates were not pronounced, which is at odds with the fact that the 'wet' survey was associated with greater antecedent precipitation values and discharges than those associated with the 'dry' survey. The change in pattern was more perceptible with '*cp*' thresholds, especially with *cp75* maps showing an uninterrupted path of saturated pixels leading to the catchment outlet for the 'wet' survey. Indicator patterns based on '*sm*' thresholds also highlighted the uninterrupted path of saturated pixels for the 'wet' survey where locations with volumetric soil moisture content of at least 40%. The only two pixels with a 50% or higher soil moisture content were immediately surrounding the catchment outlet (Figure 5.11). The use of '*sm*' indicator patterns was also useful in comparing the vertical persistence of saturated pixels. As illustrated in Figure 5.12, for example, high soil moisture content was present at all depths on Oct. 12, 2007 but only at 5 and 15 cm on July 15, 2008. The Oct. 12 survey was associated with important rainfall and high AP7 while the July 15 survey was associated with the same amount of AP7 but no current rainfall and a discharge at the catchment outlet that was seven times lower (Table 5.6).

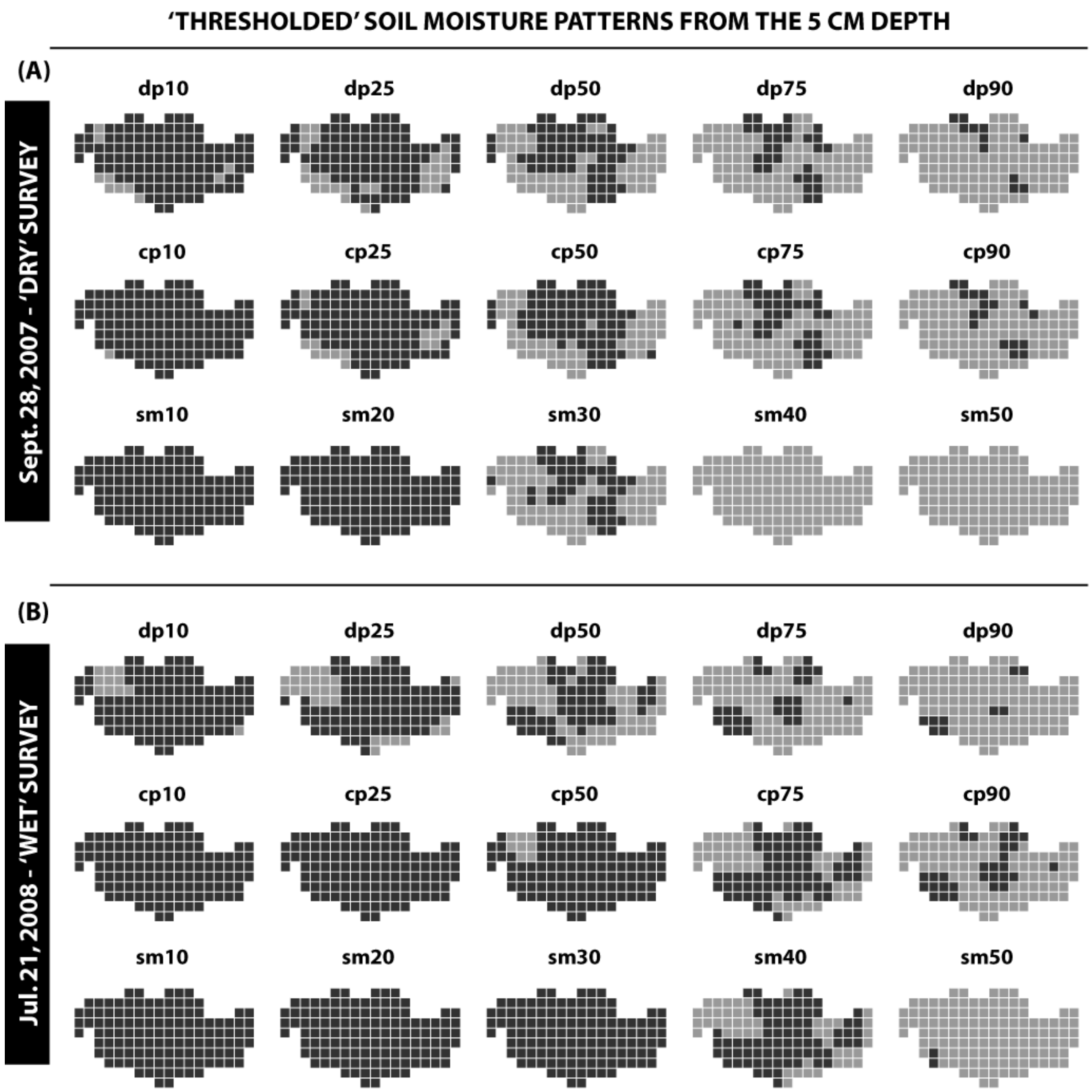


Figure 5.11. Contrasted binary soil moisture maps for two survey dates and various indicator thresholds. Dark cells have soil moisture values greater than the threshold. The raster grid is 15 m by 15 m. Refer to Table 5.7 for the meaning of acronyms.

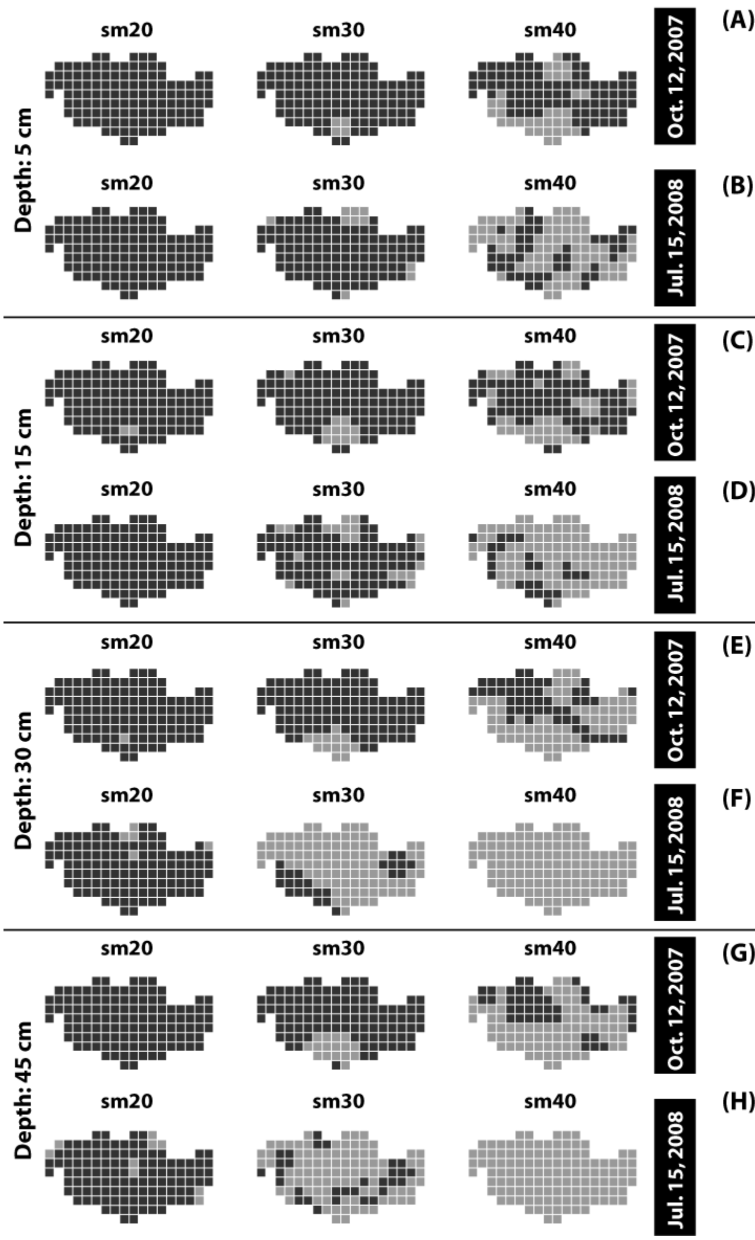


Figure 5.12. Indicator soil moisture patterns for two 'wet' surveys given the *sm20*, *sm30* and *sm40* thresholds. Dark cells have soil moisture values greater than the threshold. The raster grid is 15 m by 15 m. Refer to Table 5.7 for the meaning of acronyms.

b. Hydrologically Representative Connectivity Metrics

Global Assessment and Objective Function Values. The computed connectivity metrics allowed us to assess directional, depth-controlled and topographic effects in soil moisture patterns organization. For example, RANGE_NS values were usually greater than RANGE_OM or RANGE_EW values (Figure 5.13), which suggests that drainage from the hillslopes gullies can take place over longer distances than that from the main ephemeral stream in the Hermine catchment. Values of EFFCAREA were always smaller than those of SATAREA, even though the two metrics displayed similar patterns of variability for '*cp*' and '*sm*' thresholds (Figure 5.13). OMNI values were generally larger than both TOPO and SUBTOPO values, except for the wettest surveys. In the most humid conditions, TOPO values based on high thresholds indicator patterns were often greater than OMNI values. SUBTOPO values were always smaller than TOPO value*s* in both 2D and 3D (Figure 5.13). For high thresholds indicator patterns, STS and HD ICSLs tended to be smaller than their non-STS and Euclidean equivalents (Figure 5.13). The range in connectivity metrics values was small for low thresholds (i.e. lower than *dp25*, *cp25* or *sm20*) while variability was greater when high '*cp*' or '*sm*' thresholds were used for indicator patterns derivation. SATCLUST was the only metric showing good variability regardless of the chosen threshold in both 2D and 3D (Figure 5.13).

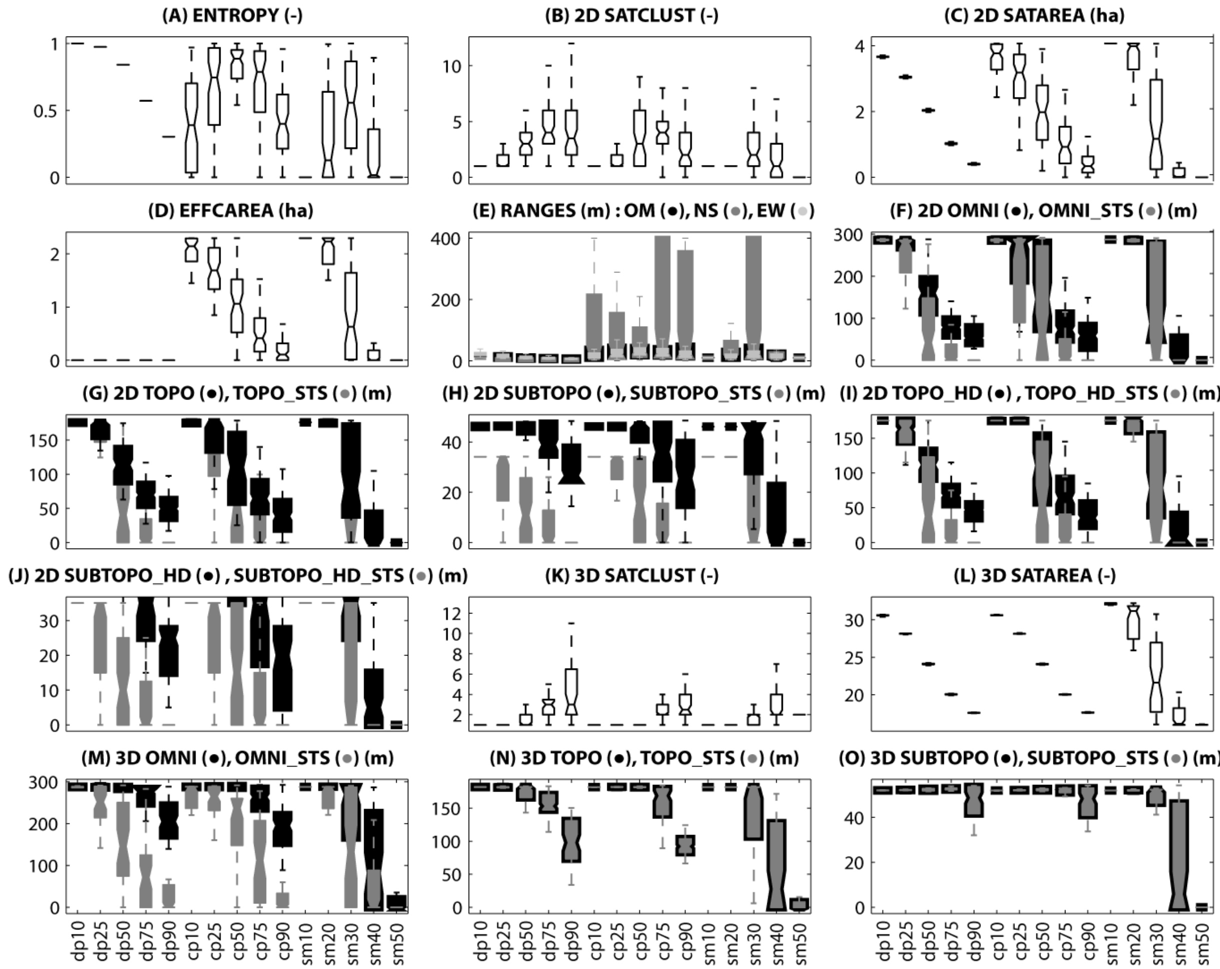


Figure 5.13. Boxplots of connectivity metrics values depending on the chosen indicator threshold. Notches are drawn to provide a robust estimate of the uncertainty about the medians for box-to-box comparison. Refer to Table 5.7 for the meaning of acronyms. For panels (E), (F), (G), (H), (I), (J), (M), (N), (O), each connectivity metric is illustrated with a different color as indicated by the small circles in the panels titles.

As the performance scores associated with each of the three decision criteria (refer to Table 5.8) were summed up, none of the computed connectivity metrics reached the perfect objective function value of 9. Several metrics however had an objective function value of 8 (see Table 5.9), which means that two of the three criteria listed in Table 5.8 were satisfied. Apart from variogram ranges, all metrics with an objective function value of 8 were derived from intermediate or high thresholds patterns, and the great majority of them were '*sm*' patterns. This is particularly true for areal and linear metrics computed from *sm50* indicator patterns at a depth of 15 cm. RANGE_NS was the connectivity measure with an objective function value of 8 at a depth of 5 cm, while a greater variety of hydrologically representative metrics was observed at depths of 30 and 45 cm. It is at depths of 30 and 45 cm that STS ICSL measures mostly satisfied the criteria of temporal variability, dependence upon meteorological factors and influence on medium catchment discharges (Figure 5.14), hence the objective function value of 8. Similarly, SUBTOPO could be labeled as hydrologically representative at 45 cm. The effectiveness of Euclidean versus hydrologic distance-based metrics in capturing hydrologically significant features in the spatial patterns was dependent upon the depths of measurement. At 15 cm, TOPO and SUBTOPO had to be computed based on high thresholds patterns (e.g. *sm50*) and using hydrologic distance in order to be considered as hydrologically representative. At 30 and 45 cm, however, TOPO and SUBTOPO were hydrologically representative regardless of whether they were calculated based on Euclidean or hydrologic distances for selected thresholds (e.g. *dp75*, *cp50*, *sm30*, see Table 5.9). In 3D, OMNI computed from *sm50* indicator patterns was the only metric that could be considered as hydrologically representative.

Table 5.9. List of most hydrologically representative connectivity metrics (objective function value = 8) for the Hermine catchment.

Depth	Connectivity metric	Threshold
5 cm	RANGE_NS	cp50
	RANGE_NS	sm20
15 cm	RANGE_OM	cp10
	RANGE_EW	cp10
	RANGE_OM	cp25
	ENTROPY	sm20
	ENTROPY	sm50
	SATAREA	sm50
	SATCLUST	sm50
	OMNI	sm50
	TOPO_HD	sm50
	SUBTOPO_HD	sm50
30 cm	TOPO_STS	dp75
	SUBTOPO_STS	dp75
	TOPO_HD_STS	dp75
	SUBTOPO_HD_STS	dp75
	RANGE_NS	cp25
	OMNI_STS	sm30
	TOPO_STS	sm30
	TOPO_HD_STS	sm30
	ENTROPY	sm50
45 cm	TOPO_STS	dp75
	SUBTOPO_STS	dp75
	TOPO_HD_STS	dp75
	SUBTOPO_HD_STS	dp75
	OMNI_STS	cp50
	TOPO_STS	cp50
	SUBTOPO_STS	cp50
	TOPO_HD_STS	cp50
	SUBTOPO_HD_STS	cp50
	RANGE_OM	cp90
	ENTROPY	sm20
	RANGE_EW	sm30
	OMNI_STS	sm30
	TOPO_STS	sm30
	SUBTOPO_STS	sm30
	TOPO_HD_STS	sm30
	SUBTOPO_HD_STS	sm30
	RANGE_EW	sm40
	TOPO	sm40
	SUBTOPO	sm40
3D	OMNI	sm50

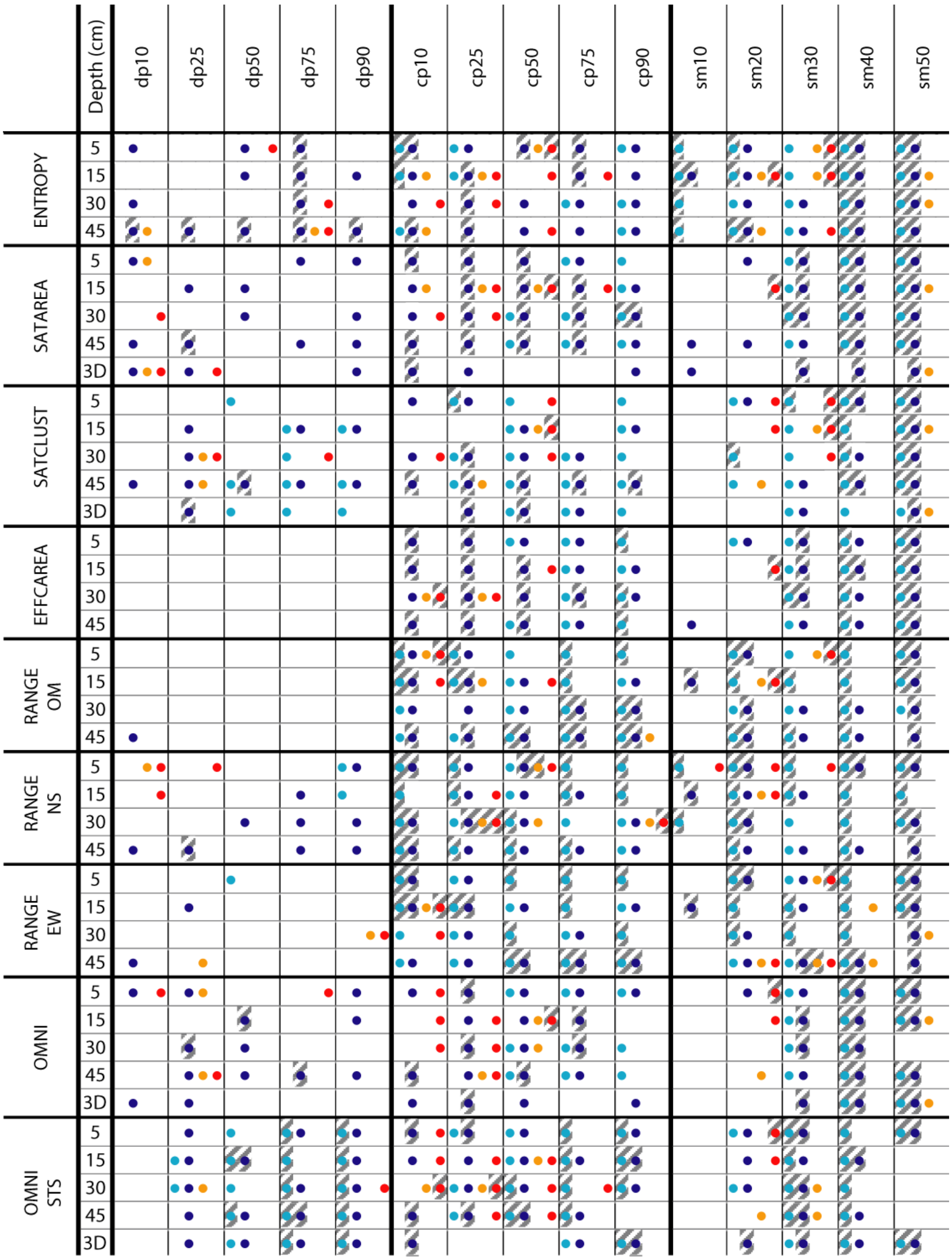

Depth (cm)
dp10
dp25
dp50
dp75
dp90
cp10
cp25
cp50
cp75
cp90
sm10
sm20
sm30
sm40
sm50
ENTROPY
SATAREA
SATCLUST
EFFCAREA
RANGE OM
RANGE NS
RANGE EW
OMNI
OMNI STS
5
15
30
45
3D

Figure 5.14

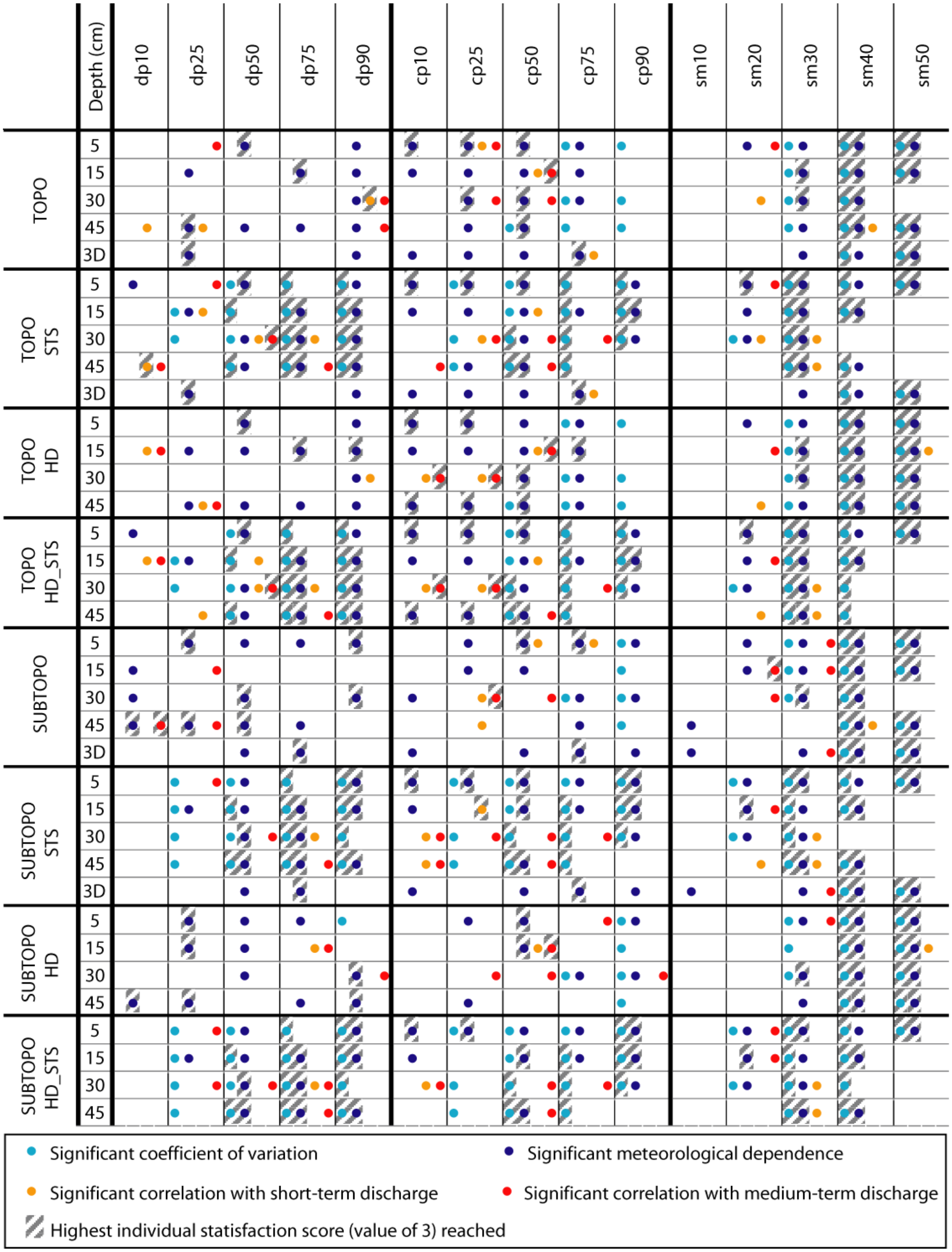


Figure 5.14 (cont'd). Satisfaction of the computed connectivity metrics to the three individual criteria for the Hermine catchment. Refer to Table 5.7 for the meaning of acronyms.

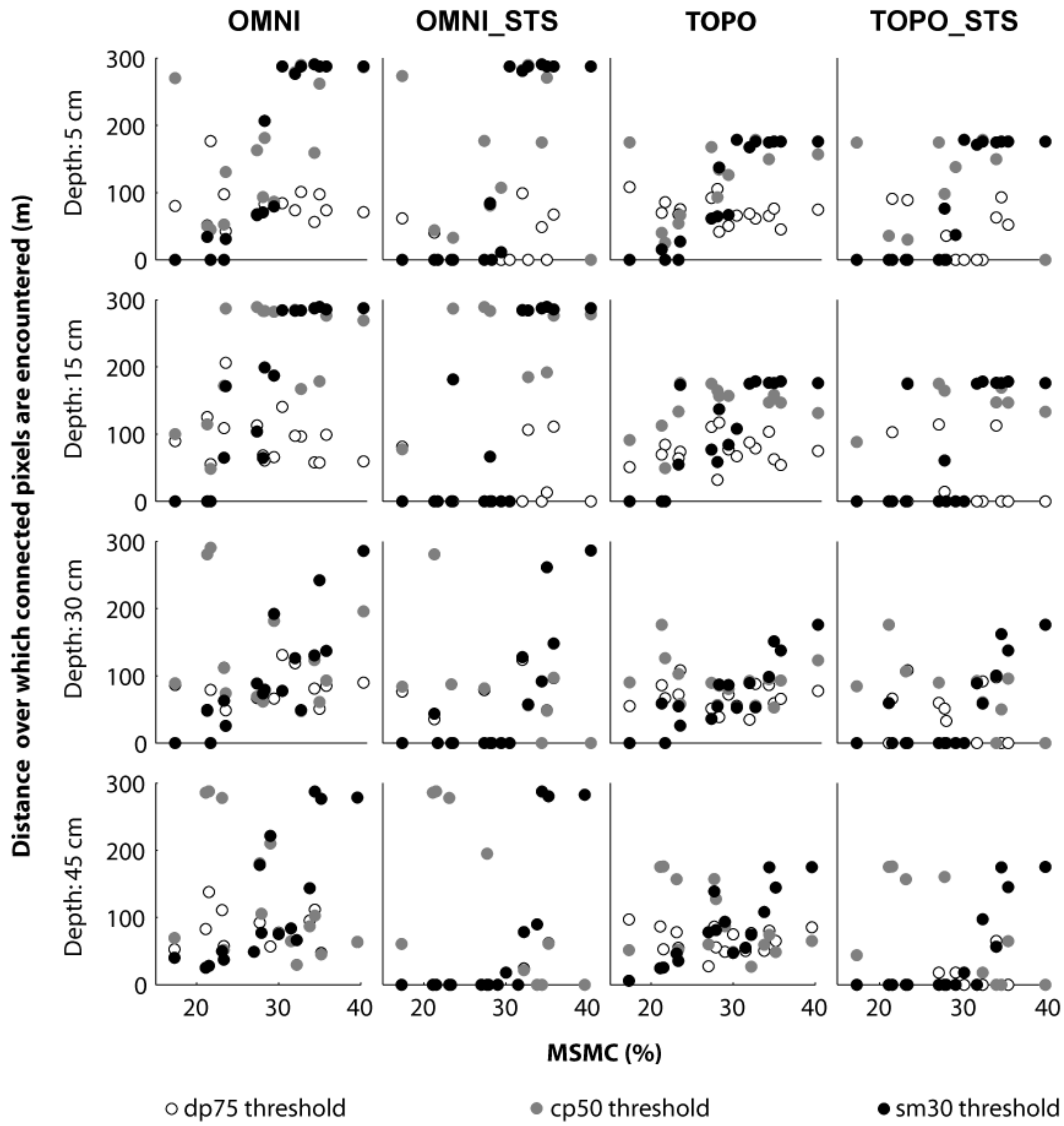


Figure 5.15. Relationships between selected connectivity metrics and MSMC given three different thresholds for indicator patterns derivation. Refer to Tables 5.6 and 5.7 for the meaning of acronyms.

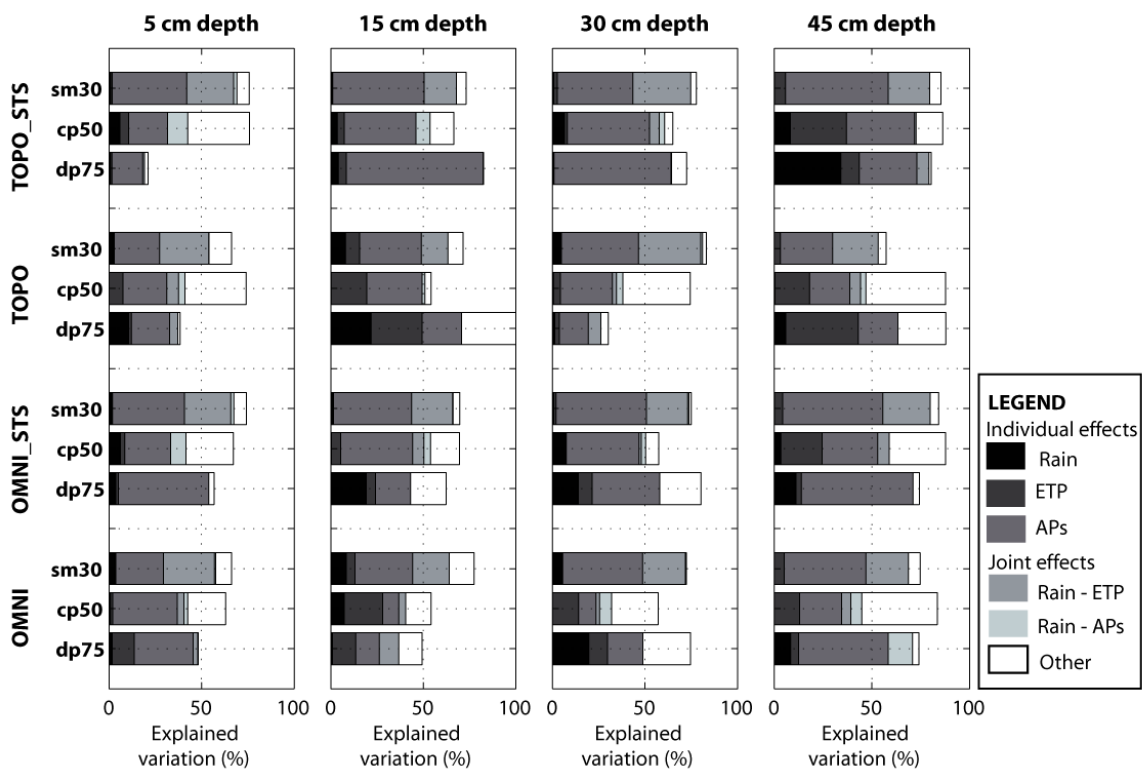


Figure 5.16. Dependence of selected connectivity metrics upon meteorological conditions given three different thresholds for indicator patterns derivation. Refer to Tables 5.6 and 5.7 for the meaning of acronyms. “APs” refers to the joint effect of AP1, AP2, AP5, AP7, AP12 and AP14.

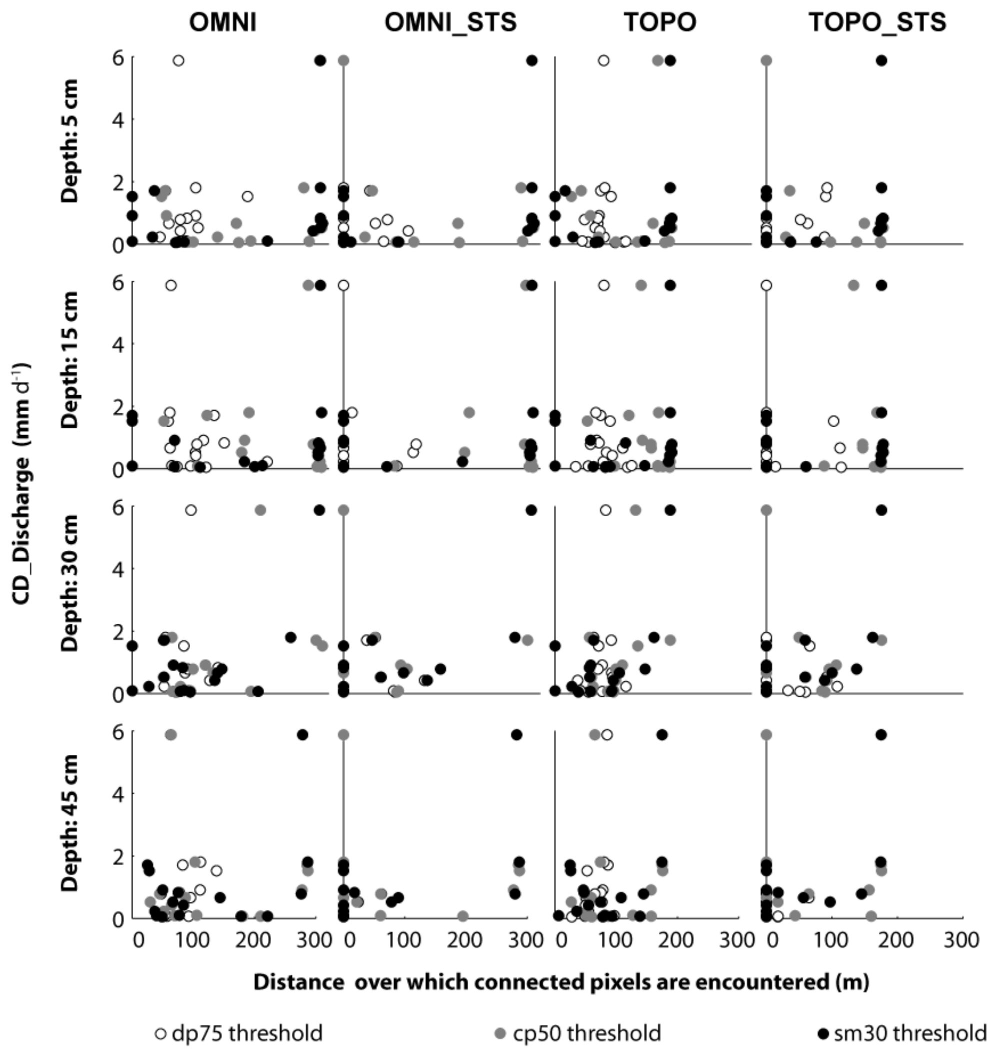


Figure 5.17. Relationships between CD_Discharge and selected connectivity metrics given three different thresholds for indicator patterns derivation. Refer to Tables 5.6 and 5.7 for the meaning of acronyms.

Metrics Satisfaction to Individual Criteria. With respect to the temporal variability, all metrics are characterized by high temporal coefficients of variation when they were computed based on intermediate to high thresholds (Figure 5.14). For example, variogram ranges had scores of 3 regarding the 'temporal change' criteria (see Table 5.8) when computed based on '*cp*' and high thresholds indicator patterns (i.e. higher than *dp75* or *sm20*). 2D areal measures like SATAREA and EFFCAREA were highly time-variable when based on *cp90* or *sm30* and higher indicator patterns. 2D and 3D ICSLs reflected important changes in the spatial organization of *sm30* and *sm40* binary patterns, or when high '*dp*' and '*cp*' thresholds were used. In 3D, however, no areal metrics was associated with high temporal variability. Another way to assess temporal change in the metrics values was through their correlation with MSMC which was highly dependent upon the chosen threshold for indicator patterns derivation. For example, scatter plots in Figure 5.15 show that while OMNI, OMNI_STS, TOPO and TOPO_STS computed based on *sm30* patterns are nonlinearly correlated to MSMC, such is not the case when the same metrics are computed based on *dp75* or *cp50* patterns.

Regarding the metrics meteorological dependence, variation partitioning results suggest the most sensitive connectivity measures were mainly computed from '*cp*' and '*sm*' indicator patterns (Figure 5.14). Both areal and linear metrics based *sm30* patterns or higher were consistently associated with high R-squares from three-way variation partitioning. For '*dp*' and '*cp*' patterns, however, metrics values were less consistently influenced by meteorological factors and when they were, high thresholds were usually involved. Figure 5.16 shows that most of the time, antecedent precipitation values had the strongest influence on four ICSL measures, and this is also true for the other connectivity metrics tested in this paper. The effect of PET was negligible for ICSL measures, unlike the four areal connectivity metrics or any metric computed based on low threshold indicator pattern (data not shown). Rainfall inputs on the days of the surveys influenced the metrics values only when high thresholds patterns were examined (e.g. *dp75*) below the 15 cm depth (Figure 5.16).

Relationships between connectivity metrics and short-term discharges were difficult to discern, as shown in Figure 5.17 for OMNI, OMNI_STS, TOPO and TOPO_STS computed from *dp75*, *cp50* and *sm30* indicator patterns. Three types of behaviors tended to emerge, namely cases where (i) low discharges were associated with medium or high connectivity; (ii) medium or high discharges were associated with no connectivity; and (iii) medium or high discharges were associated with medium or high connectivity. The latter behavior usually occurred given specific catchment antecedent conditions. Figure 5.18 shows an example where meteorological factors are weighed to assess more efficiently the relationship between CD_Discharge and OMNI_STS at a depth of 45 cm. Given the *sm30* threshold, a nonlinear relationship between discharges associated with high PET and connectivity is observed (Figure 5.18 (G)). This is coherent with the threshold-like relationship previously mentioned between discharges associated with high PET and MSMC (see Figure 5.10). Similarly, for *sm30* patterns, a nonlinear relationship between CD_Discharge and OMNI_STS can be observed when AP7 exceeds 32 mm d^{-1} or when there is rain on the survey date. Given these particular dynamics, very few significant Spearman correlation coefficients were obtained between short-term discharge and connectivity metrics values, hence the scarce satisfaction to the ‘influence on short-term discharge’ criterion (Figure 5.14). A few metrics, both areal and linear, showed a significant correlation with medium-term discharges, especially when the *sm30* threshold was used for indicator patterns derivation (Figure 5.14).

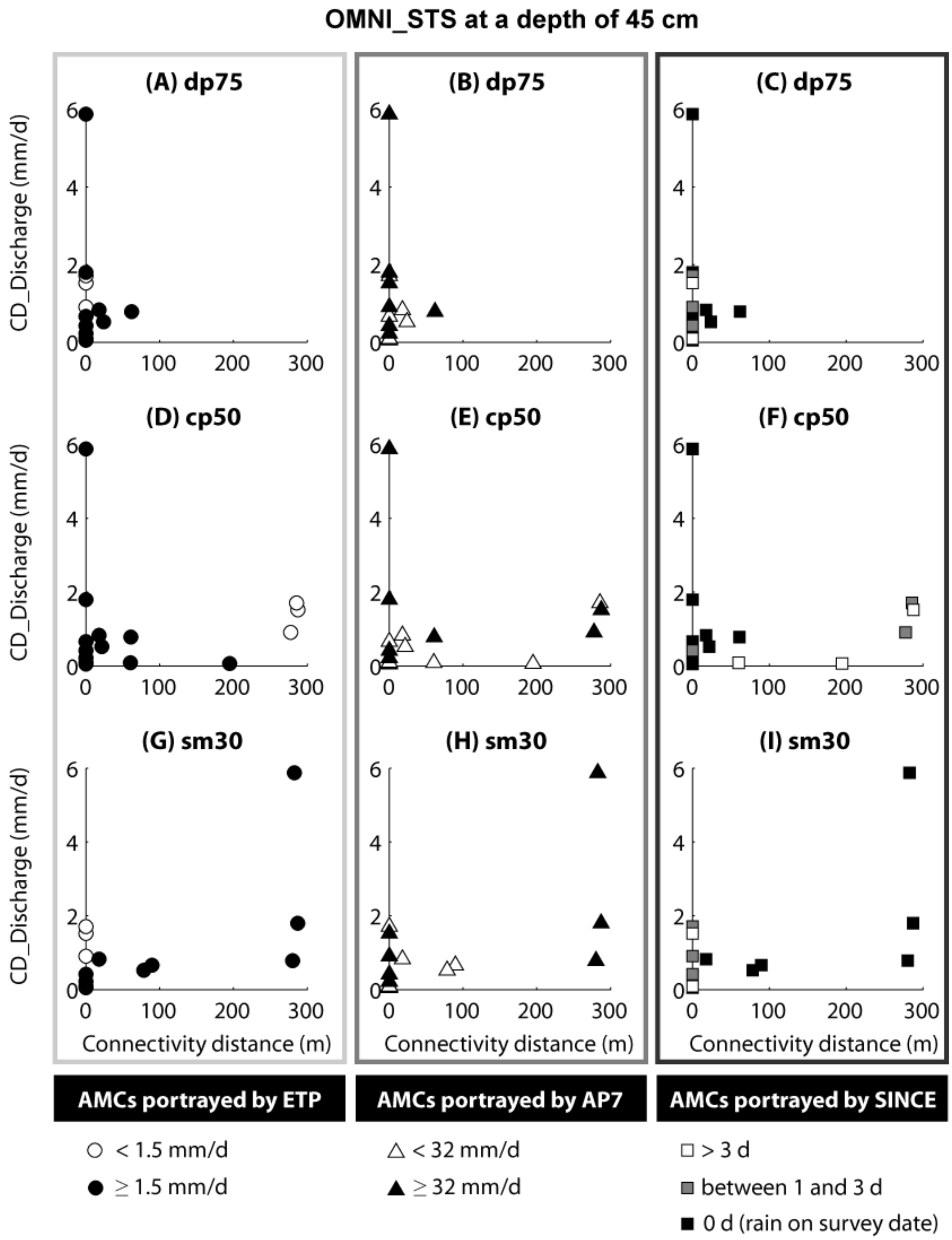


Figure 5.18. Relationships between CD_Discharge and OMNI_STS at a depth of 45 cm given specific antecedent conditions and three different thresholds for indicator patterns derivation. Refer to Tables 5.6 and 5.7 for the meaning of acronyms.

5.3.5 Discussion

a. Changing Spatial Patterns of Soil Moisture

Soil moisture patterns are regularly used in connectivity assessments as topography-controlled fingerprints of subsurface flow processes (Weiler *et al.*, 2005; Western *et al.*, 2001; Western *et al.*, 2005; James & Roulet, 2007). In the Hermine catchment, however, saturation did not occur from the valley bottom upwards. In both transient and wet conditions, several saturated areas formed on the hillslopes, especially on the south-facing more hydrophilic ones. Important discharges were induced exclusively when these saturated areas were not only interconnected but also connected to the catchment outlet.

Our findings do not differ from those of James & Roulet (2007), who stated that '*a constant pattern in shallow soil moisture [was] present across the threshold change in catchment runoff response'* in Mont-St-Hilaire. We observed very small changes in saturation zones when we examined '*dp*' indicator patterns. Even when there were some differences between patterns associated with highly contrasted surveys, they often occurred on a very small, pixel-to-pixel scale rather than involving critical dry clusters acting as barriers between saturated areas. We were however able to observe major changes in the spatial organization of soil moisture when '*cp*' or '*sm*' indicator patterns were used, and these changes were reflected in most of the computed connectivity metrics. Climatic forcings may be put forward to explain why '*dp*' indicator patterns were successful in showcasing changes in soil moisture spatial organization in temperate rangeland environments but not in humid temperate forested systems. Indeed, given two contrasted surveys, significative changes in '*dp*' indicator patterns should be observable when changes in the actual soil moisture occur not in terms of extreme values but rather in terms of central tendency measures. James & Roulet (2007) suggested that the switch between evapotranspiration-dominated and precipitation-dominated conditions in temperate rangeland environments is not present in humid temperate forested catchments. Hence, there are never dominant vertical soil water fluxes that could induce random patterns in humid systems. We agree with that explanation, since it implies that all year around humid systems are characterized by comparable soil moisture distributions, the central tendency measures of which vary over a much smaller range than temperate rangeland catchments (Figure 5.19). Time-invariant indicator thresholds are therefore better suited for pattern organization assessment, since they are based on an absolute rather than a relative estimate of catchment saturation. As for the fairly good performance of '*cp*' indicator thresholds, it can be attributed to the higher time variance of multiple-depths soil moisture distributions in comparison to single-depth distributions.

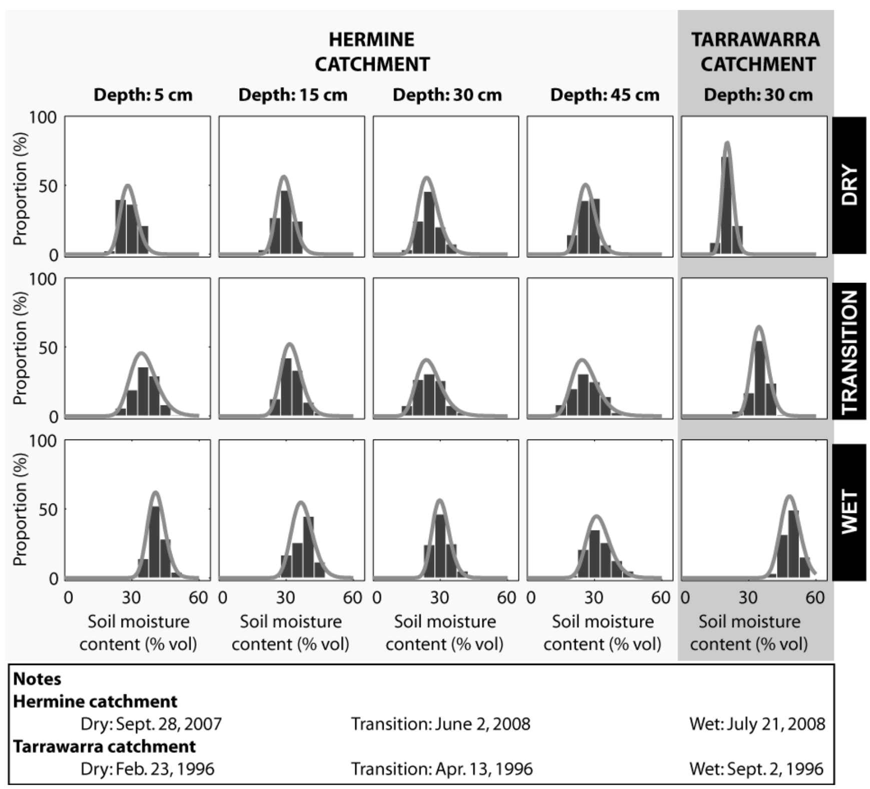


Figure 5.19. Sample statistical distributions of volumetric soil moisture content measured in the Hermine and the Tarrawarra catchments for three contrasted surveys. Soil moisture patterns data from the Tarrawarra data set homepage were used.

b. Hydrologically Representative Connectivity Metrics

Our identification of hydrologically representative (objective function value of 8) connectivity metrics was not only interesting as it helped us discriminate between soil moisture patterns but also because it changed some of our views on the Hermine catchment internal dynamics. For instance, the fact that RANGE_NS values were usually greater than RANGE_OM or RANGE_EW suggests that drainage from the hillslopes gullies is larger than that from the main ephemeral stream. For the wettest surveys, TOPO values based on high thresholds indicator patterns were often greater than OMNI values, thus indicating that topography-induced lateral water movement is important in wet conditions. Such an observation was also made by James & Roulet (2007) in the humid temperate forested Mont-St-Hilaire system located in the same physiographic area as the Hermine catchment, and it was attributed to the fact that although there are less pixels with higher-than-indicator values included in the directional analysis, a larger number of them are inter-connected, thus leading to a higher degree of connectivity. At the Hermine, SUBTOPO values were always smaller than TOPO values in both 2D and 3D, which may imply that subsurface sinks tend to store subsurface water for more or less lengthy periods before it actually flows out via the catchment outlet. The effect of evapotranspiration was mostly important for the four areal connectivity metrics, which means that evapotranspiration influences the smoothness of the patterns rather than the presence of interconnected features in these patterns. As for critical source areas in the Hermine catchment, they appear to be locations with a volumetric soil moisture content equal to or greater than 30%. Indeed, both areal and linear metrics based *sm30* patterns or higher were consistently correlated with meteorological conditions and also had a significant relationship with medium-term catchment discharges.

Hydrological processes underlying the Hermine catchment dynamics also seem dependent upon soil depths. As a matter of fact, only RANGE_NS was found to be hydrologically representative at 5 cm, thus indicating that surface continuity is more important than connectivity. This result can be linked to the catchment irregular surface micro-topography and to the fact that smooth soil moisture patterns denote that there are no major barriers to topsoil runoff routing. Hydrologically representative metrics at 15 cm were computed from *sm50* indicator patterns and proved to be highly sensitive to rainfall inputs. The fact that we could only capture 15 cm depth connectivity at a very high threshold may indicate that it is a very critical, short-lived phenomenon in that particular soil layer. Besides, all hydrologically representative directional metrics at 15 cm were based on hydrologic distances, and this result underlines the importance of rapid subsurface runoff routing via topographically-defined flow paths. STS ICSL measures were more hydrologically representative at depths of 30 and 45 cm in comparison to 15 cm, which indicates that the link between source areas and the catchment outlet takes place via a subsurface hydraulic connection rather than a near surface one.

c. Not so Hydrologically Representative Connectivity Metrics

Even though the focus was not put on the specific values of the computed metrics in this paper, it is worth mentioning that the obtained results were in accordance with the morphology of the Hermine catchment. Several options were tested with regards to the metrics calculation, and some of their performances were worse than expected. For example, the computation of 3D connectivity metrics did not result in many hydrologically representative measures. This may be attributed to the presumed downgraded influence of vertical water fluxes in humid systems (Grayson *et al.*, 1997). Also, the examination of 3D connectivity over 45 cm thick pixels may be too small of a volume in order to get sensible results. Besides, 3D ICSL measures were computed based on Euclidean distances, which is highly unrealistic given the restricted/channelized water pathways within a soil matrix. The indicator threshold issue was difficult to synthesize since the appropriate critical value varied among metrics and soil depths. The difference between areal and linear metrics was mainly in terms of their dependence upon meteorological factors, but linear measures tended to be more hydrologically representative than areal metrics. Consideration of the source-to-stream connection was important, but not in the near surface soil layers (5 and 15 cm) which may not be the root of rapid stormflow routing to the stream in the Hermine catchment. As for the use hydrologic distances, it was beneficial for the hydrologic relevance of ICSL measures at a 15 cm depth but not near the upper limit of the impervious soil layer as identified in the subsurface DEM.

Issues of measurement error and scale may also be discussed to nuance the results obtained in this paper. Indeed, Cosh *et al.* (2006) criticized the tendency of soil moisture sensors to occasionally report erroneous data. That problem is worth noting here since we were unable to use permanently installed access tubes on the whole Hermine catchment area, thus preventing us from measuring soil moisture content at the exact same locations on all 16 occasions. We however constrained ourselves to taking measurements in the same 75-100 cm radius around each sampling benchmark. Consistency between multiple measurements taken in the 75-100 cm radius were tested and found to be the largest in dryer conditions (MSMC < 25%). Hence, for the driest patterns, each soil moisture measurement was the field-calculated average of three separate measurements. We believe that some of the geostatistical connectivity metrics tested in this study may have captured that measurement error and small-scale variability via the variogram nugget (Western *et al.*, 2002). For other measures, we assumed that local measurement error was not large enough, or at least was temporally consistent in order not to influence the connectivity metrics computations. Even though we did not use continuously recording sensors, the exhaustive soil moisture dataset presented here allowed us to assess the temporal variability of connectivity metrics as it covers nearly the entire set of hydrological conditions of the Hermine catchment (Table 5.6), except for the winter and early spring seasons. When it comes to the measurement scale, however, it is highly probable that the spatial sampling resolution of 15 m was too coarse to capture fine-scale variability in soil moisture. Thus, none of the tested connectivity metrics tested in this study can really capture the effects of the complex micro-topography of the catchment forest floor that may disrupt spatial patterns. Further investigation of the behavior of connectivity metrics across spatial scales would therefore be required.

d. Hydrologic Predictability in the Hermine Catchment

Our results indicate that the Hermine catchment is characterized by a set of very diverse yet complex behaviors. In fact, hydrologic predictability can be addressed from three different standpoints, namely an estimation of (i) catchment response from antecedent conditions; (ii) connectivity from antecedent conditions; or (iii) catchment response from connectivity. Regardless of the chosen standpoint at the Hermine, predictability was limited and critical switching points difficult to assess. It was difficult to classify surveys as dry, intermediate or wet as the classification varied a great deal depending on the surrogate used to illustrate the catchment macrostate (e.g. evapotranspiration, catchment mean soil moisture content, antecedent precipitation amounts computed over more or less lengthy periods, discharges). Even though it is usually assumed that the greater the soil moisture content, the higher the degree of connectivity (Fitzjohn *et al.*, 1998; Leibowitz & Vining, 2003), this was not the case at the Hermine. Besides the magnitude of change in hydrologic conditions, frequency, duration, timing and rate of change are also important in the establishment, maintenance or disruption of connectivity (Bracken & Croke, 2007; Ali & Roy, 2009). Moreover, relationship between connectivity metrics and either short-term or medium-term discharges were often nonexistent or influenced by parameters such as evapotranspiration or days since the last storm.

Consequently, we argue that the traditional single threshold-driven theory of catchment connectivity proposed by Grayson *et al.* (1997) and Western *et al.* (2001) for the temperate Tarrawarra catchment, or even by Tromp-Van Meerveld & McDonnell (2006a) for the subtropical humid Panola hillslope, does not apply to the temperate humid Hermine catchment. The catchment dynamics illustrated by our computed connectivity metrics does not fit into the '*dichotomist view of connectivity which is either present or absent depending on whether we are above or below a unique threshold value*' (Ali & Roy, 2009). Instead, the Hermine catchment soil moisture patterns rather reflect a '*continuum of hydrologic states between completely isolated and connected saturated areas'*. This idea is in agreement with the sigmoid statistical model of threshold behavior put forward by Zehe *et al.* (2007); it portrays hydrological systems as being characterized by two stable states and an unstable range of controlling variables that dictate the transition between the two stable states. Further investigations should be conducted in temperate humid forested environments like the Hermine in order to identify the set of successive critical catchment macrostates based multi-dimensional (i.e. based on the co-occurrence of several control variables) threshold conditions. Revisiting the Mont-St-Hilaire dataset with that conceptualization in mind would also corroborate the argument made by James & Roulet (2007) about the absence of a switch between evapotranspiration-dominated and precipitation-dominated conditions in humid temperate systems.

Lastly, we would like to stress that the current study is an important addition to recent papers dealing with connectivity issues. Indeed, recent publications mostly aimed at assessing the potential of a single statistical, probabilistic or process-based measure to characterize plot-scale, hillslope-scale or catchment-scale connectivity. For instance, following the leading works of Western *et al.* (2001) and James & Roulet (2007), Antoine *et al.* (2009) evaluated different quantitative indicators of hydrological connectivity based on numerical fields of micro-topography at the plot scale. They ultimately narrowed down a 'volume to breakthrough'-like indicator that expresses the degree of surface connection as a function of surface storage filling. Relying on both surface macro-topography and vegetation patterns, Mayor *et al.* (2008) proposed a flowlength index, that is the average length of all potential runoff pathways in a target area, to illustrate connectivity at the plot scale. Lane *et al.* (2009) also suggested a topographically-defined Network Index that can be used to approximate not only the propensity to surface hydrological connectivity but also its duration at the catchment scale. Works such as those of Gomi *et al.* (2008) and Jencso *et al.* (2009) introduced some novelty in the field as they considered both static topographic variables and dynamic hydrological state variables to derive measures of connectivity. Gomi *et al.* (2008) relied on a runoff discontinuity assumption based on a spatially-variable rainfall-infiltration ratio; this allowed them to estimate mean runoff transfer distances and establish a conceptual model of overland flow connectivity between experimental plots of different sizes and covered with different vegetation. Jencso *et al.*

(2009) rather focused on shallow groundwater flow and examined an extensive water table dataset in order to define hillslope-riparian-stream connectivity. The "*time interval during which streamflow occurred and both the riparian and adjacent hillslope wells recorded water levels above bedrock*" (Jencso *et al.*, 2009, p. 5) was then linked to hillslopes' upslope accumulated areas so as the derive a catchment annual connectivity duration curve that was highly correlated to the catchment flow duration curve. In reaction to all these different study approaches to connectivity, Michaelides & Chappell (2009) criticized the existing proposed frameworks for being too vague or too specific for consistent investigations of connectivity to be undertaken across a wide range of hydrological systems. In turn, they proposed the use of geostatistical measures as "*simplified, universally applicable, quantifiable [measures] of hydrological behavior that [transcend] individual complexities in hydrological response*" (Michaelides & Chappell, 2009, p. 517). Conclusions from the current paper are at odds with that statement as we demonstrated the non-uniform performance of integral connectivity scale lengths depending on the catchment considered (e.g. temperate versus temperate humid) or the data binary discretization achieved (e.g. *dp*, *cp* or *sm* thresholds). Hence, we believe the main contribution of our paper is the identification of hydrologically representative connectivity metrics that are, indeed, statistically-based but whose definition takes into account expert-knowledge on dominant runoff processes.

In another retrospective review on study approaches to connectivity, Lexartza-Artza & Wainwright (2009) argued that purely structural (i.e. static) or functional (i.e. dynamic) approaches are insufficient and that both aspects should be considered. Works undertaken by Mayor *et al.* (2008), Antoine *et al.* (2009) and Lane *et al.* (2009) can be classified as investigations of structural connectivity as they mainly focus on topographically-defined landscape units and catchment physical characteristics. It is however worth mentioning that even though static, connectivity measures put forward by these groups of authors were argued to be significant explanatory variables for runoff yields and/or duration. In the area of purely functional approaches, Fröhlich *et al.* (2008) showed that the sole reliance concentration-discharge relationships failed to explain the link between runoff sources and the system outlet, unless catchment heterogeneity and complexity were considered to account for the temporal variability of hydraulic connectivity. The ability of given connectivity measures to capture possible shifts in dominant runoff processes has been neglected so far (Lexartza-Artza & Wainwright, 2009). Indices such as those introduced by Mayor *et al.* (2008), Antoine *et al.* (2009) and Lane *et al.* (2009) clearly aim at representing the connectivity of overland source areas and flow pathways only, while recent studies have acknowledged that threshold changes in storm runoff generation might be attributable to significant changes in runoff production processes (e.g. Gomi *et al.*, 2008; Detty & McGuire, 2010). As this calls for connectivity metrics that can illustrate the dynamics of surface/subsurface decoupling, especially in temperate humid environments, we believe that datasets such as the one examined in the current paper are the way forward. Multiple depth soil moisture measurements can be seen both as an indication of saturation excess overland flow (e.g. Grayson *et al.*, 1997; Meyles *et al.*, 2003; Western *et al.*, 2004; Western *et al.*, 2005) and a passive signal of transient saturation at the soil-confining layer interface (e.g. Van Meerveld & McDonnell, 2005). Thus, they allowed us to assess depth specific changes in connectivity in the Hermine catchment.

5.2.6 Conclusion

Our study aimed at testing several metrics towards a better assessment of hydrologic connectivity. Previous studies advocated that threshold-like changes in runoff were associated with connectivity changes in shallow soil moisture patterns in temperate rangeland catchments but not in temperate humid forested catchments. We however argued that in the latter environments, capturing critical changes in soil moisture patterns spatial organization depends on the way the chosen connectivity metric is built. Our assessments of connectivity were quite variable depending on whether we used surface or subsurface moisture patterns, 2D or 3D metrics, or indicator patterns derived using either a time-variable or a time-invariant threshold. We also showed that just a few metrics were significantly correlated with both meteorological conditions and catchment responses at the outlet, a condition that is crucial if connectivity is to serve as an effective diagnostic classification tool of hydrological behavior. More importantly, our results demonstrated that humid temperate systems like the Hermine catchment do not comply with the traditional single threshold-driven theory of catchment connectivity. The multiple complex behaviors observed at the Hermine catchment are rather in accordance with the unified definition by Ali & Roy (2009), which states that '*hydrologic connectivity is a continuum of hydrological states characterized by an increased contribution from lateral subsurface water flow that sporadically activates the topographic linkages between riparian and upland areas and thus gives rise to highly correlated spatial patterns of hydrologic state variables (e.g. soil moisture) at the hillslope and the catchment scales*'. Our conclusions stress the importance of searching for the right connectivity metrics that enable us to examine and predict multiple catchment preferential states. This is especially important in temperate humid forested environments that exhibit much larger variability in soil hydrologic properties yet less climatic fluctuations than temperate rangeland catchments.

Appendix A: Detailed Description of Connectivity Metrics Computations

A1 ENTROPY

The metric referred to as ENTROPY in the current paper is the bivariate entropy integral scale. The rationale behind it is that entropy measures disorder in contrast to connectivity that rather implies order, and it can be used to characterize the "smoothness" of a spatial field. We followed the mathematical theory exposed in Journel & Deutsch (1993) and Knudby & Carrera (2005) in order to code the computations of that metric into MATLAB (The Mathworks, Inc.). We consider two random variables $z = Z(x)$ and $z' = Z(x+h)$ separated by an Euclidean lag distance h and whose stationary bivariate probability distribution function (pdf) is $f_h(z,z')$. The entropy $H_f(h)$ of the distribution f_h is given by:

$$H_f(h) = -\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}[\ln f_h(z,z')]\,f_h(z,z')\,dz\,dz' \tag{A5.1}$$

A discrete approximate of $H_f(h)$ is rather given by:

$$H(h) = -\sum_{k=1}^{K}\sum_{k'=1}^{K}[\ln p_{k,k'}(h)]\,p_{k,k'}(h) \tag{A5.2}$$

Given

$$p_{k,k'}(h) = \mathrm{Prob}\{z = Z(x) \in \text{category}\,k,\ z' = Z(x+h) \in \text{category}\,k'\} \tag{A5.3}$$

We here describe here the mathematical theory associated with the discrete formulation that we applied to both indicator soil moisture patterns (K equals 2 categories) and continuous soil moisture patterns (K represents more than two categories to illustrate the range of soil moisture values). The relative bivariate entropy, $H_R(h)$, whose values are in the interval [0;1], is defined by:

$$\mathrm{H_R}(\mathrm{h}) = \frac{H(h) - H(0)}{H(0)} \tag{A5.4}$$

Given that:

$$H(0) \ = \ \sum_{k=1}^{K}[\ln p_k]p_k \tag{A5.5}$$

Where p_k is the proportion of locations belonging to category k. It is known that $H_R(h)$ tends to $H(0)$ when h is small (small relative disorder) while it tends to $2H(0)$ when the Euclidean lag distance increases. The integral scale of the bivariate entropy, that is the connectivity metric that we evaluate in this paper, is determined by:

$$\mathrm{ENTROPY} \ = \ \int_0^{\infty} H_R(h)\ \mathrm{d}h \tag{A5.6}$$

Hence, the higher the value of ENTROPY, the less likely we can observe connected, organized features in the spatial pattern.

A2 SATAREA

We only determined SATAREA based on indicator patterns as it illustrates the total area, in hectares, covered by pixels labelled with 1s in the indicator pattern. We defined:

$$\mathrm{2DSATAREA} \ = \ \text{Number of sampling squares labelled with "1"} \times \text{Area of a sampling square} \tag{A5.7}$$

And:

$$\mathrm{3DSATAREA} \ = \ \text{Number of sampling squares labelled with "1"} \times \text{Volume of a sampling square} \tag{A5.8}$$

Note that with this paper dataset, the area of a sampling square is $(15\ \mathrm{m})^2 = 225\ \mathrm{m}^2 = 0.0225$ ha. This area is multiplied by a height of 5 or 15 cm in order to obtain the volume of the sampling square. These straightforward computations were also executed in the MATLAB environment.

A3 SATCLUST

SATCLUST is the number of isolated clusters (or connected regions) made up from sampling squares labelled with 1s in indicator patterns. Identification and delineation of such clusters was made using the **bwlabel** function from the *Image Processing Toolbox* in the MATLAB environment and whose purpose is to label connected components in a binary image. The function is defined as follows:

$$[\mathrm{L\_2D}, \mathrm{num\_2D}] = \mathrm{bwlabel}(\mathrm{BW\_2D}, \mathrm{n\_2D}) \qquad \text{(A5.9)}$$

Where **BW_2D** and **n_2D** are input arguments while **L_2D** and **num_2D** are output arguments. For the current paper, **BW_2D** was each depth-specific indicator pattern, in turn, and **n_2D** illustrated the 2-D n-connected neighborhood (Figure 5.A1). The 8-connected neighborhood was used. In each case, the **bwlabel** function yielded a map, **L_2D**, of the same size as **BW_2D**, containing labels for saturated clusters in each indicator pattern. The ouput **num_2D** illustrates the number of individual clusters identified in the indicator patterns, therefore we have:

$$\mathrm{2DSATCLUST} = \mathrm{num\_2D} \qquad \text{(A5.10)}$$

For the 3-D computation, the function **bwlabeln** was rather used as it aims at labelling connected components in N-D binary image. The formulation of the **bwlabeln** function is very similar to that of the **bwlabel** function:

$$[\mathrm{L\_3D}, \mathrm{num\_3D}] = \mathrm{bwlabel}(\mathrm{BW\_3D}, \mathrm{n\_3D}) \qquad \text{(A5.11)}$$

BW_3D is rather a 4-dimensionnal matrix (i.e. each depth specific pattern associated with a survey occupies one dimension). Besides, the available n-connected neighborhoods are different in 3-D (Figure 5.A1); we tested both the 6-connected, 18-connected and 26-connected neighborhoods and found no significant differences in the results, probably due to the fact that our multidimensional matrices only cover a 45 cm height/depth. Results reported in this paper are thus determined by:

$$3DSATCLUST = num\_3D \qquad (A5.12)$$

It should be noted that the **bwlabel** and the **bwlabeln** functions described here date back from an old version of MATLAB *Image Processing Toolbox* and have since been replaced with more computationally efficient alternatives.

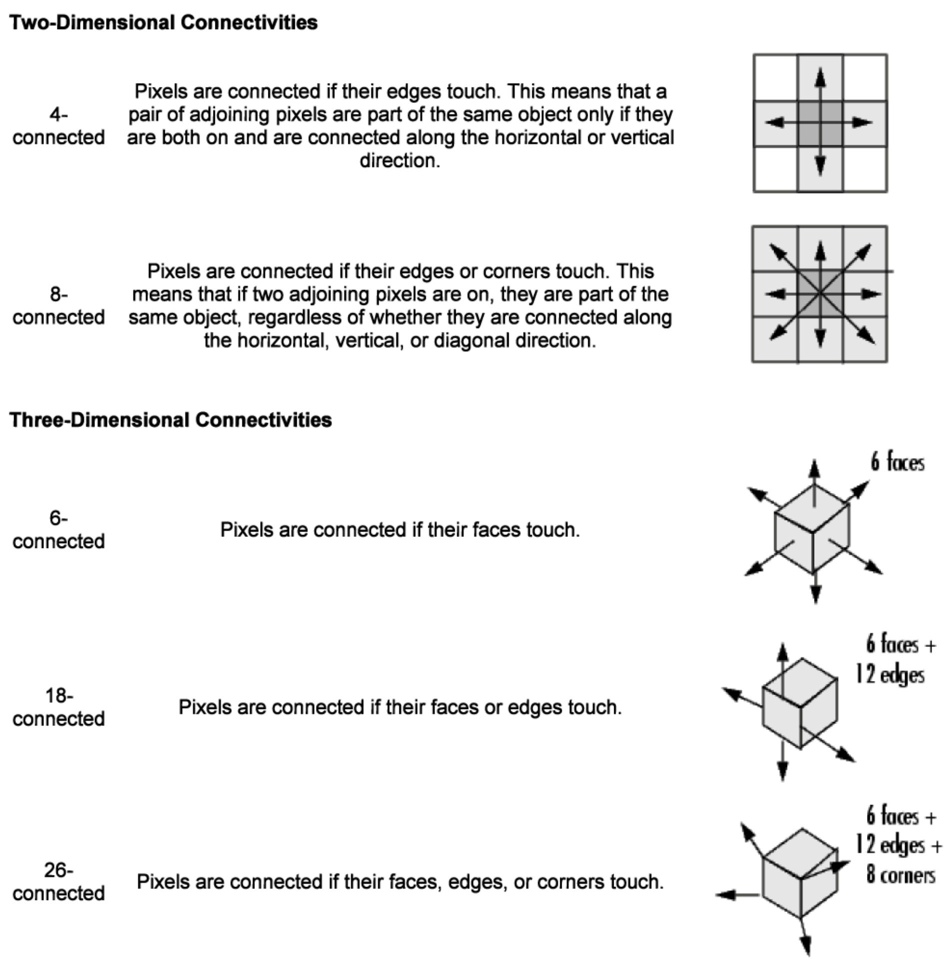


Figure 5.A1. Illustration of the n-connected neighborhoods used in the MATLAB environment for 2-D and 3-D patterns. Figure adapted from The Mathworks, Inc. Website (http://www.mathworks.com/access/helpdesk/help/toolbox/images/).

A4 EFFCAREA

With the metric referred to as "EFFCAREA" in this paper, we wanted to illustrate the dynamic character of the Hermine catchment contributing area. The term "effective" is meant to illustrate the fact the contributing area of a catchment is usually significantly smaller than that given by its physical boundaries (Aryal *et al.*, 2003). While the effective contributing area is often estimated usually from the spatial extent of soil saturation, we chose to use the several indicator soil moisture patterns evaluated in this study so as to weight the relative role of individual sampling squares in the flow contribution to the catchment outlet. The detailed steps leading to the computation of EFFCAREA values were as follows:

- The original 2 m resolution surface DEM of the Hermine catchment was converted into a 15 m resolution DEM using bilinear re-sampling so that soil moisture data and elevation data were at the same scale of observation.
- Common operations of depressions filling were achieved in MATLAB using the **imfill** function from the *Image Processing Toolbox* (The Mathworks, Inc.).
- A flow direction matrix (FlowDir) was computed as it represents the theoretical flow from sampling square to sampling square based on topography. The multiple flow direction algorithm (e.g. Tarboton, 1997) was used. Hence, elements (*i, j*) in FlowDir represent the relative amount of flow transferred from cell *i* to one or several of its downward neighbors *j* in a 8-connected neighborhood (Figure 5.A1). The transfer ratios are weighted by (or proportional) to the elevation difference between cell *i* and each downward neighbor *j*. Computation details related to the flow direction matrix can be found in Tarboton (1997) and Schwanghart & Kuhna (2010). Sparse matrix algebra was especially used in order to build a computation code for FlowDir in the MATLAB environment.

- The flow direction matrix was then altered using data from the soil moisture indicator patterns. Thus, for a given survey and a given depth, all sampling squares with an indicator value of zero were assigned a transfer ratio of zero in the altered flow direction matrix (ActiveFlowDir). In doing so, we only considered water routing between sampling squares labelled as “active areas”.
- A flow accumulation matrix (FlowAcc) was lastly computed from the ActiveFlowDir matrix. The value of EFFCAREA for a specific survey and sampling depth then corresponded to the value of FlowAcc for the catchment outlet:

$$\text{EFFCAREA} = \text{FlowAcc}(\text{Outlet}) \qquad \text{(A5.13)}$$

All algorithms and equations were implemented into the MATLAB environment relying on recursive routines that use significant amounts of computer memory. It is worth mentioning that several MATLAB computer codes and/or toolboxes are now freely available to perform topographic operations on digital elevations models (http://www.mathworks.com/matlabcentral/, Schwanghart & Kuhna, 2010) et have been proven to use less memory and perform a little bit faster than the author’s codes.

A5 Semi-variogram-Derived Metrics

Three connectivity measures used in the current paper, namely RANGE_OM, RANGE_NS and RANGE_EW, were derived from semi-variogram analysis. For continuous (i.e. original) soil moisture data, experimental semi-variograms were computed using the following equation:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} (Z(x+h) - Z(x))^2 \qquad \text{(A5.14)}$$

Where $\gamma(h)$ is the semivariance as a function of the Euclidean lag distance h, $N(h)$ is the number of sample pairs and Z is the soil moisture content evaluated at locations x and $x+h$ (e.g. Cressie, 1993; Goovaerts, 1997) For indicator patterns of soil moisture patterns, the following equation was rather used:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} (I(x+h) - I(x))^2 \qquad \text{(A5.15)}$$

In both cases, the summation was conducted over all $(x,\ x+h)$ pairs in the lag bin. When Equations A5.14 and A5.15 were applied to all sampling points available, omnidirectional (OM) experimental variograms were produced. However, to characterize the possibly different behaviors of soil moisture in different directions, directional experimental variograms were also calculated to explore soil moisture spatial organization in the north-south (NS) and in the east-west directions (EW).

With semi-variograms derived from Equations A5.14 and A5.15, the range is the one of the most important property to compare the structure of multiple spatial fields as it illustrates the rate at which spatial dependence decreases as a function of the Euclidean lag distance h. In order to h estimate these different ranges for each survey and depth-specific soil moisture patterns, two theoretical variogram models were, in turn, fitted to the experimental variograms previously determined. An exponential model was defined as:

$$\gamma(h) = c_0 \ + \mathrm{C}\ (1 - e^{h/a}) \qquad \text{(A5.16)}$$

A hole-effect (i.e. wave) model was rather defined as a cosine-exponential composite model:

$$\gamma(h) = C\ (1 - e^{-3h/a} \cos(2\pi h / b)) \qquad \text{(A5.17)}$$

Where c_0 is the nugget variance, h is the Euclidean lag distance, C is the variogram amplitude, a is the range and b is a model parameter. Depending on the directional variogram considered, Equations A5.16 and A5.17 were re-written using different notations for the nugget variance (c_0_OM, c_0_NS and c_0_EW), the variogram amplitude (C_OM, C_NS and C_EW) and its range (a_OM, a_NS and a_EW). The exponential model was chosen because of its wide use in hydrology (see discussion in Western *et al.*, 2002) and because it visually fitted most of the experimental variograms computed in this study. The cosine-exponential composite model was rather chosen to fit non-monotonic variograms that showed some repetition in the variation that was neither random nor wholly cyclic or periodic. Hence, once the omnidirectional (OM), north-south (NS) and east-west (EW) experimental variograms were fitted to one of the two theoretical models using a least-squares procedure, we could estimate:

$$\text{RANGE\_OM} = \text{a\_OM} \quad \text{(A5.18a)}$$

$$\text{RANGE\_NS} = \text{a\_NS} \quad \text{(A5.18b)}$$

$$\text{RANGE\_EW} = \text{a\_EW} \quad \text{(A5.18c)}$$

All computer codes were run in the MATLAB environment. The fitting of theoretical variogram models to experimental variograms was especially achieved using the *Optimization Toolbox*.

A6 ICSL (Integral Connectivity Scale Length) Measures

Most connectivity metrics (10 out of 17) evaluated in the current paper were based on the framework proposed by Western *et al.*, 2001). Computational details pertaining to each metric are detailed below.

A6.1 OMNI

We evaluated the omnidirectional connectivity function $\tau(h)$ using the definition proposed by Western *et al.* (2001). Given the Hermine catchment as a spatial domain D made up of indicator values I and given a subset of sampling squares S, we have:

$$\tau(h) = P\,[x \leftrightarrow x+h \mid x \in S,\ (x+h) \in S,\ I(S)=1] \tag{A5.19}$$

Equation A5.19 illustrates the probability that any two locations separated by an Euclidean lag distance h and belonging to the same spatial cluster of 1s in the indicator pattern are connected by any pathway of 1s, regardless of its trajectory.

The omnidirectional integral connectivity scale length that we here refer to as OMNI can then be computed as:

$$\text{OMNI} = \int_0^\infty \tau(h)\ \mathrm{d}h \tag{A5.20}$$

The pseudo-code provided as an electronic supplement with the paper by Western *et al.* (2001) was essentially translated into a computer code in the MATLAB environment. For labelling the connected regions, however, we used the fast **bwlabel** function from the *Image Processing Toolbox* (The Mathworks, Inc.) rather than using the recursive approach suggested by Western *et al.* (2001).

A6.2 TOPO and SUBTOPO

Using, in turn, the surface or the subsurface DEM from the Hermine catchment, we computed the topographic (directional) connectivity function $\tau_{directional}(h)$ using the following definition:

$$\tau_{\text{directional}}(h) = P\,[x \leftrightarrow x+h \mid x \in S,\ (x+h) \in S,\ I(S)=1 \mid x \in P,\ (x+h) \in P] \tag{A5.21}$$

Equation A5.21 is very similar to Equation A5.19 except that locations x and $x+h$ need to be on the same topographic flowpath P. Hence, we also used the pseudo-code from Western *et al.* (2001) as a basis to build a MATLAB computer program. Some modifications made to their original code are listed below:

- For the labelling the connected regions, the **bwlabel** function from the *Image Processing Toolbox* was used instead of the recursive approach.
- The procedure designed to map flowpaths to and from each pixel (or sampling square) was changed. Indeed, Western *et al.* (2001) used a pair of recursive algorithms to determine these flowpaths on the basis of the two steepest descent directions from each pixel (r, c) only. We rather considered a "multiple flow direction" approach in which all downward neighbors could be considered as the starting point of a flowpath from pixel (r, c). Thus, for each pixel (r, c), two maps of pointers were created: (1) a dependence map illustrating all map pixels potentially flowing into pixel (r, c), and (2) an influence map illustrating all map pixels to which pixel (r, c) potentially contributes.

Once the connectivity function was computed, the topographic (directional) integral connectivity scale length that we here refer to as TOPO (or SUBTOPO) was defined as:

$$\text{TOPO (or SUBTOPO)} = \int_0^\infty \tau_{\text{directional}}(h)\, \mathrm{d}h \qquad \text{(A5.22)}$$

A6.3 OMNI_STS, TOPO_STS and SUBTOPO_STS

The metrics OMNI_STS, TOPO_STS and SUBTOPO_STS were devised so as to illustrate the source-to-stream connectivity. Hence, we evaluated the probability that a pixel x at an Euclidean distance h from the catchment outlet O be connected to it. It can be written as follows in the omnidirectional case:

$$\tau^{\text{contributing}}(h) = P\,[x \leftrightarrow x+h \mid x \in S,\ (x+h) \in S,\ (x+h) \in O,\ I(S)=1] \tag{A5.23}$$

And rather as follows in the directional case:

$$\tau^{\text{contributing}}_{\text{directional}}(h) = P\,[x \leftrightarrow x+h \mid x \in S,\ (x+h) \in S,\ (x+h) \in O,\ I(S)=1 \mid x \in P,\ (x+h) \in P] \tag{A5.24}$$

In terms of computations, the only changes with regards to details provided in sections A6.1 and A6.2 concern the labelling of the connected regions. After using the bwlabel function, a all connected regions in which the catchment outlet was not included were disregarded prior to the calculation of the connectivity functions. The integral connectivity scale lengths were then obtained via:

$$\text{OMNI\_STS} = \int_0^{\infty} \tau^{\text{contributing}}(h)\ \mathrm{d}h \tag{A5.25a}$$

$$\text{TOPO\_STS (or SUBTOPO\_STS)} = \int_0^{\infty} \tau^{\text{contributing}}_{\text{directional}}(h)\ \mathrm{d}h \tag{A5.25b}$$

A6.4 TOPO_HD and SUBTOPO_HD

Using, in turn, the surface or the subsurface DEM from the Hermine catchment, we computed a variant of the topographic (directional) connectivity function as follows:

$$\tau_{\text{hydrologic}}(h_h) = P\,[x \leftrightarrow x+h_h \mid x \in S,\ (x+h_h) \in S,\ I(S)=1 \mid x \in P,\ (x+h_h) \in P] \tag{A5.26}$$

Where h_h is an hydrologic lag distance. Thus, instead of using the Euclidean distance, we assess connectivity using the flow routing distance estimated along theoretical, topographically-defined flowpaths.

In terms of computations, surface and subsurface flow lengths (or runoff travel distances) were calculated in ArcGIS 9.2 (ESRI 2008). These distances were then fed into MATLAB as input data to derive hydrologic distance-based metrics. No modifications of the MATLAB computer codes associated with TOPO and SUBTOPO (refer to section A6.2) were needed except to substitute Euclidean with hydrologic distances where necessary. The integral connectivity scale lengths were then computed using the common formula:

$$\text{TOPO\_HD (or SUBTOPO\_HD)} = \int_0^\infty \tau_{\text{hydrologic}}(h_h)\, \mathrm{d}h_h \qquad \text{(A5.27)}$$

A6.5 TOPO_HD_STS and SUBTOPO_HD_STS

TOPO_HD_STS and SUBTOPO_HD_STS are simply a combination of metrics previously described. Refer to sections A6.3 and A6.4 for details.

5.4 A case study on the use of appropriate surrogates for antecedent moisture conditions (AMCs)[6]

5.4.1 Introduction

A large number of non-linear hillslope and catchment rainfall-runoff responses have been documented around the world (e.g. Wipkey & Kirkby, 1978; Sidle *et al.*, 1995; Buttle & Peters, 1997; Buttle *et al.*, 2001; Van Meerveld & McDonnell, 2005, Tromp-Van Meerveld & McDonnell, 2006a; James & Roulet, 2007). Justification for such hydrological responses often lies in the temporal variability in storm size or antecedent moisture conditions (AMCs) (Longobardi *et al.*, 2003; Mishra *et al.*, 2005; James & Roulet, 2009) and the spatial connectivity between source areas. Soil moisture is often described as a major control on catchment response (e.g. Meyles *et al.*, 2003; Western *et al.*, 2004; Western *et al.*, 2005). It is notably used to determine whether a catchment is in a dry and spatially disorganized or in a wet and connected state (Grayson *et al.*, 1997). Catchment AMCs are most often associated with soil moisture contents over a fixed antecedent temporal window that can be defined as:

$$W = [t_0 - x, t_0] \tag{5.5}$$

Where t_0 is the reference time and x is the amount of time to be subtracted to account for conditions observed before the reference time. Hence, AMCs are used for various purposes, from computing direct surface runoff via the Soil Conservation Service Curve Number (SCS-CN) methodology (Mishra *et al.*, 2005) to characterizing favourable conditions for hydrologic connectivity to occur (James & Roulet, 2009).

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[6] Ali, G. A. & A. G. Roy, in review/en revision b. 'A case study on the use of appropriate surrogates for antecedent moisture conditions (AMCs)', *Hydrology and Earth System Sciences*.

The determination of a catchment AMCs remains difficult given the strong spatio-temporal heterogeneity of soil moisture across any typical catchment and the relative scarcity of spatially-detailed soil moisture data in comparison to rainfall or streamflow data that are more accessible. Owing to these difficulties, several practical approaches have been proposed to define surrogates or proxies for AMCs. Precipitation-based indices have received the largest attention as rainfall data are often available (Longobardi *et al.*, 2003). We here distinguish between antecedent precipitation (AP_x) and the antecedent precipitation index (API_n). AP_x is simply the cumulative sum of rainfall recorded over any fixed antecedent temporal window as defined in Eq. (5.6). The API_n as put forward by Kohler & Lindsey, 1951) is rather a weighted summation of daily precipitation amounts recorded since the last rainfall as described in Eq. (5.6):

$$API_n = API_{n-1} + P_{n-1} \cdot \exp(-\alpha \Delta t) \qquad (5.6)$$

Where $\Delta t = t_n - t_{n-1}$ is the time (d) elapsed between the end of the previous rainfall P_{n-1} and the beginning of the next one P_n, and α is a parameter equal to the inverse of the characteristic time of soil moisture depletion (d^{-1}). According to Kohler & Lindsey, 1951), precipitation-based indices are universally applicable and yield good results provided that they are used in conjunction with season of the year or temperature. Basin evaporation (Longobardi *et al.*, 2003) and the soil moisture index (SMI), which only includes potential evaporation and other climatic factors in its formulation (Mishra *et al.*, 2005), have also been described as potential proxies for AMCs since they relate to soil moisture depletion. Given the findings that pre-event water can play a substantial role in rainfall-runoff response (e.g. Sklash & Farvolden, 1979; Pearce, 1990; Rice & Hornberger, 1998; Kirchner, 2003) and given the wide availability of streamflow data, the antecedent baseflow index ($ABFI$) (Mishra *et al.*, 2005) and other measures related to discharge recorded just prior the reference time (Kohler & Lindsey, 1951; Longobardi *et al.*, 2003) have been proposed as surrogates for AMCs. Kohler & Lindsey, 1951) have advocated that baseflow-derived indices provide reasonably good results in humid and sub-humid regions; however, such as the API_n, baseflow indices are strongly dependent upon season of the year and do not necessarily reflect short-term changes in a catchment state. Several authors have emphasized the relative advantage of the $ABFI$ in comparison to antecedent rainfall not only because it reflects both shallow soil moisture and deeper groundwater conditions (Young & Beven, 1994) but also because it does not force the choice of an antecedent temporal window (Mishra *et al.*, 2005) and it is a better predictor of runoff generation (Longobardi *et al.*, 2003). Nonetheless, the $ABFI$ is not often used in the hydrological literature (Mishra *et al.*, 2005), with the exception of a few studies based on water table heights (e.g. James & Roulet, 2009). The number of days since the last rainfall event is another proxy for AMCs that is seldom used in catchment hydrology (Kohler & Lindsey, 1951)

Several questions arise concerning the selection of a proxy for AMCs for a specific catchment. For instance, with regards to antecedent precipitation, what duration of antecedent temporal window should be used? The term 'antecedent' is broadly used in the literature and refers to durations from one hour to 30 days. Antecedent temporal windows of seven days (e.g. Woods & Rowe, 1996; Inamdar & Mitchell, 2007; James & Roulet, 2009) and ten days (e.g. Noguchi *et al.*, 2001; Western *et al.*, 2004) are relatively popular in catchment hydrology. Several studies have relied on the dual use of AP_{10} and AP_{30} (e.g. Sidle *et al.*, 1995; Vidon *et al.*, 2009). The curve number (CN) method considers rainfall over a 5-day long antecedent temporal window (SCS, 1956), an approach taken up by some hydrological modeling studies (e.g. Brocca *et al.*, 2008). Silveira *et al.* (2000), however, compared the single use of 5-day antecedent rainfall with the combined use of 15-day antecedent rainfall and potential evaporation and found no significant differences between the two approaches. While working in a semi-arid environment, Frot & van Wesemael (2009) argued that the use of a 48-hour long antecedent temporal window was not appropriate to explain the differences in runoff for events with similar precipitation characteristics and rather chose an antecedent period of 20 days. Within the antecedent window, several scenarios can occur as there may be no rainfall, a single rainfall event, or multiple storms. These events will or will not be accounted for depending on the chosen duration (Salvadori & De Michele, 2006). Thus, Seeger *et al.* (2004) used a large selection of antecedent windows (i.e. 6 h, 24 h, and 3, 7, 15 and 21 days) in order to discriminate the effects of short-term AMCs from those of long-term AMCs in a small headwater catchment. The wide range of antecedent temporal windows in the literature is unavoidable as there are no explicit guidelines available to specify the relations between soil moisture content and antecedent rainfall during a specific time period (Mishra *et al.*, 2005). Moreover, the effectiveness of surrogate measures for AMCs may be highly dependent upon climate characteristics and scale of observation. However these issues have yet to be addressed if we are to decide between a universal or a regional proxy for AMCs.

One can also ask if it is reasonable to use a sole measure of AMCs for a given catchment. Several authors (e.g. Cappus, 1960; Betson, 1964; Hewlett & Hibbert, 1967; Dunne & Black, 1970; Aryal *et al.*, 2003; Ambroise, 2004) have shown that storm runoff usually originates from consistent parts of a catchment that often represent a small fraction of the whole topographic drainage area. This has been observed in a range of climatic regimes. Soil moisture is a critical hydrological state variable whose spatiotemporal variation indicates the presence of ‘active’ or ‘contributing’ areas or periods (Ambroise, 2004), and this relates to hydrologic connectivity. Dynamic connectivity of catchment source areas is controlled by the time-changing availability of surface/subsurface storm water, not only in terms of magnitude but also in terms frequency, duration, timing and rate (Bracken & Croke, 2007). Disconnected ‘active’ areas involve water fluxes that do not contribute to the global output at a catchment outlet, while ‘contributing’ areas to catchment response are composed of spatially connected ‘active’ areas. It is generally accepted that catchment structure and morphology are the main factors controlling not only the activation of source areas but also their threshold-driven interconnectivity. From a spatially-distributed point of view, the fact that all catchment areas are not ‘activated’ at the same time may indicate that they are responsive to different antecedent conditions and/or storm events characteristics. Similarly, the non-uniform contribution of source areas to streamflow may point towards different triggering factors. In that context, should multiple proxies for AMCs be used in order not to bias our understanding of a catchment hydrological behaviour?

Table 5.10. Links between surrogate measures for AMCs and hydrologically relevant observations from other studies focusing on the Hermine catchment. '××' means that a strong significant correlation was found, '×' means that rather weak correlations were found, and blanks mean that no significant correlations were found.

	Significant correlations identified with surrogate measures for AMCs											
Hydrologically relevant observations in the Hermine catchment	PET	AP_1	AP_2	AP_5	AP_7	AP_{10}	AP_{12}	AP_{14}	DSP	DSP_{10}	DSP_{20}	DSP_{30}
Spatial connectivity of locations whose volumetric soil moisture content exceeds 30% Source : Ali *et al.*, in review/en révision a					××							
Development of spatially coherent saturation patches on:												
▪ Areas of 0.85 to 1.4 ha at a depth of 15 cm												××
▪ Areas of 0.85 ha and less at a depth of 45 cm												××
▪ Areas of less than 0.1 ha at soil depths of 5, 15, 30 and 45 cm Source : Ali *et al.*, 2010a					×			×				
Relative contribution of geographic sources (e.g. riparian versus upslope throughfall, organic and mineral soil water) to streamflow Source : Ali *et al.*, 2010b			××		×							
Presence of high magnitude and quick timing rainfall-runoff events Source : Ali *et al.*, 2010c						×						

PET : Mean daily evapotranspiration computed after the temperature-based Hargreaves formula (Hargreaves, 1975)
DSP : Number of days since the last rainfall input
DSP_{10} , DSP_{20} , DSP_{30} : Number of days since the last rainfall intensity exceeding 10, 20 and 30 mm/d
AP_1 , AP_2 , AP_5 , AP_7 , AP_{10} , AP_{12} , AP_{14} : Cumulative precipitation from 1, 2, 5, 7, 10, 12 and 14 days before the survey

This paper investigates that specific question. We examine the hydrological behaviour of a 5 ha headwater temperate humid forested system, the Hermine, for which several catchment-wide soil moisture patterns are available. The approach relies on point-scale temporal relations between actual soil moisture content values and selected meteorological-based indices so as to identify the surrogates for AMCs that are best suited to characterize the hydrological behaviour of the system. Such a statistical analysis on data from the Hermine catchment could be particularly useful as previous studies show some inconsistencies in identifying a 'universal' AMCs surrogate measure (Table 5.10). For instance, while characterizing the emergence of spatially coherent saturation patches in the Hermine catchment (Ali *et al.*, 2010a), DSP_{30} (i.e. number of days elapsed since the last rainfall intensity exceeding 30 mm/d) appeared to be the most influential surrogate measure for AMCs: the smaller the value of DSP_{30}, the more likely the presence of 0.85-1.4 ha wide saturation patches at a depth of 15 cm. In a paper aiming to identify hydrologically representative connectivity metrics in the Hermine catchment, Ali & Roy (in review/en révision a) found that the spatial connectedness of locations whose volumetric soil moisture content exceeded 30% was rather dependent upon AP_7 (i.e. 7-day antecedent precipitation). The relative contribution of sources (i.e. organic versus mineral soil water originating from riparian or upslope areas) to streamflow were also found to be weakly correlated to AP_2 and rather strongly correlated to AP_7 (Ali *et al.*, 2010b). The occurrence of high magnitude and quick timing rainfall-runoff events was also found to be coincident with 10-day cumulative antecedent precipitation amounts ranging from 24.5 to 40.5 mm (Ali *et al.*, 2010c). These contrasting results have prompted the current paper where we wish to examine with direct measures whether the use of different AMCs measures lead to different approximations of the Hermine catchment hydrological state.

5.4.2 Methods

a. Hermine catchment

The Hermine is a 5.1 ha forested catchment located in the Lower Laurentians 80 km north of Montréal, Québec, Canada (Fig 5.20 A). The total annual precipitation to the region averages 1150 mm (± 136 mm) over the last 30 years, of which 30% falls as snow (Biron *et al.*, 1999). The catchment has a relief of 31 m and is drained by an ephemeral stream (Figure 5.20 B). Soils are 1 to 2 m deep Podzols developed over a bouldery glacial till. The presence of a confining layer at a depth of approximately 75 cm in the soil restricts root penetration, slows water infiltration and thus enhances the probability of rapid lateral shallow subsurface flow. In wet conditions, catchment-scale soil moisture patterns highly depend upon the asymmetric distribution of thick organic horizons; hydrophilic regions are preferentially located on the northern, steeper hillslopes. Near-surface soil moisture is also influenced by the catchment complex surface micro-topography due to fallen tree trunks and boulders at the soil surface. Other particular features of the Hermine include intermittent rills that are activated in very wet conditions (Figure 5.20 B) and a wet zone located in the upstream part of the valley bottom (Figure 5.20 B). Forest canopy is dominated by sugar maple and other deciduous tree species. Thus, transpiration is minimal between October and April so that changes in soil moisture and water table in that period are mostly governed by downslope drainage. The interception capacity of the forest canopy, combined with high summer potential evapotranspiration, greatly reduces the likelihood of high runoff except during heavy rainstorms or wet and cool periods. Forest canopy is, however, variable throughout the catchment, with a lower coverage density in upper parts of the southern slope near the catchment divide for example.

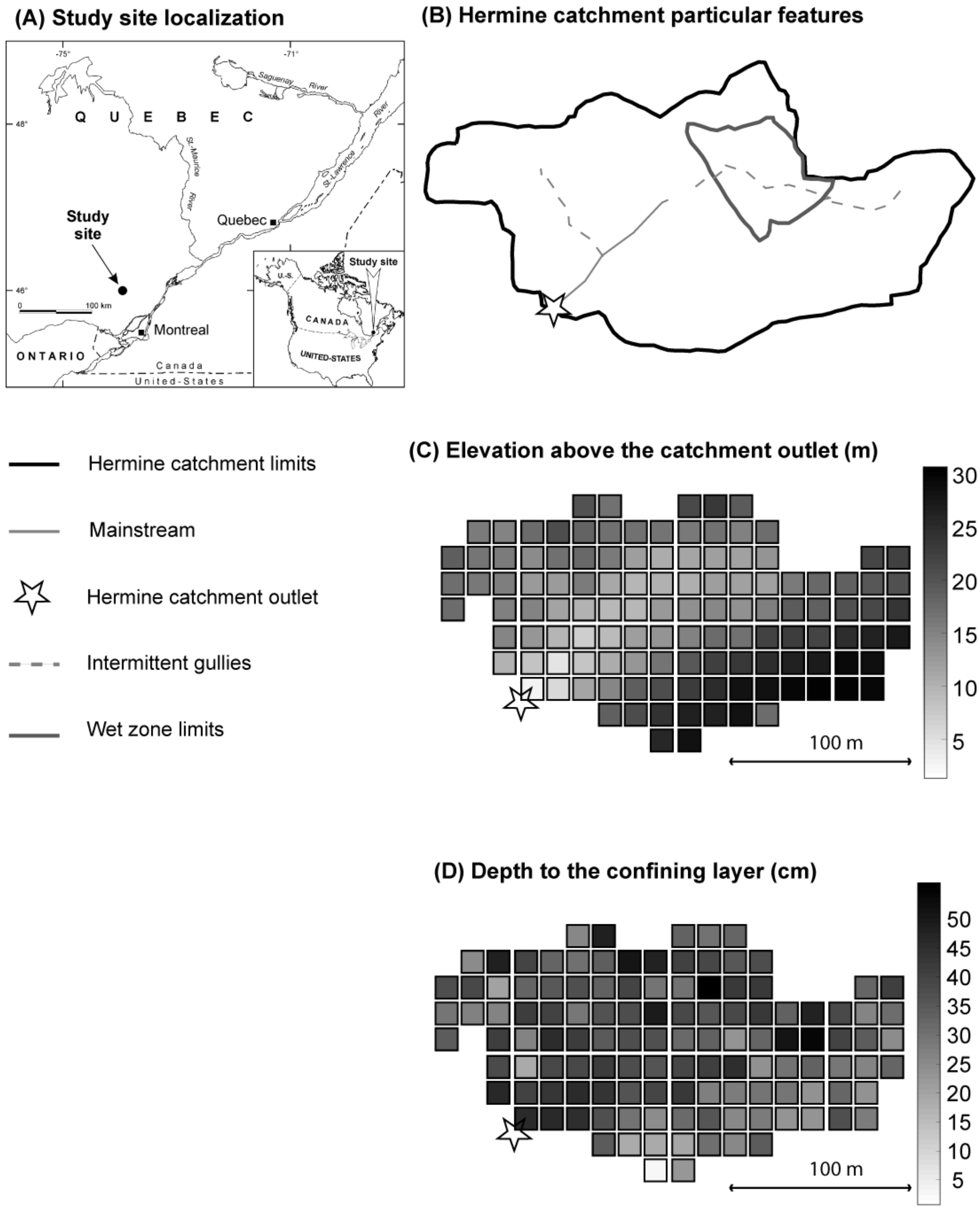

Figure 5.20 – (A) Location of the Hermine catchment; (B) Hermine catchment particular features; (C) Elevation above the catchment outlet; and (D) Depth to the confining layer for each of the 121 soil moisture sampling locations.

b. Topographic and soil moisture data

A surface digital elevation model (DEM) of the Hermine was obtained by interpolating 640 elevation points collected in the field. Elevation above the catchment outlet was then extracted for 121 sampling locations defined along a 15 by 15 m sampling grid in the catchment (Figure 5.20 C). The depth to the confining layer was measured at 257 points using a small hand auger that was forced vertically to refusal through the soil profile. For each sampling location, three auger to refusal measurements were made in a 1 m radius and checked for consistency to disregard data that are likely associated with the presence of individual clasts in the soil matrix instead of the targeted confining layer. Data were then interpolated into a subsurface DEM. In order to evaluate topographic influences on the spatial distribution of soil moisture, several secondary terrain attributes were derived from both the surface and the subsurface DEMs: local slope, contributing area and the topographic index (Beven & Kirkby, 1979) were computed using the D∞ algorithm (Tarboton, 1997), while the multi-resolution valley bottom flatness (MRVBF) index was calculated after Gallant & Dowling (2003). The MRVBF index is derived from an elevation map and identifies flat and low regions at a range of scales. Its largest values flag the broadest and flattest low areas in the catchment. The depth to the confining layer was then extracted for each of the 121 sampling locations (Figure 5.20 D), together with the values of all secondary terrain attributes.

Soil moisture contents at multiple soil depths were surveyed using a portable 30-inch long rod equipped with a capacitance-based probe (AQUATERR Instruments & Automation) that was manually pushed into the ground to the desirable depth. On 16 occasions between August 2007 and July 2008, volumetric moisture content in the top 5, 15, 30 and 45 cm of the soil profile was measured on a 0 to 60% scale along the previously defined 15 by 15 m sampling grid, for a total of 121 sampling points. Figure 5.21 illustrates the contrast between surveys conducted at the Hermine, in terms of measured soil moisture patterns for different AMCs and discharges at the catchment outlet (Table 5.11). In general, saturation patterns tend to be more pronounced at depths of 5 and 15 cm rather than 30 and 45 cm (e.g. Figure 5.21). Also, in wetter conditions, spatial patterns show higher soil moisture contents on the northern slope of the catchment. The main variability in the patterns is found from sampling time to sampling time, as we observe a strong contrast between dry, transitional and wet conditions (Figure 5.21).

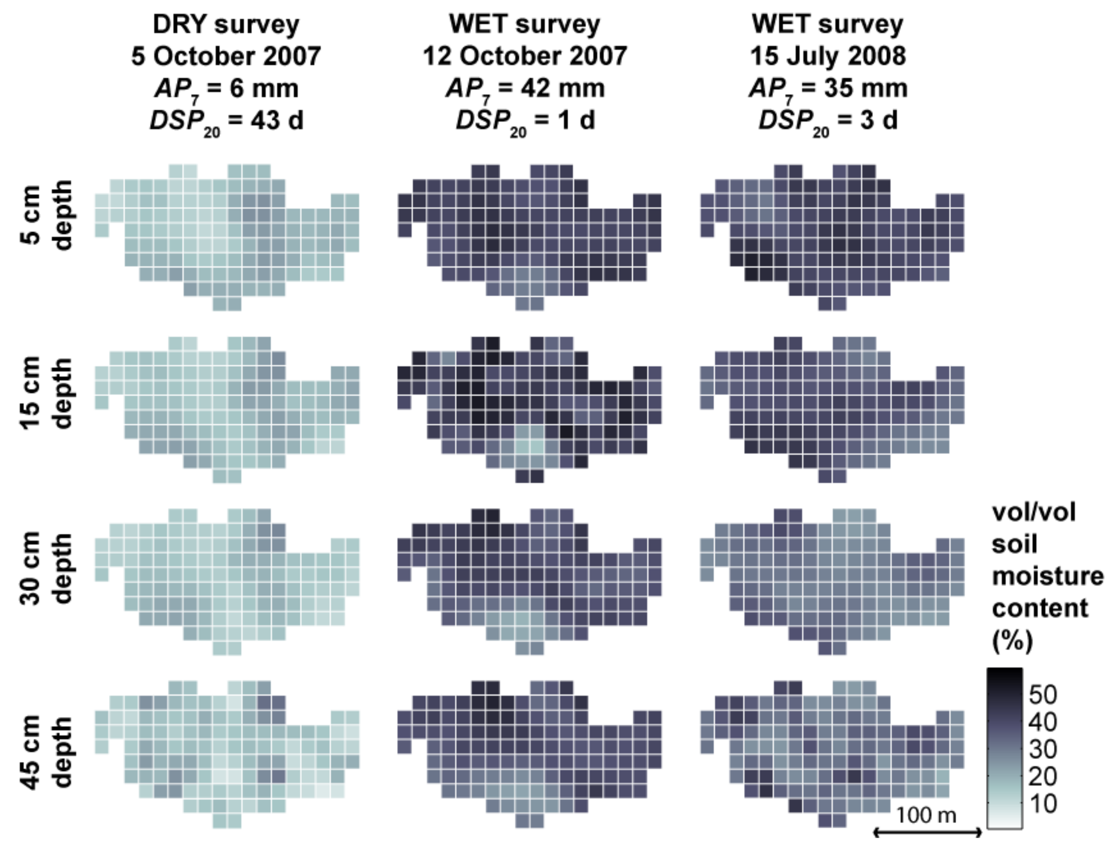

Figure 5.21 – Sample soil moisture maps obtained after three contrasted surveys in the Hermine catchment.

Table 5.11 – Surrogates for AMCs, catchment macrostate and hydrologic response for 16 soil moisture surveys in the Hermine. See meaning of abbreviations in text.

Date	AP_1	AP_2	AP_5	AP_7	AP_{10}	AP_{12}	AP_{14}
6/08/2007	0	0	4	4	36	36	36
13/08/2007	12	12	17	44	44	48	48
7/09/2007	8	8	8	8	8	22	44
14/09/2007	0	0	14	14	15	22	22
21/09/2007	0	0	0	18	22	32	32
28/09/2007	4	4	4	4	4	4	22
5/10/2007	0	0	0	6	10	10	10
12/10/2007	25	25	40	42	42	42	48
26/10/2007	0	0	15	43	43	43	67
2/11/2007	3	3	3	33	36	48	76
9/11/2007	0	0	17	17	20	20	50
20/05/2008	10	20	36	39	39	39	54
2/06/2008	2	21	27	29	29	49	61
17/06/2008	13	14	14	29	29	37	37
15/07/2008	2	3	19	43	43	54	59
21/07/2008	0	0	33	35	42	73	75

Date	DSP	DSP_{10}	DSP_{20}	DSP_{30}	PET	$MSMC$	CD_DISCH
6/08/2007	0	0	0	9	2.61	33.8	0.66
13/08/2007	0	1	7	16	2.58	23.3	0.22
7/09/2007	1	9	15	41	3.15	27.0	0.05
14/09/2007	0	3	22	48	2.19	29.0	0.07
21/09/2007	6	6	29	55	2.07	27.7	0.06
28/09/2007	0	13	36	62	1.73	27.9	0.10
5/10/2007	7	20	43	69	2.40	17.3	0.09
12/10/2007	0	0	1	76	1.49	39.6	5.87
26/10/2007	3	3	7	90	1.33	23.1	0.91
2/11/2007	1	6	6	6	1.23	21.5	1.52
9/11/2007	3	3	13	13	0.86	21.1	1.71
20/05/2008	0	2	22	141	1.87	34.4	1.80
2/06/2008	0	2	35	154	2.89	30.0	0.83
17/06/2008	0	1	50	169	2.37	32.2	0.52
15/07/2008	1	3	6	197	2.51	31.5	0.42
21/07/2008	0	0	3	203	2.44	35.2	0.78

c. Surrogates for AMCs and catchment response

For each of the 16 soil moisture survey dates, 12 temperature-based, precipitation-based, and soil moisture-based indices (Table 5.11) were derived in order to assess their potential to serve as surrogates for antecedent conditions estimated from the soil moisture measurements. Mean daily potential evapotranspiration (PET) was computed on a diurnal timescale after the temperature-based Hargreaves formula (Hargreaves, 1975). A first group of seven precipitation-based indices were used to capture the amount of rainfall added to the system over a given period *x* (AP_x) prior to the time of interest. AP_1, AP_2, AP_5, AP_7, AP_{10}, AP_{12} and AP_{14} were respectively calculated as the cumulative rainfall over the 1, 2, 5, 7, 10, 12 and 14 days prior to the survey. A second group of precipitation-based indices were used to reflect the time distribution of the antecedent water inputs. DSP (i.e. days since precipitation) was computed as the number of days elapsed since the last recording at the rain gage, while the DSP_{10}, DSP_{20} and DSP_{30} indices were computed as the number of days elapsed since the last rainfall intensity exceeding 10, 20 and 30 $mm.d^{-1}$ respectively. These indices were especially chosen for their computational simplicity and the absence of mathematical parameters (e.g. soil moisture depletion time) to be estimated. The ability of the survey mean soil moisture content ($MSMC$, computed over all depths and sampling points) to represent the catchment macrostate was also evaluated. Lastly, catchment discharges recorded on survey dates (current-day discharges, hereafter referred as CD_DISCH) were used to portray the integrated hydrological response at the catchment outlet.

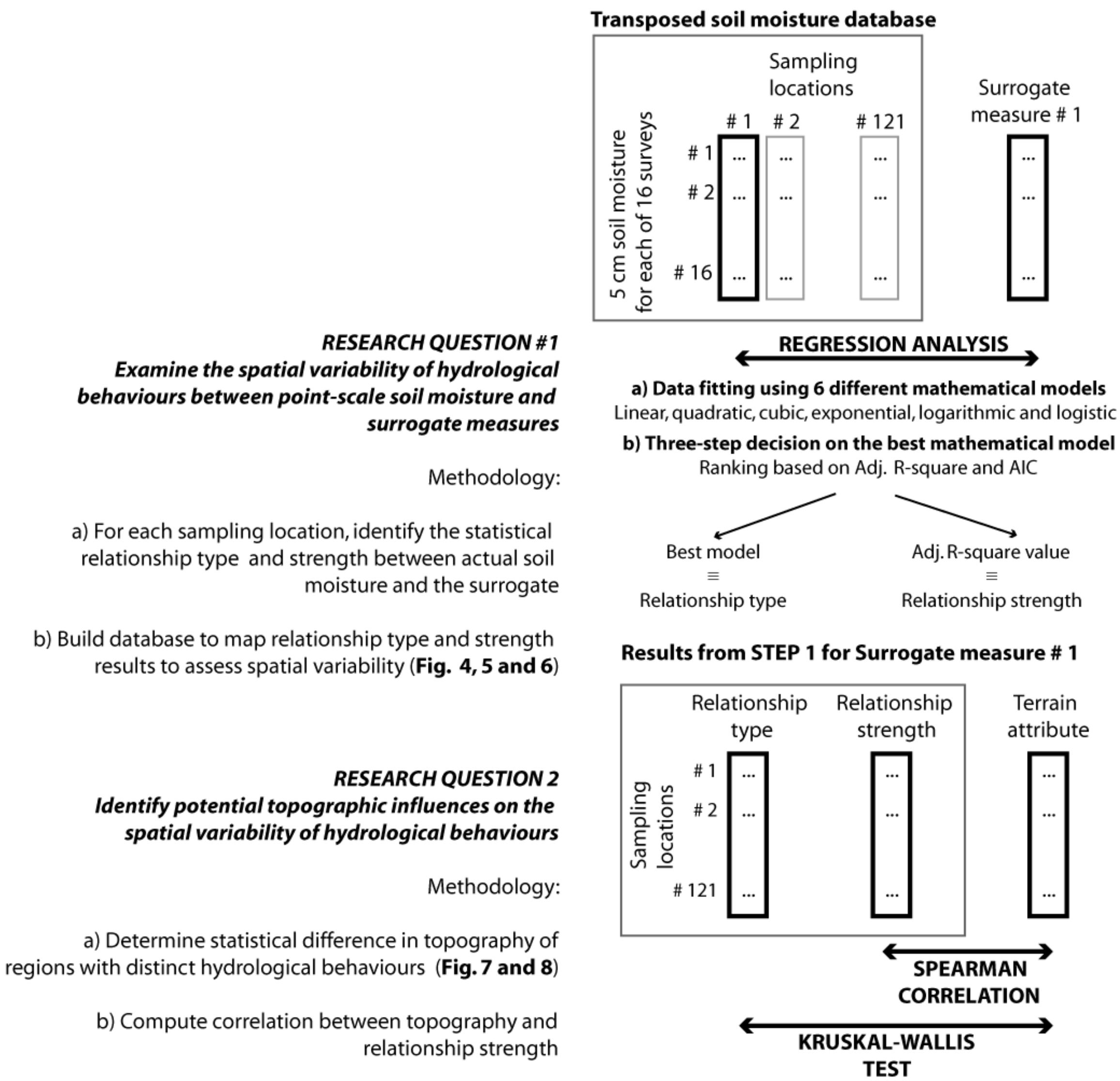

Figure 5.22 – Methodological approach used in this paper. "Adj. R-square" refers to the adjusted coefficient of determination while AIC refers to the Akaike Information Criterion.

d. Data analysis

Our methodology intended to answer two research questions (Figure 5.22). Firstly, we aimed to determine the nature and the strength of the relationships between point-scale soil moisture (i.e. soil moisture measured at each sampling point) and each of the AMCs and catchment response surrogates previously described. We hypothesized that the identified relationships would illustrate the variety of point-scale hydrologic behaviours that can be encountered within the Hermine catchment. Secondly, we examined the spatial organization of the nature and the strength of these point-scale relationships to link them with possible topographic controls.

For the determination of point-scale relationships, data cases were soil moisture survey dates (n = 16). When the aim was to evaluate the ability of AMCs measures to describe soil moisture patterns, the independent variable was the chosen surrogate for AMCs and the dependent variable was the depth-specific, point-scale soil moisture content. In order to assess the potential of $MSMC$ to represent the Hermine catchment macrostate, we rather considered $MSMC$ to be an independent variable while point-scale soil moisture was the dependent one. Lastly, in order to identify catchment areas that might contribute to streamflow discharge, the statistical procedure detailed below was also applied using point-scale soil moisture as the dependent variable and CD_DISCH as the independent one. No postulate could be made on the form of the relationship between the dependent and the independent variables since no such exercise has been done before. Six regression models (i.e. linear, quadratic, cubic, exponential, logarithmic and logistic), which represent six different types of possible relationships, were fitted to the data and compared so as to select the one with the best fit. Model equations can be written as follows:

Linear model

$$\mathrm{Y} = a \cdot \mathrm{X} + b \tag{5.7}$$

Quadratic (monotonic increasing) model

$$\mathrm{Y} = a \cdot \mathrm{X}^2 + b \cdot \mathrm{X} + c \tag{5.8}$$

Cubic (monotonic increasing) model

$$\mathrm{Y} = a \cdot \mathrm{X}^3 + b \cdot \mathrm{X}^2 + c \cdot \mathrm{X} + d \tag{5.9}$$

Exponential model

$$Y = a \cdot e^{b \cdot X} \tag{5.10}$$

Logarithmic model

$$Y = a + b \cdot \ln(X) \tag{5.11}$$

Logistic model

$$Y = \frac{c}{1 + a \cdot e^{-b \cdot X}} \tag{5.12}$$

Where Y is the dependent variable, X is the independent variable, and *a*, *b*, *c* and *d* are model parameters. There was no physical basis for the choice of the six mathematical models; the aim was rather to explore the dataset using different models with various degrees of complexity. In each case, a least squares-like regression method was used for all models, which means that the fitting of each model to the data had to minimize the squared differences between observed and predicted values. Selection of the best mathematical model among the six tested was then performed in three steps.

First, the adjusted coefficient of determination (Adj. R-square) was used to discard any model that would only explain a small proportion of the variance in the data. Throughout this paper, we refer to R-square as the proportion of variance in the dependent variable that is explained by the chosen regression model. It can be computed for any linear or nonlinear model:

$$\text{R-square} = 1 - \frac{\text{residual SS}}{\text{total SS}} \tag{5.13}$$

where SS refers to a sum of squares. Total SS is the total amount of variability in the dependent variable while residual SS is the amount of variability that still cannot be accounted for after the regression model is fitted to the data. Given that the value of R-square often increases when a nonlinear model is used instead of a linear relationship, the use of the Adj. R-square is more adequate in the context of multiple models evaluation and comparison as it assesses the goodness of fit while taking into consideration the numbers of degrees of freedom of the numerator and the denominator of R-square (Legendre & Legendre, 1998):

$$\text{Adj. R-square} = 1 - (1 - \text{R-square}) \left(\frac{\text{total d.f.}}{\text{residual d.f.}} \right) \tag{5.14}$$

Hence, the Adj. R-square "penalizes" models bearing a large number of parameters. For the current analysis, if all six models failed to produce an Adj. R-square value exceeding 0.3, then the relationship between point-scale soil moisture and the surrogate measure being evaluated was labelled as "not significant". Otherwise, only the models with an Adj. R-square exceeding 0.3 were kept for further consideration towards choosing the best fitting model.

As a second step in the best model selection, the models with an Adj. R-square exceeding 0.3 were ranked according to their corrected Akaike Information Criterion value. The Akaike Information Criterion or AIC (Akaike, 1974) is also a measure of the goodness of fit of a mathematical model but on the contrary to the Adj. R-square, it is not grounded in the statistical theory of hypothesis testing but rather in the information theory. The AIC estimates the Kullback–Leibler information loss by approximating the observed data with the fitted model (details regarding model selection using information theory can be found in Burnham & Anderson (2002). The fit of any regression model to any dataset can be summarized by the Akaike Information Criterion (AIC) defined by the equation:

$$\text{AIC} = \text{N} \cdot \ln\left(\frac{\text{residual SS}}{\text{N}}\right) + 2\text{K} \tag{5.15}$$

where N is the number of data points and K is the number of parameters fit by the regression plus one. The definition of K as the number of parameters plus one is justified by the fact that the regression is "estimating" not only the values of the parameters but also the sum of squares. It is worth noting that the computation equation of the AIC consists of two additive terms, namely one term representing the lack of model fit to the data and another term related to the number of parameters; hence, the AIC can be seen as a measure of both the accuracy and the complexity of the chosen model. In cases where $N/K < 40$ as in this study, a second order corrected AIC, hereafter referred to as AIC_c, is used:

$$\text{AIC}_c = \text{AIC} + \frac{2\text{K}(\text{K}+1)}{\text{N-K-1}} \tag{5.16}$$

When comparing several mathematical models, it is the one with the lowest AIC_c that is the best or that is most likely to be correct. Hence, in this study, mathematical models with an Adj. R-square exceeding 0.3 were ranked by sorting their associated AIC_c scores in ascending order, and the top-ranked model chosen as the best one.

The third and last step in the best model selection process consisted in confirming the choice made at the end of step 2. Indeed, if the AIC_c scores between the top two-ranked models are very close, there is not much evidence to choose one model over the other. We therefore used the following equation to compute the probability that the top ranked model is indeed the best one:

$$\text{probability} = \frac{e^{-0.5(AIC_{c_2} - AIC_{c_1})}}{1 + e^{-0.5(AIC_{c_2} - AIC_{c_1})}} \qquad (5.17)$$

This probability can thus be seen as an uncertainty measure as it expresses the likelihood that the top-ranked model is the best among the set of models being evaluated.

The possible influence of catchment topography, both surface and subsurface, was studied with regards not only to the nature (e.g. linear versus quadratic, versus cubic, etc.) but also to the strength of the point-scale relationships between actual soil moisture and surrogate measures. Nonparametric Kruskal-Wallis tests were run to assess whether the different types of point-scale relationships were spatially associated with specific topographic properties. The Kruskal-Wallis test is identical to one-way analysis of variance except that the data are replaced by their ranks. Hence, it is used to compare samples from three or more groups. The null hypothesis states that all group medians are equal, while the alternative hypothesis states that at least one group median is different from the others. In this study, each mathematical model is a group and we compare the topography underlying the locations subjected to different relationships between point-scale relationships between actual soil moisture and surrogate measures. When the p-value associated with the statistical test is less than 0.05, we reject the null hypothesis and suggest that the differences in relationship types can be explained by topography. Spearman correlation coefficients were also computed between the strength of the point-scale relationships (i.e. R-square values) and the values of the terrain attributes.

5.4.3 Results

a. Point-scale relationships

Each symbol in Figures 5.23 and 5.24 illustrates the best mathematical model between point-scale soil moisture content and a given surrogate measure. Following the three-step procedure previously described, it appears that on average, the models chosen as the best ones had a probability of being correct ranging from 52 to 100% (Table 5.12). Figures 5.23 and 5.24 illustrate the spatial heterogeneity in the Hermine when it comes to the relation between point-scale actual soil moisture measurements and any catchment-wide, meteorological-based proxy for AMCs. Figures 5.23 and 5.24 also show that the spatial patterns are highly dependent not only upon the chosen surrogate for AMCs but also upon the soil depth considered. For instance, only 10% of the soil moisture sampling sites at a 5 cm depth are related to PET (Figure 5.24). The best regression model for that relationship is a quadratic one; however Adj. R-square values do not exceed 0.38. A similar result is obtained at a depth of 15 cm where only 10% of the sampling locations are related to PET, and that proportion drops to zero when depths of 30 or 45 cm are considered.

For precipitation-based indices computed from cumulative rainfall, especially AP_1, AP_2 and AP_5, linear relationships are mostly present at a 5 cm depth while nonlinear relationships tend to dominate from a depth of 15 cm and below (Figure 5.23). Regarding the point-scale relationships between soil moisture and AP_1 (or AP_2), exponential models dominate at the 15 cm depth while quadratic models rather dominate at the 30 and 45 cm depths. It is at a depth of 30 cm that most locations with a significant relationship between AP_1 (or AP_2) and soil moisture content measurements were found, with a mean relationship strength (i.e. Adj. R-square) of 0.4. With AP_5, linear and exponential models are mostly present at the 5 and 15 cm depths while cubic and quadratic relationships make up most of the patterns at depths of 30 and 45 cm. Significant relations between AP_5 and point-scale soil moisture content measurements are the strongest ($0.30 \leq$ Adj. R-square ≤ 0.73) and the most widespread over the Hermine catchment area.

Table 5.12 – Catchment-wide average of Akaike weights or probabilities associated with the best mathematical model chosen to illustrate the relationships between point-scale soil moisture content and surrogate measures.

		Point-scale soil moisture			
		5 cm	**15 cm**	**30 cm**	**45 cm**
Surrogate measures	$RAIN$	0.76	0.76	0.66	0.69
	PET	0.83	0.83	*	*
	AP_1	0.65	0.65	0.88	0.89
	AP_2	0.56	0.56	0.83	0.85
	AP_5	0.57	0.57	0.62	0.66
	AP_7	*	1.00	1.00	1.00
	AP_{10}	*	*	0.59	1.00
	AP_{12}	0.79	0.79	0.56	0.57
	AP_{14}	*	0.70	0.83	0.87
	DSP	0.55	0.55	0.54	0.52
	DSP_{10}	0.65	0.65	0.56	0.57
	DSP_{20}	*	1.00	0.71	0.74
	DSP_{30}	0.59	0.59	0.56	0.60
	CD_DISCH	0.86	0.86	0.92	0.95
	$MSMC$	0.62	0.62	0.63	0.61

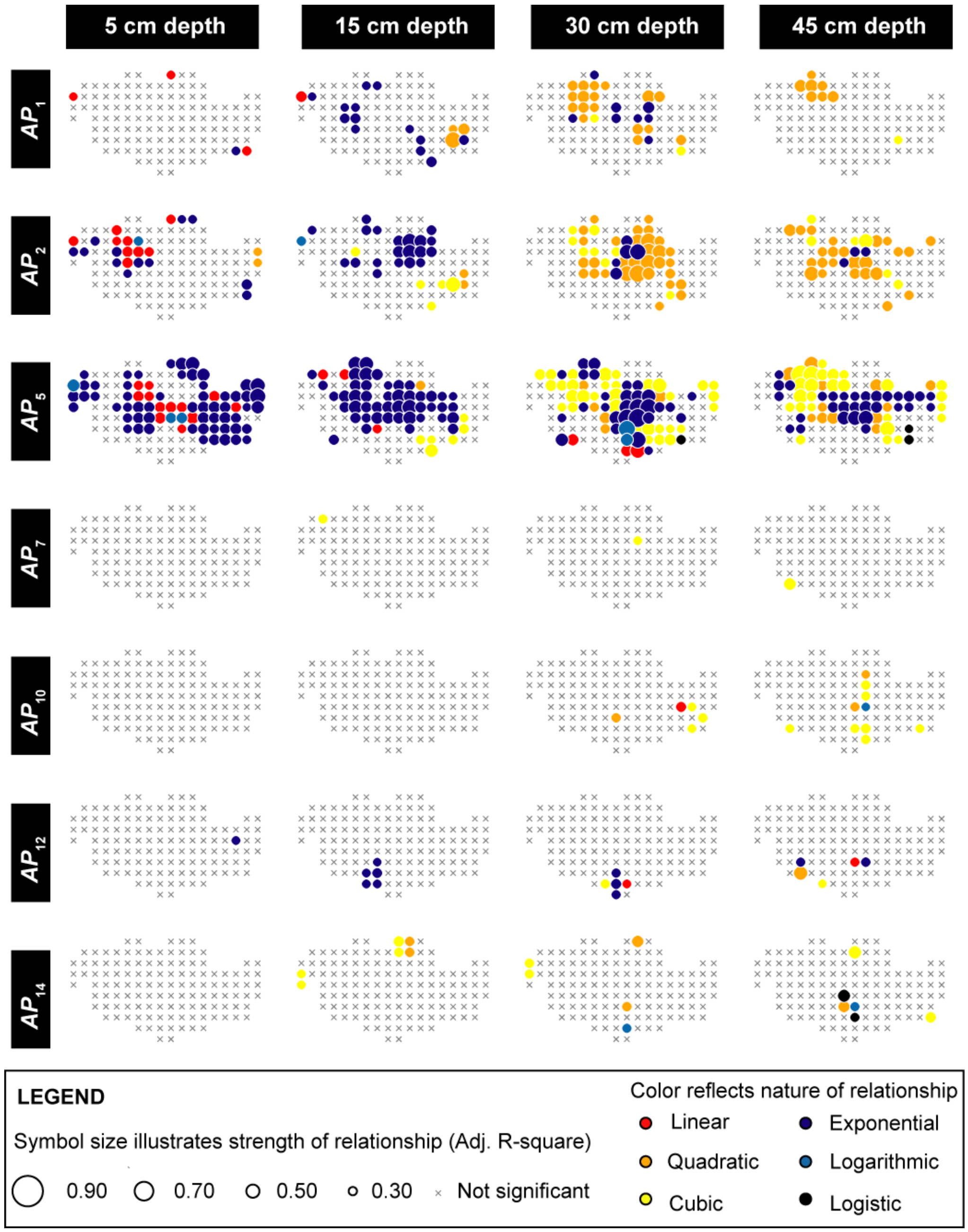

Figure 5.23 – Nature and strength of the relationships between point-scale soil moisture content and AP_x indices (x = 1, 2, 5, 7, 10, 12 or 14 days) used as surrogates for AMCs. "Adj. R-square" refers to the adjusted R-square.

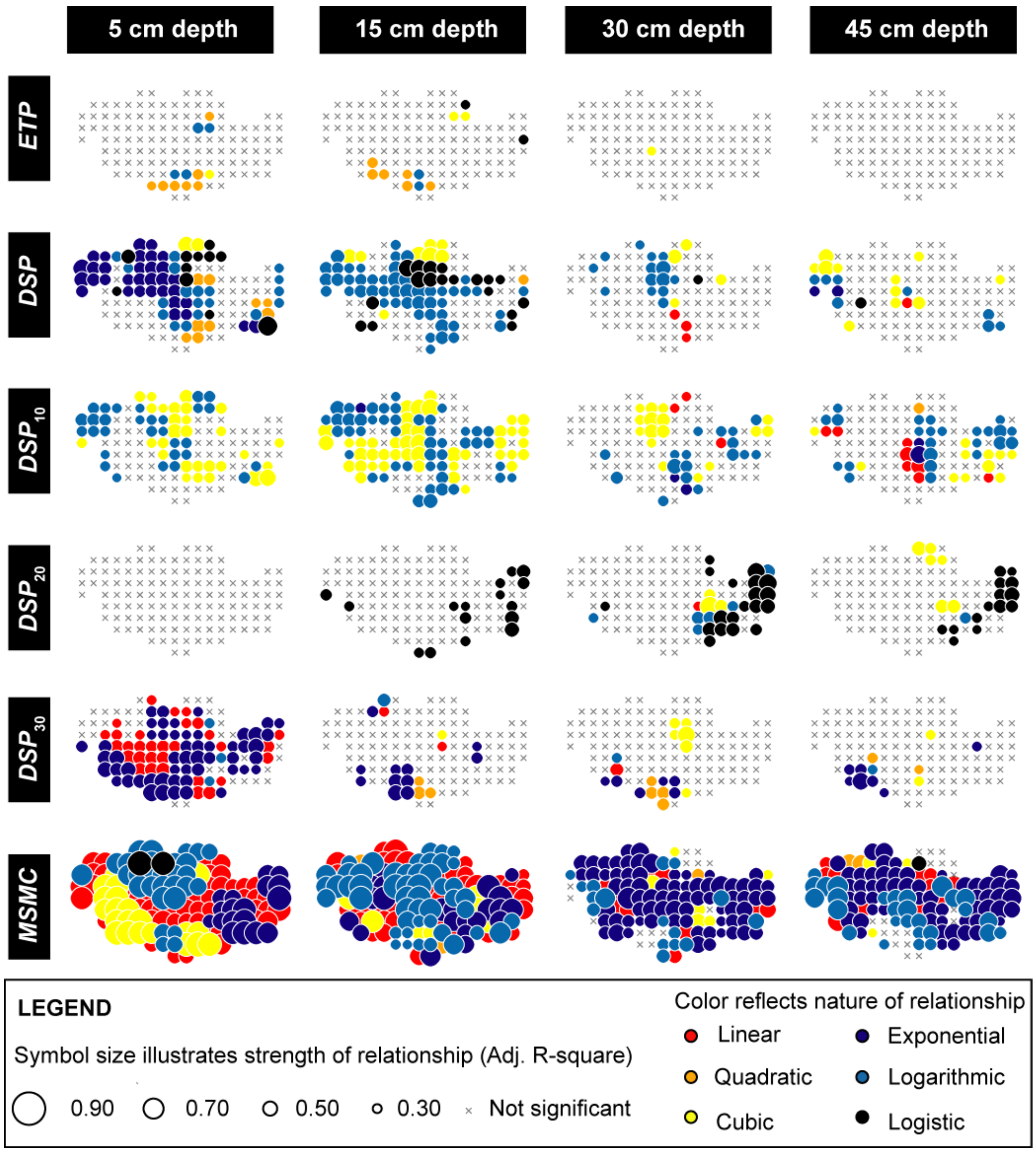

Figure 5.24 – Nature and strength of the relationships between point-scale soil moisture content, *PET* and DSP_x indices (x = 0, 10, 20 or 30 mm/d) used as surrogates for AMCs, and *MSMC* used as a surrogate for the Hermine catchment macro-state. "Adj. R-square" refers to the adjusted R-square.

On the contrary, patterns associated with AP_7, AP_{10} and AP_{14} show very few, if any, significant relations. Relationships between AP_{12} and point-scale soil moisture content measurements are of interest not because of their magnitude but rather because they are only made out from four to six locations confined to the catchment southern slope (Figure 5.23), which is opposite to the patterns associated with AP_1, AP_2 and AP_5. Indeed, with AP_{12}, the small cluster of locations subjected to significant relationships on the southern slope is opposed to the widespread presence of significant models on the northern hillslope and in the catchment upstream area when AP_1, AP_2 or AP_5 are used as surrogates for AMCs (Figure 5.23).

Spatial patterns of point-scale relationships were also different depending upon the chosen rainfall intensity-based measure of AMCs. Figure 5.24 shows that for all soil depths, a large proportion of sampling locations are significantly, yet weakly related to DSP at depths of 5 and 15 cm (mean Adj. R-square of 0.42). Exponential relationships between DSP and soil moisture dominate at 5 cm while logarithmic relationships rather dominate at 15 cm. With DSP_{10}, cubic and logarithmic relationships were present at depths of 5 and 15 cm. With DSP_{20}, significant logistic models were found particularly at the 30 and 45 cm depths in the headwater, upslope portion of the study area near the catchment divide (Figure 5.24). As for significant relationships between DSP_{30} and point-scale soil moisture content measurements, they were the most obvious at the 5 cm depth with a mix of linear and exponential regression models.

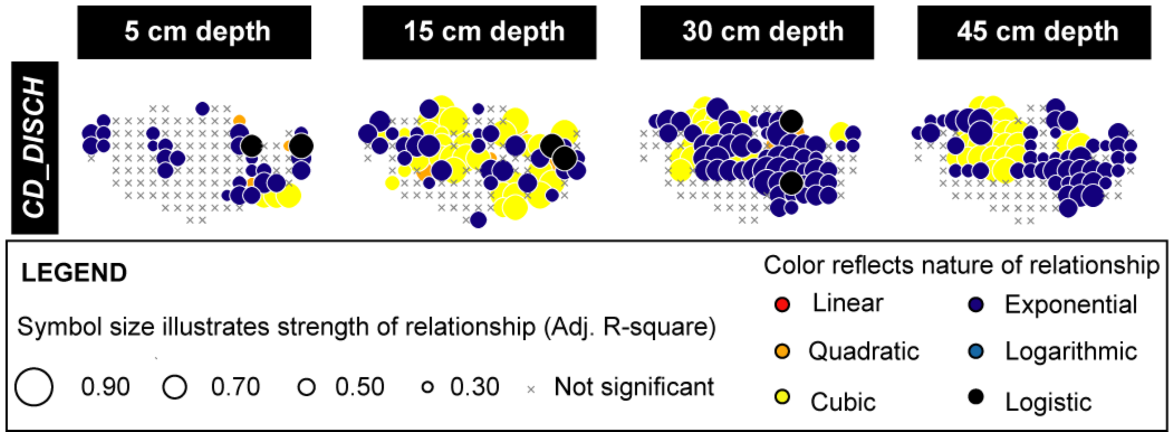

Figure 5.25 – Nature and strength of the relationships between point-scale soil moisture content and CD_DISCH used as a surrogate for the Hermine catchment response. "Adj. R-square" refers to the adjusted R-square.

For almost all sampling locations at all depths, significant relationships between soil moisture content measurements and $MSMC$ are found (0.32 ≤ Adj. R-square ≤ 0.91). The vast majority of these relationships are linear, quadratic, cubic and exponential (Figure 5.24). The proportion of sampling locations sharing nonlinear relationships with $MSMC$ is 58% at a depth of 5 cm and reaches 66% at a depth of 15 cm and even 90% at depths of 30 and 45 cm. As far as the variable CD_DISCH is concerned, the presence of statistically significant relations is highly dependent upon soil depth (Figure 5.25). At the 5 cm depth, very few locations are characterized by a significant relationship between point-scale soil moisture and CD_DISCH. At the three other soil depths investigated, exponential and cubic models dominate while the strength of the relationships is greater than at 5 cm (mean Adj. R-square value of 0.62, maximum Adj. R-square ranging from 0.80 to 0.90 from the 15 cm depth below). At 30 and 45 cm, the spatial patterns of significant relationships resemble the spatial patterns obtained with AP_1, AP_2 and AP_5.

The relationships between $MSMC$ and surrogate measures for AMCs and between $MSMC$ and CD_DISCH were also examined (Figure 5.26) and compared to the point-scale relationships illustrated in Figures 5.23, 5.24 and 5.25. $MSMC$ was only found to be correlated with AP_5, DSP and DSP_{10} given weak Adj. R-square values (≤ 0.4).

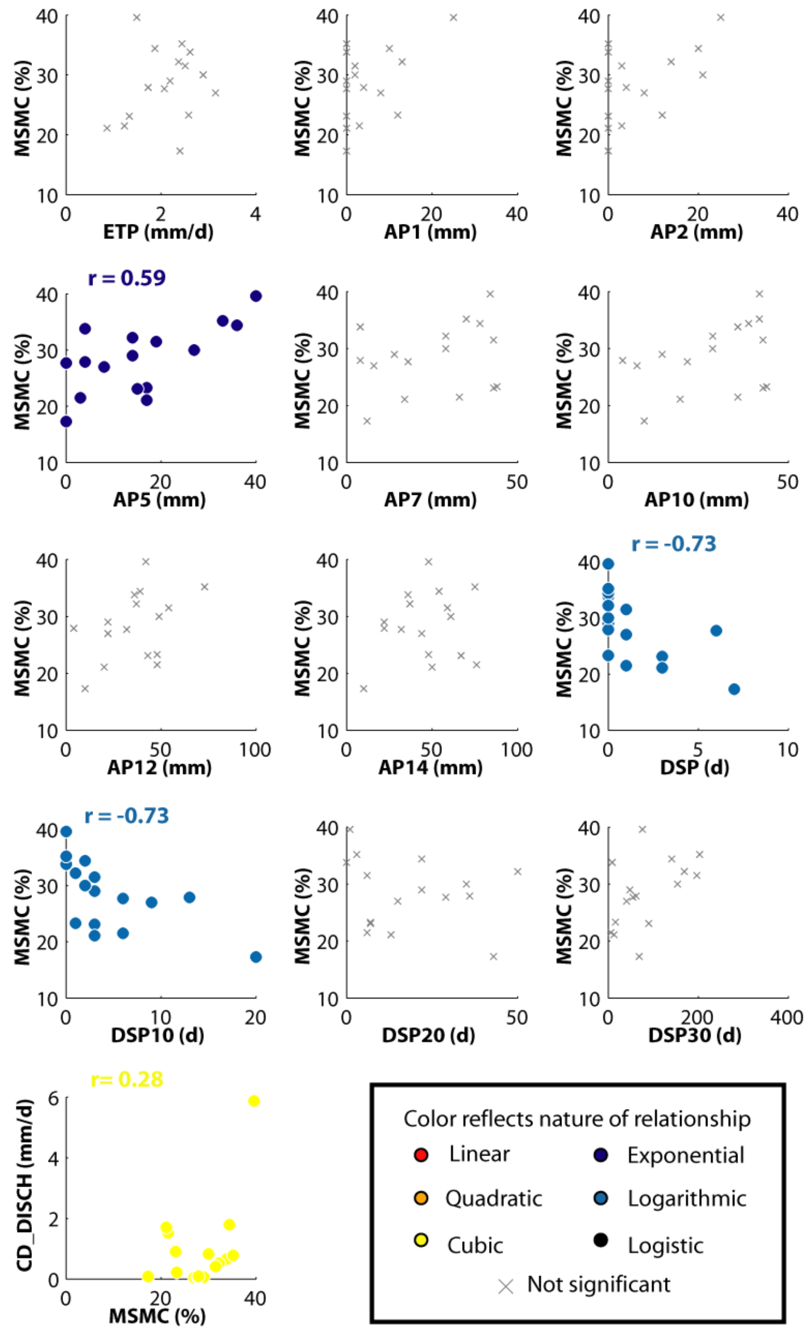

Figure 5.26 - Relationships between the mean soil moisture content ($MSMC$) and surrogate measures for AMCs and catchment response. "r" refers to the Spearman correlation coefficient.

Among the six mathematical models tested (e.g. linear, quadratic, cubic, exponential, logarithmic and logistic), the exponential one was best suited to explain the relationship between $MSMC$ and AP_5 while $MSMC$ and DSP and DSP_{10} were rather linked in a logarithmic manner. The exponential (or logarithmic) model was also the most widespread when relationships between point-scale soil moisture contents and AP_5 (or DSP and DSP_{10}) were examined (Figures 5.23 and 5.24). However, the use of $MSMC$ rather than point-scale soil moisture measurements prevented us from knowing that the strengths of the relationships were highly variable in space and were often associated with Adj. R-square values exceeding 0.4 (Figures 5.23 and 5.24). A strong (Adj. R-square = 0.88) cubic relationship was found between $MSMC$ and CD_DISCH (Figure 5.26); this was a surprising given Figure 5.25 showing that exponential relationships dominate between point-scale soil moisture contents and $MSMC$ at all depths but 15 cm.

b. Topographic influences

Regardless of soil depth, no significant Spearman correlation coefficient was found between the strength (i.e. Adj. R-square) of the identified point-scale relationships and the values of any surface or subsurface terrain attribute. Nonparametric Kruskal-Wallis tests showed that the nature of the mathematical model chosen to illustrate the relationship between point-scale soil moisture contents and surrogate measures was seldom controlled by topographic variables (Tables 5.13 and 5.14).

p-values reported in Table 5.13 indicate that elevation above the catchment outlet can be used to infer the nature of the point-scale relationships between soil moisture and DSP_{20}. Figure 5.27 shows that at depths of 15, 30 and 45 cm, relationships between DSP_{20} and point-scale soil moisture tend to be not significant or cubic at intermediate elevations above the catchment outlet (~ 20 m) and rather logarithmic or logistic at high elevations above the outlet (> 25 m), especially in the most upstream part of the catchment (see Figure. 5). For surrogate measures such as AP_1, AP_5, $MSMC$ and CD_DISCH, a clear influence of elevation above the catchment outlet on the point-scale relationships was not discernable. For $MSMC$, in particular, linear and nonlinear relationships expand across the whole range of elevation values (Figure 5.27), thus making it difficult to discern any clear spatial pattern. As for the influence of surface elevation on the relationships between CD_DISCH and point-scale soil moisture measurements, it is only perceptible at depths of 5 and 45 cm (Table 5.13, Figure 5.27) given the relative location of cubic and exponential models. The influence of the surface compound topographic index (CTI) and the MRVBF index of the surface and of the confining soil layer on the patterns of point-scale relationships between selected AMCs proxy variables (AP_2, AP_5, DSP) and soil moisture was also examined (Figure 5.28). Even though some minor differences can be perceived in the nature of the point-scale relationships as a function of the values of the subsurface MRVBF index (Figure 5.28), these differences are not significant (refer to p-values reported in Table 5.14). The same conclusion applies to the nature of the point-scale relationships as a function of CTI or the surface MRVBF index (Figure 5.28, Table 5.13).

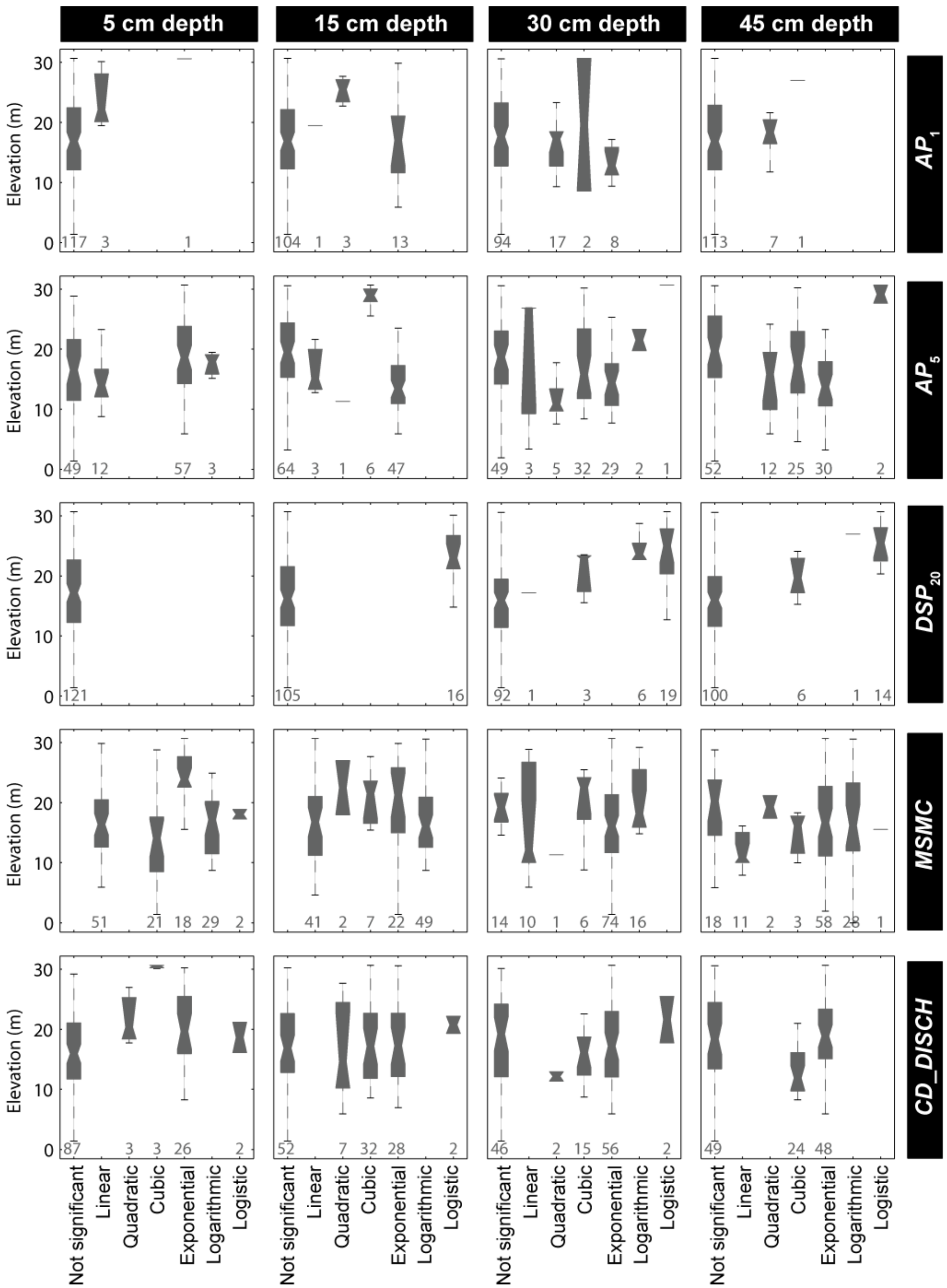

Figure 5.27 – Influence of surface topography (elevation above the catchment outlet) on the nature of the relationship between point-scale soil moisture (columns) and selected proxies for AMCs, catchment macrostate and catchment response (rows) in the Hermine. Grey numbers illustrate the number of data used to plot each box.

Table 5.13 – Influence of catchment surface topography (rows) on the nature of the point-scale relationships between soil moisture content and various surrogates (columns). Reported p-values are significant and suggest that at least one relationship type is associated with a median value of the studied topographic variable that is significantly different from the others.

	PET	AP_1	AP_2	AP_5	AP_7	AP_{10}	AP_{12}	AP_{14}	DSP	DSP_{10}	DSP_{20}	DSP_{30}	$MSMC$	CD_DISCH
5cm														
Elevation									0.0372			0.0012		0.0047
Slope													0.0034	
Cont. area														
Topo. index														
MRVBF													0.0260	
15cm														
Elevation			0.0006	0.0000					0.0304		0.0005		0.0106	
Slope			0.0398				0.0310		0.0095					
Cont. area													0.0444	
Topo. index													0.0178	
MRVBF									0.0220					
30cm														
Elevation			0.0074	0.0499					0.0179		0.0001		0.0000	
Slope														
Cont. area														
Topo. index			0.0408											
MRVBF														
45cm														
Elevation			0.0077	0.0003						0.0437	0.0000	0.0257	0.0000	0.0002
Slope						0.0429								
Cont. area														
Topo. index														
MRVBF														

Table 5.14 – Influence of the soil confining layer topography (rows) on the nature of the point-scale relationships between soil moisture content and various surrogates (columns). Reported p-values are significant and suggest that at least one relationship type is associated with a median value of the studied topographic variable that is significantly different from the others.

	PET	AP_1	AP_2	AP_5	AP_7	AP_{10}	AP_{12}	AP_{14}	DSP	DSP_{10}	DSP_{20}	DSP_{30}	$MSMC$	CD_DISCH
5cm														
Depth to layer														
Slope														
Cont. area				0.0433										
Topo. index														0.0336
MRVBF													0.0105	0.0482
15cm														
Depth to layer											0.0062		0.0311	
Slope								0.0427						
Cont. area														
Topo. index											0.0345			
MRVBF														
30cm														
Depth to layer							0.0000					0.0000		
Slope														
Cont. area														
Topo. index														0.0206
MRVBF														
45cm														
Depth to layer														
Slope														
Cont. area												0.0442		
Topo. index														
MRVBF														

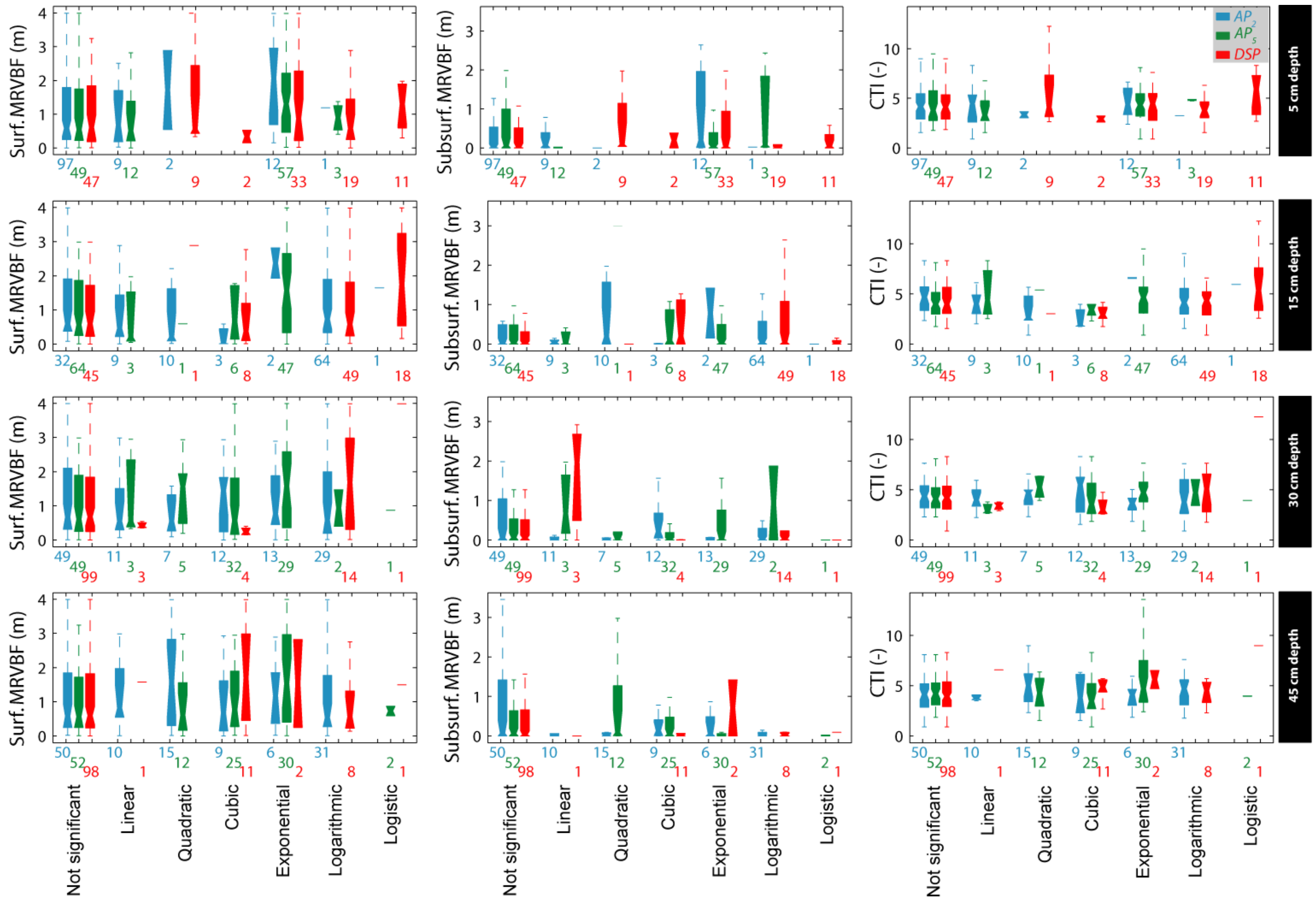

Figure 5.28 – Influence of various topographic properties (surface and subsurface multi-resolution valley bottom flatness and compound topographic index) on the nature of the relationship between point-scale soil moisture and selected surrogate measures for AMCs. Blue, green and red numbers illustrate the number of data used to plot each box of the same color.

5.4.4 Discussion

The simple exercise conducted in this paper yielded new insight into the spatial representativity of proxy variables for AMCs or catchment response. While the relationships between actual soil moisture and several surrogate variables do exhibit strong spatial patterns (see examples in Figures 5.23, 5.24 and 5.25), some others show rather poor spatial organization, thus casting doubt on the use of a single surrogate to illustrate a catchment state of wetness. Reaching such a conclusion was only possible through the use of an exhaustive soil moisture dataset that covers nearly the entire set of hydrological conditions of the Hermine catchment (Table 5.11), except for the winter and early spring seasons. Even though the patterns illustrated in Figures 5.23, 5.24 and 5.25 only portray the spatial distribution of statistical relationships between actual soil moisture measurements and surrogate indices, they may reveal critical hydrological information. Hence, we argue that the simple statistical analyses conducted in this paper give a better understanding of the spatial heterogeneity of hydrological patterns and processes in the Hermine catchment.

It is not surprising that the 10% of the near-surface catchment area subjected to the influence of PET are located on the upper parts of the southern slope, near the catchment divide and in a few other zones (Figure 5.24) where canopy density is lower. On much of the Hermine catchment area, especially near the catchment head and on the northern slope, shallow soil moisture seems to be dominantly controlled by AP_2 and AP_5 (Figure 5.23). Statistically significant, even though weak, relations between soil moisture measurements and AP_{12} (Figure 5.23) suggest that soil wetness is not persistent in the long-term except for a small portion of the catchment corresponding to a low-elevation wet zone and to thin soils developed over a bedrock outcrop. Linear relationships between point-scale soil moisture and AP_1, AP_2 and AP_5 are mostly present at 5 cm but regardless of the soil depth considered, they are outnumbered by nonlinear polynomial (i.e. quadratic and cubic) and exponential relationships (Figure 5.23). This may be linked to the fact that the soil storage capacity is a function of the amount and timing of precipitation in addition to evapotranspiration (Ritcey & Wu, 1999), or simply to the transmissivity mechanisms governing the vertical drainage of water in the soil.

Locations for which soil moisture is strongly related with catchment discharge may be indicative of catchment areas where triggering conditions for stormflow initiation are met. In that respect, it is worth noting that at depths of 30 and 45 cm, in particular, the spatial patterns of significant relationships between actual soil moisture measurements and CD_DISCH resemble the spatial patterns of significant relationships between actual soil moisture and AP_5 (Figures 5.23 and 5.25). Our approach makes it possible to distinguish near-surface from deeper potential ‘contributing’ areas. It is also interesting to compare locations subjected to cubic or exponential relationships with CD_DISCH (Figure 5.25) as the two mathematical models mainly differ by their rate of increase. We could argue that the particular locations of exponential relationships hint towards rapidly enhanced subsurface water fluxes leading to the catchment outlet following water inputs to the catchment. It would be reasonable to assume that locations subjected to exponential relationships with CD_DISCH are associated with the absence of depressions to fill in the topography of the soil-confining layer interface. It would also be reasonable to set them in opposition to the other locations which may be subjected to a soil storage threshold to exceed before any lateral water fluxes can occur (Spence & Woo, 2003; Tromp-Van Meerveld & McDonnell, 2006b; Kusumastuti *et al.*, 2007), hence the slower increasing, cubic relationships with CD_DISCH. Even though plausible, this hypothesis is not confirmed by the Kruskal-Wallis tests results in Tables 5.13 and 5.14. In fact, there are no statistically significant differences in subsurface terrain attributes between locations sharing exponential relationships with CD_DISCH and locations sharing cubic relationships with CD_DISCH. This conclusion highlights the main drawback of the purely statistical approach with regards to hypothesis testing, as the obtained regression models may not necessarily reflect causal relationships. Hence, we can only formulate hypotheses that would have to be tested against additional field data. For instance, in order to confirm or infirm the influence of subsurface topographic features on the rate of increase of catchment discharge with respect to point-scale soil moisture, the fluctuations of water storage at the soil-confining layer interface could be investigated.

Concerning the results on $MSMC$, the important spatial extension of statistically significant relations with point-scale soil moisture content at all four depths indicates that it is a good surrogate for describing the catchment soil moisture macrostate. This is in accordance with the methodology of several previous studies (e.g. Thierfelder *et al.*, 2003; Grant *et al.*, 2004; James & Roulet, 2009) that relied on the use of the catchment mean shallow soil wetness for process understanding or modeling purposes. We, however, found that the less shallow the soil depth considered, the more locations whose soil moisture measurements were nonlinearly related to $MSMC$ (Figure 5.24). The identified relationships between $MSMC$ and surrogate measures for AMCs and between $MSMC$ and CD_DISCH fell short of capturing the heterogeneity of the point-scale mechanisms. This result requires further investigation as to how representative the $MSMC$ really is over different catchment areas and with changing depths.

It must be stressed that the sole reliance on indices often used in catchment hydrology, namely AP_7 and AP_{10}, would have led us to rely on a surrogate measure that is not related to soil moisture measurements in the Hermine. Even though soil moisture proxies based on antecedent rainfall can give good results (e.g. Kohler & Lindsey, 1951; Longobardi *et al.*, 2003), the choice of the antecedent temporal window is crucial. In our case, AP_5 is the best index to use as a surrogate for AMCs in the Hermine catchment while AP_1, AP_2 and AP_{12} yield fairly good results. Kohler & Lindsey (1951) have argued that indices simply computed from the number of days since the last rain are 'obviously insensitive and should not be used if accurate results are required' (p.2). This statement does not reflect the results obtained for the Hermine catchment, especially when not only the days since the last rain but also the rainfall intensity are considered. We suspect that Kohler and Lindsey's argument might be true in the large river basins with multiple tributaries as they refer to in their paper but not in a small headwater catchment like the Hermine. Statistically significant relationships were obtained between point-scale soil moisture measurements and DSP, DSP_{10}, DSP_{20} and DSP_{30}. For DSP_{20}, a weak significant topographic control was even identified as logarithmic or logistic point-scale relationships with soil moisture were mostly present at high elevations above the catchment outlet (> 25 m) (Figure 5.27). It is also worth mentioning that previous-day discharges were also used as surrogates for AMCs (data not shown) but they were not involved in any significant relationship with point-scale soil moisture measurements; this result is contradictory to the affirmation of Kohler & Lindsey (1951) who argued that baseflow-derived indices provided reasonably good results in humid and sub-humid regions.

It is interesting to compare results obtained from previous studies in the Hermine catchment (Table 5.10) with the conclusions of the current paper. For instance, the same soil moisture content dataset was analyzed to characterize the emergence of spatially coherent saturation patches in the Hermine catchment (Ali *et al.*, 2010a). The importance of DSP_{30}, in particular, was then revealed: the smaller the surrogate measure for AMCs, the more likely the presence of 0.85-1.4 ha wide saturation patches at a depth of 15 cm and the more likely the presence of saturation patches of less than 0.85 ha at a depth of 45 cm. These conclusions are consistent with the patterns illustrated in Figure 5.24. Furthermore, results from Ali *et al.* (2010a) corroborate the fact that relations between actual soil moisture and AP_7 or AP_{14} are very rare and can only be perceived at the scale of very small saturation patches (< 0.1 ha). This comparison sheds light on the scale-dependent spatial representativity of AMCs surrogate measures. Ali *et al.* (2010a), however, did not identify any significant relations between soil moisture patterns and AP_2, while it only captured the influence of AP_5 on 0.54-0.85 ha patches and the influence of AP_{12} on 0.02-0.1 ha patches. These results are opposite with some of the AP_2 patterns illustrated in Figure 5.23 and the reason for this is unclear. Ali & Roy (in review/en révision a) also found that the spatial connectedness of locations whose volumetric soil moisture content exceeded 30% was dependent upon AP_7. The relationship between connectivity and AP_7 then had the form of a step function, which may explain why it was not captured by any of the tested regression models in the current paper. By stating that the relative contribution of geographic sources (i.e. organic versus mineral soil water originating from riparian or upslope areas) to streamflow are strongly correlated to AP_2 and rather weakly correlated to AP_7, Ali *et al.* (2010b) echo the conclusions of the present study about the appropriateness of AP_2 as a proxy for the Hermine catchment AMCs and the insignificance of AP_7 in that regard. On the contrary to the current paper, Ali *et al.* (2010c) found that AP_{10} had an influence on the catchment behaviour only when the cumulative antecedent rainfall amounts lay in the range of 24.5 to 40.5 mm. There again, such a relationship between catchment discharge and AP_{10} can be schematized as a rectangular function that does not bear any resemblance with any of the regression models tested in this paper. Hence, these results highlight the sensitivity of the results to the nature of the relations and of the ensuing regression model that is used.

Our results are catchment specific. They pertain to a small forested watershed with relatively steep slopes in a temperate humid climate. The small scale of the headwater basin and its relief may play a role on the optimal antecedent temporal window size that has been identified (i.e. 5 days) through the analysis. The approach, however, has a general value as the simple analysis described in this paper can be repeated for several catchments under various climatic regimes and for which spatially-detailed soil moisture data are available. This will allow the hydrological community to compare findings and maybe derive guidelines regarding the choice of proxy measures of AMCs in catchments with specific climatic and topographic characteristics. Lastly, it is worth mentioning that the rationale behind our statistical analysis comes from several studies that have described soil moisture as a major control of catchment response and an indicator of the location of active subsurface flow paths (e.g. Grayson *et al.*, 1997; Meyles *et al.*, 2003; Western *et al.*, 2004; Western *et al.*, 2005). However, while Van Meerveld & McDonnell (2005) have also agreed that soil moisture may co-vary with streamflow, they have rather identified transient saturation at the soil–bedrock interface or near a soil layer of reduced permeability to be a real trigger for lateral subsurface stormflow. This was latter confirmed with the fill and spill hypothesis (Tromp-Van Meerveld & McDonnell, 2006b). Tromp-Van Meerveld & McDonnell (2006c) also showed that in catchments such as the Panola study site (Georgia, USA), pre-event soil moisture variations were not the main control on the distribution of subsurface saturation during winter storms. The hypothesis according to which shallow soil moisture is a passive signal of transient saturation at the soil-confining layer interface in the

Hermine catchment should therefore be verified in order to shed light on the patterns illustrated in Figures 5.23, 5.24 and 5.25.

5.4.5 Conclusions

This paper aimed at determining whether or not multiple surrogates for AMCs had to be used in order to describe the moisture conditions within a catchment. With regards to the Hermine catchment, the answer to that question is affirmative. Without making any assumption on active processes, we computed the point-scale temporal relations between actual soil moisture measurements and commonly used meteorological-based indices so as to identify the surrogates for AMCs that are best suited to the Hermine catchment. Two principal results stood out. Firstly, it was shown that the sole reference to AMCs indices often used in catchment hydrology (i.e. AP_7 or AP_{10}) does not help predicting the catchment moisture conditions when linear, quadratic, cubic, exponential, logarithmic or logistic relationships are considered. Secondly, the relationships between point-scale soil moisture measurements and surrogates for AMCs were not spatially homogeneous, thus revealing a mosaic of linear and nonlinear catchment 'active' and 'contributing' sources whose location was seldom controlled by surface terrain attributes or the topography of the soil-confining layer interface. These results represent a step forward for the Hermine catchment as they point towards depth-specific processes and spatially-variable triggering conditions that are not controlled by topography. Such hydrological behaviour may also exist in other catchments. The analysis also raises several questions on the use of surrogate AMCs measures and on the generalization of results obtained with a single surrogate. Further investigations are, however, necessary to establish robust, causal relationships between soil moisture and meteorological-based proxies for AMCs and then derive guidelines concerning the best surrogate choice.

5.5 Paragraphe de liaison “5-6”

Chacun des articles reproduits aux sections 5.2, 5.3 et 5.4 constitue un gain de connaissances important en ce qui a trait au comportement hydrologique du bassin versant de l’Hermine. En plus d’être novatrice en hydrologie, l’utilisation de l’analyse spatiale par vecteurs propres (MEM : *Moran’s eigenvector maps*, section 5.2) a permis de démontrer que dans le cas particulier de notre site d’étude, les processus hydrologiques qui ont un impact marqué sur le débit à l’exutoire interviennent à une échelle intermédiaire entre le profil topographique (ou le versant) et le bassin tout entier. Les aires saturées couvrant des superficies supérieures à 0,85 ha sont critiques pour la genèse de forts débits de crue tandis que les zones saturées considérées à des échelles spatiales inférieures n’ont que peu d’impact sur la réponse hydrologique. De fait, lorsque ces aires saturées atteignent une superficie critique de 0,85 ha, elles peuvent être considérées comme des aires contributives à l’écoulement en raison de leur forte association avec le débit du cours d’eau, d’où l’idée d’une connectivité hydrologique accrue. L’influence de la topographie sur les patrons d’humidité du sol a également pu être discriminée selon les échelles spatiales considérées. Ces résultats représentent une avancée importante par rapport à ce qui avait été conclu à la fin des chapitres 3 et 4. Si l’approche « boite noire » ne permettait pas d’apprécier les régions du bassin versant de l’Hermine qui influencent le plus les changements de connectivité hydrologique et si l’approche « boite grise » ne permettait de le faire que de manière partielle, l’approche « boite blanche » utilisée ici est plus précise car elle se base sur des données à fort niveau de discrétisation spatiale.

Le raisonnement adopté dans les articles des sections 5.3 et 5.4 est en opposition avec celui de la section 5.2. En effet, alors que l’utilisation de l’analyse spatiale par vecteurs propres visait l’identification de sous-régions au comportement critique dans le bassin versant de l’Hermine, les métriques spatiales (section 5.3) et les indices de conditions d’humidité antécédentes (section 5.4) s’efforcent plutôt de résumer l’état du bassin versant tout entier. L'utilisation de mesures intégratrices reflétant le comportement global, donc émergent, d'un bassin versant est en accord avec le principe de connectivité hydrologique, et ce sans égard au fait que la mesure ait été dérivée à partir de patrons spatiaux d'humidité du sol (i.e. métriques spatiales) ou de données météorologiques (i.e. indices de conditions d'humidité antécédentes). Le choix d'utiliser une mesure particulière au détriment d'une autre doit cependant être effectué en fonction de la capacité de ladite mesure de capter les changements hydrologiques majeurs qui interviennent dans le bassin versant au cours du temps. C'est ainsi que dans la section 5.3, une comparaison exhaustive de métriques spatiales a été réalisée en vue de déterminer lesquelles étaient les plus à même de détecter les changements de connectivité hydrologique dans le bassin versant de l'Hermine. Ce faisant, la preuve a également pu être faite que les propriétés statistiques des patrons d'humidité du sol en milieu forestier tempéré humide étaient nettement différentes de celles observées en milieu tempéré sec de prairie, d'où la nécessité d'utiliser des méthodes de calcul différentes afin de dériver les métriques spatiales adéquates dans les deux types de milieux. L'exercice réalisé dans la section 5.4 a, quant à lui, permis de revisiter le concept des aires variables actives et contributives. Si les résultats obtenus sont spécifiques à l'Hermine, ils émettent néanmoins l'hypothèse que les bassins versants forestiers tempérés humides puissent être constitués tant de régions dont la contribution au débit sortant est directement proportionnelle au contenu en eau de leurs sols que de régions soumises à des effets de seuils et qui contribuent de manière non linéaire au débit. La double existence de sources contributives « linéaires » et de sources contributives « non linéaires » serait donc une manière différente de conceptualiser l'hétérogénéité spatiale des bassins versants. Du point de vue de la connectivité hydrologique, il serait important d'évaluer l'impact de l'agencement spatial des sources linéaires et non linéaires sur les débits mesurés à l'exutoire des bassins versants. Par ailleurs, la présence de ces deux types de sources de ruissellement met en évidence la nécessité d'utiliser non pas un mais plusieurs indices de conditions d'humidité antécédentes afin de bien illustrer les dynamiques contrastées.

La revue critique et commentée de la section 2.2 a souligné l'existence de plusieurs approches d'étude de la connectivité hydrologique. Le but premier de cette thèse était donc d'illustrer chacune de ses approches à l'aide de données hydro-météorologiques de nature différentes et d'outils d'analyse également variés. Les résultats des articles présentés dans les sections 3.2, 4.2, 5.2, 5.3 et 5.4 ont permis de montrer que les approches de type « boite noire », « boite grise » et « boite blanche » conduisaient à des gains de connaissances importants mais avec divers niveaux de détail et à des échelles différentes. Ces articles ont aussi pu démontrer la multiplicité des facteurs à considérer pour caractériser la connectivité hydrologique. Deux questions découlent donc naturellement de ces résultats. Premièrement, les gains de connaissances supplémentaires réalisés avec les approches de type « boite grise » et « boite blanche » sont-ils en accord ou en contradiction avec les conclusions tirées à l'issue de l'analyse de type « boite noire » ? Il s'agit là d'une préoccupation importante, car la confirmation de la cohérence des approches permettrait de statuer sur l'équivalence théorique et pratique des multiples définitions de la connectivité hydrologique. Deuxièmement, étant donné la grande complexité des processus qui sous-tendent la connectivité hydrologique, on est en droit de se demander s'il est réaliste d'espérer reproduire adéquatement le comportement des bassins versants forestiers tempérés humides en utilisant des modèles hydrologiques. Des éléments de réponse à ces deux questions sont apportés dans le sixième et dernier chapitre de cette thèse.

CHAPITRE 6

LA CONNECTIVITÉ HYDROLOGIQUE, UNE PROPRIÉTÉ PRÉVISIBLE ?

6.1 Modèle perceptuel du fonctionnement hydrologique de l'Hermine

Tel que mentionné dans l'introduction générale de cette thèse, l'hydrologie cherche essentiellement à répondre à quatre questions, à savoir 1) comment le débit d'un cours d'eau est-il produit, 2) d'où vient l'eau, 3) quels chemins emprunte-t-elle pour rejoindre le cours d'eau, et 4) quelle est sa vitesse de transit ? (Joerin, 2000). Les éléments de réponse à apporter à ces questions constituent l'essence même du concept de connectivité hydrologique que Pringle (2001) a vaguement défini comme étant le mouvement de l'eau à travers toutes les étapes du cycle hydrologique. La revue critique et commentée de la section 2.2 a permis d'identifier trois types d'approches expérimentales pour tenter d'évaluer le degré de connectivité hydrologique d'un bassin versant. Ces trois approches ont été appliquées au bassin versant de l'Hermine et les résultats obtenus font l'objet des sections 3.2, 4.2, 5.2, 5.3 et 5.4. Le but de la présente section est de faire la synthèse de tous les résultats obtenus afin d'élaborer un modèle perceptuel du fonctionnement hydrologique du bassin de l'Hermine.

D'entrée de jeu, il est bon de souligner que d'un point de vue purement théorique, les trois approches devraient mener à des résultats convergents. L'étude des relations entre la pluie et les débits via l'approche de type « boite noire » devrait conduire à la conclusion d'un comportement non linéaire du bassin versant concerné. Ce comportement non linéaire tient de l'existence d'effets de seuils non seulement au niveau local, pour l'activation des processus de genèse de l'écoulement mais aussi à l'échelle des versants pour ce qui est de l'expansion et de la contraction des aires contributives variables. L'examen des processus de genèse de l'écoulement et des chemins que cet écoulement emprunte jusqu'à l'exutoire est le propre de l'approche de type « boite grise » tandis que les aires contributives peuvent être visualisées grâce aux patrons spatiaux de variables hydrologiques comme l'humidité du sol (approche « boite blanche »). Il n'est donc pas surprenant de constater que les trois approches utilisées dans les chapitres 3, 4 et 5 révèlent toutes un comportement non linéaire pour le bassin versant de l'Hermine.

L'utilisation d'un arbre de classification dans la section 2.2 a permis de mettre en évidence de nombreuses valeurs critiques de variables météorologiques pour expliquer le passage de réponses hydrologiques lentes et de faible magnitude à des réponses hydrologiques rapides et de forte magnitude, par exemple. L'application répétée de la méthode *EMMA* à différents jeux de données illustrant des scénarios hydrologiques contrastés a aussi permis de montrer que les contributions relatives des sources de ruissellement de proche surface augmentaient brusquement dans certaines situations (section 4.2). Les analyses effectuées dans les sections 5.3 et 5.4 ont quant à elles souligné la présence majoritaire de dynamiques non linéaires à l'Hermine. Il est toutefois nécessaire de préciser ce qu'on entend ici par comportement non linéaire, par opposition avec ce qui est généralement sous-entendu dans la littérature. En effet, l'allusion à un comportement « non linéaire » pourrait être prise dans un sens très général, à savoir des relations entre la pluie et le débit qui n'obéissent pas au modèle mathématique $y = ax + b$ mais qui peuvent prendre n'importe quelle autre forme (e.g. quadratique, cubique, inverse, logarithmique, rectangulaire, sigmoïde, etc.). La plupart des études antérieures en hydrologie (e.g. Grayson

& Western, 1998; Tromp-Van Meerveld & McDonnell, 2006a ; James & Roulet, 2007) ont associé les comportements non linéaires à des fonctions de type « échelon » ou « de Heaviside » (voir schématisation à la Figure 6.1, autrement se reporter aux Figures 1.6 et 1.8). Ce type de fonction mathématique sert à représenter des processus qui n'ont que deux réalisations, soit « l'absence » en deçà d'un certain seuil et « la présence » au-dessus de ce même seuil. De fait, ces études considèrent la connectivité hydrologique comme une propriété dichotomique dont la présence dépend de l'atteinte et/ou du dépassement d'une condition critique. Certaines relations établies dans cette thèse semblent confirmer cette perception (voir Figures 5.10 et 5.18 G, H et I) ; d'autres plaident cependant en faveur d'un comportement non linéaire qui s'apparenterait à une fonction sigmoïde pour le bassin versant de l'Hermine (voir schématisation à la Figure 6.1 ; autrement se reporter à la Figure 5.15). Ce faisant, on n'adhère pas à l'idée d'une connectivité dichotomique mais plutôt à celle d'une propriété qui se conjuguerait selon plusieurs degrés croissants dans un bassin versant. Cela est accord avec la définition de la connectivité hydrologique proposée à la fin de la section 2.2 et qui fait référence à un continuum d'états hydrologiques associés à des réponses hydrologiques d'importance croissante.

La Figure 6.1 illustre les deux principaux types de comportements non linéaires mis en évidence dans cette thèse. Elle souligne aussi les dynamiques qui permettent le passage des situations de « faible connectivité » aux situations de « forte connectivité » dans le bassin versant de l'Hermine. Par exemple, l'approche de type « boite grise » a permis de conclure que la différence entre les scénarios hydrologiques « secs et déconnectés » et les scénarios hydrologiques « humides et connectés » était la contribution relative des sources de ruissellement de surface symbolisées par le pluviolessivat. Ce résultat laisse supposer que la variation d'intensité du lien hydraulique entre les sources et l'exutoire détermine l'augmentation du degré de connectivité du bassin versant. Par le biais de l'approche « boite blanche », la comparaison de nombreuses métriques spatiales a révélé une intensité de saturation critique pour l'Hermine puisque c'est l'arrangement spatial des zones dont l'humidité volumétrique dépasse 30 % qui est le plus fortement corrélé aux débits enregistrés à l'exutoire. L'analyse spatiale par vecteurs propres a d'ailleurs permis de statuer que les zones saturées devaient s'étendre sur une aire minimale de 0,85 ha de manière à ce que des réponses hydrologiques significatives soient mesurées. Quant à l'approche « boite noire », elle établit une distinction entre les types de réponses hydrologiques (e.g. faible ou forte magnitude, *timing* lent ou rapide) en se basant sur des volumes critiques de précipitations, et ce tant sur une base événementielle (variable TOTRAIN) que sur une base intra-saisonnière (variable AP10, voir section 3.2).

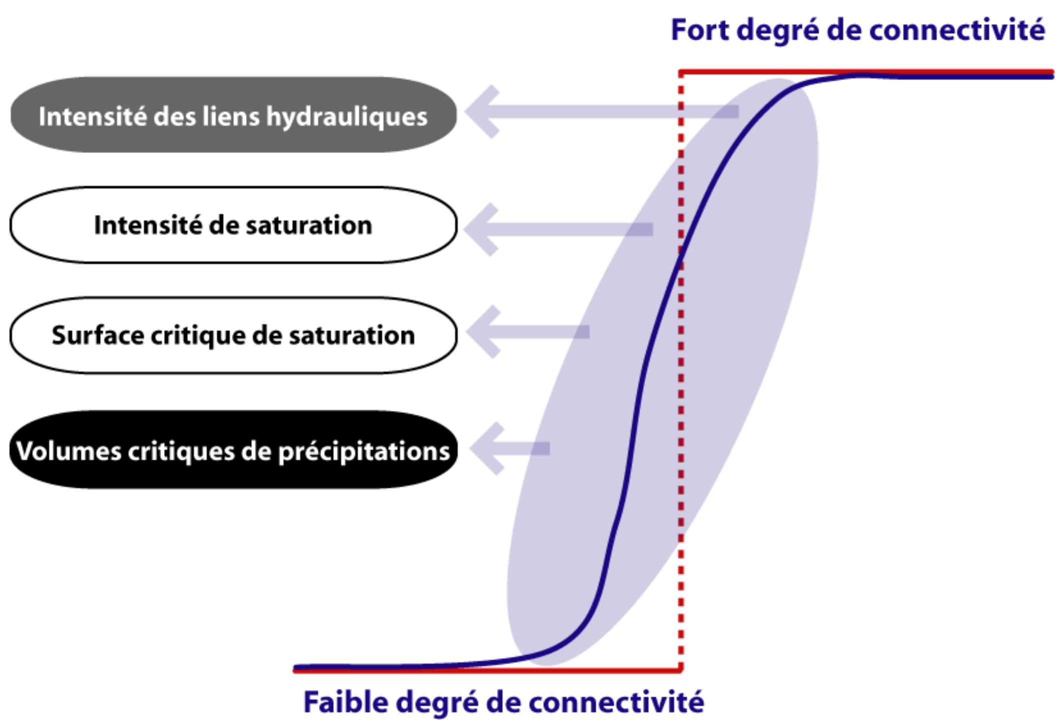

Figure 6.1 – Représentation schématique des types de comportements non linéaires observés dans le bassin versant de l'Hermine et des dynamiques sous-jacentes qui expliquent le passage de la situation de faible connectivité à la situation de forte connectivité. Les traits rouges illustrent la fonction « échelon » tandis que la courbe bleue illustre plutôt une fonction sigmoïde. Les bulles grise, blanches et noire font référence aux approches de type « boite grise », « boite blanche » et « boite noire » utilisées dans la thèse.

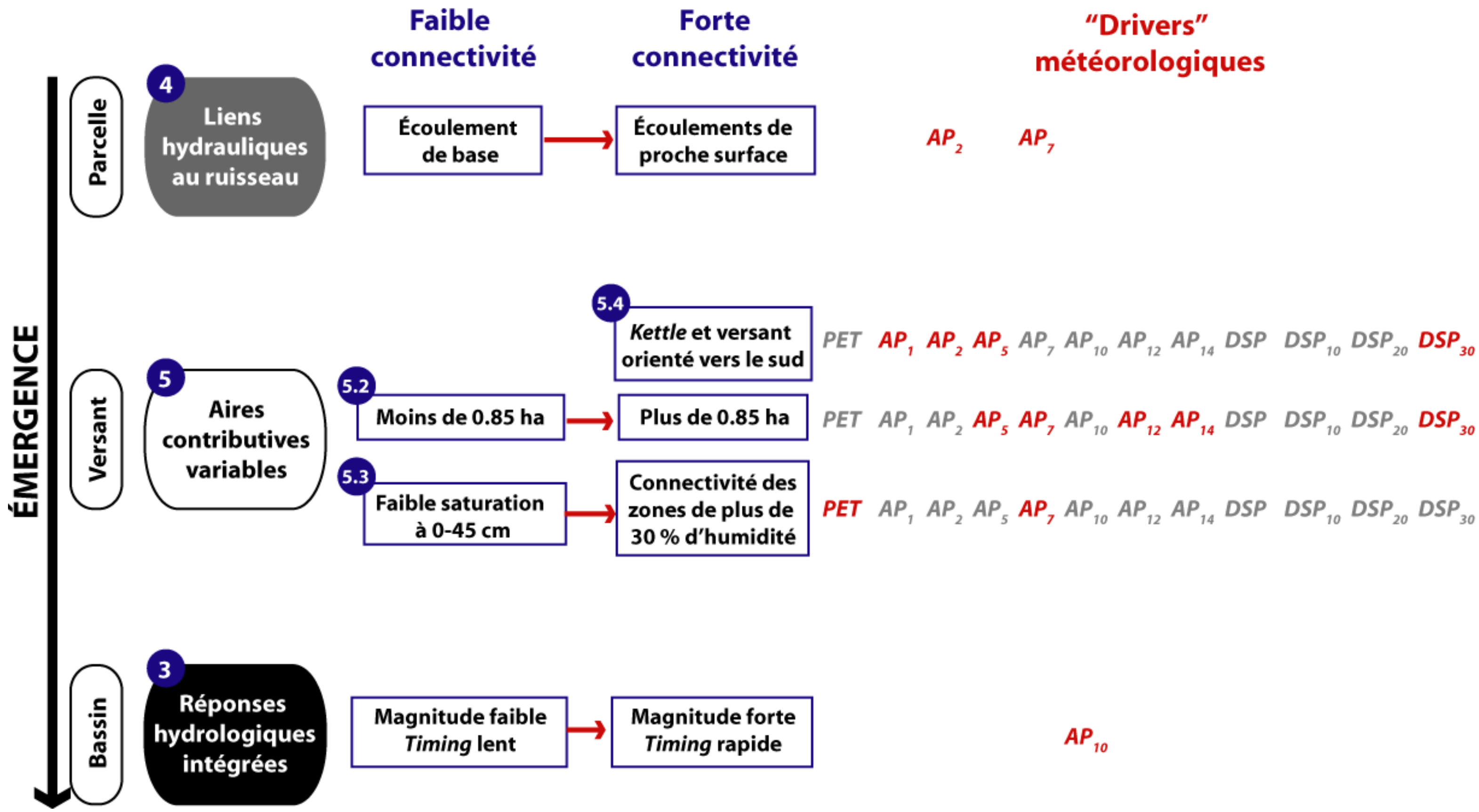

Figure 6.2 – Résumé des principaux résultats obtenus dans la thèse. Les dynamiques de faible et de forte connectivité sont illustrées. Les bulles grise, blanche et noire font référence aux approches de type « boite grise », « boite blanche » et « boite noire ». Les chiffres blancs dans les bulles bleues font référence à des chapitres ou des sections de la thèse. Les *drivers* (variables) météorologiques identifiés en gris ont été testés sans succès tandis que ceux surlignés en rouge sont ceux dont l'influence sur la dynamique associée a pu être démontrée.

Les principaux résultats obtenus dans cette thèse sont résumés à la Figure 6.2 afin de vérifier leur cohérence interne. Les approches de type « boite grise », « boite blanche » et « boite noire » intervenant à différents niveaux de discrétisation spatiale, la mise en commun des résultats obtenus permet donc d'évaluer tant les dynamiques localisées que les réponses hydrologiques émergentes du bassin versant de l'Hermine. Ainsi, dans les situations de faible connectivité, les hydrogrammes de crue se caractérisent par une faible magnitude et un *timing* lent, ce qui est en accord avec la prédominance de l'écoulement de base via la nappe phréatique profonde. On observe alors un faible degré de saturation dans le bassin versant. À l'inverse, des écoulements de proche surface sont présents en situation de forte connectivité, ce qui va de pair avec des hydrogrammes de crue de forte magnitude et dont le synchronisme (*timing*) est rapide. Par ailleurs, le *kettle* (zone humide à la naissance du ruisseau) ainsi que le versant orienté vers le sud sont identifiés comme les aires actives qui influencent le plus les débits mesurés à l'exutoire (voir section 5.4), d'où leur classification en tant qu'aires contributives. Les dynamiques identifiées par les approches « boite grise », « boite blanche » et « boite noire » pour chacun des états hydrologiques (faible versus forte connectivité) sont donc cohérentes entre elles. Cependant il n'en va pas de même pour l'identification des variables critiques qui permettent le passage d'un état à l'autre. La Figure 6.2 illustre un échantillon de la gamme de *drivers* météorologiques potentiels qui ont été testés dans le cadre de cette thèse. Chacune de ces variables était un moyen d'approximer les conditions d'humidité antécédentes à l'Hermine puisque selon la théorie hydrologique renouvelée, ce sont elles qui contrôlent le degré de connectivité hydrologique (e.g. Western & Grayson, 1998 ; James, 2005 ; Tromp-Van Meerveld & McDonnell, 2006a). L'exercice réalisé dans la section 5.4 a permis de conclure que toutes les zones du bassin versant étudié n'étaient pas « activées » par les mêmes *drivers* météorologiques. Il a notamment été montré que les patrons d'humidité du sol pouvaient être approximés en ayant recours à des mesures telles que le cumul de précipitations sur une période antécédente de cinq jours ou moins, ou le nombre de jours écoulés depuis l'avènement d'un épisode de pluie important (e.g. intensité supérieure à 30 mm/j). La meilleure performance des cumuls de précipitations enregistrés sur de courtes périodes, soit cinq jours ou moins, est probablement attribuable à la petite taille du bassin versant de l'Hermine et donc à l'échelle spatiale des processus hydrologiques actifs. L'exercice de la section 5.4 réalisé sur le seul bassin de l'Hermine ne permet cependant pas de vérifier cette hypothèse ; ce résultat confirme la présence de phénomènes hydro-météorologiques complexes dans l'espace et dans le temps et sans pour autant permettre de prédire la réponse hydrologique de l'Hermine pour une gamme complète de conditions. Dans le même ordre d'idées, il faut mentionner qu'à aucun moment il n'a été possible d'attribuer l'organisation spatiale de l'humidité du sol à un contrôle topographique local. L'analyse spatiale par vecteurs propres a démontré que des influences topographiques n'étaient perceptibles qu'à une échelle macro, soit en comparant des zones de 0,85 à 1,4 ha plutôt qu'en comparant des sites ponctuels d'échantillonnage entre eux. Cette conclusion a été confirmée par les résultats de la section 5.4 selon lesquels les régions échantillonnées situées à moins de 20 m au-dessus de l'exutoire se comporteraient différemment de celles situées au-delà de cette élévation. Cela rejoint donc l'idée que les fonds de vallée et les versants sont des unités morphologiques au comportement distinct (Flügel, 1995 ; Gallant & Dowling, 2003). On retrouve cependant un forte variabilité au sein même de chaque type d'unité topographique, qu'il s'agisse des zones planes proximales au cours d'eau, des pentes ou des sommets de versants. Les résultats de la section 5.4 sont également révélateurs en ce qui a trait au contrôle exercé par l'interface entre la matrice de sol et l'horizon peu perméable, et cela peut être mis en parallèle avec des travaux récents portant sur l'importance de la topographie de subsurface (Freer *et al.*, 1997 ; Van Meerveld & McDonnell, 2005 ; Tromp-Van Meerveld & McDonnell, 2006b). Ce contrôle topographique est cependant lui aussi localisé dans l'espace, ce qui rend difficile l'utilisation de la topographie à l'échelle du bassin versant tout entier pour estimer la localisation probable des aires contributives.

La question est maintenant de savoir dans quelle mesure le comportement d'un système aussi hétérogène que l'Hermine, tant dans le temps que dans l'espace, peut-il être simulé à l'aide d'un modèle hydrologique.

6.2 Pistes de solution pour la modélisation hydrologique de l'Hermine

Dans le premier chapitre de cette thèse, des indices de similarité topo-hydrologique ont été décrits comme des outils de choix pour tenir compte de la connectivité hydrologique lors de l'utilisation de modèles de simulation numérique du comportement des bassins versants (se référer à la section 1.3). Le choix de mettre de l'avant des modèles tels que *TOPMODEL* (*TOPography-based MODEL*) (Beven & Kirkby, 1979), *RHESSys* (*Regional Hydro-Ecologic Simulation System*) (Tague & Band, 2001) et *DHSVM* (*Distributed Hydrology Soil Vegetation model*) (Wigmosta *et al.*, 1994) venait du fait qu'ils sont fondés sur le calcul de tels indices et illustrent donc la dynamique des aires contributives variables à la base même du concept de connectivité hydrologique. Par ailleurs, ces trois modèles en particuliers sont reconnus pour leur considération explicite des écoulements latéraux entre les diverses unités du paysage (Tague & Band, 2004), et cela correspond tout à fait à l'une des définitions de la connectivité hydrologique proposée par Stieglitz *et al.* (2003). À première vue, le bassin versant de l'Hermine semblait satisfaire aux hypothèses d'application de ce genre de modèles hydrologiques (section 2.4.1). Les résultats expérimentaux décrits dans les chapitres 3, 4 et 5 laissent cependant entrevoir un comportement beaucoup plus complexe que celui originellement supposé et au sein duquel la topographie de surface n'exerce pas un rôle dominant.

La question de la variabilité temporelle du fonctionnement hydrologique du bassin versant de l'Hermine est particulièrement difficile à résoudre, notamment en ce qui a trait à la caractérisation i) des états préférentiels, et ii) des conditions d'humidité antécédentes. En effet, les différents degrés de connectivité hydrologique observables dans un système peuvent être considérés comme des états préférentiels. Or, si l'on se réfère à la littérature sur les indices de similarité topo-hydrologique, il a été démontré à de maintes reprises que ceux-ci permettaient généralement de bien simuler la distribution spatiale des contenus en eau des sols dans des conditions humides mais pas dans des conditions sèches (e.g. Grayson *et al.*, 1997 ; Piñol *et al.*, 1997 ; Shaman *et al.*, 2002 ; Stieglitz *et al.*, 2003). Pour tenter de remédier à cela, Grayson *et al.* (1997) ont proposé l'utilisation d'un indice topographique dont la formule de calcul diffèrerait dépendamment de la présence de conditions sèches ou humides. L'indice « sec » serait construit de manière à tenir compte de l'évapotranspiration qui provoque le drainage vertical de l'eau tandis que les formulations actuelles seraient conservées pour les conditions humides afin de représenter les flux latéraux d'eau dans le sol. Si cette solution est théoriquement valide et a le potentiel de donner de bons résultats pour certains sites d'étude, ce n'est cependant pas une panacée. Il est raisonnable de penser que dans un bassin versant qui serait soumis à un comportement non linéaire apparenté à une fonction « échelon » (voir exemple à la Figure 6.1), les chances de succès seraient bonnes étant donné que la transition entre l'état sec de faible connectivité et l'état humide de forte connectivité se fait rapidement (Grayson *et al.*, 1997). Dans une situation où le comportement non linéaire s'apparenterait plutôt à une fonction « sigmoïde » (voir exemple à la Figure 6.1), ce qui sous-entend une transition lente entre les états extrêmes et la présence de nombreux états intermédiaires, un échec est à anticiper. Dans un tel cas de figure, il n'y aurait probablement pas d'autres solutions que de réaliser une simulation continue basée sur des pas de temps courts de manière à mettre les variables d'état du système à jour de manière régulière.

Par ailleurs, la connaissance des conditions d'humidité antécédentes est cruciale pour prédire le comportement hydrologique variable des bassins versants, d'autant plus qu'elles servent à initialiser les modèles hydrologiques avant le début d'une simulation (Berthet *et al.*, 2009). Pour le bassin versant de l'Hermine, des travaux supplémentaires sont nécessaires en vue de trouver une mesure « universelle » des conditions d'humidité antécédentes qui soient adaptées non seulement à toutes les zones mais également à tous les processus actifs. L'article de la section 5.4 a permis d'aboutir à la conclusion que l'indice *AP5*, soit la somme cumulative des précipitations enregistrées 5 jours avant la mesure d'un patron spatial d'humidité du sol, était le meilleur indice afin d'estimer la localisation probable des aires actives et contributives. Ce même indice *AP5* n'était cependant d'aucune aide pour prédire le moment où la surface critique de saturation de 0,85 ha est atteinte ni le moment où les zones dont l'humidité volumétrique excède 30 % sont spatialement connectées. L'utilité de l'indice *AP5* pour la prédiction des changements d'intensité des liens hydrauliques (approche « boite grise ») et du dépassement des volumes critiques de précipitations (approche « boite noire ») n'a pas été évaluée dans cette thèse.

Il est important de souligner que cette incapacité à évaluer les conditions critiques permettant le passage d'un état préférentiel à un autre n'est pas exceptionnelle. Une longue série d'articles scientifiques publiés depuis le milieu des années 2000 (Zehe & Blöschl, 2004 ; Blöschl & Zehe, 2005 ; Zehe *et al.*, 2005 ; Zehe *et al.*, 2007) a démontré qu'il était d'autant plus difficile de prédire la réponse hydrologique d'un système lorsqu'on se situait très près d'un seuil de transition entre deux états préférentiels, et ce même si l'on a une connaissance parfaite des processus sous-jacents. Il est raisonnable de penser que plus la transition se fait sur une longue période (i.e. comportement non linéaire apparenté à une fonction sigmoïde), plus il y aura de l'incertitude associée à notre capacité de prédire les conditions critiques qui sous-tendent cette transition. À cet égard, Zehe & Blöschl (2004) ont affirmé qu'il était relativement aisé de caractériser les états préférentiels extrêmes à défaut de circonscrire les mécanismes transitoires, et c'est ce que l'on observe avec les résultats de cette thèse. Afin de minimiser ce problème lors de l'utilisation de modèles hydrologiques, l'une des solutions envisageables serait de réaliser des simulations en trois phases distinctes, soit i) une phase de *pre-forecasting*, ii) une phase de test, et iii) une phase de validation. La phase de *pre-forecasting* a notamment été proposée par Berthet *et al.* (2009) afin de forcer le modèle à reproduire les conditions observées sur une fenêtre temporelle antérieure à la période d'intérêt pour la simulation. Une fois que les paramètres du modèle seraient réglés pour simuler correctement les conditions d'humidité antécédentes, les phases de test et de validation seraient exécutées de manière traditionnelle comme c'est généralement le cas en modélisation.

La question de l'hétérogénéité spatiale du bassin versant de l'Hermine n'est pas moins épineuse à régler en vue du choix d'une structure de modélisation hydrologique. Les résultats de la section 5.4 laissent entendre qu'il y a peu de similarité topo-hydrologique entre les zones du bassin, ce qui suppose que des modèles tels que *TOPMODEL* ou *RHESSys* auraient des performances mitigées, voire carrément mauvaises si appliqués à l'Hermine. Étant donné l'apparente inadéquation de l'approche semi-distribuée dans cette situation, deux alternatives seraient envisageables : i) ignorer complètement la variabilité spatiale interne du bassin versant et opter pour un modèle hydrologique global, ou ii) migrer vers une structure de modélisation qui soit presque totalement distribuée spatialement. Les modèles hydrologiques globaux sont généralement mis de côté parce qu'ils simplifient à l'extrême les processus actifs dans un bassin versant. Toutefois, en travaillant sur le système de Panola (Géorgie, États-Unis), Clark *et al.* (2009) ont montré que les versants avaient un comportement hydrologique linéaire tandis que la réponse émergente du bassin versant était plutôt non linéaire. Cette différence de comportement en fonction de l'échelle spatiale considérée était attribuable au fait qu'au niveau de chaque versant, les mécanismes (linéaires) de dépassement de la capacité de stockage et de production d'écoulement de crue n'interviennent pas à la même vitesse, d'où la réponse globale non linéaire du bassin. Afin de représenter adéquatement cette dynamique, Clark *et al.* (2009) ont donc utilisé un modèle hydrologique non spatialement distribué mais considérant trois réservoirs linéaires aux caractéristiques différentes fonctionnant en parallèle. Le choix d'utiliser trois réservoirs parallèles plutôt que deux ou quatre, par exemple, était justifié par le fait que l'application de la méthode *EMMA* (*end-member mixing analysis)* avait révélé l'existence de trois principales sources de ruissellement à Panola. Il serait intéressant de déterminer dans quelle mesure une telle approche pourrait être appliquée au bassin versant de l'Hermine. Il serait particulièrement important d'évaluer les impacts de l'absence de prise en considération de la variabilité intra-versant, et donc intra-réservoir, sur la performance d'une telle approche de modélisation pour un bassin versant tel que l'Hermine.

Autrement, l'usage des modèles hydrologiques totalement distribués est, également, souvent déconseillé à cause des très longs temps de calcul auxquels ceux-ci sont associés. Pour un bassin versant comme l'Hermine, la solution pourrait donc être de dériver des indices de similarité topo-hydrologique plus « complets » que ceux qui existent à l'heure actuelle. En effet, la similarité topo-hydrologique est actuellement définie uniquement à partir de la topographie de surface, soit la pente locale du terrain en un point *i* et l'aire topographique de surface drainée en ce point *i* (Beven & Kirkby, 1979). Cela laisse entendre que les mécanismes de dépassement de la capacité de stockage et de production d'écoulement de crue interviennent à la même vitesse en tous points du bassin versant, ce qui est hautement improbable. Par exemple, Grayson *et al.* (1997) ont fait valoir que selon les zones du bassin versant de Tarrawarra (Australie) considérées, la mise en place d'un écoulement hypodermique latéral n'avait lieu que lorsque la saturation relative de la colonne de sol varie entre 60 et 80 %. Dans le même esprit, lors d'une étude menée dans le bassin expérimental de Panola (Géorgie, États-Unis), Freer *et al.* (2002) ont montré qu'au-dessus d'une certaine valeur seuil d'humidité, un écoulement préférentiel était créé à l'interface entre le sol et la roche-mère. En effet, les zones profondes du sol peuvent restreindre le degré d'inter-connectivité des zones d'un versant, à cause de l'existence de « poches » de sol sec. Cependant, lorsque ces poches deviennent suffisamment humides, l'écoulement latéral se fait vers le bas de la pente, de manière et assurer la connexion de la crête du versant et de la vallée (Stieglitz *et al.*, 2003). Les résultats du chapitre 5 de cette thèse démontrent bien que dans le cas de l'Hermine, les patrons d'humidité diffèrent en fonction de la profondeur de sol considérée. En particulier, les résultats de la section 5.4 permettent de décrire l'Hermine comme une mosaïque de points aux comportements linéaires et non linéaires vis-à-vis du débit, ce qui met bien en évidence la présence de processus différenciés dans l'espace. Bien que les résultats obtenus dans cette thèse ne soient pas formels à cet égard, le rôle de la topographie de subsurface mérite également d'être exploré pour le bassin de l'Hermine. Des travaux supplémentaires sont donc nécessaires afin d'évaluer la pertinence d'intégrer de tels éléments à une définition révisée de la similarité topo-hydrologique en vue de la modification des structures de modélisation.

6.3 Pour expliquer la complexité de l'Hermine : raisons contingentes ou mécanismes hydrologiques multiples ?

À l'issue de cette thèse, plusieurs zones d'ombre subsistent quant à la compréhension du fonctionnement hydrologique du bassin versant de l'Hermine. En effet, un comportement hydrologique simple avait été anticipé pour l'Hermine en raison de la présence d'unités topographiques bien définies. Il est aujourd'hui difficile de comprendre et d'expliquer pourquoi les versants nord et sud, en apparence similaires, offrent des patrons spatiaux d'humidité du sol contrastés. L'impossibilité d'identifier la topographie de surface ou celle de subsurface comme facteur de contrôle dominant sur les processus actifs à l'Hermine laisse présager la présence de facteurs de contrôle multiples dont l'interaction détermine la réponse hydrologique du bassin versant. Des études supplémentaires, préférablement axées sur l'analyse concurrente de variables multiples, sont donc nécessaires afin de tenter de mieux circonscrire ces facteurs de contrôle.

L'Hermine est un bassin versant idéal pour tester des hypothèses en raison de sa faible superficie, de sa topographie contrastée et des différences entre les versants en ce qui a trait à l'exposition. Le choix d'un bassin forestier comme site d'étude pour cette thèse n'était pas anodin car jusqu'à présent, l'hypothèse des états préférentiels et de la connectivité hydrologique n'avait été prouvée avec grand succès que dans les régions tempérées sèches de prairies où la variabilité spatio-temporelle des processus et les effets de saisonnalité sont moindres. La présence d'un bon corpus de données historiques de débit et de composition chimique des eaux de ruissellement a également plaidé en faveur de l'Hermine. Il est cependant naturel de se demander si la complexité des résultats obtenus est spécifique au site étudié, ce qui limiterait leur potentiel de généralisation.

Dans le but de trancher sur la spécificité de l'Hermine, le Tableau 6.1 offre une comparaison intéressante avec quelques bassins versants expérimentaux de différentes tailles, localisés dans des milieux différents et dont le comportement hydrologique fait l'objet de nombreuses publications scientifiques. L'Hermine se compare bien au système Westcreek du Mont-St-Hilaire en ce qui a trait au régime climatique, à la couverture du sol (forêt) et à la présence d'un horizon de sol peu profond et de faible perméabilité (fragipan). Le système Westcreek est cependant drainé par un cours d'eau pérenne plutôt qu'éphémère, et il ne se caractérise pas non plus par la présence de nombreux blocs rocheux qui affecteraient tant la topographie de surface que de subsurface. Cependant s'il est vrai que l'Hermine possède une combinaison particulière de propriétés qui font son unicité, on pourrait en dire autant de la plupart des bassins versants expérimentaux en milieu tempéré.

Tableau 6.1 – Caractéristiques des principaux bassins versants expérimentaux en milieu tempéré utilisés à titre de « modèles » en hydrologie

	MAIMAI M8 New Zealand	**TARRAWARRA Australia**	**HERMINE Quebec, Canada**	**ST-HILAIRE (WESTCREEK) Quebec, Canada**	**WESTERN UPPER PANOLA Georgia, USA**	**HAUTE-MENTUE Switzerland**
Drainage Area	3.8 ha	10.5 ha	5.1 ha	147 ha	10 ha	1250 ha
Landscaping	Steep terrain, highly dissected	Undulating local terrain Hillslopes vary from strongly convergent to divergent	Open-book shaped catchment	Hilly terrain	Surface topography relatively planar Bedrock topography highly irregular, with a dendritic shaped hollow	Gentle morphology
Mean elevation A.S.L.	100 – 150 m	100 m	400 m	296 m	250 m	850 m
Slopes	34°	11 – 14 %	12.9°	15.9 %	13°	From 0 to 30 %
Aspect	1 North-facing and 1 South-facing slope	From East through South to North-West	1 North-facing and 1 South-facing slope	n/a	Southeast facing (instrumented hillslope)	n/a
Streams	Perennial (?)	No channels	Ephemeral	Perennial	Ephemeral	Perennial

	MAIMAI M8 New Zealand	TARRAWARRA Australia	HERMINE Quebec, Canada	ST-HILAIRE (WESTCREEK) Quebec, Canada	WESTERN UPPER PANOLA Georgia, USA	HAUTE- MENTUE Switzerland
Soils	Silt-loamy, stony Podzolized, yellow-brown earths of the Blackball Hill soils Extensive macropore and preferential flow pathways Typical depth of 1 m	Upper slopes: Duplex soils Lower slopes : Gradational grey massive earth Typical depth of 40 cm to 2 m Perched water tables during the wetter months Presence of an impeding layer	Orthic or gleyed humo-ferric and ferro-humic podzols Compacted/hardened BC horizon at 75 cm depth	Brunisols, Gleysols, Podzols Typical depth of 0 to 1.5 m In valley bottoms, possibility of perched water tables due to the presence of a low-permeability layer or fragipan within 30-50 cm of the surface	Light colored sandy loam No clear layering, except for a 0.15 m deep organic soil horizon Typical depth of 0 to 1.86 m	Cambisoils Organic hydromorphic (pseudogley) soils Typical depth of 30 to 2 m
Bedrock	Early Pleistocene conglomerate (clasts of sandstone, granite, and schist in a clay-sand matrix) Nearly impermeable	Siltstone, sandstone and limestone Depth of 0.5 – 1.5m of hillslopes, deeper in drainage lines	Precambrian anorthosite covered by till (1±2 m), except on bare outcrops in the downstream area and on some of the catchment divides	Essexite, predominantly gabbros	Granite Presence of bedrock outcrops	Sandstone
Land Cover	Forest	Pastures	100 % forested	100 % forested	93 % forested	55 % forests, 43 % pastures
Climate	Humid	Temperate	Temperate, humid	Humid, continental	Humid, subtropical	Temperate, humid
Mean Annual Temperature	n/a	8.3^{o}	3.98^{o}	5.25^{o}	16.3 ^{o}	7^{o}

	MAIMAI M8 New Zealand	TARRAWARRA Australia	HERMINE Quebec, Canada	ST-HILAIRE (WESTCREEK) Quebec, Canada	WESTERN UPPER PANOLA Georgia, USA	HAUTE-MENTUE Switzerland
Past and present instrumentation / data	Instrumentation covering the whole catchment Pits Suction lysimeters Maximum rise piezometers Weir Tensiometer networks Wells Dye tracing (streamflow and subsurface flow source and mean velocity) Isotope tracing Trenched hillslope	Instrumentation covering the whole catchment Rain gauges Weather station Neutron access tubes (soil moisture patterns / profiles – High resolution) Piezometers (Shallow water table) Flume (surface runoff) Saturated hydraulic conductivity Particle size distribution Horizon depths and textures Surface micro-topography	Instrumentation covering the whole catchment Weir ISCO stream water sampler Weather station Suction lysimeters Wells TDT probes for soil moisture continuous monitoring (only on a north-south transect crossing the stream)	Instrumentation covering the whole catchment Groundwater wells Piezometers Suction lysimeters Weirs Throughfall tipping-bucket gauges Extensive spatial surveys of shallow soil moisture (TDR) Isotopic and biogeochemical tracing	Instrumented hillslope only Air temperature, relative humidity, precipitation Access tubes (soil moisture patterns / profiles – High resolution) TDR push-in probes Crest stage gauges Wells Piezometers Heat sapflow measurements (transpiration) 20-m long trench excavated down to bedrock and equipped with tipping bucket gages (subsurface flow measurements) Depth to bedrock	Instrumentation covering multiple sub-catchments Weather station Rainfall simulator Flumes Hydrometric stations TDR Environmental tracing Dye tracing Piezometers
References	McGlynn *et al.*, 2002	Western & Grayson, 1998	Biron *et al.*, 1998 Turgeon, 2004	James, 2005	Tromp-Van Meerveld & McDonnell, 2006a, b, c	Joerin, 2000 Balin, 2004

Par exemple, le bassin versant de Maimai est souvent cité pour illustrer les processus d'écoulement très rapides. Dans le contexte particulier de Maimai, toutefois, ces processus très rapides sont attribuables à un réseau dense de macropores et de chemins d'écoulement préférentiel hypodermique, une condition qui n'est pas rencontrée dans tous les bassins versants où le délai entre les précipitations et les débits de pointe enregistrés à l'exutoire sont courts. Un autre bassin versant très connu, soit celui de Tarrawarra, en Australie, se caractérise par l'absence de cours d'eau, ce qui est problématique étant donné que la réponse hydrologique globale est souvent évaluée à l'aide des débits mesurés à l'exutoire. Par ailleurs, le groupe de Melbourne (Andrew Western, Andrew Chiew, Günter Blöschl) ayant travaillé sur le bassin de Tarrawarra ont toujours utilisé, sans justification aucune, une profondeur de 30 cm pour mesurer l'humidité du sol, et ce sans qu'il soit effectivement démontré que cette profondeur de sol soit représentative de la dynamique hydrologique du bassin versant. Autrement, la plupart des résultats de recherche publiés sur le bassin de Panola sont issus d'une série d'expériences réalisées sur une parcelle unique de versant, caractérisée par une topographie de surface plane et une topographie de subsurface (interface entre le sol et la roche mère) accidentée qui contrôle l'écoulement hypodermique. Toutes ces contingences font en sorte que la généralisation des résultats de recherche en hydrologie est difficile, non seulement dans le cas de l'Hermine mais aussi dans le cas des autres bassins versants expérimentaux étudiés de par le monde. C'est la raison pour laquelle cette thèse se veut principalement une forte contribution méthodologique. En effet, s'il n'est pas possible d'affirmer que les hypothèses de mécanismes hydrologiques proposées dans ce travail de recherche sont généralisables, les outils analytiques et approches méthodologiques décrites sont néanmoins transférables à d'autres contextes spatiaux ou temporels.

Certains aspects techniques pourraient, néanmoins, limiter l'opérationnalisation ou la portée de cette thèse de doctorat. Par exemple, les travaux de terrain nécessaires à la réalisation de la thèse sont fortement tributaires de la fiabilité et de la robustesse des instruments de mesure, notamment ceux qui permettent la collecte des données d'humidité du sol. Étant donné le grand déploiement spatial requis, tant sur le plan latéral que d'un point de vue vertical avec les quatre profondeurs de mesure, l'utilisation de sondes installées en permanence dans le sol et reliées à des *dataloggers* n'était pas possible. Plusieurs instruments portatifs ne peuvent pas être utilisés dans le bassin versant de l'Hermine, par exemple, parce qu'ils ne permettent la mesure de l'humidité qu'à une seule profondeur fixe. D'autres, très performants et fiables du point de vue de la réplicabilité des mesures, n'ont pas non plus été choisis parce que leur installation permanente dans le bassin aurait considérablement perturbé la structure du sol. L'instrument qui a finalement été retenu, soit *AQUATERR*, fournit des résultats satisfaisants mais nécessite, de la part de l'utilisateur, une recalibration fréquente et un report manuel des valeurs mesurées, ce qui rallonge considérablement les journées d'échantillonnage. Cela a donc eu pour effet de limiter le nombre de campagnes de mesure effectuées. Un échantillonnage événementiel de très haute fréquence (toutes les six heures ou moins) était impossible ou aurait nécessité la suppression d'une partie des sites de mesure. Il a néanmoins été possible de capter une bonne partie de la variabilité des phénomènes observés à l'Hermine en ce qui a trait aux patrons spatiaux d'humidité du sol. Pour les données géochimiques, le recours à dix ans de données historiques a été préconisé plutôt que de recueillir de nouvelles données pendant la courte période (cinq ans) du doctorat. Les données de terrain dont il a été question n'ont pas toutes été recueillies de manière simultanée, et cela s'explique essentiellement par le fait que l'on voulait profiter de l'existence de données historiques pour compléter les données nouvellement échantillonnées. Cet asynchronisme ne pose cependant pas problème pour l'analyse de données, et ce pour deux raisons. D'une part, les données de natures différentes sont utilisées pour répondre à des sous-objectifs spécifiques différents. D'autre part, l'objectif de la thèse n'était pas d'étudier la séquence temporelle des événements hydrologiques, comme c'est généralement le cas dans les études de ce genre, mais plutôt de sélectionner de courts épisodes jugés significatifs puis de les examiner individuellement du point de vue de la connectivité. L'utilisation d'un tel volume de données n'était donc pas problématique, en autant qu'il était possible de sélectionner plusieurs épisodes d'intérêt et aux conditions variées pour étudier l'établissement de la connectivité hydrologique.

CONCLUSION GÉNÉRALE

La connectivité hydrologique est un concept qui a d'abord été exploité par les écologistes (e.g. Pringle, 2001 ; Amoros & Bornette, 2002 ; Calabrese & Fagan, 2004). Si les hydrologues essaient depuis peu de se l'approprier non seulement à des fins de compréhension des processus de genèse de l'écoulement (e.g. Bracken & Croke, 2007) mais aussi à des fins de gestion des bassins versants (e.g. Lexartza-Artza & Wainwright, 2009), cela ne se fait pas sans heurts en raison des connaissances hétéroclites sur le phénomène. Le but de ce travail doctoral était donc d'alimenter la réflexion de la communauté des hydrologues en précisant la définition, la mesure, l'agrégation spatiale et la prédiction des processus liés à la connectivité hydrologique. Après une revue de la littérature pertinente présentée au Chapitre 1, un cadre méthodologique pour l'étude de la connectivité a été proposé au Chapitre 2. Trois approches d'évaluation de cette connectivité dites de type « boite noire », « boite grise » et « boite blanche » ont ensuite fait l'objet des chapitres 3, 4 et 5. La question de la prédiction de la connectivité a, quant à elle, été abordée via un court essai au Chapitre 6.

D'entrée de jeu lors de la proposition du cadre méthodologique, il a été argumenté que la connectivité hydrologique ne devait pas être perçue comme une propriété dichotomique mais plutôt comme un continuum d'états préférentiels d'un bassin versant. Par la suite, il a été montré que les résultats issus des trois approches convergeaient en ce qui a trait à la caractérisation des états préférentiels extrêmes dans le bassin versant de l'Hermine, et ce même s'il s'est avéré difficile de circonscrire les conditions critiques qui permettent le passage d'un état de connectivité à un autre. Ainsi, il a été possible de clarifier les définitions et les utilités qui sont prêtées au concept de connectivité hydrologique.

Plusieurs points méritent d'être soulignés concernant le caractère novateur de la présente recherche. En effet, cette thèse s'articule autour d'un seul et même concept : la connectivité hydrologique. Cet aspect conceptuel est, en soi, original car en hydrologie des bassins versants, les recherches portent généralement sur des quantités ou mécanismes préalablement définis et physiquement mesurables plutôt que sur des notions abstraites. En conséquence, les objectifs poursuivis tout au long de la thèse sont conformes à la nouvelle perspective qu'adopteront les hydrologues d'ici les prochaines années, c'est-à-dire que l'étude des particularismes de petite échelle sera peu à peu abandonnée au profit de l'examen des propriétés émergentes des bassins versants. La thèse présente donc de nombreux attraits en proposant à la communauté des hydrologues une définition unifiée de la connectivité, un cadre méthodologique, des approches de mesure sur le terrain, des outils techniques permettant de tirer un maximum d'informations des données recueillies et des pistes de solution en ce qui a trait à la modélisation des systèmes hydrologiques complexes.

Bien que l'une des contributions majeures de cette recherche à la théorie hydrologique renouvelée soit la proposition d'une définition unifiée de la connectivité, cette thèse n'avait pas la prétention de déterminer laquelle des approches de type « boite noire », « boite grise » ou « boite blanche » était la plus appropriée afin de mesurer cette propriété des bassins versants. À cet égard, Michaelides & Chappell (2009) ont préconisé la seule utilisation des méthodes géostatistiques afin de caractériser la connectivité hydrologique. Dans le même esprit, Lexartza-Artza & Wainwright (2009) ont élaboré une liste de directives qui font clairement référence à une approche de type « boite blanche ». Au vu des résultats obtenus dans cette thèse, on peut plutôt argumenter que puisque les trois approches conduisent à des conclusions équivalentes pour ce qui est de la caractérisation des états extrêmes de connectivité, le recours à l'une ou l'autre devrait dépendre des ressources disponibles, non seulement en termes de données et de discrétisation spatiale mais aussi en termes de capacité à utiliser divers outils techniques d'analyse de ces données.

Des travaux supplémentaires sont cependant nécessaires afin de combler plusieurs lacunes de compréhension qui persistent malgré les analyses effectuées. Par exemple, les mécanismes de transition et les effets de seuil qui sous-tendent les comportements non linéaires doivent être circonscrits de manière plus précise tout en vérifiant la convergence des résultats entre les approches de type « boite noire », « boite grise » ou « boite blanche ». Il s'agit là d'un élément essentiel à la prédiction empirique et numérique de la réponse hydrologique des bassins versants. Aussi, puisque les modèles hydrologiques doivent être considérés comme des hypothèses à vérifier, de nombreuses structures de modélisation gagneraient à être développées et testées sur le bassin versant de l'Hermine afin d'identifier les processus d'écoulement dominants et leur variabilité spatio-temporelle. Enfin, l'application des trois approches décrites dans cette thèse devrait être répétée sur plusieurs bassins versants de divers milieux et de diverses tailles, sur plusieurs périodes, afin d'évaluer le potentiel de la connectivité hydrologique de servir d'outil pour effectuer des transferts d'échelles. Les conclusions spécifiques au fonctionnement hydrologique de l'Hermine sont très peu probablement généralisables, cependant les outils analytiques et les approches méthodologiques décrites sont néanmoins transférables à d'autres contextes spatiaux ou temporels. Cette nécessité de s'aligner sur des outils analytiques performants et comparables est, par ailleurs, nécessaire afin de comparer les résultats issus de différents bassins versants expérimentaux. La multiplication d'études similaires à celles conduites dans cette thèse devrait, donc, permettre d'enrichir nos connaissances sur la mesure, la modélisation et l'agrégation des dynamiques hydrologiques linéaires et non linéaires.

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