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EFFECTS OF FOREST MANAGEMENT ON WATER RESOURCES IN CANADA: A RESEARCH REVIEW

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by

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PRESIDENT'S NOTE

Forest watershed management has been an important topic in NCASI's technical program since the 1970s. Research by NCASI and others has established a sound scientific basis for measuring and controlling impacts on water resources associated with timber harvesting, road construction and other practices.

This report is a review of scientific literature on effects of forestry practices on water resources with emphasis on research conducted in Canada. The report covers watershed studies, stand-level research, and simulation models. The authors address effects of harvesting and other forestry practices on metrics of water quantity (e.g., peak flow, annual flow) and water quality (e.g., stream temperature, nutrient concentrations).

The review summarizes studies conducted at more than 25 research watersheds distributed across Canada. Results of these studies demonstrate that impacts of forest management on water resources are highly variable and depend on topography, subsurface geology, climate, forest type, and other factors. Conservation measures such as riparian buffers are generally effective in mitigating effects of forestry practices, but need to be tailored to local conditions.

Future research should focus on defining critical processes that mediate effects of forestry practices on water resources. These processes are known to vary substantially within and among regions. Reliable methods for identifying critical processes in forest watersheds would enable more effective application of conservation principles in sustainable forestry systems.

Ronald A. Yeske

December 2009

MOT DU PRÉSIDENT

L'aménagement des bassins versants des forêts a toujours été un sujet d'étude important dans le programme technique de NCASI, et ce, depuis les années 70. Les travaux de recherche de NCASI et d'autres organisations ont permis d'établir un fondement scientifique solide pour mesurer et limiter l'impact de la récolte du bois, de la construction des chemins forestiers et d'autres pratiques sur les ressources en eau.

Le présent rapport est une revue de la littérature scientifique sur les effets qu'ont les pratiques forestières sur les ressources en eau, et plus particulièrement une revue des travaux de recherche réalisés au Canada. Au cours de cette revue, les auteurs se sont intéressés aux études sur les bassins versants, aux travaux de recherche à l'échelle des peuplements et aux modèles de simulation. Dans le présent rapport, ils abordent les effets qu'ont la récolte et les autres pratiques forestières sur des paramètres reliés à l'eau en termes de quantité (par ex. débit de pointe, débit annuel) et de qualité (par ex. température du cours d'eau, concentration des nutriments).

Cette revue est un résumé des études réalisées sur plus de 25 bassins versants répartis sur l'ensemble du territoire canadien. Les résultats obtenus dans ces études démontrent que l'impact de l'aménagement des forêts sur les ressources en eau est extrêmement variable et est déterminé par la topographie, la géologie de sous-surface, le climat, le type de forêt et d'autres facteurs. Les mesures de conservation telles que les bandes de protection riveraines sont généralement efficaces pour atténuer les effets des pratiques forestières, mais il faut les adapter aux conditions locales.

Les futurs travaux de recherche devraient mettre l'accent sur la détermination des processus critiques qui ont une influence sur les effets causés par les pratiques forestières sur les ressources en eau. Les chercheurs savent que ces processus varient beaucoup à l'intérieur d'une région et d'une région à l'autre. En développant des méthodes fiables pour déterminer les processus critiques dans les bassins versants, il serait alors possible d'appliquer plus efficacement les principes de conservation pour aménager les forêts de façon durable.

Ronald A. Yeske

Décembre 2009

EFFECTS OF FOREST MANAGEMENT ON WATER RESOURCES IN CANADA: A RESEARCH REVIEW

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ABSTRACT

Although forestry practices commonly occur at the stand level, watersheds are used as the study unit for hydrological and water quality issues. Watersheds are natural or artificial drainages on which all precipitation and emanating spring discharges collect and flow to a common outlet. To establish a cause-and-effect relationship of ecosystem response to disturbance, it is essential to determine watershed level impact by removing biases that could occur at smaller scales. However, since the hydrologic cycle is driven by numerous processes that occur at smaller scales (e.g., evapotranspiration and snow melt), stand-level research is also vital in understanding responses at the watershed scale.

More than 25 research watersheds in Canada have been used to examine the hydrologic and water quality impacts of forestry practices. Research has shown that effects of forest management on hydrology and water quality are highly variable in both magnitude and duration. Factors such as topography, sub-surface geology, forest type, watershed composition and extent of harvest all play a part, and are difficult to separate.

Although a common goal in hydrological research is to transfer information gained at one scale of study to larger or smaller scales, or to transfer knowledge from one region to another, the field of forest watershed research is rife with scaling issues and uncertainty in transferability. The watershed research community is moving toward embracing these challenges. For example, several watershed research projects in Canada are incorporating information about stand-level processes in simulation models.

Watershed studies should be conducted in the ecozones in which the results will be applied for forest management. There is a need for continued and increased collection of field data at established research watersheds and at new research sites. When evaluating priorities for new research watersheds, explicit consideration should be given to processes of regional significance, e.g., fog drip in the Maritimes; permafrost in the Boreal Cordillera; and large-scale harvesting and fire disturbance occurring in the Boreal Shield and Boreal Plains.

KEYWORDS

disturbance, ecosystem, ecozones, forest, forestry practices, hydrology, precipitation, quality, quantity, road-building, scale, silviculture, simulation models, stand, topography, transferability, watershed

RELATED NCASI PUBLICATIONS

Canadian watershed handbook of control and mitigation measures for silvicultural operations. (April 2009).

Technical Bulletin No. 938 (August 2007). *Synthesis of technical information on forest wetlands in Canada*.

Technical Bulletin No. 908 (September 2005). *Riparian forest management and the protection of biodiversity: A problem analysis*.

Technical Bulletin No. 922 (August 2006). *Structural and functional roles of riparian management areas in maintaining stream values in the Acadian Forest*.

Technical Bulletin No. 799 (February 2000). *Riparian vegetative effectiveness*.

Technical Bulletin No. 775 (January 1999). *Assessing effects of timber harvest on riparian zone features and functions for aquatic and wildlife habitat*.

Technical Bulletin No. 631 (June 1992). *The effectiveness of buffer strips for ameliorating offsite transport of sediment, nutrients, and pesticides from silvicultural operations*.

Technical Bulletin No. 602 (February 1991). *The new Alsea watershed study*.

Technical Bulletin No. 514 (February 1987). *Oregon's riparian zone for timber, fish, and wildlife*.

L'IMPACT DE L'AMÉNAGEMENT DES FORÊTS AU CANADA SUR LES RESSOURCES EN EAU: REVUE DES TRAVAUX DE RECHERCHE

BULLETIN TECHNIQUE N^{O} 969
DÉCEMBRE 2009

RÉSUMÉ

Bien que les pratiques forestières ont généralement cours au niveau du peuplement, on se sert des bassins versants comme champ d'études pour en apprendre davantage sur les questions d'hydrologie et de qualité de l'eau. Les bassins versants sont des systèmes de drainage naturels ou artificiels sur lesquels l'eau provenant des précipitations et des débits de pointe printaniers s'accumule et s'écoule vers un point de déversement commun. Pour être en mesure d'établir une relation de cause à effet entre la réponse d'un écosystème et une perturbation, il est essentiel de déterminer l'impact de cette perturbation à l'échelle du bassin versant en éliminant les biais susceptibles d'être induits à des échelles plus petites. Cependant, les travaux de recherche réalisés à l'échelle des peuplements sont aussi essentiels pour mieux comprendre les réponses à l'échelle du bassin versant, car le cycle hydrologique est régi par de nombreux processus qui surviennent à des échelles plus petites (par. ex, l'évapotranspiration et la fonte des neiges).

Au Canada, on a étudié plus de 25 bassins versants où l'on a examiné l'impact des pratiques forestières sur le cycle hydrologique et la qualité de l'eau. Les travaux de recherche ont montré que les effets de l'aménagement forestier sur l'hydrologie et la qualité de l'eau sont extrêmement variables en termes d'étendue et de durée. La topographie, la géologie de sous-surface, le type de forêt, la composition du bassin versant et l'étendue de la récolte jouent tous un rôle et sont difficiles à dissocier les uns des autres.

Bien que les études hydrologiques ont pour objectif commun le transfert des connaissances acquises à une certaine échelle pour les appliquer à une échelle plus petite ou plus grande, ou le transfert des connaissances acquises sur une région pour les appliquer à une autre région, les problèmes d'échelle sont monnaie courante dans le domaine de la recherche sur les bassins versants des forêts, ce qui rend incertaine la transférabilité des connaissances. Le milieu de la recherche sur les bassins versants fait des progrès dans la résolution de ces problèmes. Par exemple, plusieurs projets de recherche sur les bassins versants au Canada intègrent maintenant des renseignements sur les processus à l'échelle des peuplements dans les modèles de simulation.

Il serait souhaitable de réaliser les études sur les bassins versants dans les écozones où l'on appliquera les résultats pour aménager les forêts. Il existe un besoin de poursuivre et d'accroître la cueillette de données de terrain dans les bassins versants présentement à l'étude et dans de nouveaux sites de recherche. Au moment d'évaluer les priorités dans l'étude de nouveaux bassins versants, il faudrait clairement prendre en compte les processus importants à l'échelle régionale (par ex. le ruissellement du brouillard dans les Maritimes, le pergélisol dans la cordillère boréale ainsi que la récolte à grande échelle et les gigantesques feux de forêts dans le bouclier canadien et les plaines boréales).

MOTS CLÉS

bassin versant, construction de chemins, échelle, écosystème, écozones, forêt, hydrologie, modèles de simulation, perturbation, peuplement, pratiques forestières, précipitation, qualité, quantité, sylviculture, topographie, transférabilité

AUTRES PUBLICATIONS DE NCASI DANS CE DOMAINE

Canadian watershed handbook of control and mitigation measures for silvicultural operations. (avril 2009).

Bulletin technique n^o 938 (août 2007). *Synthèse de l'information technique sur les milieux humides forestiers du Canada*.

Bulletin technique n^o 908 (septembre 2005). *Aménagement forestier des bandes riveraines et protection de la biodiversité: Analyse de la problématique*.

Bulletin technique n^o 922 (août 2006). *Rôles structurel et fonctionnel des zones d'aménagement des rives dans le maintien des caractéristiques naturelles des cours d'eau de la forêt acadienne*.

Bulletin technique n^o 799 (février 2000). *Riparian vegetative effectiveness*.

Bulletin technique n^o 775 (janvier 1999). *Assessing effects of timber harvest on riparian zone features and functions for aquatic and wildlife habitat*.

Bulletin technique n^o 631 (juin 1992). *The effectiveness of buffer strips for ameliorating offsite transport of sediment, nutrients, and pesticides from silvicultural operations*.

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EFFECTS OF FOREST MANAGEMENT ON WATER RESOURCES IN CANADA: A RESEARCH REVIEW

1.0 INTRODUCTION

Relationships between forests and water resources have long been subjects of speculation, controversy, and scientific inquiry (West 1990; Ice and Stednick 2004). For example, perceptions that forests have important roles in water resource conservation were important factors leading to the creation of forest reserves more than a century ago in the United States. Since then, hundreds of field studies have been conducted on various aspects of forest watersheds and their management (Ice and Stednick 2004).

The purpose of this report is to review scientific literature on effects of forest management on water resources with emphasis on research conducted in Canada. The specific objectives are to a) assess the effects of various forestry practices on water quantity and quality, b) evaluate the reliability of watershed-level studies and their transferability across Canada, c) identify where mechanistic effects are significant, and d) determine information gaps and opportunities for further research aiming to sustain forest productivity as well as protect stream water quality.

2.0 METHODS FOR MEASURING EFFECTS OF FOREST MANAGEMENT PRACTICES ON WATER RESOURCES

Watersheds are natural or artificial drainages in which all precipitation and emanating spring discharges collect and flow to a common outlet (Black 2004). The term watershed is synonymous with drainage basin or catchment.

Hornbeck and Swank (1992) defined watershed as a land area through which precipitation is distributed into components of the hydrological cycle. These authors refer to watershed-level studies as watershed ecosystem analyses, since the basic premise is that chemical, physical and biological processes occurring within an ecosystem are interrelated.

Watershed is the spatial scale at which aquatic impacts are driven by altered hydrologic cycles (Carignan and Steedman 2000). The earliest watershed-level study, conducted in 1902 in the Emmental region of Switzerland (Whitehead and Robinson 1993), compared water yield and erosion in a fully forested catchment with one consisting of 69% pasture and 31% forest. In recent decades, watershed-level studies have been used to determine effects on forest hydrology of the size, shape, topography, and position of timber harvest units (Stanley and Arp 2002).

Although many insights have been gained from watershed studies, research at smaller spatial scales is essential to understanding the processes that regulate watershed responses to forest management, natural disturbance, and climate variability (Whitehead and Robinson 1993). For example, stand-level studies have been useful in defining the effects of management practices on evapotranspiration, precipitation interception, and biogeochemical processes. One of the earliest physical process studies was conducted by Horton (1919), who examined the interception of rainfall by a tree canopy (McCulloch and Robinson 1993).

More recently, watershed and stand-level studies have examined the effects of forestry practices on water quality parameters. Interest in water quality is driven in part by the fact that streams and wetlands located downstream of forested watersheds are used for a variety of purposes including municipal and agricultural water supplies and recreation (Putz et al. 2003). Parameters of concern include temperature and concentrations of suspended sediments, major ions, nutrients such as nitrogen and phosphorus, cyanobacterial toxins, dissolved organic carbon, and dissolved oxygen.

Watershed-level studies have been criticized for their expense, non-representativeness, requirement for long calibration periods, difficulty in interpreting results, and lack of transferability of results (Whitehead and Robinson 1993; Buttle, Creed, and Moore 2005). However, Alila and Beckers (2001) point out that stand-level field experiments have their own limitations (e.g., cost, duration, transferability of findings), and the fact that sparse monitoring programs in a few areas have a high probability of missing critical events such as large floods, landslides and debris flows.

Table 2.1 compares the general attributes and potential benefits of forest hydrology studies conducted at the watershed and stand levels. In summary: watershed studies integrate and measure effects at broad scales with the expectation of reducing bias that could occur on smaller areas, whereas stand-level studies have critical roles in defining mechanisms that control hydrologic responses to treatments.

2.1 Watershed-Level Studies

The earliest watershed studies were designed to determine the balance between precipitation and streamflow, and how this balance is affected by forestry and other land use practices. However, it was soon recognized that watershed studies could also be used to understand how forestry practices affect stream water quality through influences on erosion/sedimentation and the cycling of nutrients and pollutants (Hornbeck and Swank 1992).

Research watersheds are usually less than 100 ha and carefully selected to represent regional landscapes (Hornbeck and Swank 1992). Selected stream reaches within study watersheds are monitored using structures such as gauging stations, flumes, and weirs to determine effects of treatments on aspects of hydrology and water quality. Treatments of interest include percent of watershed cut; density of roads; harvest methods; and silvicultural activities.

Watershed-level studies have been conducted around the world and in most of regions of the U.S. (see Ice and Stednick 2004). Watershed studies in Canada are summarized in Table 2.2 and their locations in Canada's Ecozones are mapped in Figure 2.1. Criteria for inclusion in Table 2.2 were a) the study site is in Canada; b) the study links forestry to water quantity/quality; and c) a watershed-level approach was/is being taken.

Table 2.1 Comparison of Watershed- and Stand-Levels Studies in Examining, for Example, the Influence of Harvesting on Forest Hydrology

	Watershed	Stand
Spatial scale (typical)	10 - 10000 km^2 (typically < 100 km^2)	1 - 100 m^2 (typically < 100 m^2)
Temporal scales (typical)	many (10 or more) years	days - 1 year (a season)
Response variables	Peak flow, low flow, annual flow, timing of flow	Interception, evaporation/transpiration, albedo, snow depth, snow melt rate etc.
Indicator variables	% harvest, topography, tree species composition etc.	Leaf area index, vegetation/species composition, slope, opening size etc.
Approach	Data driven - results provide magnitude of effect at scale but no information on process	Process driven - results provide magnitude of effect and information regarding the process
Conclusions	e.g. Annual water yield increases with % watershed harvested.	E.g., Decreased interception and evapotranspiration accounts for the increased runoff after harvesting.
Advantages	Hydrology examined at the scale at which the response occurs	Hydrology examined at the scale at which the process can be identified and examined
Limitations	Expensive, lack of replication, long wait for results	Less expensive, replication is possible, short wait time for results

Table 2.2 Canadian Watershed-Level Studies That Have Examined the Influence of Forestry Practices on Water Quantity and/or Quality

Watershed or Project	Ecozone, Province (location)	Project Design	Study Area Description	Project Details	Major Findings	Authors
Hayward Brook	Atlantic Maritime, NB (45º52'N, -65º11'W)	Retrospective/ Quasi-paired basin	areas = 1.3 - 6.1 km^2 mean slope along stream channels = 3.4 - 5.2 degrees	Stream temperature: compared five sub-basins with varying levels of harvesting (3.2-25.7% during 2 logging events), 1 yr pre- and post-harvest observations recorded for second logging event, different RMA widths and varying amounts of logging in RMAs	0.3-0.7°C increase in stream temperature after logging, greatest change occurred in stream with greatest portion of logging (16.8% of basin), removal of 28% of RMA did not affect stream temperatures, no relationship observed between RMA width and level of stream warming	Bourque & Pomeroy (2001)
Nashwaak Experimental Watershed (Hayden Brook (HB) and Narrows Mountain Brook (NMB))	Atlantic Maritime, NB (46º18'N, -67º02'W)	Paired basin C) Predictive modelling	HB (control): area = 660 ha slope = 11.4% NMB: area = 391 ha slope = 7.6%	A) Hydrologic response: 7 yr pre- and 1 yr post-harvest monitoring B) Hydrologic response and water quality: 7 yr pre- and 14 yr post-harvest monitoring C) Hydrologic response: 7 yr pre- and 14 yr post-harvest monitoring D) Water quality and sediments: 7 yr pre- and 2 yr post-harvest monitoring undisturbed basin (HB), 92% clear cut basin (NMB)	A) peak flow increase 65%, annual yield increased 142 mm (recalculated in 1988 = 241 mm increase 1st post-harvest year) B) post-harvest yields 6 yrs post-harvest=8.9%, 12 yrs=9.2%; P, K, Ca, Mg increased less than 17% post-harvest but lasted 10-15 yrs, increased NO3-N for 3 yrs post-harvest C) positive and negative contributions to water budget after harvesting , snowmelt advanced by ~ 2 wks D) nitrate increase from 0.3 mg/L to 13.4 mg/L post-harvest, 19.1 kg/ha N loss over 3 yrs, more N loss in elevated and sloping part of watershed; sediments increased from 5 mg/L to maximum of 250 mg/L post-harvest, sedimentation less from streams without nearby roads, effect of roads on sediments persisted 3 yrs	A) Dickison et al. (1981; 1983; 1988) B) Jewett et al. (1995) C) Meng et al. (1995) D) Krause (1982 a, b)
Catamaran Brook (Little Southwest Mirimachi River, Middle Reach (MR) and Upper Tributary 1 (UT1))	Atlantic Maritime, NB (46º52'N, -66º06'W)	Paired basin	Little Southwest Mirimachi River (control): area = 134000 ha MR: area = 2700 ha UT1: area = 450 ha (slope information not reported)	Streamflow: 6 yr pre- and 2yr post-harvest monitoring undisturbed (control) basin compared to MB 2-3% cut and UT1 23-24% cut	peak flow did not change in basin that was 2-3% cut but increased in basin 23-24% cut	A) Caissie et al. (2002)

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Table 2.2 Continued

Watershed or Project	Ecozone, Province (location)	Project Design	Study Area Description	Project Details	Major Findings	Authors
Rivière Verte	Atlantic Maritime, QB (47º49'N -69º15'W)	Paired basin	Control Peatland: area = 18 ha Drained Peatland: area = 20 ha (slope information not reported)	Water quality and quantity: 1 yr pre- and 6 yr post-draining monitoring drained peatland compared to forested peatland	base flow increased in drained basin by 25%, temperatures in drained peatlands increased 7 oC and decreased minimum temperatures of 2 oC, maximum water temperatures reached 25 oC, nutrient availability increased (N, Na, K and Ca) after drainage, suspended sediments increase up to 200 fold temporarily during and right after drainage	Prevost et al. (1999)
Copper Lake	Boreal Shield, NFD (48º49'N, -57º46'W)	Paired basin	No RMA: area = 114 ha 20 m RMA: area = 124 ha	Temperature: measured 3 yr pre-harvest and 2 yr post-harvest control (no harvest), no RMA (18% cut), 20 m RMA (26% cut)	1st post-harvest year temperature greater in both treatments compared to control, 2nd year similar temperatures in control and RMA-stream but much higher in no-RMA stream	Curry et al. (2002)
Montmorency Forest Ruisseau des Eaux-Vole´es Experimental Watershed (REVEW)	Boreal Shield, QC (47º16'N, -71º09'W)	Paired basin	A) Basin 6 (control): area = 394 ha slope = 14.1% Basin 7A: area = 122 ha slope = 18.7 B) Basin 7A (control), Basin 6 (treatment)	Peak flow: 7 yr pre- and 5 yr post- harvest monitoring A) compared undisturbed basin to basin 85% clearcut B) compared undisturbed basin to basin patch cut 31%	A) 63% increase in peak flow of logged basin after 61% of basin was cut, for the 5 yr period after harvesting 85% of the basin, maximum increase in peak flow was 57% (average 54%) B) no significant change in peak flow	A) Guillemette et al. (2005) B) Plamondon & Ouellet (1980); Plamondon et al. (1998)

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Table 2.2 Continued

Watershed or Project	Ecozone, Province (location)	Project Design	Study Area Description	Project Details	Major Findings	Authors
Haute-Mauricie and Côte-Nord (both in the Gouin Reservoir)	Boreal Shield, QC (48º30'N, -74º27'W)	Paired basin	A) & C) control basins: area = 0.61-4.81 km^2 slope = 4-9.4% burnt basins: area = 0.75-21.75 km^2 slope = 4.4-10% harvested basins: area = 0.9-12.87 km^2 slope = 3.3-10.9% B) Haute-Mauricie: mean area = 0.94 km^2 mean slope = 7% length of stream with no RMA = 3000 m Côte-Nord: mean area = 2.38 km^2 mean slope = 13% length of stream with no RMA = 1000 m	A) Element export: post-harvest comparison of 9 harvested, 9 burnt and 16 undisturbed basins B) Temperature, nutrients, sediments, pH, conductivity and DO: Côte-Nord: 2 basins cut (26% and 62%, both with 10 m RMA), 5 undisturbed basins, Haute-Mauricie: one almost completely cut (30 m RMA), one undisturbed C) Element concentrations: same design as A)	A) magnitude of increase in export of Ca2+, Mg2+, Cl-, Na+, total P and K+ related to the % of basin cut and remained increased 3 yrs post-harvest B) maximum temperatures increased 4.5 oC and 6.5 oC in the treated basins of both sites, DO in most disturbed basin decreased to 6.4 ppm after logging (0 ppm during logging), increased K and iron in all logged basins, increased conductivity in logged basins, RMAs in logged site prevented increases in suspended sediments except where streams were crossed by skidders (increases by up to 10 ppm), peaks in sediments for logged streams were 104 and 45 ppm compared to 4 and 7 ppm for their respective controls C) increases in K+ and Cl- in lakes of logged basins, lakes with large drainage ratios exhibited greatest changes, greatest changes in DOC observed in basin more than 30% logged	A) Lamontagne et al. (2000) B) Plamondon et al. (1982) C) Carignan et al. (2000)
Moose River Basin	Boreal Shield, ON&QB (50oN 80oW)	Retrospective/ Quasi-paired basin	Medium: control basin area = 401 km^2 treatment basin area = 1140 km^2 Large: control basin area= 10 000 km^2 4 treatment basins (range) = 6 760 to 11 900 km^2 (see reference for a description of relief ratio used to describe slope)	Hydrologic responses: 2 medium (one quasi-control), 4 large (one quasi-control) at various levels of fire and harvest disturbance	no disturbance related changes in runoff and peak flow yield or timing, or low flow timing, harvest dominated disturbance associated with baseflow increase	Buttle and Metcalfe (2000)

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Table 2.2 Continued

Watershed or Project	Ecozone, Province (location)	Project Design	Study Area Description	Project Details	Major Findings	Authors
Coldwater Lakes (CLEW)	Boreal Shield, ON (49º51'N, -91º51'W)	Quasi-paired basin	Basin area = 106 ha, 194 ha and 70 ha (L26, L39 and L42, respectively) (slope information not reported)	A) Water quality: 5 yr pre- and 3 yr post-harvest monitoring B) Phytoplankton: 5 yr pre-harvest and 4yr post-harvest monitoring A) and B) of 3 basins (L26=33% cut with no shoreline disturbance, L39= 77% cut and shoreline deforestation, L42=74% cut and shoreline deforestation	A) modest changes in DOC, nutrients and major ion concentrations, RMAs did not influence lake water quality B) all lakes showed biovolumes increase in taxa after harvest, increased number of taxa and decreased interannual variability in community structure	A) Steedman (2000) B) Nicholls et al. (2003)
Experimental Lakes Area	Boreal Shield, ON (49º39'N, -93º43'W)	Retrospective	Basin area = 35 - 170 ha consisting of 2 undisturbed, 3 one yr old cuts, 3 four yr old cuts (slope information not reported)	Element concentrations: various basins: undisturbed and clearcuts of various ages	concentrations increased after logging but returned to pre-cut level by second year, losses may have reached 35% N, 20% P, and substantial amounts of Ca and Mg	Nicholson et al. (1982)
Turkey Lakes	Boreal Shield, ON (47º02'N, -84º25'W)	A) Paired basin; Process based modelling B & C) Paired basin	A) SB32 (control): area = 6.74 ha SB31: area = 4.62 ha (see reference for how slope was incorporated in topographic indices) B) basin 32 (control): area = 6.7 ha basin 34 (2 phase shelterwood cut): area = 68 ha basin 33 (selection cut): area = 24 ha basin 31 (clearcut): area = 4.5 ha (slope information not reported) C) basin 33 and basin 34 (described above) compared to 2 control basins (control basins not described)	A) Hydrological processes: control basin= undisturbed, treatment basin=80-90% tree removal B) Water yield and quality: C) Sediments yields: B & C) selective (40% cut), shelter (50% cut), clearcut (all trees > 20 cm diameter), control (no cut)	A) no relationship between streamflow and depth to water and groundwater residence times, increased daily melt rate and water yield with harvesting (latter via surface and near-surface flow), responses not solely due to harvesting, event water contributed more to increases flow from harvested watershed B) maximum short-term increase of 73 mm (11%) but overall changes due to clearcutting not distinguishable from interannual variability, growing season streamflow increased, significant N export from clearcut, Ca2+ leached from clearcut=to stem-only harvest; overall magnitude and duration of impacts of harvesting controlled by timing, size and dispersion of cutting C) despite no RMAs, no sediment increase in shelter cut, sediment in clearcut streams increased 1900 times	A) Monteith et al. (2006 a, b) B) Foster et al. (2005) C) Kreutzweiser & Capell (2001)

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Table 2.2 Continued

Watershed or Project	Ecozone, Province (location)	Project Design	Study Area Description	Project Details	Major Findings	Authors
TROLS, AB	Boreal Plains, AB (54º53'N, -112º10'W)	A) Quasi-paired basin B) Paired basin C) Quasi-paired basin D) Retrospective/ Paired basin	A) control basins (3): area = 455 - 742 ha slope = 1.1 - 3.9% Treatment basins (9): area = 109 - 5669 ha slope = 3.0 - 8.0% B) compared 2 sub-basins within 53 ha basin (slope information not reported) C) control basins (3): area = 602 - 797 ha slope = 1.1 - 3.9% Treatment basins (9): area = 135 - 6752 ha slope = 3.0 – 8.0% (slope information not reported) D) area = 52.4 ha mean slope = 8% consisting of : sub-basin A (34% cut) = 14.6 ha sub-basin B (88% cut) = 5.5 ha sub-basin C (73% cut) = 18.3 ha sub-basin D (control)	A) Nutrients and plankton: monitored lakes of 12basins 2 yrs pre- and post-harvest (controls=0-9% harvest, and treatments = 3 - 35% harvest, mean = 15%) B) Soil, ground water and surface water P: 2 sub-basins 100% cut, one sub-basin clearcut in top portion, one sub-basin not harvested C) Total P: monitored lakes of 12 basins pre- and post-harvest (controls = 0 - 8% harvest, and treatments = 4 - 30% harvest) D) Hydrologic response: 1 yr post-harvest comparison of 3 harvested sub-basins (34%, 73%, 88%) to uncut sub-basin	A) P increased in most lakes after harvest (40%), especially shallow, weak thermal stratification, shorter residence times, large drainage basins; increase in cyanobacterial and cyanotoxin in shallow lakes; RMA width did not influence responses B) P in soil related more to topographic position rather than harvesting, subsurface soils were poor in P in topographic positions where mineral soils were prevalent C) 57% of variability in P was due to subsurface hydrologic linkages between terrestrial and aquatic systems D) observed low snow accumulation, discontinuous frost in wetlands, high soil storage in hillslopes and low probability of spring rainfall and concluded that these factors resulted in little runoff during snowmelt, impacts of logging inconclusive due to large interannual variation in rainfall and spatial variability in soil storage	A) Prepas et al. (2001) B) Macrae et al. 2005) C) Devito et al. (2000) D) Devito Creed, & Fraser (2005)
FORWARD Swan Hills	Boreal Plains, AB (54º21'N, -116º09'W)	Paired basin; Process based, predictive modelling	basin area and slope not reported	A) Stream hydrology and water quality: 16 streams: a nested design with small and large burned streams comparing logged and burned basins at various scales B) Water yield: current and enhance silviculture, limited data used for calibration, no discussion of calibration	A) No results reported B) Only un-validated predictions reported; 11-19% and 23-29% increase in water yield predicted under current and enhanced scenario, respectively, 2-20% increase in maximum peak flow predicted under current scenario and 4-5% higher than this for enhance scenario	A) Smith, Prepas, et al. (2003) B) Van Damme et al. (2003)

(Continued on next page.)

Table 2.2 Continued

Watershed or Project	Ecozone, Province (location)	Project Design	Study Area Description	Project Details	Major Findings	Authors
Caribou Mountains and Cameron Lowlands	Taiga Plain, AB (58º52'N, -115º22'W) Taiga Plains, AB (59º22'N, -118º09'W)	Paired basin	Caribou Mountains (2 basins): MH sub-basin: area = 208 ha, channel slope = 7% MR sub-basin: area = 142, channel slope = 9% Cameron Lowlands (4 basins): area = 280 - 540 ha channel slope = 0.5%	Hydrologic processes: end-member mixing analysis (EMMA), to compare 4 yrs pre-disturbance (harvesting) differences in hydrologic responses of sloped and lowland basins	Hydrologic patterns for sloped basins is distinct from lowland basins, lowland sites would be sensitive to water yield changes but less sensitive to soil disturbance, water yield was comparatively low in sloped basins	McEachern et al. (2006)
Marmot Creek (Cabin and Middle Creek sub-basins)	Boreal Plains, AB (50º56'N, -115º08')	Paired basin	Middle Creek (control): area = 300 ha elevation range = 1760 m - 2800 m Cabin Creek: area = 236 ha elevation range = 1730 m - 2750 m	Suspended sediments and hydrologic response: 5 yrs pre- and 2 yrs post-harvest monitoring of sediments and 9 yr pre- and 8 yr post-harvest Streamflow monitoring,: 23% clear cut basin compared to control	No significant changes in suspended sediment concentrations detected after road building or harvest and remained low throughout the study. 6% increase in water yield observed in cut basin (significant at p=0.2)	Swanson et al. (1986)
Hinton-Edson	Boreal Plains, AB (53º28'N, -117º22'W)	Quasi-paired basin/ Retrospective	Controls: area = 8.8 - 23.9 km^2 Harvested: area = 17 - 22.1 km^2 (slope information not reported)	18 watersheds: 9 control (0-21% cut) and 9 treatment (35-84% cut) by 1974 average harvest age 10 yrs	compared harvest to control watersheds; 59% increase in spring flow, 27% increase in Apr.-Sept. flow, 1.5-2 times increase in storm peak flows	Swanson & Hillman (1977)

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Table 2.2 Continued

Watershed or Project	Ecozone, Province (location)	Project Design	Study Area Description	Project Details	Major Findings	Authors
UBC Research Forest (Malcolm Knapp)	Pacific Maritime, BC (49º16'N, -122º34'W)	Paired basin	B) East Creek (control): area = 38 ha A Creek: basin area not reported Surrounded by 105 ha clearcut (slope information not reported) C) Stream C (control in upper portion of watershed B): area = 44 ha stream slope = 3 main channel length = 855 m Stream A: area = 23.1 ha stream slope = 5 main channel length = 670 m Stream B: area = 68 ha stream slope = 5.5 main channel length = 610 m (units for slope measurements not reported)	A) Hydrologic response: undisturbed basin, 71% clearcut basin (50% of soils disturbed) B) Stream temperature: clearcut and undisturbed forest C) Temperature: 2 yr pre- and 7 yr post-harvest monitoring, Stream A 61% clearcut compared to stream B 19% clearcut and slash burned	A) 22% decrease in peak flow after harvesting and delay in timing of peak flow B) maximum stream temperatures increased up to 5 oC after harvest, although some downstream cooling was observed, generally temperature increased with downstream distance, 25% of cooling was a result of hyporheic exchange C) control stream temperatures did not exceed 17 oC, stream A maximum = 21.8 oC and stream B maximum = 20.3 oC, increased temperatures lasted 7 yr in both but persisted longer in stream B, increased winter temperature in stream A, decreased winter temperature in stream B	A) Cheng et al. (1975) B) Moore et al. (2005) C)Feller (1981)

(Continued on next page.)

Table 2.2 Continued

Watershed or Project	Ecozone, Province (location)	Project Design	Study Area Description	Project Details	Major Findings	Authors
Stuart-Takla A) Baptiste Creek B) Nation River	Montane Cordillera, BC (55º15'N, -125º15'W)	Paired basin	B4 (control): area = 48 ha stream gradient = 30 o B3: area = 43 ha stream gradient = 26 o length of channel cut = 900 m B5: area = 150 ha stream gradient = 7 o length of channel cut = 1060 m B) Hip sub-basin (control): area not reported 118/16 sub-basin: area = 308 ha length of reach = 372 m 118/48 sub-basin: area = 400 ha length of reach = 607 m (slope information not reported)	A) Water yield and suspended sediments: 2 yrs pre- and 4 yrs post harvest monitoring 55% harvested in two basins one with low and the other with high riparian retention B) Stream temperature: 1 yr pre- and 3 yrs post- harvest monitoring of streams, 13 (118/16) and 9% (118/48) of two harvested basins both with high riparian retention, 11 streams monitored for 1 yr to create comparative cooling model	A) increase in flow and sediments in both harvested basins, stronger response with less riparian vegetation retained B) despite downstream cooling from headwater lakes, 2 to 4 oC increase in maximum temperature	A) MacDonald et al. (2003) B) Mellina et al. (2002)
Redfish Creek (Nelson Forest Region)	Montane Cordillera, BC (49º37'N, -117º03'W)	Retrospective; Process based modelling	A) Laird Creek (control): (area and slope not reported) 10% of Redfish Creek harvested between 1969 and 1972 (number of years of pre- and post harvest data not reported) area = 25.8 km^2 maximum slope = 0.5 km /km	A) Water yield: predicted the impact on future harvesting from past logging activities B) Sediment budgets	A) 10% harvesting from the past has resulted in a 13% increase in peak flow, and predicted that harvesting 22% of watershed above H80 elevation would increase peak by up to 22% B) see 'Gold Creek' under the heading 'Watershed or Project'	A) Whitaker et al. (2002; 2003) B) Jordan (2006)

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Table 2.2 Continued

Watershed or Project	Ecozone, Province (location)	Project Design	Study Area Description	Project Details	Major Findings	Authors
Gold Creek (Nelson Forest Region)	Montane Cordillera, BC (48º25'N, -115º40'W)	Retrospective/ Paired basin	Laird Creek: area 15 km^2 Redfish Creek: area = 26.2 km^2 RU1 sub-basin: area = 1.15 km^2, cut area = 0.19 km^2 RU2 sub-basin: area = 0.68 km^2, cut area = 0 km^2 Gold Creek: area = 95 km^2 GA sub-basin: area = 2.55 km^2, cut area = 0.68 km^2 GB sub-basin: area = 3.38 km^2, cut area = 0.23 km^2 GC sub-basin: area = 2.73 km^2, cut area = 0 km^2 (slope information not reported)	Sediment sources and yields: compared two large basins (undisturbed and 10% harvested) and three small sub-basins (10% logged, 27% logged and undisturbed)	Low sediment yields in all basins, larger yields in large logged basin from roads, sediment yield decreased after road construction and use in small logged sub-basin from revegetation, lack of use and gravelling	Jordan (2006)
Bowron River	Montane Cordillera, BC (53º21'N, -121º23'W)	Single basin/ Time-series analysis	area = 3590 km^2 clearcut area = 900 km^2	Annual, monthly, and maximum daily flow, annual 7-day low flow, summer mean flow and peak flow: 25% of basin salvage logged over 10 yr period	7-day low flow during snowmelt decreased, summer mean and peak flows increased, no impact on annual, monthly, maximum daily or annual 7-day low flow	Wei & Davidson (1998)
Upper Penticton Creek	Montane Cordillera, BC (49º39'N, -119º23'W)	Paired basin; Process based modelling	240 Creek sub-basin (control): area = 5 km^2 241 Creek sub-basin: area = 5 km^2 (less than 30% over 75% of study area)	Hydrologic response: control and 17% clearcut 4 year pre- and 4 years post-logging	Model reproduced differences in streamflow between basins, captured hydrologic response of both basins, No pre- and post-harvest comparisons of hydrologic response were made	Thyer et al. (2004)

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Table 2.2 Continued

Watershed or Project	Ecozone, Province (location)	Project Design	Study Area Description	Project Details	Major Findings	Authors
Camp Creek	Montane Cordillera, BC (52º44'N, -119º16'W)	Paired basin	Greata Creek (control): area = 40.7 km^2 Camp Creek: area = 33.9 km^2 (slope information not reported)	Hydrologic response: undisturbed basin, 30% cut basin (infested by pine beetle)	21% increase in annual yield, 93.6% increase in flow during early snowmelt months, 21% increase in peak flows, peak flow 13 days advanced, half flows 9 days advanced	Cheng (1989)
Jamieson	Pacific Maritime, BC (49º31'N, -123º01'W)	Paired basin	Elbow Creek (control): area = 120 ha mean channel gradient = 35% mean annual discharge up to 0.07 m3/s Jamieson Creek: area = 299 ha more than half the area slope ≥ 50% stream channel gradient < 30% mean annual discharge up to 0.31 m3/s	Hydrologic response: 7 yrs pre-harvest and 6 yrs post-harvest monitoring, compared undisturbed basin and 19.2% clearcut basin which was harvested over a 7 yr period	no change in summer storm peak flows, 13.5% increase in winter storm peak flows (rain on melting snow) following harvest	Golding (1987)
Anderson/Sullivan and Windermere/ Sinclair	Montane Cordillera, BC (49º18'N, -117º14'W) and (50º33'N, -115º52'W)	Retrospective/ Paired basin	Anderson: Area = 907 ha mean channel gradient = 22% Sullivan: area = 622 ha mean channel gradient = 24% Windermere: area = 8420 ha mean channel gradient = 9 % Sinclair: area = 9430 ha mean channel gradient = 9%	Magnitude and timing of peak flow: undisturbed compared to 17% cut and undisturbed to 32% cut	no statistical difference in magnitude of peak flow detected, in Windermere (32% cut), significant increase in time to peak flow detected	McFarlane (2001)

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Table 2.2 Continued

Watershed or Project	Ecozone, Province (location)	Project Design	Study Area Description	Project Details	Major Findings	Authors
Carnation Creek	Pacific Maritime, BC (48º54'N, -124º59'W)	Paired basin	Carnation Creek: area = 9.5 km^2 slope = 40 - 80% control sub-basins: C and E areas = 145 and 264 ha harvested sub-basins: B and H areas = 930 and 12 ha (slope information not reported)	Water yield: B sub-basin 40% cleared over 7yrs H sub-basin monitored 3 yr pre- and 4 yrs post-harvest, 90% clearcut	B sub-basin little change H sub-basin 20% increase in peak flow, 78% increase in summer low flow	Hetherington (1982; 1987)
Flume Creek	Pacific Maritime, BC (49º28'N, -123º38'W)	Paired basin	F6 (control): area = 16 ha mean channel slope = 13% F4: area = 39 ha mean channel slope = 17% F5: area = 61 ha mean channel gradient = 6.5%	Peak flow: monitored 2 yr pre- and 2 yr post-harvest, 2 treatment and one control watershed; F4: variable retention (82% cut over 44% of watershed) F5: strip shelterwood cut (50% cut over 32% of watershed)	F4: statistically significant increases in peak flow (194%) with 100% of large flows affected F5: statistically significant increases in peak flow (123.2%) with 100% of large flows affected	Hudson (2001)

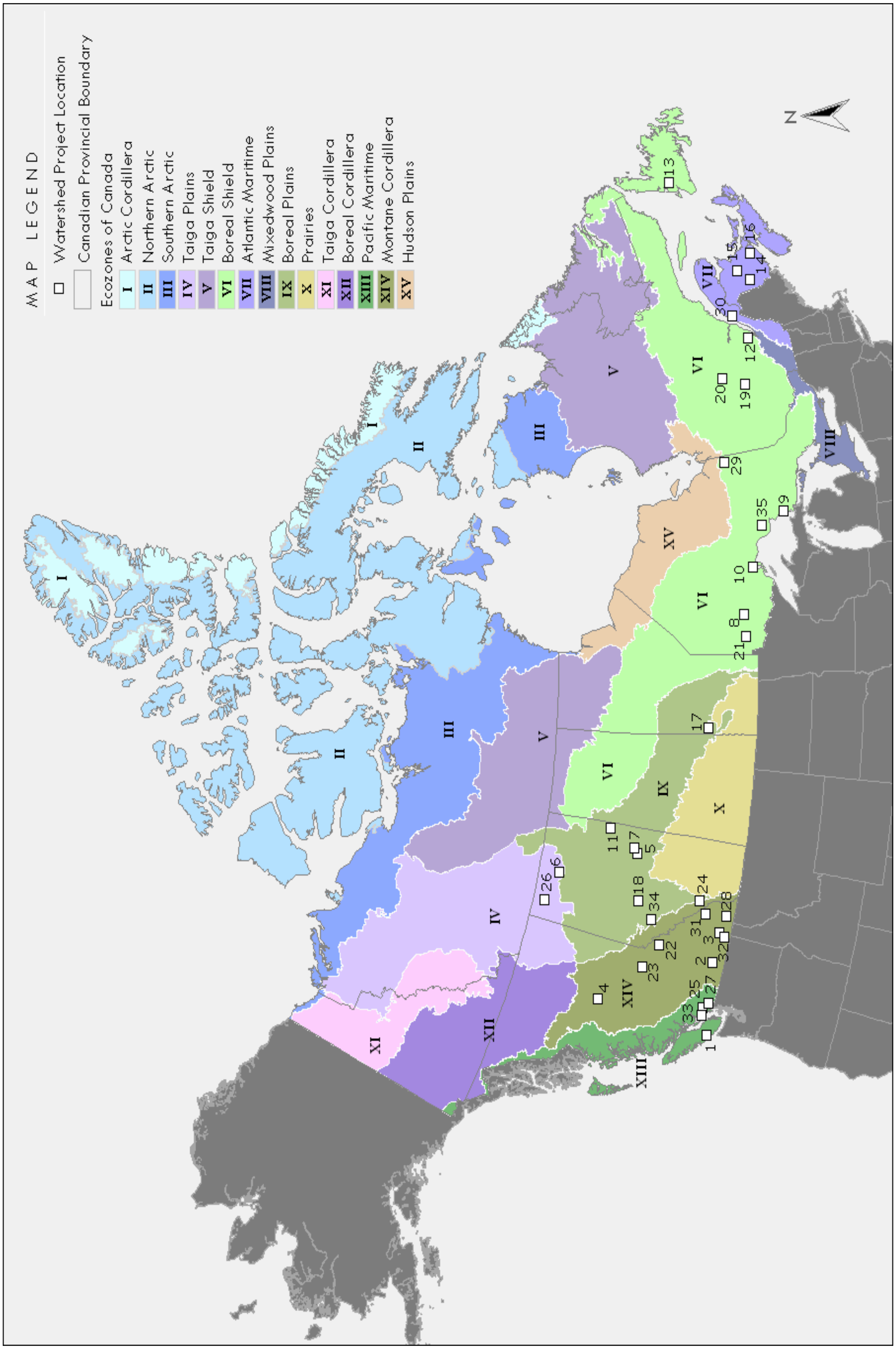

Figure 2.1 Map of the Forested Ecozones and the Location of Watershed Projects in Canada

ID	RESEARCH WATERSHED	ECOZONE
1	Carnation Creek	XIII Pacific Maritime
2	Upper Penticton Creek	XIV Montane Cordillera
3	Redfish Creek/Laird Creek	XIV Montane Cordillera
4	Nation River (a) and Fraser River (b) drainage basins (Stuart-Takla)	XIV Montane Cordillera
5	TROLS Lakes	IX Boreal Plains
6	Caribou Mountains	IV Taiga Plains
7	Moose Lake (NCE & TROLS)	IX Boreal Plains
8	Coldwater Lakes	VI Boreal Shield
9	TLW	VI Boreal Shield
10	Black Sturgeon	VI Boreal Shield
11	NCE, AB	IX Boreal Plains
12	REVEW	VI Boreal Shield
13	Copper Lake	VI Boreal Shield
14	Nashwaak	VII Atlantic Maritime
15	Catamaran Brook	VII Atlantic Maritime
16	Hayward Brook	VII Atlantic Maritime
17	Duck Mountains	IX Boreal Plains
18	Swan Hills	IX Boreal Plains
19	Haute-Mauricie	VI Boreal Shield
20	Tirasse and Côte-Nord	VI Boreal Shield
21	Experimental Lakes Area	VI Boreal Shield
22	Camp Creek and Honey Creek	XIV Montane Cordillera
23	Bowron River	XIV Montane Cordillera
24	Marmot Creek	IX Boreal Plains
25	Jamieson Creek	XIII Pacific Maritime
26	Cameron Lowlands	IV Taiga Plains
27	UBCRF (Malcolm Knapp)	XIII Pacific Maritime
28	Gold Creek	XIV Montane Cordillera
29	Moose River Basin	VI Boreal Shield

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ID	RESEARCH WATERSHED	ECOZONE
30	Rivière Verte Basin	VII Atlantic Maritime
31	Sinclair & Windermere	XIV Montane Cordillera
32	Anderson & Sullivan	XIV Montane Cordillera
33	Flume Creek	XIII Pacific Maritime
34	Hinton-Edson	IX Boreal Plains
35	White River Riparian Harvesting Impact Project	VI Boreal Shield

2.1.1 *Paired Watershed Studies*

Most studies of the hydrological consequences of forest harvesting have employed the paired basin approach (Bosch and Hewlett 1982; Stednick 1996). Paired basins are either adjacent or very close to one another geographically so that both watersheds are affected by the same climatic factors. According to Moore and Wondzell (2005), the success of paired watershed studies depends on how similar the control and treatment basins are with respect to their geology, soils, topography and vegetation. Prior to disturbance of the treatment watershed, there is a calibration period to allow quantification of differences in flow between the two watersheds that are attributable to differences in their geology and topography (Whitehead and Robinson 1993). A sound understanding of the basins' hydrology is required when interpreting results from such studies in order to distinguish harvesting-related streamflow changes from those attributable to other factors (Fuller, Simone, and Driscoll 1988).

McFarlane (2001) suggested the following guidelines for paired basin studies: a) hydrologic similarities between the basins should be assessed throughout the pre-treatment data collection period, b) the two basins being compared should be 1000 ha (2400 acres) or less in size, c) the treatment should be executed during a single event and the percentage harvested should be extensive (>30%), and d) the amount of pre- and post-treatment data should be sufficient so that there is a high power of detecting a change if one exists (>10 years for both pre- and post-treatment).

2.1.2 *Single Watershed Studies*

This method examines a single watershed during a calibration and treatment period. During the calibration period, streamflow data are related statistically to weather data to develop a hydroclimatic model. During the treatment period, the model is used to estimate what streamflow would have been in the absence of treatment. Effects of treatment on streamflow are calculated as differences between observed and estimated values. Unfortunately, uncertainty in model estimates can obscure treatment effects. Increasing the length of the calibration period can improve model estimates but cannot overcome some inherent limitations of the single watershed approach. For example, if weather data are collected from a single station, model estimates of streamflow are based on weather data that are most likely not representative of conditions in the entire watershed (Chang 2005). The popularity of the paired watershed method is due in part to its generally greater power to detect treatment effects.

2.1.3 *Retrospective Studies*

An alternative to paired watershed experiments is to use existing streamflow and precipitation data. Retrospective studies involve an after-the-fact pairing of harvested watersheds with undisturbed watersheds for which some pre-harvesting data exist (Moore and Wondzell 2005). Buttle and Metcalfe (2000) performed a retrospective study examining a number of different sized watersheds in northeastern Ontario using data from Landsat imagery and Water Survey of Canada daily mean discharges between 1985 and 1990. Since there was no nearby watershed that did not experience land cover changes during the study period examined, Buttle and Metcalfe (2000) employed a "quasi-paired basin approach" with partial control at a given scale in the basin that had the least forest disturbance during the period. Limitations of retrospective studies were discussed by McFarlane (2001).

2.1.4 *Nested Watershed Studies*

Nested watershed studies can provide insights into hydrological processes across spatial scales by measuring treatment effects in large watersheds and sub-basins of those watersheds. When coupled with process modeling (Section 2.3), nested watershed studies can measure treatment effects and provide information on causal mechanisms (Alila et al. 2005). Some examples are Caspar Creek in

California, Mica Creek in Idaho, the Alto Watershed Study in Texas, and Hinkle Creek in Oregon (e.g., Hubbart et al. 2007). Nested watershed studies can be larger than 100 ha. For example, the Mica Creek Watershed Study is 28 km^2.

2.2 Stand-Level Studies

Watersheds may be an order of magnitude (or more) larger in size than the forest stands they contain (Table 2.1). Effects of forest management on water resources at the stand scale may be greatly diminished when assessed at the scale of a watershed owing to this size differential.

Stand-level studies are often the best approach to measuring and understanding stand-level effects. For example, stand-level information on the hydrological cycle and biogeochemistry of forests is obtained from studies that examine how the removal of trees influences responses including the interception of rainfall, snow accumulation and melt, hydrologic recovery, infiltration and generation of overland and subsurface flow, antecedent soil moisture, soil frost, nutrient cycling, etc.

Due to the myriad of responses that are measured using stand-level studies, there are a wide variety of methods used to answer questions at this scale. The actual size of stands used in an experimental design depends on the question being asked, and the size of stands available, which will vary depending on geographic region, topography, and disturbance history.

One popular approach is the use of upstream/downstream and before/after/control/impact (BACI) designs. Upstream/downstream sampling is often conducted above and below a stream reach that is influenced by a treatment applied to adjacent areas, allowing inferences about the stand-level effects of that treatment. BACI designs require sampling for some period before and after treatment is applied. Synoptic survey methods for watershed studies (Holloway and Dahlgren 1999) can be used to obtain a snapshot of watershed conditions to guide selection of stream reaches for study and provide information about watershed processes and internal patterns of variation that can influence water quality responses to treatment.

BACI studies of stream reaches are often used to measure influences of riparian management practices on the hydrology and water quality of forested streams and wetlands. For example, several studies have focused on how the presence or absence of riparian management areas (RMAs) (i.e., strips of forest vegetation retained on either side of streams) affects stream responses to management practices outside of RMAs (see also Sections 4.3 and 5.1).

Studies of RMAs have traditionally focused on their effectiveness in mitigating effects of forestry practices on water quality rather than on their hydrological role, although some work has been done with regard to their influence on hyphoreic exchange (surface/groundwater interface), diel fluctuations in discharge, and channel morphology (Moore and Wondzell 2005). Common measurements in RMA effectiveness studies include stream temperature, stream exposure to light, concentrations of sediment and nutrients in streams, inputs of fine and large organic debris into streams, and deposition of sediment within RMAs.

Some early RMA studies (e.g., Likens et al. 1970) used simple designs involving before-after measurements of the effects of harvesting to a stream's edge (i.e., no RMAs retained). Many recent studies have used more elaborate designs in which non-harvested control streams are compared to streams with RMAs of differing widths and/or to streams where RMAs are selectively harvested (e.g. MacDonald, MacIsaac, and Herunter 2003).

2.3 Watershed Modelling

Watershed modeling can help scientists and managers understand the basic hydrology of watersheds and effects of management at a range of spatial and temporal scales. For example, models can be used to assess the ecological implications of changes in water quantity and quality measured in field studies (Scherer and Pike 2003; Buttle, Creed, and Moore 2005).

Various kinds of watershed models and their definitions, design, calibration, use, and limitations have been thoroughly described (e.g., Putz et al. 2003). Watershed models are sometimes classified on the basis of their data requirements. Metcalfe and Buttle (1999) describe distributed hydrological models as those that require data about watershed characteristics and parameters at locations distributed throughout the watershed, whereas lumped models require aggregated information about whole basins and sub-basins. Putz et al. (2003) discuss the strengths and limitations of these two types of models. In principle, distributed models should perform better than lumped models because they can account for spatial variability in the physical characteristics of the watershed. However, distributed models have a huge data requirement, and missing data are often averaged or interpolated from available data, thus negating to some extent the theoretical advantage of this type of model.

Alila and Beckers (2001) suggested a multi-scale approach to understanding watershed responses. Simulation models of physically based processes can be used to link physical processes measured at the stand level to basin-scale hydrology, thus supplementing information derived from experimental watersheds. Unlike field experiments, in a model the watershed can be held in a specific land-use state and be forced to respond to long-term climate data. The simulated long-term output record is specific to that land-use state. The watershed can then be advanced in time and forced with the same climate record, producing a record for the new land-use state (Alila and Beckers 2001). Comparing two output records will reveal when management-related changes in water quality and quantity become significant compared with natural temporal variability in watershed condition.

The value of hydrological models depends in part on the quantity and quality of data available for model calibration and validation. According to Scherer and Pike (2003), high quality data sets that contain a range of natural variability lead to better calibrations irrespective of record length. Using a model to predict data outside its calibrated range may lead to incorrect conclusions and bad management decisions.

Story and Buttle (2001) examined precipitation data quality and long-term water balances in the Moose River Basin of northeastern Ontario and western Quebec. They found significant underestimation of annual precipitation prior to 1950. Their results showed that streamflow time series from large river basins can facilitate assessment of the validity of apparent precipitation trends, and highlight the need to maintain and expand Canada’s hydrometric network.

There has been remarkable progress in the use of geographic information systems (GIS) in hydrologic modelling (Putz et al. 2003). Modelers are using GIS technology in combination with digital elevation models (DEM) (also known as digital terrain models) to create spatially explicit representations of watershed characteristics and processes. For example, Case, Meng, and Arp (2005) developed a GIS-based model of relationships among flow accumulation, drainage class, and soil and vegetation type within small headwater catchments in New Brunswick. They found that watershed characteristics were more closely related to field-assessed flow accumulation than to DEM, and they suggested that their models would have been improved by an increase in DEM resolution.

Blöschl and Sivapalan (1995) describe the sequence of steps involved in the development of any hydrological model: a) collecting and analyzing data; b) developing a conceptual model that describes the important characteristics of the watershed; c) translating the conceptual model into a mathematical model; d) calibrating the model to fit part of the historical data; and e) validating the model against the remainder of the historical data. Sivapalan et al. (2003b) argue that model development has tended to diverge from this ideal in response to advances in understanding of individual processes and increases in the availability of different types of data (e.g., DEM). They suggest that the first two steps are often omitted in favour of approaches that rely exclusively on the description of many individual processes and an *a priori* perception of how they interact.

Similarly, Sidle (2006) argues that with improvements in remote sensing technology, many of the modeling methods used these days are conspicuously avoiding direct field measurement of hydrologic processes in favour of more easily gathered surrogates (e.g., DEM, natural tracers, biological indicators, etc.). While each of these surrogates is useful when combined with direct hydrological measurements, Sidle (2006) believes that each has severe limitations when used without the necessary hydrologic information.

Grayson et al. (1992b) are critical of physically based hydrologic modeling. After their unsuccessful attempt to predict soil movement within a catchment (Grayson et al. 1992a), these authors re-examined some of the underlying assumptions of many physically based models (Grayson et al. 1992b). From their review of the literature at the time, they concluded that although models appeared conceptually sophisticated, they were based on assumptions that are often invalid or questionable. These assumptions are often derived at a scale different from that to which they are applied, and from field data that are insufficient to estimate spatial variability of parameters or even fully validate a model. They believe that although models are useful for understanding processes and their interactions, for management purposes the use of simpler, less pretentious models where results are generally qualitative may be a more realistic approach. They suggest that resources should be allocated away from further model development and into field data acquisition (Grayson et al. 1992b).

3.0 EFFECTS OF FOREST MANAGEMENT ACTIVITIES ON HYDROLOGY AND WATER QUALITY

This section presents results of research on the influence of forestry practices on water quantity, water temperature, nutrients and elements, and sediments. Each sub-section begins with a topic overview followed by a discussion of research conducted in the Ecozones of Canada.

Discussions of Canadian research draw heavily from results of watershed studies summarized in Table 2.2 as well as other studies being conducted in Canada that, while not specifically examining the effects of forestry practices on hydrology and water quality, have nevertheless provided significant insight into the processes that drive the hydrological cycle. Topics addressed in these studies include the role of various runoff processes in forest landscapes; the degree of hydrological coupling between hillslopes and receiving waters; and the influence of this coupling on basin streamflow characteristics. Much of this work has been conducted in context of larger multi-disciplinary studies such as the Boreal Ecosystem-Atmosphere Study (BOREAS) and the Canadian contribution to the Global Energy Water Cycle Experiment (Sellers et al. 1995; Pietroniro and Soulis 2003).

3.1 Water Quantity

3.1.1 *Overview*

Many watershed studies have measured effects of forestry practices on various aspects of stream discharge (Ice and Stednick 2004). Results have been reviewed previously (e.g., Bosch and Hewlett 1982; Hewlett 1970; Hibbert 1967; Hornbeck et al. 1993; MacGregor 1994; Bell, Brown, and Hubbard 1974; Scherer 2001; Stanley and Arp 2002).

Effects of timber harvesting on annual flow have been investigated extensively. In general, harvesting results in an increase in annual water yield; however, the observed responses vary widely between studies. Some of the variation in results may be accounted for by the area within the watershed consisting of bogs, fens or wetlands (NCASI 2007). It has been suggested that wetlands act as buffers against large fluctuations in watershed flows by absorbing water during peak flows and releasing water during periods of low flow. As a result, wetland area should be documented and considered in the analysis of harvest effects on annual flow.

Scherer and Pike (2003) found no studies that specifically evaluated the effects on annual water yield of silvicultural practices other than harvesting. They cite Reiter and Beschta's (1995) opinion that the effects of silvicultural activities on water yield are of limited significance.

Effects of harvesting on peak flows are often examined in watershed studies because of flooding concerns. In addition, increases in peak flows can cause increases in stream scouring and bank undercutting, which in turn can affect water quality and aquatic habitats downstream through the transport of sediment (Alila and Beckers 2001).

Roads constructed to facilitate timber harvesting and forest management can affect the magnitude and timing of peak flow in several ways (reviewed by Reiter and Beschta 1995; Gucinski et al. 2001; Wemple, Jones, and Grant 1996). Compacted road surfaces limit water absorption; road cutbanks can intercept slower subsurface flows and transform them into more rapid surface flows; and road ditches and culverts can reroute water into streams (Scherer and Pike 2003).

Scherer and Pike (2003) note that reviews by MacDonald, Wohl, and Madsen (1997) and Austin (1999) found significant variability in peak flow responses to harvesting that could not be explained by watershed characteristics or management activities. No single variable (e.g., amount of forest removed, harvesting method, silvicultural treatment, etc.) could account for peak flow changes.

The timing of peak flows may be advanced by timber harvest operations that cause faster and earlier snowmelt (Winkler 1999). According to a review by Scherer and Pike (2003), the effect may range from an advancement of 18 days to no change.

Effects of harvesting on low flows are also of interest in watershed studies (Tague and Grant 2004). In many studies, harvesting has caused an increase in low flows attributable to a decrease in transpiration due to the removal of trees (reviewed in Scherer and Pike 2003). Increases in low flows resulting from harvesting can help reduce effects of seasonal drought on water supplies and aquatic habitats.

Scherer (2001) performed a meta-analysis of 17 papers that reported changes in basin-wide water yield due to harvesting and found highly variable changes in peak flow (0-66% increase), peak flow timing (0-18 days in advance), annual water yield (0-111% increase) and low flow (0-37% increase). Watershed area did not account for significant amounts of this variability. Absolute water yield increases following harvesting tended to be smaller during dry years than during wet years.

Effects of harvesting on water yield can be due in part to increases in the amount of solar radiation reaching the ground (Scherer and Pike 2003). Increases in solar radiation can affect other hydrologic processes such as snowmelt, evapotranspiration, soil freezing, etc. (Winkler 1999).

Hyrdologic effects of harvesting are also due to reductions in leaf area, interception, and evapotranspiration associated with tree removal. These reductions lead to increases in soil moisture and amounts of water available for streamflow. Hydrologic responses tend to persist longer in clearcut watersheds than in patch-cut watersheds (Thomas and Megahan 1998).

Several authors have examined effects of post-harvest vegetation recovery and regrowth on duration of hydrologic response in experimental watersheds (Douglass and Swank 1972; Hornbeck et al. 1993; Thomas and Megahan 1998). Indicators of vegetation recovery include shrub cover and canopy cover. Vegetation growth rates can be considered in predictions of hydrologic recovery times (Summers 1982). Hornbeck et al. (1993) reported that effects of harvest were prolonged by post-harvest herbicide treatments designed to delay vegetation recovery. Long-term studies to clearly determine recovery times of watersheds after disturbance are generally lacking.

Changes in species composition during forest regeneration or succession can affect watershed hydrology. For example, a change in riparian vegetation from conifers to deciduous species after harvest has been reported to reduce dry weather streamflow (Hicks, Beschta, and Harr 1991).

Evapotranspiration is generally recognized as a critical process regulating hydrologic responses to forest management (Stanley and Arp 2002; Aust and Blinn 2004). However, as part of BOREAS, Sellers et al. (1995) studied surface-atmosphere exchanges of water and found relatively small evaporation and transpiration rates in the Boreal Shield of central Saskatchewan and northern Manitoba during the growing season. Sellers et al. (1997) noted that these small rates are not represented correctly in most atmospheric models for this region.

Gibson (2001) used measurements of an isotope of oxygen (^{18}O) and deuterium (D) in surface waters as an indicator of water balance changes in forests of northern Canada and found that the method allowed the discrimination between evaporation and transpiration. Extending this method to estimate throughflow, residence time, and watershed discharge, Gibson, Prepas, and McEachern (2002) concluded that the approach provided a useful tool for examining the hydrological consequences of forest disturbance.

Interception of rain, snow, and fog by foliage plays important roles in the water cycle of forest ecosystems. Some of the intercepted water is lost to the atmosphere by evaporation; however, some reaches the ground via throughfall or stemflow (Spittlehouse 1998). Evaporation of intercepted rain and snow reduces the total amount of water reaching the ground as well as the peak throughfall intensity (Keim and Skaugset 2003). Interception of fog, however, may increase total water inputs to forests and hence forest harvesting may reduce streamflow (Harr 1982, 1983).

Interception varies with tree species (reviewed by Helvey 1971). Winkler (2001) found that crown volume, length, and density explain the largest portion of variability in snow accumulation. Dickison and Daugherty (1982) found that proportion of hardwoods in a stand accounts for up to 75% of variance of snow depth.

In the Pacific Northwest, harvested openings typically accumulate 30-50% more snow than areas with intact forest canopies (Troendle and King 1987; Golding 1982; Winkler, Spittlehouse, and Golding 2005). Harvesting does not change the amount of snow deposited on the entire watershed but rather redistributes it (Stegman 1996; Wheeler 1987). The greater accumulation of snow in harvested areas is due primarily to a decrease in interception, with directed deposition being a secondary factor (e.g., Troendle and King 1985).

In areas where snow is the dominant type of precipitation, melting snow is the main source of water for streamflow and often the cause of spring floods (Chang 2005). In the mountainous regions of Canada at the stand level, forest harvesting increases snow accumulation and causes more rapid melt compared with unharvested stands (Toews and Gluns 1986). Increases in snow melt and reduced transpiration due to the removal of trees results in locally increased soil moisture and hillslope runoff (Troendle and Reuss 1997). In the interior of British Columbia, Winkler (2001) found that the square root of tree basal area was the best predictor of snow melt.

Murray and Buttle (2003) examined the influence of clearcutting and slope aspect on snow accumulation and melt on a ridge of the Turkey Lakes Watershed in Ontario. Although accumulation in the clearcut was greater than in uncut forest, the degree of difference varied with slope aspect and year. Snowmelt was much greater and earlier on south-facing sites than on north-facing sites. In one year of the study, the south-facing uncut forest sites lost all snow cover 27 days before the north-facing clearcut. Murray and Buttle (2003) concluded that the effect of aspect on spatial variation in melt was larger than the effect of clearcutting.

Golding and Swanson (1978) studied snow accumulation and melting in harvest units of various sizes in Alberta. Harvest unit size was measured relative to heights of dominant trees (H) in surrounding uncut forest (B.C. Ministry of Forests 2001). Snow accumulation and ablation were measured in openings ranging from 0H (uncut forests) to 6H in diameter. Snow accumulation was greatest in 2H openings (0.05-0.5 ha). Melting was slowest in smaller 1H openings (0.5-1.2 ha).

According to Lee and Smyth (2003), RMAs are relatively small in boreal watersheds (~2% of area) and therefore these areas do not likely mitigate water yield increases following harvesting. This view is consistent with results of a study by Steedman (2000) that found no difference in water yield between two boreal lakes; one with extensive watershed and shoreline harvesting and the other with moderate watershed harvesting and a retained RMA. In contrast, Buttle, Dillon, and Eerkes (2004) characterized RMAs as zones of transmission of ground water and hillslope water to the stream channel, and as a deflector of precipitation and snowmelt when the riparian water table rises to the surface. During times when subsurface inputs are minimal, two-way exchanges of water between the stream and the riparian aquifer (hyporheic exchange) can become important (Moore and Wondzell 2005). Transpiration by vegetation in the riparian zone may extract water from the riparian aquifer, producing a daytime decrease in streamflow, followed by recovery at night (e.g., Bond et al. 2002).

Harvesting can affect forest hydrology by altering soil properties through erosion, compaction, rutting, destabilized slopes, loss of organic matter, etc. For example, soil compaction can reduce water infiltration rate and soil hydraulic conductivity, and thus increase potential for soil erosion and changes in landscape hydrology (Chanasyk et al. 2003; Rab 1996; Harr, Fredriksen, and Rothacher 1979; Hetherington 1982; Johnson et al. 1991; McNabb, Startsev, and Nguyen 2001; Whitson, Chanasyk, and Prepas 2003, 2005). Hydrologic consequences of soil compaction can include enhanced overland flow and raised water tables (Lamontagne et al. 2000) as well as changes in baseflow. Corns (1988) estimated that compacted soils in western Alberta would require 10 to 21 years to return to pre-disturbance conditions, with surface layers requiring more time than those below. In the Boreal Plain region of Alberta, differences in infiltration characteristics caused by harvesting were evident three years after winter harvest (Whitson, Chanasyk, and Prepas 2003, 2005).

Effects of timber harvesting on soil properties depend on several factors, including harvesting systems, soil texture and drainage class, and weather conditions (e.g., Rummer 2004; Stone and Elioff 2000; Green and Stuart 1985; Beese et al. 2003; Schmidt and Blinn 2007). For example, harvesting when soil moisture content is low can help reduce rutting and compaction (Corns and Maynard 1998; McNabb, Startsev, and Nguyen 2001). Many companies restrict harvesting and hauling activities during wet weather to minimize potential for excessive site disturbance.

3.1.2 *Research in Canada's Ecozones*

Atlantic Maritime Ecozone

The Nashwaak Experimental Watershed Project (NEWP) in New Brunswick was initiated in 1970 as a paired-watershed study. After a six-year calibration period, 92% of the Narrows Mountain Brook watershed was clearcut in 1978 while the other adjacent uncut watershed was kept as control.

NEWP documented extreme precipitation levels from Hurricane David in 1979. During this event, a 65% increase in peak flow was attributable to harvesting. This increase in peak flow contributed to a substantial increase in annual discharge during the first year after harvest (Dickison, Daugharty, and Randall 1981, 1983; Dickison, Palmer, and Daugharty 1988; Daugharty and Dickison 1982).

Jewett et al. (1995) calculated the effects of harvest on annual water yields at NEWP for the first six years post-harvesting (8.9% increase) and for the first 12 years after harvest (9.2% increase). Meng et al. (1995) and Jewett et al. (1995) noted that effects of harvest were approximately the same in years 6 to 12 as in years 1 to 6 despite increases in evapotranspiration associated with regrowth of vegetation. They suggested that increases in evapotranspiration may have been offset by other effects of vegetation regrowth such as a) increases in water inputs via canopy interception of fog and cloud water; and b) reductions in evaporation from the soil surface due to reductions in soil surface temperatures.

Caissie et al. (2002) studied effects of harvesting on streamflow in two sub-basins at Catamaran Brook, New Brunswick. Harvesting of 2-3% of the watershed area in the Middle Reach basin did not change the annual and seasonal water yield. Harvesting of 23-24% in the Tributary 1 basin increased peak flow but not total stormflow. The authors suggested that increases in peak flow could affect bank erosion and sediment transport.

Prevost, Plamondon, and Belleau (1999) studied the effects of peatland drainage on streamflow in a pair of headwater basins (20 ha and 18 ha) in the Rivière Verte watershed. They reported that draining of the peatland increased base flow by 25%.

Boreal Shield Ecozone

Harvesting has not always resulted in an observed increase in annual water yield. At the Turkey Lakes Watersheds (TLW) in Ontario, a paired basin study was performed comparing control (no harvesting), selective harvesting (watershed canopy reduced by 40%), shelterwood harvesting (watershed canopy reduced by 50%), and clearcut harvesting (all trees > 20 cm diameter removed) (Kreutzweiser and Capell 2001). Soil water, water quality, stream sediments, and streamflow were measured from 1991 to 2000. Harvesting occurred in 1997. Shelterwood harvesting and clearcutting had similar effects on streamflow. Changes in runoff due to clearcutting were generally not distinguishable from interannual variation in streamflow, although a maximum short-term increase in water yield of 73 mm (11%) was observed. As well, growing season streamflow was increased (i.e., stream did not dry up; Foster, Beall, and Kreutzweiser 2005). Selective harvesting did not have significant effects on water yields.

Guillemette et al. (2005) examined effects on streamflow of harvesting in a paired basin study at Montmorency Forest, Quebec. Maximum peak flow increased by 63% when harvesting reached 61%. During the five-year period after the basin had been 85% harvested, the maximum increase in bankfull flow was 57%. Guillemette et al. (2005) attributed the high peak flow response to the connections of skid trails and road ditches with branches of the stream in that watershed. Previously at Montmorency Forest, patch cutting 31% of a 394 ha basin using chain saws did not significantly modify rainfall generated peak flows and stormflows (Plamondon et al. 1998; Plamondon and Ouellet 1980).

Guillemette et al. (2005) compared their results at Montmorency Forest to 50 world-wide paired basin studies that examined peak flows after harvesting. They concluded that watershed harvesting should not exceed 50% and that the occurrence of bankfull discharge increases above 50% could affect stream morphology as well as the aquatic ecosystem.

Buttle and Metcalfe (2000) performed a retrospective examination of the effects of forest disturbance on streamflow of two medium and four large watersheds (400-1200 km^2) in the Moose River Basin of northeastern Ontario. Disturbance was assessed for these watersheds using two classified Landsat images, one at 100 m resolution and the other at 25 m resolution (both summer scenes) for which they were able to distinguish cutover areas from burned areas and assess disturbance patterns with respect to the drainage network. They also obtained discharge information for the period of record as well as precipitation records which allowed them to categorize peak flows by their generating event. They used a quasi-paired basin approach to assess streamflow response to land use change with partial control at a given scale provided by the basin with the least forest disturbance during the period. Although they found no definitive streamflow changes in runoff or peak flow magnitude and timing, harvest dominated disturbance was associated with statistically significant baseflow increases attributed to reduced interception and evapotranspiration (Buttle and Metcalfe 2000). Further, the timing of low flow periods (when baseflow dominates) was independent of the degree of basin disturbance. These results support the notion that forest disturbance effects are scale-dependent, and are most significant during low-flow periods.

As part of BOREAS, Metcalfe and Buttle (2001) examined the hydrologic dynamics of an undisturbed treed peatland watershed in the boreal forest near Thompson, Manitoba. The watershed occupies a poorly drained landscape dominated by wetlands in the discontinuous permafrost zone. They examined the hydrological linkages between various landscape elements: poorly drained discontinuous permafrost on snowmelt conditions and active layer development, and surface storage conditions on runoff components and pathways, along with their influence on streamflow. Further, they examined how interannual changes in antecedent wetness, melt intensity and ground thawing may affect such linkages. They concluded that interannual differences in runoff conditions provide important insight for the development of distributed hydrologic models for boreal forest watersheds.

From earlier work on the same watershed, Metcalfe and Buttle (1999) noted that water storage and evaporation in small wetlands and ephemeral surface depressions is a fundamental component of the watershed water balance in this type of landscape. These distinct components could be overlooked by inappropriate spatial lumping of landscape units when scaling up variables or in the production of digital terrain models.

Boreal Plains Ecozone

Devito, Creed, and Fraser (2005) compared runoff in three harvested (34%, 73%, and 88% cut) and one undisturbed sub-watershed of the Moose Lake Basin for a period of five years starting one year after harvesting. Their general observations were that runoff due to snowmelt in the Boreal Plain is small compared with Boreal Shield and the Boreal Cordillera due to low total snow accumulation, discontinuous frost layers in wetlands, high soil storage in hillslopes and a very low probability of spring rainfall. Results regarding the influence of harvesting on runoff were inconclusive due to large temporal variation in rainfall and spatial variation in bedrock characteristics and soil storage. They concluded however, that although there is a low potential for harvesting to affect water yields at this site, the valley bottom ephemeral draws may be susceptible to harvesting effects during most years.

McEachern, Prepas, and Chanasyk (2006) used end-member mixing analysis and isotopes of water (deuterium and ^{18}O) to describe the hydrologic processes for six boreal forest watersheds in the discontinuous permafrost of northern Alberta. The amount of water entering a stream from different source areas in a watershed was reconstructed from knowledge of source area chemical characteristics

(Hooper and Christophersen 1992). Termed end-members, the waters delivered from soil horizons and precipitation form a physical basis for modelling water sources. Their data represented pre-disturbance conditions during two average precipitation years for small basins which would undergo clearcutting. Their results indicate that the hydrological pattern for sloped topography is distinct from lowland sites. Lowland sites would be sensitive to water yield changes associated with timber removal and, despite being less sensitive to soil disturbance, are likely more sensitive to harvesting disturbance during wet years than mountain sites where water yield was comparably low, owing to a reduction in soil strength as water tables rise.

Swanson et al. (1986) conducted a paired basin experiment in the Marmot Creek watershed of Alberta. Middle Creek sub-basin (300 ha) was undisturbed and the Cabin Creek sub-basin (212 ha) was 23% cut. After eight years of post-harvest monitoring, a statistically insignificant 6% (17 mm) increase in annual water yield was observed ($p = 0.2$).

Montane Cordillera Ecozone

Swanson and Hillman (1977) studied streamflow in 18 watersheds (from 7-26 km^2) near Hinton, Alberta. The watersheds had various percentages of their area harvested (average age of cut was 10 years). The nine control watersheds (between 0% and 21% harvested) were compared to nine treatment watersheds (between 35% and 84% harvested). Streamflow during the gauged monitoring season (April–September) ranged between 97 mm and 217 mm in control watersheds, and between 117 mm to 282 mm for harvested watersheds. A 27% (39 mm) increase in gauged season runoff was attributed to harvesting. During the spring melt, the harvested watersheds yielded 37 mm or 59% more runoff than the control watersheds. Swanson and Hillman (1977) estimated that effects of harvesting on streamflows during snow melt could persist for 30 years.

In British Columbia, Golding (1987) conducted a paired-watershed study in the Jamieson experimental watershed (which had a 75% slope over half its area). The treated watershed was 19% harvested over six years. While summer storm peak flows showed no change during the study, winter storm peaks (rain falling on melting snowpacks) were increased by 14% after harvesting likely due to reduced ablation from canopy interception and increased snowpack.

Wei and Davidson (1998) examined the effects of large-scale timber harvesting on mean, peak and low flows for the Bowron watershed in central British Columbia. By 1975, nearly 25% of the watershed was harvested in a 10-year salvage operation following a widespread spruce bark beetle infestation. Due to the size of the watershed (approximately 3590 km^2), a paired/replicated watershed study was not feasible, and so Wei and Davidson (1998) performed a time-series analysis. Timber harvesting had no significant effect on annual mean flow, monthly mean flow, and annual maximum daily and annual seven-day low flow. They speculated that the size and complexity of the Bowron watershed could have buffered the annual flow changes resulting from harvesting. Seasonally, timber harvesting within the spring snowmelt period did not appear to affect the mean maximum, daily seven-day low flow or monthly mean flow during the spring snow melt period. However, the seven-day low flow during snowmelt decreased due to harvesting. As well, harvesting significantly increased summer mean and peak flows, and the authors suggested this was due to the decrease in evapotranspiration during the summer. These results further support the hypothesis that harvesting effects are scale-dependent, with large-scale watersheds being most affected by harvesting during low flow periods, as suggested by Coats and Miller (1981) and discussed by others (e.g., Buttle and Metcalfe 2000).

Cheng et al. (1975) found a delay in the timing of peak flows and a 22% decrease in peak flow volume in the University of British Columbia's Research Forest after 71% of a watershed was clearcut and the soils were disturbed over 50% of the cut area. While the ground disturbance did not reduce the soil infiltration capacity (hence, no overland flow resulted), entrances to some subsurface stormflow pathways were closed. Cheng et al. (1975) suggest this caused more water to move through the soil matrix resulting in an increase in the temporary water storage capacity of the soil, resulting in the increased time to peak and the reduction in the magnitude of the peak flow.

Cheng (1989) examined changes in streamflow in the Camp Creek watershed in British Columbia after forest disturbance by pine beetle (*Dendroctonus ponderosae*) infestation and clearcutting of 30% of the basin area. Annual water yield post-disturbance was 21% greater than predicted for pre-disturbance conditions. During the early stages of snowmelt, post-disturbance streamflow was 94% greater and peak flows were 21% greater than predicted for pre-disturbance conditions. Disturbance advanced the timing of peak flows and half flows by 13 days and nine days, respectively.

Cheng, Reksten, and Hetherington (1982) studied low flows in 51 tributary streams in the Okanagan Valley. They were able to relate variations in low flows to watershed physiographic and climatic factors. They proposed dividing the Okanagan Basin into sub-areas with similar low flow conditions. They suggested that by installing gauges in one or two representative watersheds within each sub-area, more meaningful estimates of low flow characteristics could be obtained (Cheng, Reksten, and Hetherington 1982).

McFarlane (2001) conducted a retrospective analysis of the effect of cumulative harvesting on water yield in two pairs of basins in British Columbia. Anderson Creek watershed (907 ha) was the undisturbed control for Sullivan Creek (622 ha) which had been 17% cut over a period of approximately 30 years. Sinclair Creek (9430 ha) watershed was the undisturbed control for Windermere Creek watershed (8420 ha) which had been 32% cut over a period of approximately 25 years. Using a number of statistical tools, McFarlane (2001) found that no single tool was adequate for analyzing changes in peak flow, and through a power analysis found that increased sample numbers were required for both watershed pairs to detect any change in flow with 80% power. Although an increase in peak flow was observed in Sullivan Creek, most of this change could be attributed to changes in peak flow for the control watershed suggesting that a factor other than forest harvesting could have been responsible. In the other watershed pair, a change in the timing of the peak flow was correlated with harvesting activities in Windermere Creek (McFarlane 2001). Such paired watershed designs have been suggested to be useful for detecting cumulative effects (e.g., Loftis and MacDonald 2000).

MacDonald et al. (2003) examined effects of harvesting on streamflow in a paired watershed experiment in the Baptiste watershed in British Columbia. Three basins were compared: forested control, 55% clearcut with low riparian retention (removal of all trees >15 cm DBH for pine and >20 cm DBH for spruce within 20 m of the stream); and 55% clearcut with high riparian retention (all timber >30 cm DBH removed within 20 m of the stream). Harvesting increased peak flows and mean daily discharge during freshet (spring thaw). Effects of harvesting were highly variable but generally greater for the basin with low riparian retention (15% to 193% increase in daily yield, -8% to 367% increase in peak flow) than for the basin with high riparian retention (1% to 29% increase in daily yield, 2% to 50% increase in daily peak flow). Harvesting effects on streamflow were still evident five years after harvesting and were attributed to both vegetation removal and road construction. The authors noted, however, that some of their data suggested a poor relationship between control and treatment streams and therefore their results should be interpreted with caution.

Pacific Maritime Ecozone

Hetherington (1982, 1987) conducted paired watershed studies in the Carnation Creek watershed in British Columbia. In one watershed, clearcutting 90% of basin area caused a 20% increase in peak flow and a 14% (360 mm) increase in annual water yield. Clearcutting also advanced the timing of peak flows and caused a 78% increase in minimum summer daily flow during the first two years after harvest. In another watershed, no effect on annual water yield could be detected as a result of clearcutting 40% of basin area over a seven-year period (with harvest area distributed among cut blocks ranging in size from 5 to 64 ha).

Hudson (2001) performed a paired watershed experiment that examined the influence of partial harvesting on peak flows in the Flume Creek watershed located north of Vancouver, British Columbia. Two treatment watersheds were compared to an undisturbed control watershed. One treatment watershed was 82% harvested over 44% of its area using a variable retention method (grouped and dispersed retention), and the other was 50% harvested over 32% of its area using a strip shelterwood method. The peak flows of both treatment watersheds were significantly increased after harvesting. For the variable retention watershed, the highest pre- and post-harvest peak flows were measured at approximately 0.2 and 0.5 m^3/s respectively, and the mean percent increase in peak flow for large flows was 194%. For the strip shelterwood watershed, the highest pre- and post-harvest peak flows were measured at approximately 0.35 and 0.5 m^3/s, respectively, and the mean percent increase in peak flow for large flows was 123%. Hudson (2001) found that the magnitude of the increase in peak flow was proportional to the forest canopy removed, expressed as a percentage of the watershed area of the creek.

3.2 Water Temperature

3.2.1 *Overview*

Stream water temperature influences the chemical, biological, and ecological integrity of streams (Bourque and Pomeroy 2001). For example, temperature affects the level of dissolved oxygen in water (e.g., Horne and Goldman 1994) and, hence, the development, metabolism, and respiration of aquatic organisms (e.g., Eckert, Randall, and Augustine 1988) and the environmental toxicity of effluents (Hondzo and Stefan 1994).

Many factors affect stream water temperature, such as surface turbulence, stream size, source water temperature (surface versus groundwater), stream water travel time and upstream land use conditions (Bourque and Pomeroy 2001). Story, Moore, and MacDonald (2003) found that the warming effects of harvesting and road construction on an upper stream reach were mitigated downstream largely by bed heat conduction and hyperheic exchange (60%) with groundwater inflow accounting for the rest.

Riparian canopy closure affects stream temperature by influencing the amount of direct solar radiation reaching streams (Beschta et al. 1987). Various studies have shown that retaining canopy cover in riparian management areas (RMAs) moderates the immediate effects of timber harvest on stream temperatures. Water temperatures in stream segments without RMAs typically increase after harvest, but return to pre-disturbance levels as streamside vegetation returns (Moring 1975; Patric 1980; Johnson and Jones 2000).

Lee and Smyth (2003) noted that the effectiveness of RMAs in moderating stream temperatures has been documented in many more studies in the U.S. than in Canada. They also commented on the lack of baseline knowledge and data to evaluate the effects of stream temperature on aquatic and terrestrial riparian communities within the boreal forest.

Mitchell (1999) modeled stream temperature responses to several factors including air temperature, timber harvest, and retention of canopy cover in RMAs. Results demonstrated the importance of several factors that should be considered when establishing RMA widths to mitigate effects of harvest on stream temperatures. These factors include the relationship between stream size/volume and radiation (temperature of smaller streams will be more affected by radiation load than larger streams) and the aspect of the stream (south-facing streams will be subject to more solar radiation).

3.2.2 *Research in Canada's Ecozones*

Atlantic Maritime Ecozone

Caissie, El-Jabi, and St-Hilaire (1998) successfully modeled daily stream temperatures in Catamaran Brook, New Brunswick using air temperature as a predictor. St-Hilaire et al. (2000) used the CEQUEAU model with data from Catamaran Brook to evaluate effects of timber harvest on stream water temperatures. They concluded that stream temperature predictions could be improved by considering the effects of harvest on canopy cover and soil temperatures. St-Hilaire et al. (2003) showed that canopy removal may influence stream temperatures by affecting the amount of radiation reaching the soil surface and the volume of water moving from harvested areas to the stream.

Bourque and Pomeroy (2001) measured stream temperature responses to harvesting outside of RMAs at the Hayward Brook Watershed in New Brunswick. They reported increases in stream temperatures (0.3-0.7°C) that coincided with forest harvesting activities. Extent and aspect of the harvested area appeared to have greater influence on stream temperature response than RMA width.

Boreal Shield

Curry, Scruton, and Clark (2002) examined the effect of clearcutting and RMA retention on stream temperature in three sub-catchments in the Copper Lake watershed in Newfoundland. A stream with a 20-m RMA had 26% of its watershed harvested. Another stream with no RMA had 18% of its watershed harvested. There was no harvesting in the control watershed. Temperature effects were measured during the incubation period of brook trout (*Salvelinus fontinali*s). During the first year after harvesting, stream temperatures were higher in both harvested watersheds than in the control. During the second year, stream temperatures were similar in the control and 20-m RMA watersheds, but remained elevated in the no-RMA watershed. Water temperatures in brook trout incubation habitat were similar to surface water temperatures, reflecting the dominance of down welling hyporheic flow over upwelling groundwater

Plamondon, Gonzalez, and Thomassin (1982) studied effects of harvesting on stream temperatures in the Côte-Nord (CN) and Haute-Mauricie (HM) watersheds. They reported post-harvest increases in maximum daily temperatures of 4.5°C at CN and 6.5°C at HM. Pre-harvest temperatures were in the range of 8.5–10.6°C. At HM, dissolved oxygen (DO) concentrations in stream water decreased by 6.4 ppm (from 7.4 ppm before harvest) and reached 0 ppm during harvesting in June. DO was not affected at CN. Differences in temperature and DO responses between sites were attributed to differences in disturbance (greater at HM), slope (4% at CN vs. 1% at HM), the length of stream exposed to the sun (1000 m at CN compared to 3000 m at HM), and lack of turbulence at HM.

Prevost, Plamondon, and Belleau (1999) performed a paired watershed experiment using two small (20 and 18 ha) headwater watersheds in eastern Quebec. They reported that draining forested peatlands to increase nutrient availability and tree growth rates had increased weekly maximum temperatures (7°C) and reduced weekly minimum temperatures (2°C). Maximum water temperature at the outflow of the drained basin reached 25°C or more. The authors suggested that draining a large peatland area could affect downstream water temperatures in streams supporting salmonids.

Barton, Taylor, and Biette (1985) examined the relationship between RMA width and length on stream temperature in southern Ontario, and found that the retention of longer and wider RMAs resulted in lower stream temperature. They also discovered that longer RMAs could be narrower and achieve the same amount of temperature control as wider RMAs.

Montane Cordillera Ecozone

Gomi, Moore, and Dhakal (2006) performed a six-year study that examined the effects of clearcut harvesting with and without RMAs (10 and 30 m wide) on headwater stream temperature in coastal British Columbia. Streams with 10 and 30 m RMAs did not exhibit a marked increase in temperature. In streams without RMAs, increases in water temperatures were in the range of 2-8°C. The north-south orientation of streams with RMAs may have facilitated stream temperature regulation (Gomi, Moore, and Dhakal 2006).

MacDonald, MacIsaac, and Herunter (2003) examined stream temperature changes in eight first-order streams in the Stuart-Takla Fisheries-Forestry Interaction Project in British Columbia. Treatments were a) low-retention RMAs (removal of all merchantable timber); b) high-retention RMAs (removal of large merchantable timber > 30 cm diameter at breast height (DBH) within 20-30 m of the stream), and c) patch cut (high retention along the lower 60% of the stream and removal of all riparian vegetation in the upper 40% of the watershed). Increases in temperatures were 1–2°C for wind-firm high-retention streams vs. 6°C for low-retention streams.

Mellina et al. (2002) found that even after reducing riparian canopy to about half its pre-treatment value, downstream cooling of streams in the Nation River drainage basin in north-central British Columbia still occurred and was attributed to the small lakes located upstream of the study reaches. Surveying the lake-headed and non-lake-headed streams with a range of forest management histories, they concluded that stream reaches exhibit downstream cooling for some distance below small lakes, even through cutblocks. Despite this, there was a warming of up to ~2-4°C of maximum daily temperatures during August at the downstream end of cutblocks (Mellina et al. 2002).

Story, Moore, and MacDonald (2003) examined water temperature patterns and their physical controls for two small, clearing-heated streams in shaded reaches downstream of forestry activity in the central interior of British Columbia. Cooling of these streams of up to 4°C occurred downstream of clearings. Energy balance estimates suggested that groundwater inflow caused about 40% of cooling in daily maximum temperature, while bed heat conduction and hyporheic exchange caused about 60%. The authors recommended expansion of research on the hydrologic characteristics of specific streams and their catchments that may account for differences among streams in thermal response to forest disturbance (Story, Moore, and MacDonald 2003).

Pacific Maritime Ecozone

Moore et al. (2005) conducted a paired watershed study of the thermal regimes of headwater streams within a clearcut and undisturbed forest in the University of British Columbia's Malcolm Knapp Research Forest. Maximum daily temperatures increased up to 5°C after harvesting and were positively associated with maximum daily air temperature and negatively associated with discharge. Although water was cooled with downstream distance where there was relatively concentrated lateral groundwater inflow, the general trend was for the temperatures to increase with downstream distance. Heat exchange associated with hyporheic flow cooled the stream during the daytime up to 25%.

Feller (1981) conducted a paired watershed study on the Malcolm Knapp Research Forest to examine the effects of clearcutting and slash burning on stream temperature. Relative to the uncut control, maximum stream temperatures were 3–5°C higher in the harvested watershed. Temperature effects lasted seven years in the unburned portion of the clearcut watershed and somewhat longer in the area where clearcutting was followed by slash burning. Clearcutting increased winter water temperatures, whereas slash burning caused a decrease in winter temperatures.

3.3 Nutrients and Elements

3.3.1 *Overview*

Forest harvesting can affect biogeochemical cycles through several mechanisms, including alteration of nutrient sinks and sources; increases in soil temperature and humidity; changes in soil structure caused by harvesting equipment; and the flushing of nutrients and dissolved organic carbon from organic surface soils to surface water (Carignan and Steedman 2000). Post-harvest increases in nutrient mobility can increase nutrient exports and affect water quality (Putz et al. 2003). Harvest effects on nitrogen mobility and export are mediated by microbial processes affecting mineralization and nitrification. Export of phosphorus is related to soil erosion and is therefore affected by landscape position, soil properties, and post-disturbance precipitation patterns (Putz et al. 2003; Chanasyk et al. 2003). The mineralization, dissolution, or desorption of P associated with soil particles will contribute to the loading of P in aquatic systems (Chanasyk et al. 2003).

Christopher et al. (2006) examined the mechanisms causing the difference in stream water solute concentrations between two nearly adjacent sub-watersheds in New York with similar atmospheric inputs of N. They found that the differences observed in stream water Ca^{2+} and NO_3^- concentrations were mostly explained by differences in tree species composition, soil properties and their interactions.

3.3.2 *Research in Canada's Ecozones*

Atlantic Maritime Ecozone

Krause (1982a) studied effects of harvest on nutrient cycling at the Nashwaak Experimental Watershed Project (NEWP) in New Brunswick. Nitrate nitrogen was undetectable to 0.3 mg/L in stream water before harvest. After harvesting hardwood stands, nitrate nitrogen in stream water increased to 13.4 mg/L and the cumulative post-harvest loss of N over three years was 19.1 kg/ha. Nitrogen losses were greater in elevated and sloping parts of the watershed compared to low lying areas. Harvest of conifer stands did not cause a significant increase in nitrate nitrogen export.

Jewett et al. (1995) monitored the chemistry of precipitation, soils and streams at the NEWP. Post-harvest increases in nitrate concentration in soil percolates were associated with an increase in acidity. Nitrate in soil solution declined toward pre-harvest levels during the third post-harvest year. The decline in soil nitrate was attributed to nitrate uptake by rapidly recovering forest vegetation.

Jewett et al. (1995) also reported post-harvest increases in export of phosphorus, potassium, calcium and magnesium. Cumulative effects of harvest on these nutrients were considered small because post-harvest annual export rates did not exceed pre-harvest export rates by more than 17%. These effects, however, were noticeable for up to 10-15 years post-treatment.

Boreal Shield Ecozone

Plamondon, Gonzalez, and Thomassin (1982) measured concentrations of calcium (Ca), potassium (K), and iron (Fe) in stream water at the Côte-Nord (CN) and Haute-Mauricie (HM) watersheds in Quebec. At CN, partial harvesting caused increases in mean nutrient concentrations as follows: Ca from less than to 2 ppm to 3.3 ppm; K from 0.3 ppm to between 0.7 and 1.2 ppm; Fe from less than 1 ppm to 4.4 ppm. At HM, increases in mean concentrations due to clearcutting were as follows: K from 0.2 ppm to more than 3 ppm; Fe from less than 1 ppm to 2 ppm.

Prevost, Plamondon, and Belleau (1999) measured effects of drainage on nutrient availability in peatland soils. Increases in availability were observed within 5 m of the draining ditches for nitrogen, sodium (Na), K and Ca. Elevated levels of K and Ca were also observed at a 15 m distance. The increases in nutrient availability were associated with slight decreases in pH and marked increases in conductivity at all distances from the ditches.

Maynard and MacIsaac (1998) studied effects of patch cutting on nutrient cycling in Saskatchewan's boreal forest. Differences between harvested and non-harvested plots were not significant for most nutrient pools. Total potassium in the forest floor was 18% lower on harvested plots three years after harvesting. There was also an increase in aspen foliar nitrogen for two years following harvest.

Simard et al. (2001) compared forest soils from recent clearcuts, wildfires and undisturbed forest stands in Quebec's boreal forest. Clearcut areas had a higher total mass of forest floor nutrients than either control or burned stands. The authors concluded that clearcuts may have a greater capacity than burned stands to supply nutrients to support productivity in the long term.

Duchesne and Houle (2006) monitored nutrient concentrations in atmospheric deposition and stream water at the Tirasse watershed in Quebec over a seven-year period. Concentrations of sulfate (SO_4), nitrate (NO_3), ammonium (NH_4), and basic cations in bulk deposition were among the lowest reported for northeastern North America and Europe. Much of the sulfur in atmospheric deposition was exported in stream water. In contrast, 90% of the inorganic N in atmospheric deposition was retained in the catchment. Canopy leaching of K contributed 91% of the total K in throughfall, with lower values observed for Ca (75%) and Mg (60%).

Duchesne and Houle (2006) suggested that harvesting was the main cause of K export in Boreal Shield watersheds, and that complete whole-tree harvesting could represent a 66% loss in the total base cation pool. They estimated that stem-only harvesting (foliage and branches left on the ground) would reduce base cation export (relative to whole-tree harvesting) by 57%, 47% and 56% for K, Ca and Mg, respectively.

Carignan, D'Arcy, and Lamontagne (2000) compared element concentrations in lakes of central Quebec (Gouin Reservoir in Haute-Mauricie) with watersheds that were either undisturbed, or had been affected by either harvesting or wildfire. Effects of watershed disturbance on lake water chemistry generally increased with degree of disturbance and with drainage ratio (drainage basin area divided by lake volume). Among lakes with large drainage ratios, effects of watershed disturbance by harvesting included elevated concentrations of total phosphorus, total organic nitrogen, potassium, chloride and calcium. Lakes with watersheds disturbed by wildfire had much higher concentrations of nitrate and sulfate compared to lakes with watersheds that were harvested or undisturbed.

Lamontagne et al. (2000) estimated element export rates from the drainage areas of nine harvested, nine burnt, and 16 reference Boreal Shield lake watersheds in Haute-Maurice, Québec, for three years following harvesting or fires (average of 45% and 90% disturbance of the drainage area, respectively; both in 1995). Harvesting and fires generally increased element export rates. Among harvested watersheds, element export rates increased with percent of watershed affected by harvesting. Export rates for K were 3-8 times higher in burned and harvested watersheds than in neighboring undisturbed watersheds. Harvesting also increased export rates for dissolved organic carbon in DOC. Effects of harvest on export rates were greatest during the year following harvest and persisted for three years. According to Pinel-Alloul et al. (2002), exports of nutrients and carbon from Boreal Shield watersheds can have a profound effect on water quality.

Lamontagne et al. (2000) propose a number of mechanisms to explain increases in DOC after harvesting including increased decomposition and the addition of slash to these areas. In addition, a higher water table resulting from decreased evapotranspiration could cause runoff to bypass the DOC-sorbing mineral soil (Hinton, Schiff, and English 1997). Lamontagne et al. (2000) suggest that increased DOC export following harvesting could affect also the transport and cycling of contaminants including methyl mercury (Garcia and Carignan 1999).

Steedman (2000) measured effects of watershed disturbance by clearcutting on water chemistry in deep headwater lakes in northwestern Ontario. These lakes were part of the Coldwater Lakes Experimental Watershed in boreal-Great Lakes transition forest on the Boreal Shield. After five years of pre-treatment monitoring, three watersheds were partially harvested (L26 = 33% removal with no disturbance of shoreline forest; L39 = 77% removal and shoreline deforestation; and L42 = 74% removal and shoreline deforestation). Effects of harvesting on dissolved organic carbon and nutrients were modest during three years of post-harvest monitoring. The lakes sampled in this investigation had relatively long renewal times compared to those studied by Carignan, D'Arcy, and Lamontagne (2000). Steedman (2000) concluded from this study that since RMAs did not influence lake water quality, they may be more important for preservation of aesthetic values and terrestrial habitat than for protection of water quality of lakes.

Nicholls, Steedman, and Carney (2003) examined phytoplankton in the lakes studied by Steedman (2000). Effects of harvest were not statistically significant, but several trends in the data were noted by the authors. For example, total mean biovolumes of several phytoplankton taxa were higher after harvest than before harvest in all three lakes.

In the Experimental Lakes Area of northwestern Ontario, Nicholson, Foster, and Morrison (1982) examined element concentrations in samples from several basins containing undisturbed forest and clearcuts of various ages. Concentrations generally increased after harvesting but returned to pre-harvest levels by the second year. Nutrient export rates (product of concentration and flow) remained elevated for several years after harvest. As a percentage of the tree-plus-soil nutrient pool, estimates of cumulative nutrient export reached 35% for N, 20% for P, and lesser but still substantial portions for Ca and Mg.

Foster, Beall, and Kreutzweiser (2005) examined the effects on nutrient cycling of different harvesting regimes in a paired-watershed study in the Turkey Lakes watershed. Short-term increases in nitrogen export after clearcutting represented a significant input to surfaces waters. Amounts of calcium leached from the soil after clearcutting were equivalent to calcium removals in stem-only harvest. Selective harvesting (50% canopy removal) had much smaller effects than clearcutting on NO_3^-, Ca^{2+} and sediment in stream water. The authors found that the magnitude and duration of effects could be controlled by the timing, size and dispersion of harvesting within a watershed, and concluded that gradual removal harvesting operations offered greater protection of soils and natural regeneration and thereby increased protection of water quality.

Boreal Plain Ecozone

Prepas et al. (2001) monitored 11 of Alberta's Boreal Plain lakes for nutrients and plankton before and after variable harvesting of 15% (range 0-35%) of their watersheds. Phosphorus concentrations in the lakes increased 40% in the harvested watersheds. Increases were most pronounced in lakes that are shallow (mean depth = 3.1 m, range = 0.7 – 14.4 m) and have a) weak thermal stratification, b) large drainage basins, and c) shorter residence times. Increases in cyanobacteria were also measured after harvest, primarily in shallow lakes. There was no evidence that RMA width (20, 100, and 200 m) influenced lake response to harvesting.

Carmosini, Devito, and Prepas (2002) conducted a stand-level study of nitrogen transformations in harvested and mature aspen-conifer forests in Alberta's boreal plain. Gross ammonification and NH_4 immobilization rates were consistently higher in harvested soils, whereas net ammonification rates were similar in the mature and harvested soils. Harvested mineral soils had elevated NH_4 concentrations, which Carmosini, Devito, and Prepas (2002) suggest may reflect periods of higher net ammonification not captured in this study. Post-harvest increases in soil N mineralization and nitrification in the boreal plain were also reported by Walley, VanKessel, and Pennock (1996) and Maynard (1997). In a study in British Columbia, nitrate concentrations in streams were elevated for approximately two years after watershed disturbance by clearcutting, but some nutrient concentrations in streams fell below pre-harvest levels between two and eight years post-harvest (Feller and Kimmins 1984).

In southern Alberta, release of phosphorus (P) from litter was found to be very fast during the first post-harvest year and declined thereafter (Prescott et al. 1993). As will be shown below, however, P export from soils to surface waters is affected by several factors.

Evans et al. (2000) assessed the spatial and temporal trends in total dissolved P (TDP) in shallow subsurface water within 100 m of a lake and the effects of forest harvesting and RMAs on these trends. TDP concentrations in soil less than 1.7 m deep did not differ between sub-catchments, whereas TDP concentrations in soils deeper than 1.7 m were lower in the harvested sub-catchment. This difference, however, was attributed to differences in the clay content between sub-catchments rather than to harvesting. As well, mean daily TDP export coefficients were similar in the un-harvested and harvested sub-catchments.

Macrae et al. (2005) studied the effects of harvesting on P cycling in an aspen-dominated watershed in Alberta. Within the watershed, two sub-catchments were clearcut, another was clearcut across the top portion of the sub-catchment, and a fourth sub-catchment in the lower reaches of the watershed was not harvested. Results indicate that water-extractable P in soil (and potential for export of dissolved P in runoff) was related to topographic position (i.e., upland, low-lying or wetland) rather than harvesting. Extractable P levels were generally high in forest floor and organic surface soils and much lower in mineral soils. The authors suggested that post-harvest increases in dissolved P exports to surface waters are not likely in this system due to strong adsorption of P by mineral soils.

Devito et al. (2000) reported that landscape characteristics (including surface and subsurface hydrologic linkages between terrestrial and aquatic systems) accounted for 57% of the variation in post-harvest changes in total P concentrations in lakes in Alberta. Changes in total P tended to be relatively small in lakes where P exports from adjacent slopes were moderated by longer local and intermediate flow systems and relatively large in lakes with extensive areas of adjacent wetlands.

Manunta et al. (2002) focused on P transport from agricultural lands, but their studies were conducted at the scale of watersheds nested within ecodistricts (i.e., broad ecological zones with distinctive arrangements of landforms, relief, surficial geologic material, soil, water bodies, vegetation, wildlife and land uses (Parks Canada 2004). Manunta et al. (2002) identified locations across the province of Alberta that may contain areas with relatively high risk of elevated P in runoff. They argued that since water quality is usually measured at the watershed level, the effect of soil P Index components upon water quality should be evaluated at this scale. Similar applications of such risk assessment may possibly be devised for assessing the effects of forestry practices to P runoff risk in watersheds.

3.4 Sediments

3.4.1 *Overview*

Distributions of soil types and landforms within a watershed are important factors regulating movement of water, nutrients and sediment (Chanasyk et al. 2003). Sediments enter streams by surface erosion, landslides, and stream bank erosion. While large increases in sediment inputs to streams are problematic, some amount of sediment is necessary to maintain ecological functions of stream ecosystems.

Rates of sediment inputs to streams can be affected by forestry practices such as road construction, log skidding, prescribed burning and scarification (Hetherington 1987). Stream sediment concentrations tend to increase after harvest, especially when access roads cross areas that contribute runoff to streams (Grayson et al. 1993; Kreutzweiser and Capell 2001). However, various best management practices have been designed to mitigate the effects of forest operations on sediments (see Section 4.2).

3.4.2 *Research in Canada's Ecozones*

Atlantic Maritime Ecozone

Krause (1982b) studied the effects of forestry operations on sediment concentrations in streams in the Nashwaak Experimental Watershed Project in New Brunswick. Prior to road construction and harvest, sediment concentrations rarely exceeded 5 mg/L. After cutting, sediment concentrations were frequently elevated and reached approximately 250 mg/L in a stream branch situated below a new road. The effect of road construction on suspended sediments was still noticeable in the third year following harvest. Increases in sediment were less frequent and lower in magnitude in stream branches not affected by road construction. An RMA along the main stream branch was effective in reducing effects of harvesting on suspended sediments.

Boreal Shield Ecozone

Plamondon, Gonzalez, and Thomassin (1982) examined the change in suspended inorganic sediments due to clearcutting in the Haute-Mauricie and Côte-Nord watersheds of Quebec. Natural concentrations were normally no greater than 5 ppm, and this did not change for the logged sites where RMAs were retained. In the streams that were crossed by skidders, however, the mean concentrations increased by up to 10 ppm. Peaks in suspended sediments for two streams were 104 and 45 ppm, compared to 4 and 7 ppm for their respective controls.

Prevost, Plamondon, and Belleau (1999) examined the effects of draining a peatland on suspended sediments. Increases in sediment loads by a factor of 100-200 were observed during and a few weeks following the ditching period but decreased to pre-ditching levels thereafter.

Kreutzweiser and Capell (2001) examined fine sediment accumulation in streams in the Turkey Lakes Watershed in Ontario. Stream sediments were measured in harvested watersheds where no RMAs were retained. Harvest treatments were selection cut (30-40% removal); shelterwood cut (50% removal); diameter limit cut (approximately 85% removal); and control (no harvest). Fine sediment deposition and bedload were greatest in the control watershed where road improvement had taken place. Road improvement activities were performed to accommodate increased traffic associated with harvesting and included grading, removal of boulders from the road bed and cleaning the ditches draining the roads. As well, the increases in sediment observed at the selection cut and the shelterwood cut were associated with road building activities in the area. In contrast, in the shelterwood cut watershed where logging roads were not a factor, no measurable increases in sediment deposition were observed despite the absence of RMAs, while sediment deposits in the diameter limit cut watershed increased from approximately 500 g/m^2 average pre-harvest to approximately 3000 g/m^2 average post-harvest. Sedimentation in the latter watershed was attributed to heavy ground disturbance and channeled flowpaths from skidder activity in riparian areas. Kreutzweiser and Capell (2001) suggested that RMAs may not be required to prevent sediment in streams where surrounding forest is selectively harvested at up to 50% removal.

Boreal Plain Ecozone

Gently sloping terrain limits potential for erosion and sedimentation in much of the Boreal Plain. In Alberta, for example, Swanson et al. (1986) reported no significant changes in suspended sediment concentrations between a control and 23% harvested sub-basin of Marmot Creek.

In the Cabin Creek sub-basin of Marmot Creek, Swanson and Hillman (1977) monitored streamflows before and after clearcutting. Pre- and post-harvest peak flows were 577 L/s and 458 L/s. This suggests that clearcutting did affect peak flows and associated potential for bank erosion.

Fine textured soils in the Boreal Plain Ecozone are susceptible to compaction during forestry operations. Whitson, Chanasyk, and Prepas (2003) reported that effects of compaction persisted for up to three years after winter harvesting with no post-harvest scarification.

Montane Cordillera Ecozone

Christie and Fletcher (1999) investigated effects of harvesting on sediment geochemistry in the Baptiste Creek watershed in the north-central interior of British Columbia. By sampling sediments before and after a harvesting event, upstream and downstream of the cut site, they found that stream sediments have unique multi-element geochemical fingerprints. This chemical signature did not change as a result of clearcut harvesting. Christie and Fletcher (1999) attributed this lack of effect to RMAs retained along the stream. Roads and stream crossings did cause local changes in sediment geochemistry in streams by creating new sources of sediment supply.

MacDonald et al. (2003) also examined the effects of harvesting practices on sediment delivery to streams in Baptiste Creek. In two watersheds that were 55% harvested, an increase in total suspended solids was detected the spring after harvest. The increase in sediment was most notable in one of the watersheds. Sediment increases in this watershed were attributed initially to a low level of tree retention in the RMA but subsequently were traced to a log landing and stream crossing. Two years after decommissioning of the road and crossing site, sediment levels were back to pre-harvest levels. MacDonald et al. (2003) concluded that a) RMAs effectively protected stream banks from mechanical damage; b) windthrow of trees in RMAs may eventually contribute sediments to streams; and c) BMPs should focus on controlling sediment inputs associated from road crossings, road drainage, and road maintenance and deactivation.

Jordan (2006) used sediment budget concepts to assess the effects of forestry practices on the sediment regimes of streams in the Kootenay region of British Columbia. Sediment budgets were constructed for Laird Creek (undeveloped); Redfish Creek (long history of forestry development; 10% logged); and three smaller sub-basins within Gold Creek (10% logged, 27% logged and undeveloped). Several findings from this study are noteworthy.

- Annual sediment yields in Redfish Creek and Laird Creek were among the lowest reported in the province.
- Annual sediment yields were greater in Redfish Creek than in Laird Creek. Sediment source surveys indicated that erosion from logging roads was an important source of sediment in Redfish Creek (Jordan and Commandeur 1998; Jordan 2001).

- In Gold Creek, rates of sediment delivery from roads to streams were very low (0.05 to 0.2 T/km^2/year) despite high road density, and decreased in the years following road construction. The decreases were attributed to revegetation of roads and ditches, the reduced road traffic due to the completion of harvesting, and armoring of road surfaces with course gravel.
- Differences among watersheds in geology and groundwater regime can influence susceptibility to erosion and stream sedimentation.
- In comparison to roads and crossings, harvested cut blocks are negligible sources of sediment inputs to streams (Jordan 2001, 2006; Toews and Henderson 2001).

4.0 DISCUSSION

4.1 Effects of Forestry Operations on Hydrology

A 1982 review of watershed-level studies of annual water yield found increased annual flow after timber removal but with a large variation in amounts between basins (Bosch and Hewlett 1982). Whitehead and Robinson (1993) suggest these differences in response are due to differences in climatic conditions and the broad types of forest cover examined. More definitive conclusions regarding forestry effects on watershed-level hydrology are difficult to draw (Alila and Beckers 2001) since each response involves many processes (e.g., water yield changes are influenced by evapotranspiration, interception, stem- and through flow, etc.). Additional complications are associated with variation in forest management practices including silvicultural systems and harvesting methods; the location within the watershed that harvesting takes place; and road construction methods (Alila and Beckers 2001).

Several current efforts to understand effects of forestry operations on hydrology emphasize use of models to integrate stand-level process studies with watershed-scale information. For example, Monteith et al. (2006a) examined the effects of forest harvesting on groundwater properties, water flowpaths, and streamflow response four years after harvest in the Turkey Lakes Watersheds in central Ontario. They used a paired watershed approach to defined streamflow response to harvesting (undisturbed basin and 80-90% tree removal in treatment basin). They also measured groundwater depths and used digital elevation models (DEMs) to develop spatially explicit characterizations of water source areas expressed in terms of topographic indices of hydrological behaviour within the basins. They hypothesized that understanding relationships between groundwater properties and indices of basin topography would allow prediction of areas of surface saturation which is important for streamflow generation and for flushing solutes from receiving waters (Welsh et al. 2001). Unfortunately, Monteith et al found that their indices and models did not consistently explain groundwater properties (e.g., residence time, intra-basin variation in groundwater depth) and relationships between streamflow and groundwater properties (Monteith et al. 2006a). Other research has also noted limitations of topographic metrics as predictors of hydrologic processes and properties in drainage basins (e.g., Moore and Thompson 1996; Buttle et al. 2001; Buttle, Dillon, and Eerkes 2004).

Monteith et al. (2006a) did find, however, that their integrated research approach was useful in explaining effects of harvesting on streamflow during snowmelt. They found that increases in streamflow were attributable not only to effects of harvesting on daily melt rates but also to increases in the proportion of flow in surface and near-surface pathways. They concluded that the increase in streamflow and runoff from the harvested basin was not solely attributable to harvesting; the spring runoff from the harvested basin relative to the forested control was not consistently larger than under pre-harvest conditions.

Thyer et al. (2004) used the process-based Distributed Hydrology Soil Vegetation Model (DHSVM) (Wigmosta, Vail, and Lettenmaier 1994) to link forest management effects measured at the stand level to the watershed-level hydrology of two catchments at the Upper Penticton Creek (UPC) Watershed Experiment in the Okanagan region of south-central British Columbia. The treatment watershed was 17% clearcut. The control watershed was used to calibrate the model and to evaluate the model's performance on the treatment watershed without recalibration in order to test the transferability of model parameters between the basins. Not only was the model able to reproduce differences in streamflow characteristics between the two catchments without parameter adjustment, it also was able to capture many of the crucial hydrologic responses (e.g., canopy rainfall interception between small and large storms, tree transpiration over a six day summer period and differences in soil moisture levels between a dry and wet summer) of both control and treatment watersheds over a four year pre- and post-harvest period.

Whitaker et al. (2003) used DHSVM (Wigmosta, Vail, and Lettenmaier 1994) to interpret data from the Redfish Creek Watershed in the interior of British Columbia. The overall model performance for the simulation of catchment processes was found to be good. However, there were some issues relating to the distribution of meteorological variables over the watershed, as well as a lack of data on the spatial variability of soil properties and saturation patterns. These issues were reflected in the poor simulation of the hydrograph for one tributary where forest roads were not included in the model and data were lacking on the spatial variability of soil properties.

Whitaker et al. (2002) used DHSVM to evaluate the Interior Watershed Assessment Procedure (IWAP) guidelines regarding peak flow sensitivity to harvesting at different elevations. Model simulations for snowmelt-dominated watersheds such as the Redfish Creek indicated that harvesting above the H80 elevation (where 80% of the watershed is covered with snow during the time of peak flow) would have a greater effect on peak flows than harvest below this elevation. Their results also suggest that the present 9.9% harvest level has led to a 13% increase in peak flow, while sustained high flows are approximately 7% higher than under pre-harvest conditions.

Schnorbus and Alila (2004) used simulated climate data and hydrologic models to evaluate effects of several management scenarios for the Redfish Creek watershed in southern British Columbia. Results indicated that peak flow responses to harvesting depend on total harvest area and spatial distribution of harvest units in the watershed. Harvest at higher elevations had greater influence on peak flow than harvest at lower elevations. Small and large discharge events responded similarly to forest harvesting for hourly and daily return periods.

Van Damme et al. (2003) created water yield simulation models for the western edge of the boreal plain ecozone as part of a Forest Management Agreement (FMA) with the Government of Alberta. The models estimated the change in annual water yield and peak flow for two management scenarios. The first scenario, business as usual (BAU), reflected traditional harvesting and silvicultural practices where maximum allowable cutblock sizes were 50 ha (123 acres). The second scenario, enhanced timber production (ETP), included no restrictions on cutblock sizes as well as practices such as conifer tree planting, spacing and thinning. Model results indicated increases in annual water yield of 11-19% for BAU and 23-29% for ETP. Modeled increases in peak flow ranged from 2-20% for both scenarios with increases for the ETP scenarios 4-5% higher than for the BAU scenario. Van Damme et al. (2003) characterized the effect of both regimes as modest because flows remained within the normal range of variation for the region. Hydrologic differences between the scenarios were attributed to greater concentration of harvest in time in the ETP scenario. In other words, harvest activity occurred over a longer period of time in the BAU scenario which allowed for greater hydrologic recovery by regeneration.

Weyerhaeuser Canada (1999) used a hydrologic model to assess hydrologic responses to harvesting in Saskatchewan. This study examined three climate scenarios (high, average and low precipitation) and two types of basins (high relief and larger low relief basin).

- For an ecosystem management scenario (10% of the watershed harvested), increases in annual water yield of 8%-10% were simulated for all climate scenarios. If harvesting was followed by a wet year, the predicted increase in peak flow was in the range of 10%-19%. The model also predicted no change in the timing of peak flow.
- For a scenario representative of current timber management, maximum predicted increases in annual water yield and peak flows were 14% and 20%, respectively. No change in the timing of peak flow was predicted.
- Under a maximum harvest scenario, all of the merchantable timber was harvested to simulate an upper bound of disturbance for comparison. Maximum predicted increases in annual yield and peak flow were 25% and 39%, respectively, for the larger watershed under wet conditions. No change in the timing of peak flows was predicted.

Sivapalan, Takeuchi, et al. (2003a) describe an initiative that was launched by the International Association of Hydrological Sciences (IAHS). The IAHS Decade on Predictions in Ungauged Basins (PUB) is evaluating the feasibility of improving the resiliency of hydrological models through diminished use of calibration in parameterizing models and replacing calibration with *a priori* parameter selection (Pomeroy et al. 2005). As part of this initiative, Pomeroy et al. (2005) intensively observed the most uncertain hydrological processes of two research areas established in the 1990s (i.e., Wolf Creek Research Basin located in the sub-arctic mountains of the Yukon Territory, and the Prince Albert Model Forest consisting of several small basins in the southern boreal forest of central Saskatchewan). Observations supported development of algorithms that describe primary hydrological processes and pathways in these watersheds. The models that resulted had good performance in uncalibrated simulation of the observed hydrology, and Pomeroy et al. (2005) have high confidence in transferring their models to other ungauged basins.

Canada's project on Forest Watershed and Riparian Disturbance (FORWARD) is an attempt to integrate data from watershed ecosystem analysis into landscape management (Smith, Prepas, et al. 2003). By quantifying the dynamics of ecological components in small watersheds, the project leaders hope to understand and extrapolate the effects of natural or human disturbance to areas outside of these watersheds. Working in conjunction with the Department of Fisheries and Oceans, and the Clean Environment Commission of Manitoba, Louisiana-Pacific Canada Ltd. is participating in the FORWARD project by developing an ecologically based, multi-scale forest management approach for the aquatic ecosystems of the Duck Mountains in Manitoba. Their 20-year Forest Ecosystem Management Plan will provide a strategic context for future management and operational planning and will be based on a natural disturbance emulation approach to ecosystem management that integrates watershed management with landscape-level planning (Donnelly 2003). Specific objectives include collecting appropriate watershed data; selecting and adapting a stream hydrological and water quality simulation model; incorporating data and models in decision support tools; and applying these tools in forest planning and management at the watershed scale (Smith, Prepas, et al. 2003). At present, watershed analysis methods are being used to track cumulative harvest amounts and model potential effects on hydrology. Donnelly (2003) suggests that models could be developed that incorporate stand-level riparian management strategies so that forest planning takes a more landscape-based approach. FORWARD is also conducting research in Alberta and proposes to develop a modelling component that combines hydrologic and water quality simulation modelling with intensive field monitoring (Putz et al. 2003).

4.2 Effects of Forestry Operations on Water Quality

Watershed and stand-level studies have played important roles in identifying key sources of water quality impairment associated with forestry operations (e.g., roads and stream crossings) and in demonstrating the effectiveness of best management practices (BMPs) for controlling impacts (Arthur, Coltharp, and Brown 1998; Ice 2004; Ice et al. 2004; NCASI 2000; Wynn et al. 2000). Forestry BMPs include guidelines on a wide range of topics including riparian management areas, road construction, road operation and maintenance, road decommissioning and reclamation, timber harvesting, site preparation and regeneration, silvicultural chemicals, fire management, stand tending practices, operations in wetlands, cold climate practices, and fish habitat enhancement practices (Ice 2002).

Stuart and Edwards (2006) conclude that BMPs have been effective in controlling adverse changes to instream sediment and water chemistry and that when used properly, BMPs protect watershed resources while allowing the removal of wood products. They also conclude that the forest floor is the key watershed attribute which controls runoff, sedimentation and nutrient loading while the actual removal of trees has a small affect on water resources. They caution, however, that efforts to determine the effectiveness of BMPs must take into account natural forest conditions and separate the effects of harvesting from historic land uses and current activities on the watershed.

In their discussion of sediment risk management research, Nietch, Borst, and Schubauer-Berigan (2005) acknowledge the uncertainties in sediment source allocation models, BMP performance estimation, watershed scaling and *in situ* sediment monitoring. They suggest that focusing on watersheds and the accompanying space and time scales within a framework that combines assessment and management strategies would help to show linkages among specific projects.

Research from across Canada indicates that Riparian Management Areas (RMAs) act as effective sediment filters on forested landscapes. However, research also suggests that effects of forestry operations on erosion and sedimentation are less the result of timber harvesting and forest management operations and more the result of road and stream crossing construction and improvement. With respect to sediment loading, and depending on the amount of harvesting on a landscape, the benefits of RMA guidelines may be primarily related to their effects on road system design (e.g., roads located outside of RMAs).

Erosion and sedimentation associated with roads and stream crossings can be controlled effectively in most circumstances by implementing BMPs (Grayson et al. 1993; Ice 2005; NCASI 2009; Rummer 2004; Croke and Hairsine 2006; Aust 1994). Examples of relevant BMPs include: constructing roads sufficiently away from water bodies to minimize discharge of fill material into water; designing stream crossings to prevent the restriction of flood flows; stabilizing and maintaining fills to prevent erosion from the road right-of-way; minimizing the operation of equipment in the stream channel; gravelling and revegetating the road surface to reduce sediment loss; implementing cross-draining to avoid ponding or impoundment on the upstream side of a road; minimizing fill to avoid impeding overland flow without causing road failure through rutting; selecting appropriate road drainage spacing to avoid drain scour and hence, sediment delivery to streams; preventing gully formation at the drainage outlet; minimizing road grades; minimizing road stream crossings and using bridges, culverts or fords at such crossings; cutting trees adjacent to roads so that they dry more rapidly; installing and/or decommissioning stream crossings during low flow and dry weather conditions; not locating roads on unstable slopes and ensure that road drainage systems are not connected to stream networks.

Alila and Beckers (2001) discuss the value of experimental watersheds and models in assessing the effectiveness of BMPs and other management guidelines in maintaining watershed processes. Santhi et al. (2006) applied the Soil and Water Assessment Tool (SWAT) watershed model to quantify the effects of implementing BMPs on sediments and nutrients and found from their simulations of pre- and post- BMP implementation that the benefits were tangible at the watershed level. Matteo, Randhir, and Bloniarz (2006) evaluated watershed-wide effects using simulation modelling to examine the effectiveness of BMPs on urban water quality, quantity, and open space in rural, suburban, and urbanized environments. They found that forest BMPs make the watershed more adaptive to adverse conditions. Zhen et al. (2006) developed software that uses GIS information, integrates BMP processes simulation models and applies system optimization techniques for BMP planning and selection for watersheds. The modelling system was used to identify the most cost-effective combinations of management practices to help minimize the frequency and size of runoff events to the Anacostia River in Washington.

Topographic indicators are recognized for influencing the mobilization of specific nutrients. For example, depressions and flat zones may be source areas for dissolved organic carbon, dissolved organic nitrogen, and total phosphorus, whereas gentle slopes with large upslope contributing areas may be source areas of NO_3-N and NH_4-N (Creed and Beall 2003). Drainage ratio has been used as an indicator for changes in the surface water quality of lakes in response to natural and/or anthropogenic disturbances. Lakes with large drainage ratios (large watershed area:small lake area) have enhanced potential for nutrient loading (via surface drainage) and short water residence times, and lakes with small drainage ratios (small watershed area:large lake area) have reduced nutrient loading and longer residence times. This indicator was correlated to surface water quality parameters on both the Boreal Shield and Boreal Plain (see Pinel-Alloul et al. 2002).

Creed and Band (1998a) used models to interpret data on exports of nitrogen from forests to streams at the Turkey Lakes Watersheds (TLW) in Ontario. They hypothesized that N flushing in watersheds was regulated by topography and would occur when the water table was at or near the surface in soils that had accumulated N (Creed et al. 1996). To evaluate the hypothesis, they created a process-based model in which NO_3-N export was a function of topographic indices and estimated effects of harvest on N mineralization and nitrification (Vitousek and Melillo 1979; Reynolds and Edwards 1995). The investigators found that export of dissolved inorganic and organic N from the TLW was highly variable, but that field data were generally consistent with their model of inorganic N export mechanisms (Creed and Band 1998b). They suggested that with some improvements, their model could be used to assess NO_3-N exports in other regions and at larger scales.

4.3 Riparian Management Areas

Studies at the watershed and stand levels have demonstrated that areas directly adjacent to streams and lakes have important ecological functions that maintain water quality. Functions of riparian areas include moderation of stream temperature and light (e.g., Brosofske et al. 1997; Curry, Scruton, and Clark 2002; MacDonald, MacIsaac, and Herunter 2003); filtration of sediments (e.g., Castelle, Johnson, and Connolly 1994; Gomi, Moore, and Hassan 2005; Kreutzwieser and Capell 2001); regulation of nutrients entering streams (e.g., Ensign and Mallin 2001; Castelle, Johnson, and Connolly 1994); and inputting of fine and large organic debris into streams (e.g., Bilby and Likens 1980; Gregory et al. 1991; Kreutzweiser, Capell, and Beall 2004).

It is now common practice in North America to establish riparian management areas (RMAs) that are managed according to local government guidelines in order to control adverse effects on water resources of timber harvest and other forestry practices. Lee et al. (2004) examined regional differences in RMA guidelines across North America. They divided provinces and states into six broad ecological regions and compared guidelines within and among these regions. They found that regions varied in guideline complexity. The Pacific region tended toward more complex guidelines, while the Midwest retained relatively simple guidelines.

RMA guidelines in many jurisdictions consider various site-specific factors that are used to modify RMA width and other parameters (Lee, Smyth, and Boutin 2004). Common modifying factors include water body type, presence of fish, and slope. In the Pacific Ecozone, flow rate and downstream sediment threat were among the factors influencing RMA width. Drainage basin area was noted as a modifying factor used in both the Boreal and Northeast regions.

Harvest within RMAs is permitted in all Canadian provinces except Newfoundland and Labrador, where no harvesting is allowed (Decker 2004; Goose et al. 1998; Scruton et al. 1997). In Manitoba, approval to harvest in RMAs must be obtained from an Integrated Resource Management Team (Manitoba Natural Resources 1996). Manitoba is also the only province to consider terrestrial habitat in their guidelines for RMA width.

4.4 Use of Indicators in Watershed Management

In context of sustainable forest management in Canada, a criterion is a category or class of processes characterized by a set of indicators. These indicators are quantitative or qualitative parameters monitored periodically to assess change (Canadian Forest Service 1995; Buttle, Creed, and Moore 2005). Essential attributes of such indicators include a) scientifically sound; b) operationally feasible; c) socially responsible and internationally credible; d) measured following a standard method; e) easily measurable and cost effective; f) easily interpretable and directly linked to environmental changes generated by local management activities, but relatively insensitive to more global sources of variation; g) integrated; and h) linked to prescriptions (Kneeshaw et al. 2000).

The Canadian Council of Forest Ministers (CCFM 1997) has identified sustainable forest management criteria, including the conservation of soil and water resources. Several studies have reviewed progress in development and use of indicators of soil protection and water quality in sustainable forestry (Curran, Maynard, et al. 2005; Curran, Miller, et al. 2005; Cline et al. 2006; Carver 2001; Hartanto et al. 2003)

Several authors have suggested using extent of harvesting in a watershed as an index of hydrologic effects (Putz et al. 2003). For example, MacGregor (1994) calculated a 4.5 mm increase in annual streamflow for every percent removal of forest cover within the watershed. However, hydrologic theory predicts that the magnitude and duration of harvesting effects on water yield will vary from one location to another due to differences in disturbance, topography, climate, vegetation type, and soil hydraulic properties.

The government of British Columbia has adopted a method called the Interior Watershed Assessment Procedure (IWAP) to assess cumulative effects from past forest harvesting practices (Carver 2001). Some of the indicators employed in IWAP reflect the extent of harvesting, road density, channel/riparian information and the density of landslides. Carver (2001) argues that one index cannot adequately represent the hydrologic complexity within watersheds, and that the suite of indicators used in IWAP has potential to improve risk assessment and adaptive management.

Equivalent Clearcut Area (ECA) is an indicator used in IWAP to estimate the potential hydrologic effects of forest development on peak flow (Scherer 2001) and is defined as “the area that has been harvested, cleared or burned, with consideration given to the silvicultural system, regeneration growth, and location within the watershed” (B.C. Ministry of Forests 2001). In a meta-analysis of studies of hydrologic effects of harvesting, Scherer (2001) found that relationships between ECA and increases in peak and annual flow are not very strong, and that watershed size does not explain variability in hydrologic response to ECA. Scherer (2001) concluded that ECA should not be used in isolation as an indicator of hydrologic effects until mechanisms that generate and influence streamflow are more clearly understood.

H60 is the elevation above which 60% of a basin lies. ECA calculations in IWAP consider the location of harvest units relative to H60 because a) snow typically covers the upper 60% of a watershed at the time of peak flow in interior BC; and b) it is assumed that timber harvesting above the H60 line will result in greater peak flows than harvesting below this line (Gluns 2001; Whitaker et al. 2002). A peak flow hazard index of 1 is assigned to cut blocks below the H60 line and an index of 1.5 is assigned to those above.

Devito et al. (2000) proposed several indicators for use in assessing hydrologic responses of lake watersheds in the boreal plain. Indicators were developed in context of a conceptual model of surface and subsurface flow paths from source areas to the lake.

5.0 KNOWLEDGE GAPS AND RESEARCH NEEDS

5.1 Riparian Management Areas

RMAs serve multiple and often competing purposes. Lack of fundamental knowledge about RMA functions in boreal forests suggests limited understanding of the effectiveness of alternative designs and the possibility that fixed-width guidelines result in under-protection or over-protection of aquatic resources (Buttle, Creed, and Moore 2005; Smith, Russell, et al. 2003).

There is a need for more research into the roles of RMAs in mitigating the full range of ecological effects of forest harvesting (Buttle 2002; Prepas et al. 2001). This research must have a large field component since many ecological functions of riparian zones will be difficult if not impossible to capture in simulation models (Alila and Beckers 2001). However, Chen, Carsel, et al. (1998) and Chen, McCutcheon, et al. (1998) developed a model that can be used to simulate stream temperatures and assess the effects of riparian management scenarios by considering shading dynamics of topography and riparian vegetation.

Recent work by Vidon and Hill (2004) demonstrated an approach to understanding hydrologic processes that affect the water quality functioning of riparian zones. They examined several different riparian areas and were able to determine the interacting effects on riparian functions of upland aquifer size, topography and bedrock characteristics. Their model identifies hydrologic categories of riparian zones, each with a varying capacity to buffer streams from contaminant inputs.

5.2 Need for Long-Term Data Sets

Canadian watershed-level research is currently limited by a lack of new long-term monitoring projects or the discontinuation of existing projects, since watershed-level studies require long duration and high quality data (Buttle, Creed, and Moore 2005; Sidle 2006). As Buttle, Creed, and Moore (2005) pointed out, management and science must co-operate so that adaptive ecosystem management strategies can be studied.

As noted by Buttle and Metcalfe (2000), many of the earlier watershed-level studies in Canada collected data for a relatively short period of time (e.g., two or three years); hence, such studies provided only a limited ability to assess the potential effects of disturbance on basin hydrological dynamics against the backdrop of natural hydrological variation. Long-term monitoring of runoff responses to annual and seasonal variation in precipitation and evapotranspiration is necessary to determine the similarity of paired basins prior to experimental manipulation and to fully assess post-treatment watershed responses to disturbance and recovery. For example, Devito, Creed, and Fraser (2005) reported that it could take up to 10 years post-harvest to achieve aspen regeneration sufficient to reach pre-harvest transpiration capacity on the Boreal Plain.

5.3 Subsurface Hydrology

Water flow paths within a basin exert a strong control on water and solute fluxes.

- Alila and Beckers (2001) note that the ability of a model to predict the quantity of flow intercepted by a road depends on whether runoff is generated through the correct overland and/or subsurface flow mechanisms.
- Jordan (2006) noted that impermeable geology can cause most runoff to be routed to streams via surface and shallow subsurface flow. This results in high connectivity between forest roads and stream channels with the potential of increased sediment delivery to streams.
- Evans et al. (2000) found that subsurface water plays an important role in regulating exports of dissolved phosphorus from soils to streams.
- Price et al. (2005) summarize the importance of groundwater and surface water interactions in the study of wetland hydrology. They note that interactions of wetlands with groundwater can influence the amplitude and duration of base flow and water-level fluctuations.

Temporal and spatial variability in flow paths should be taken into account when monitoring and modeling watershed responses to disturbance (Monteith et al. 2006a; Welsh et al. 2001; Beven and Kirkby 1979; Buttle et al. 2001). However, interactions between overland flow and variable saturated subsurface flow are complex and challenging to represent in mathematical models.

Several investigators have examined the feasibility of using topographic indices as surrogates for information about water flow paths in watershed models. As discussed in Section 4.1, topographic indices have not been reliable predictors of hydrologic processes and watershed responses to disturbance.

Buttle, Creed, and Moore (2005) suggest the first step in understanding subsurface hydrology is to determine what, if any, relationship exists between surface features and subsurface flow paths. Similarly, Devito et al. (2005) suggest that information on bedrock and surface geology could indicate the likelihood that subsurface flow may dominate hydrologic processes, and the scale at which it may occur.

Sidle (2006) suggested that ignoring subsurface flow can introduce major errors in models of the timing of headwater storm runoff and fluxes of nutrients and pollutants to streams. Todd, Buttle, and Taylor (2006) noted that modelers often do not have access to data about causes of observed changes in streamflow. For example, a period of low flow measured in a watershed study might be modeled as a response to low connectivity to groundwater when the real cause is a blocked culvert.

Residence time represents the average length of time it takes water in precipitation to move from the ground surface to a point of sampling in a stream or lake. Longer residence time implies greater opportunities for water in subsurface flow paths to undergo geochemical transformation by interacting with soil and subsurface strata (Hill 1990; Anderson et al. 1997).

Monteith et al. (2006b) used a paired watershed study at the Turkey Lakes Watersheds (undisturbed basin and 80-90% tree removal in treatment basin) to examine whether Cl^- is a suitable surrogate tracer for ^{18}O to assess how harvesting has affected groundwater residence times. They found Cl^- to be an adequate surrogate for ^{18}O for use in contrasting event water (water from a single precipitation event) from pre-event components. Use of Cl^- increased the number of locations at which groundwater residence times could be estimated. Results indicated that event water made a significantly larger contribution to total streamflow and peak streamflow in the harvested watershed than in the control watershed. However, differences between watersheds in residence time were less apparent during snowmelt and not sufficient to support a conclusion that an effect of harvesting effects had occurred.

5.4 Scaling Issues

Hydrological processes occur at a wide range of scales and can span approximately eight orders of magnitude in space and time (Blöschl and Sivapalan 1995). To scale means to transfer information from a given scale to either a smaller or larger scale in either space or time. The concept of scaling is intricately linked to challenges associated with understanding cumulative effects of forestry practices on aquatic ecology, floods, water supply and generation of hydroelectricity (Buttle and Metcalfe 2000; Coats and Miller 1981).

There are a number of difficulties in up-scaling information (e.g., from the stand-level to the watershed-level; or from small watersheds to larger watersheds). Variables of interest (e.g., streamflow) are affected by interactions among several processes (e.g., rainfall, transpiration, snow melt, infiltration, etc.). Moreover, watershed characteristics and processes vary in space and time. Although processes should be observed at the scale they occur, often questions that are asked regarding responses at the watershed level can only be answered using information at a small scale (e.g., point samples of precipitation, streamflow, soil moisture, etc.). As well, processes important at one scale may not necessarily be important at other scales (Blöschl and Sivapalan 1995). Sivapalan et al. (2003b) believe this to be the main problem in scaling models; the change of dominant processes with changing scales.

A recurring opinion among researchers is that small plot studies (at the stand level) should be integrated within watershed-level studies to enable development and testing of mechanistic models of watershed processes and responses to management, climate, and other drivers of change. This opinion is reflected in the design of recent watershed studies in Canada (e.g., Whitehead and Robinson 1993; McCulloch and Robinson 1993; Alila and Beckers 2001; Buttle, Creed, and Moore 2005; Putz et al. 2003; Monteith et al. 2006a, 2006b; Van Damme et al. 2003; Thyer et al. 2004).

Sivapalan (2003) discussed integration of studies at smaller and larger scales in terms of bottom-up and top-down approaches. A bottom-up approach emphasizes field studies to gain understanding of processes controlling hydrologic responses of interest. The top-down approach involves examining larger-scale data (e.g., rainfall and runoff) with or without the benefit of detailed information on processes operating at smaller scales. Sivapalan, Blöschl, et al. (2003) discuss the advantages and disadvantages of both approaches, but consider them to be complimentary and not competing.

Devito et al. (2005) discuss the scaling concept of defining the hydrologic response unit (HRU) and identify potential problems with defining HRU solely on the basis of surface topography. They note that water table gradients can slope against topography and argue for consideration of several factors when defining an HRU. In order of decreasing spatial scale, these factors include climate, bedrock geology, surficial geology, soil type and depth, topography and drainage network. Hydrologists should determine which factor explains the greatest variation in the dominant hydrologic processes without masking the influence of factors lower in the order. The scale at which dominant hydrologic processes act must be considered in order to determine the most suitable methodological and modelling strategies for a given region (Devito et al. 2005). This approach encourages explicit determination of the scale at which water resources interact with the surrounding environment without any *a priori* assumptions about the watershed area.

6.0 CONCLUSIONS

Research in Canada and elsewhere has shown that effects of forest management on hydrology and water quality are highly variable in both magnitude and duration. Factors such as topography, sub-surface geology, forest type, watershed composition and extent of harvest all play a part, and are difficult to separate. Nonetheless, some authors have suggested that their results should be used to draw conclusions about management guidelines. While this may be useful in some cases, care should be taken to consider the limited transferability of results within and between regions. For example, Creed and Band (1998 a, 1998b) discussed sources of natural variation in forest nitrogen cycles that would make the simple extrapolation of results from a single basin to an entire region a questionable exercise.

Canada's forestry community has made substantial investments in more than 25 research watersheds distributed across the nation's forested ecozones. Nevertheless, additional research is needed to better define effects of forest management and support cost-effective improvements in environmental stewardship.

Watershed studies should be conducted in the ecozones in which their results will be applied. Long-term studies are essential. Established watershed research sites should be maintained and new sites should be established where needed to fill gaps in the current network.

When evaluating priorities for new research sites, explicit consideration should be given to processes of regional significance—e.g., fog drip in the Maritimes; permafrost in the Boreal Cordillera; large-scale harvesting and fire disturbance occurring in the Boreal Shield and Boreal Plains (Buttle, Creed, and Moore 2005). Devito et al. (2000) noted that watershed studies in the eastern portion of the boreal forest (humid climate and comparatively simple hydrogeologic settings) lack transferability to western boreal forests with drier climates, deeper surficial glacial deposits, and larger groundwater flow systems.

Both watershed-level and stand-level studies play a vital role in our understanding of the potential effects of forestry practices on water quantity and quality. Many authors have expressed the ongoing need for the combination of these approaches in the development of models that allow the effective extrapolation of knowledge across scales, and from one region to another. For example, Buttle, Creed, and Moore (2005) stated that the results from many watershed studies are empirically based and therefore cannot be extrapolated in either time or space. They believe that in order to discriminate between the "noise" of individual water responses to climatic variability and the "signal" (actual response), process-based monitoring and modelling approaches must be incorporated into the experimental design of watershed studies.

Complex interactions between hydrology, chemistry and ecology ensure that process studies remain a vital element of watershed studies. Processes and responses to treatments must be examined at their appropriate scales to remove bias that can occur on smaller scales. The watershed is the scale at which cause-and-effect relationships can be established from the stand point of ecosystem responses to disturbance (e.g., flooding, drought, and drinking water quality).

Indicators based on simple measures of topography and harvesting are being used to monitor effects of forestry practices on hydrology and water quality. Such indicators have limited validity and their use as surrogates for specific field data may limit our understanding of relevant hydrological processes. Further, it is unclear what level of protection is required to meet environmental goals, and which indicators are most appropriate for quantifying that goals are being met. More generally, there is a need to better define the significance of watershed responses to forest management with respect to effects on organisms and ecosystems (Scherer and Pike 2003; Buttle, Creed, and Moore 2005).

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