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THE IMPACT OF CLIMATE CHANGE ON RIVERS AND RIVER PROCESSES IN CANADA

P. Ashmore and M. Church

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Cover illustration

View of the à Mars River near La Baie, in the Saguenay valley, Quebec, following extreme flooding during July 18 to 21, 1996. At this section of the river, floodwaters widened the channel up to several times and caused the collapse of a bridge. Photograph taken on July 27, 1996, by G.R. Brooks. GSC 1997-42EE

Critical reviewers

G. Brooks
B. Rannie

Authors' addresses

P. Ashmore
Department of Geography
University of Western Ontario
London, Ontario N6A 5C2

M. Church
Department of Geography
University of British Columbia
Vancouver, British Columbia V6T 1Z2

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FOREWORD

Change may be a welcomed or feared challenge. It is welcomed when the outcome is known and expected to be good; it is feared when the outcome is unknown or expected to be bad. Global climate change is the most significant change currently facing humanity. Climate change may be feared, because of the many unknowns that are involved. What will the rate and level of climate change be? How will global climate change be distributed, or impact on various regions? How will the complex Earth ecosystems be affected? Most importantly, how will humanity adapt?

One element of the global climate change picture that resides within the mandate of the Geological Survey of Canada is surface geological processes. Surface geological processes include the various forces which act to change the Earth's surface. The ones we are most familiar with are water and wind. These act on the surface by eroding materials from one place and depositing them in another. Climate plays a major role in driving these processes and changes in climate will result in changes in their nature and intensity.

Through time we have gained knowledge which allows us to predict the impact of surface geological processes and hence to mitigate or avoid their harmful effects. For example, application of process knowledge has resulted in development of local practices such as river flow regulation for flood control, hydroelectricity, drinking and municipal water supplies, irrigation, and recreational use. If future global climate changes result in changes in water discharge or sediment supply to rivers, then it may be necessary to make adaptive responses to these changes. Developing and implementing new adaptation strategies requires research, planning, and time. Therefore, the sooner we gain information on what to expect, the better prepared we will be to take action when change occurs.

The Geological Survey of Canada is preparing overview reports on the more common geological processes occurring in Canada. Each of these reports includes a map showing the aerial distribution of the process activity today and areas where this process is most sensitive to climate change. Each looks at how different factors control process activity, discusses the sensitivity to climate change, and considers the impact of different aspects of the process on human activity. These are not intended as research documents which predict what might be expected in each part of the country, but as warnings to draw attention to potential 'hotspots' or areas where the process in question is likely to be most affected by global climate

AVANT-PROPOS

Le changement est un défi qu'on accueille à bras ouverts ou qu'on redoute. Il est le bienvenu lorsque ses effets sont connus et qu'on prévoit qu'ils seront positifs; il est craint lorsque ses résultats sont inconnus et qu'on pressent qu'ils seront nuisibles. Le changement climatique de la planète constitue le changement le plus important auquel l'humanité est confronté actuellement. Il nous fait peur en raison des nombreux impondérables qu'il recèle. À quel rythme et à quel niveau se fera-t-il ? Comment sera-t-il réparti sur la planète ou quel sera son impact sur les diverses régions? Comment affectera-t-il les écosystèmes complexes de la Terre? Et avant tout, comment l'humanité va-t-elle s'y adapter?

Les processus géologiques superficiels sont un élément du changement climatique planétaire faisant partie du mandat de la Commission géologique du Canada. Ces phénomènes comprennent les diverses forces qui exercent une action sur le changement de la surface de la Terre. Les processus qui nous sont les plus familiers sont l'eau et le vent. Ces deux éléments influent sur la surface terrestre en érodant les matériaux situés dans un endroit et en les déposant ailleurs. Le climat joue un rôle de premier plan dans l'activation de ces processus; les changements climatiques modifieront leur nature et leur intensité.

Les connaissances que nous avons acquises au cours des ans nous permettent de prévoir quel sera l'impact des processus géologiques superficiels et d'en atténuer les effets néfastes ou de les éviter. La connaissance de ces processus a permis d'élaborer des pratiques locales, telles que la régularisation du débit fluvial pour contrôler les crues, l'hydroélectricité, l'alimentation en eau potable et l'eau destinée aux agglomérations ou utilisée à des fins de plaisance et l'irrigation. Si les futurs changements climatiques planétaires entraînent des modifications dans le débit de l'eau ou dans l'apport en sédiment des cours d'eau, nous devrons sans doute chercher des réponses adaptées à ces changements. L'élaboration et la mise en oeuvre de nouvelles stratégies d'adaptation ne peut se faire sans recherche, planification et temps. Par conséquent, la rapidité que nous mettrons à acquérir de nouvelles données sur ce à quoi nous devrons nous attendre, nous permettra de mieux nous préparer à prendre des mesures lorsque ces changements se produiront.

La Commission géologique du Canada prépare actuellement des rapports qui donnent une vue d'ensemble des processus géologiques les plus courants au Canada. Chaque rapport renferme une carte présentant la répartition par zone de l'activité actuelle de ces processus et les zones où ils sont le plus sensibles au changement climatique. Chacun examine comment divers facteurs contrôlent l'activité de ces processus et étudie leur sensibilité au changement climatique ainsi que l'incidence de ces différents éléments sur l'activité humaine. Il ne s'agit pas de documents de recherche dont le but est de prévoir ce à quoi on peut s'attendre dans chaque région du pays, mais de mises en garde afin d'attirer l'attention sur les «points chauds» potentiels ou sur les régions où le processus en question est susceptible d'être le plus fortement affecté par le changement climatique change. The anticipation is that this first step will foster and focus further research which will determine potential impacts more precisely and provide information for planning adaptive measures.

The other reports published in this series are: *Sensitivity of eolian processes to climate change in Canada* (GSC Bulletin 421), *Sensitivity of the coasts of Canada to sea-level rise* (GSC Bulletin 505), and *Geomorphological processes in alpine areas of Canada: the effects of climate change and their impact on human activities* (GSC Bulletin 524).

On a final note, readers should be aware that the review manuscript for this publication was submitted in 1995. Consequently, some aspects of the work presented here may have been superseded by subsequent work. This is especially true in the case of the effects of climate change on streamflow for which there are now more sophisticated predictions.

S.A Wolfe and R.J. Fulton,
Co-ordinators,
Impact of Global Climate Change on Geological
Processes Project

planétaire. Ce que nous espérons, c'est que cette première étape va inciter les chercheurs à effectuer d'autres recherches en profondeur qui détermineront avec plus de précision les incidences potentielles et qui fourniront des données permettant de planifier les mesures d'adaptation.

Les autres rapports publiés dans cette collection sont les suivants : *Sensitivy of eolian processes to climate change in Canada* (Bulletin 421 de la CGC), *Sensitivity of the Canadian coast to sea-level rise* (Bulletin 505 de la CGC) et *Geomorphological processes in the alpine areas of Canada: the effects of climate change and their impacts on human activities* (Bulletin 524 de la CGC).

Enfin, nous avisons les lecteurs que le manuscrit de l'article contenu dans ce bulletin a été soumis en 1995. Par conséquent, il se peut que certains aspects des travaux présentés ici soient dépassés par des travaux exécutés ultérieurement. Ceci est tout particulièrement le cas des incidences du changement climatique sur l'écoulement fluvial dont les prévisions sont maintenant plus perfectionnées.

S.A Wolfe et R.J. Fulton
Coordonnateurs
Projet d'étude des répercussions du changement climatique à
l'échelle du globe sur les processus géologiques

Preface

This is the fourth overview in the Geological Survey of Canada's project: "Impact of Global Climate Change on Geological Processes". These overviews provide information on the possible impacts of global change and the potential magnitude of the problem.

This bulletin examines the relationship between climate and fluvial processes in Canada. A major assertion by the authors is that "a warmer Earth will be a wetter Earth". Whereas some regions may become more arid due to global climate change, there is likely to be greater circulation of water in the atmosphere, in the rivers, and in the oceans of the world as a result of global warming. Thus, it is essential the we draw our attention to the potential impacts of climate change on fluvial processes in Canada.

This report describes fluvial and related geological processes, and discusses how predicted global climate change could result in changes to water discharge and sediment supply to rivers, as well as modifications to the rates of fluvial erosion and sedimentation. The authors utilize their knowledge of fluvial processes to differentiate regions within Canada, and to highlight the sensitivity and vulnerability of these regions to climate change.

This report was prepared under the auspices of the Global Change Program of the Geological Survey of Canada.

M.D. Everell
Assistant Deputy Minister
Earth Sciences Sector

Préface

La présent synopsis est le quatrième publié par la Commission géologique du Canada dans le cadre de son Projet d'étude des répercussions du changement climatique à l'échelle du globe sur les processus géologiques. Ces documents renferment des données sur les incidences possibles du changement climatique et sur l'ampleur possible du problème.

Le présent bulletin examine le lien qui existe au Canada entre les processus climatiques et les processus fluviatiles. Les auteurs apportent une confirmation d'importance, à savoir que «Une Terre plus chaude sera une Terre plus arrosée». Alors que le changement climatique planétaire rendra certaines régions plus arides, le réchauffement de la planète accroîtra la circulation de l'eau dans l'atmosphère, les cours d'eau et les océans du globe. Il est donc essentiel que nous portions attention aux incidences potentielles du changement climatique sur les processus fluviatiles du Canada.

Ce rapport décrit les processus fluviatiles et les processus géologiques qui leur sont associés, et explique comment les changements climatiques prévus à l'échelle de la planète vont modifier le débit de l'eau et l'apport en sédiments dans les cours d'eau ainsi que le taux d'érosion fluviale et de sédimentation. Les auteurs se basent sur leurs connaissances des processus fluviatiles pour différencier les régions du Canada et pour mettre en évidence la sensibilité et la vulnérabilité de ces dernières au changement climatique.

Ce document a été préparé dans le cadre du Programme sur les changements à l'échelle du globe de la Commission géologique du Canada.

M.D. Everell
Sous-ministre adjoint
Secteur des science de la Terre

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THE IMPACT OF CLIMATE CHANGE ON RIVERS AND RIVER PROCESSES IN CANADA

Abstract

Rivers are sensitive to natural climate change as well as to human impacts such as flow modification and land-use change. Climate change could cause changes to precipitation amounts, the intensity of cyclonic storms, the proportion of precipitation falling as rain, glacier mass balance, and the extent of permafrost; all of which affect the hydrology and morphology of river systems. Changes to the frequency and magnitude of flood flows present the greatest threat.

Historically, wetter periods are associated with significantly higher flood frequency and magnitude. These effects are reduced in drainage basins with large lakes or glacier storage. Alluvial rivers with fine-grained sediments are most sensitive, but all rivers will respond, except those flowing through resistant bedrock. The consequences of changes in flow include changes in channel dimensions, gradient, channel pattern, sedimentation, bank erosion rates, and channel migration rates.

The most sensitive and vulnerable regions are in southern Canada, particularly those regions at risk of substantial increases in rainfall intensity and duration. In northern rivers, thawing of permafrost and changes to river-ice conditions are important concerns. The type and magnitude of effects will be different between regions, as well as between small and large river basins. Time scales of change will range from years to centuries.

These changes will affect the use that we make of rivers and their floodplains, and may require mitigative measures. Radical change is also possible. Climatic impacts will be ubiquitous and will be in addition to existing and future direct human impact on streamflow and rivers.

Résumé

Les cours d'eau sont sensibles au changement climatique naturel et aux facteurs anthropiques, tels que la modification de leur écoulement et le changement d'affectation des terres. Le changement climatique est susceptible de modifier la hauteur des précipitations, l'intensité des cyclones, la proportion des précipitations tombant sous forme de pluie, le bilan massique des glaciers et l'étendue du pergélisol, phénomènes qui ont tous une incidence sur le régime hydrologique et la morphologie des réseaux hydrographiques. Les modifications de la fréquence et de l'ampleur des débits de crues constituent le danger le plus grand.

Sur le plan historique, les périodes de fortes précipitations sont associées à des crues dont la fréquence et l'ampleur sont considérables. Leurs effets sont moindres dans les bassins versants comportant de vastes lacs ou des glaciers. Les rivières alluviales dont le lit renferme des sédiments à grain fin sont les plus vulnérables, mais tous les cours d'eau seront affectés à l'exception de ceux qui s'écoulent sur un substratum rocheux résistant. Les conséquences de ces changements dans le débit sont, entre autres, la modification de la taille, du gradient et du tracé des cours d'eau, de la sédimentation, des taux d'érosion des berges et des taux de migration des lits.

Les régions du sud du Canada sont les plus sensibles et les plus vulnérables, en particulier les régions qui risquent d'être soumises à des précipitations d'une intensité et d'une durée considérablement accrues. Les facteurs les plus préoccupants dans les cours d'eau du Nord sont le dégel du pergélisol et les modifications que subiront les glaces de rivière. Le type et l'ampleur de ces effets seront différents selon les régions et la taille des bassins fluviaux. Ces changements s'échelonneront sur des années, voire des siècles.

Ces changements auront des conséquences sur l'utilisation que nous ferons des cours d'eau et de leurs plaines d'inondation, et pourraient nécessiter la prise de mesures d'atténuation. On pourrait aussi assister à un changement radical. Les incidences sur le climat seront ubiquistes et s'ajouteront aux incidences directes actuelles et futures des facteurs anthropiques sur l'écoulement fluvial et les cours d'eau.

SUMMARY

Climatic change is likely to cause changes to river systems in Canada. The major effect on rivers will be through changes in precipitation amount, intensity, and type. This will lead to changes in streamflow regime and, hence, stream processes. The major concern is with climate wetting rather than climate warming because streamflow is much more sensitive to changes in precipitation than to changes in temperature. Potential changes to hydrological processes include increased precipitation, the proportion falling as rain, shifts in cyclonic storm tracks, increased intense rain, reductions in snow accumulation, reduction of glacier mass, permafrost thawing, and changes to the dominant flood-generating processes. These could all affect the dynamics and morphology of Canada's rivers. This is a concern for river resources and hazards. The effect on the frequency-magnitude distribution of flood discharges is especially important for anticipating changes in river morphology and stability.

This report neither attempts to predict change nor assumes a particular climate scenario. It is intended to promote awareness of the possibility of change and provides the basis for anticipating the consequences, at a regional scale, for the future utilization of rivers and their valleys. Insight into the likely changes to streamflow and fluvial processes as a consequence of climate change are largely matters of qualitative inference based on historical and spatial analogues, physical principles, and summary predictions from climate models. The likely type and direction of change are identified, but these are based on assumptions and models which may not bear the test of time. The only assumption made here is that during the next century human activity will lead to overall warming accompanied by a more active hydrological cycle.

Historical records show that in many regions of Canada fairly small, decade-scale changes in annual precipitation are associated with larger changes in average streamflow, and substantial upward shifting of flood frequency curves. Thus, there is a concern that future increased precipitation will be amplified by the hydrological system to produce much larger increases in flood discharges. These could cause substantial changes to river channel morphology, dynamics, and stability. There is also the possibility that reduced winter snowpack will reduce the size of snowmelt floods.

SOMMAIRE

Le changement climatique modifiera vraisemblablement les réseaux hydrographiques du Canada. Les changements dans le type, l'intensité et le volume des précipitations seront les principaux facteurs qui affecteront les cours d'eau. Ils entraîneront des modifications dans le régime d'écoulement et donc dans les processus fluviatiles. Ce qui est le plus préoccupant, ce n'est pas le réchauffement du climat mais son humidification, car le réseau hydrographique est de loin plus sensible aux changements des précipitations qu'aux changements de température. Les modifications éventuelles que subiront les processus hydrologiques sont, entre autres, l'accroissement des précipitations et la proportion qui tombera sous forme de pluie, les changements de direction de la trajectoire des précipitations cycloniques, l'augmentation des pluies intenses, la réduction du manteau neigeux et de la masse des glaciers, le dégel du pergélisol et les changements auxquels seront soumis les principaux processus à l'origine des crues. Tous ces facteurs sont susceptibles d'affecter la dynamique et la morphologie des cours d'eau du Canada et donc les ressources des cours d'eau, et de provoquer aussi des risques. Leur incidence sur la répartition de la fréquence et de l'ampleur des débits de crue est particulièrement importante pour prévoir les changements dans la morphologie et la stabilité des cours d'eau.

Le but du présent rapport n'est pas de prévoir les changements ni de simuler un scénario particulier sur le climat, mais de promouvoir une prise de conscience sur la venue possible de ces changements. Notre intention est également de fournir des données de base permettant de prévoir, à l'échelle régionale, les conséquences de ces changements sur l'utilisation future des cours d'eau et de leurs vallées. Un aperçu des modifications possibles de l'écoulement fluvial et des processus fluviatiles résultant du changement climatique est en grande partie question de déduction qualitative qui est basée sur des analogues historiques et spatiaux, sur des principes physiques fondamentaux et sur des prévisions sommaires tirées de modèles de climat. Le type et la direction du changement possible sont mis en évidence, mais ils sont fondés sur des hypothèses et des modèles qui pourraient ne pas résister à l'épreuve du temps. La seule hypothèse que nous émettons dans ce document est qu'au cours du prochain siècle, l'activité humaine entraînera un réchauffement de la planète qui sera accompagné d'un cycle hydrologique plus actif.

Les données historiques révèlent que dans de nombreuses régions du Canada, les modifications relativement minimes que subissent les précipitations annuelles, à l'échelle d'une décennie, sont associées à des changements plus importants de l'écoulement fluvial moyen et à une élévation sensible des courbes de fréquence des crues. Par conséquent, il est à craindre que l'accroissement des précipitations ne soit amplifié par le système hydrologique, ce qui augmentera de façon sensible les débits de crue. Ces phénomènes pourraient modifier considérablement la morphologie, la dynamique et la stabilité des cours d'eau. Il se pourrait aussi que la réduction du manteau neigeux l'hiver réduise le volume des crues provoquées par la fonte des neiges.

River morphology and dynamics are essentially controlled by the water and sediment supplied from the surrounding landscape. The water and sediment delivery can be altered by climate change and also artificially by land use or flow regulation. Basic principles of fluvial geomorphology, together with case studies of natural and artificial flow regime changes, are sufficient to show that rivers are sensitive to changes in flow and sediment load. Furthermore, the magnitude and direction of change can be anticipated with some knowledge of the changes to flow and sediment supply. For example, increased streamflow causes channel enlargement, increased channel migration rates, channel incision, and changes to channel pattern. Fine-grained, alluvial channels are the most sensitive, whereas bedrock or boulder channels are least sensitive.

In Canada many rivers flow through erodible glacial deposits and have the superficial appearance of alluvial streams. But these semialluvial streams may not be as responsive to streamflow changes as true alluvial channels. At the same time, sufficiently small increases in streamflow may take them across a threshold from their current inactive state into a much more active and unstable state. Thus, even with knowledge of the expected changes to streamflow regime, there is uncertainty in the expected response of rivers.

The hydrological and geomorphic response to climate change will differ between regions. The map depicting the potential impact of climate change on rivers identifies major physiographic and hydrological regions within which the hydrological response is expected to be fairly homogeneous. These regions are also differentiated on the basis of topography, surficial materials, permafrost, and geology, all of which affect fluvial processes and response; however, within each region there are a variety of types of rivers which will respond differently to a given climate change. The response will also differ between drainage basins of different sizes, because of differences in the importance of convectional, cyclonic, or snowmelt events. Furthermore, lakes and wetlands will moderate the runoff changes in some regions. Rivers with extensive glacial sources will have a more subdued response, but rapid ice retreat will cause substantial increases in streamflow until the ice is gone.

Human activity has already modified land use, flow regimes, and rivers in much of southern Canada. Existing flow regulation schemes may counteract the effects of climate change on large rivers, but few small rivers and streams are controlled to the same extent. Land-use change, such as urbanization and agriculture, tends to cause increased runoff and higher flood flows. Climate change effects may be smaller than the existing land-use

La morphologie et la dynamique des cours d’eau sont principalement contrôlées par l’eau et les sédiments en provenance du paysage environnant. Cet apport d’eau et de sédiments pourrait être modifié par le changement climatique et, artificiellement, par l’affectation des terres ou la régularisation du débit. Les principes fondamentaux de la géomorphologie fluviale ainsi que les études de cas sur les changements naturels et artificiels du régime d’écoulement suffisent pour montrer que les cours d’eau sont sensibles aux changements d’écoulement et de la charge solide. En outre, on pourra prévoir l’ampleur et la direction que prendra le changement si l’on possède des connaissances sur les modifications de l’écoulement et de l’apport en sédiment. Ainsi, un écoulement fluvial plus important élargira les cours d’eau, accroîtra leurs taux de migration, accentuera leur incision et modifiera leur tracé. Les cours d’eau à lit mobile constitués de matériaux à grain fin sont les plus vulnérables alors que les cours d’eau à lit sur substratum rocheux ou formé de blocs sont les moins sensibles.

Au Canada, de nombreux cours d’eau s’écoulent sur des dépôts glaciaires érodables et ont l’apparence superficielle de cours d’eau alluviaux. Mais ces cours d’eaux semi-alluviaux peuvent ne pas être aussi sensibles aux changements de l’écoulement fluvial que les véritables cours d’eau à lit mobile. Parallèlement, l’accroissement suffisamment petit de l’écoulement fluvial peut leur faire franchir un seuil qui les fera passer à un état beaucoup plus actif et instable. Par conséquent, même si l’on possède des connaissances sur les changements prévus au régime de l’écoulement fluvial, on ne connaît pas avec exactitude comment les cours d’eau supporteront ces changements.

La réaction du système hydrologique et du relief au changement climatique sera différente selon les régions. La carte présentant l’impact éventuel du changement climatique sur les cours d’eau met en évidence les principales régions physiographiques et hydrologiques à l’intérieur desquelles la réponse du système hydrologique devrait être relativement homogène. La différentiation de ces régions est également basée sur la topographie, les matériaux superficiels, le pergélisol et la géologie, caractéristiques qui affectent toutes les processus fluviatiles et leur réaction au changement. Toutefois, chaque région renferme divers types de cours d’eau qui supporteront différemment un changement climatique donné. Les bassins hydrographiques de diverses dimensions réagiront aussi différemment, en raison des différences dans l’importance des précipitations convectives et cycloniques ou des phénomènes engendrées par la fonte des neiges. En outre, les lacs et les zones humides atténueront les changements du ruissellement dans certaines régions. Les cours d’eau alimentés par de vastes glaciers réagiront moins fortement, mais le recul rapide des glaciers augmentera sensiblement l’écoulement fluvial jusqu’à la disparition des glaces.

L’activité humaine a déjà modifié l’affectation des terres, les régimes d’écoulement et les cours d’eau dans presque tout le sud du Canada. La régularisation du débit est susceptible de contrebalancer les effets du changement climatique sur les grosses rivières, mais il existe très peu de petites rivières ou de ruisseaux qui sont contrôlés à ce point. Le changement dans l’affectation des terres, tel que l’urbanisation et l’agriculture, a tendance à accroître le ruissellement et les débits de crue. Les impacts, but they will add to the existing effects and, in general, have not yet been anticipated in engineering design and planning.

The areas of greatest vulnerability are the populated areas of southern Canada, where hydrological and stream-channel sensitivity are also the highest. This includes the Atlantic coast and the southern Ontario and Quebec lowlands where a shift to rainfall-dominated flow regimes could cause substantial increase in flood flows. In the southern Prairies channel shrinkage is possible. The southern Cordillera is likely to experience increased stream flow and this may be of greatest concern in very steep, high-energy, coastal streams. The effect of streamflow changes will depend on local channel types and characteristics. Rivers of the Canadian Shield and other regions of northern Canada are less sensitive to change. A major concern in these regions is that the loss of permafrost could cause significant changes to sediment delivery and channel stability.

If substantial increases in streamflow do occur, river morphology and dynamics will change. In some cases the changes may occur catastrophically because of large floods. In those cases there is significant risk to structures and buildings close to rivers or on floodplains. Climate changes similar to those seen in the historical climate record are more likely to produce gradual changes in river-channel dimensions, bank erosion rates, channel pattern, and channel gradient. In some cases, these effects will be less significant than those that have already been produced by human activity.

conséquences du changement climatique pourraient être moins importantes que l'impact causé par l'affectation actuelle des terres. Cependant, elles viendront s'ajouter aux effets existants et, en règle générale, elles n'ont pas été prévues dans les travaux de conception et de planification techniques.

Les régions les plus vulnérables sont les zones urbaines du sud du Canada où la sensibilité du régime hydrologique et des lits des cours d'eau est la plus forte. Ces régions englobent la côte Atlantique et les basses terres du sud de l'Ontario et du Québec où une modification des régimes d'écoulement dominés par les pluies pourrait augmenter considérablement les débits de crues. Dans le sud des Prairies, on pourrait assister au rétrécissement des cours d'eau. Dans le sud de la Cordillère, l'écoulement fluvial pourrait s'amplifier, phénomène qui serait des plus préoccupant dans les cours d'eau côtiers à très fort gradient et à haute énergie. L'incidence des modifications de l'écoulement fluvial sera fonction des types de cours d'eau locaux et de leurs caractéristiques. Les cours d'eau du Bouclier canadien et des autres régions du Nord canadien sont moins sensibles au changement. Dans ces régions, le plus inquiétant, c'est que la disparition du pergélisol pourrait modifier sensiblement le débit solide et la stabilité des lits.

L'accroissement sensible de l'écoulement fluvial changera la morphologie et la dynamique des cours d'eau. Dans certains cas, ces changements pourront être catastrophiques si les inondations sont importantes. Ils seront sources de risques considérables pour les ouvrages d'art et les édifices construits près des cours d'eau ou sur des plaines d'inondation. Il est plus que probable que les changements climatiques semblables à ceux consignés dans les données historiques sur le climat modifieront graduellement les dimensions des cours d'eau, les taux d'érosion des berges, ainsi que le tracé et le gradient des cours d'eau. Cependant, dans certains cas, ces incidences seront moins importantes que celles déjà provoquées par l'activité humaine.

INTRODUCTION

Rivers are a both a valuable resource and a natural hazard. Rivers are valued for water supply, energy, fisheries, transportation, recreation, scenic quality, and habitat. At the same time, the natural processes of flooding, bank erosion, and channel migration are hazards. Historically, the major river systems of Canada were the foundation for much aboriginal life, they also directed the early commerce and settlement of the land by Europeans. Any change to the rivers and river processes may have a significant effect on the river environment, infrastructure, and society.

The sensitivity of rivers to climate and land-use change

River morphology and dynamics constantly adjust to the delivery of water and sediment from the watershed which control the streamflow quantity and sediment load (Fig. 1). Any change to the watershed conditions that affect streamflow and sediment load will result in changes to river systems. There are many potential causes of such change, including climate change, human manipulation of river flows, and modification of the land surface. Climate change is the most pervasive of these because it causes widespread alteration of hydrological and erosional processes leading to changes in fluvial processes (Fig. 1). Any future changes in climatic conditions may affect the morphology and dynamics of rivers throughout Canada.

Historical records clearly show that climate change influences fluvial processes. Even small changes in average climatic conditions may cause large changes in the infrequent, but large flood events that have the greatest effect on river morphology (Knox, 1983, 1993). Climatic fluctuations over periods of decades to centuries are known to have caused significant morphological change to rivers in Europe and Australia (Warner, 1987; Erskine and Warner, 1988; Rumsby and Macklin, 1996). Changes of this kind have also been documented in many parts of the world over much longer time periods in response to Holocene and Late Pleistocene climate changes (Baker, 1983; Starkel et al., 1991; Knox, 1993). Climatic change and river response will occur in the future even

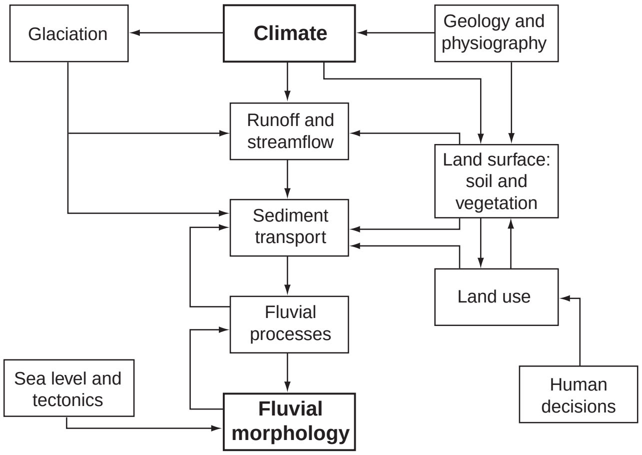


Figure 1. *Control of river morphology and dynamics by climate and drainage basin characteristics.*

without human-induced climate change, but human activity has the potential to cause more rapid climate change than observed in the historical and geological record (Houghton et al., 1996).

Climate change is not the only past and future cause of change in river systems. The direct effects of human activity may be more immediate, and possibly more dramatic, than any climatic effect, and could either exacerbate or mitigate the impact of climatic change. Furthermore, many rivers have already been substantially altered by human activity (cf. Hirsch et al., 1990). Channellization, flow regulation, or changes in land use, especially urbanization, significantly alter the water discharge, sediment transport, and morphology of rivers. The consequences of these activities include channel erosion and incision, alterations to flood frequency and magnitude, erosion of floodplains, damage to engineered structures, and loss or degradation of stream habitat. Climatic change is likely to cause similar effects and it is crucial to assess whether, and under what circumstances, these direct impacts will mask or outweigh the effects of climate change (Newson and Lewin, 1991; Miller et al., 1993). Where climatic change is the primary control on fluvial erosion, flooding, and river ecosystems, it will be necessary to adjust human activities to mitigate the effects of climate change. Even where human impact dominates, the additional effects of climate change on fluvial systems may require adjustment in human practices.

Purpose: expectation and prediction of change

The purpose of this report is to assess the potential effects of climatic change on Canadian river systems by reviewing the basis for prediction and identifying and projecting which river types and regions will be most sensitive to hydrological change. These effects are placed in the context of climatic changes that are forecast to occur over the next 50 to 100 years as a result of anthropogenically induced changes to the atmosphere. General expectations, rather than particular atmospheric change or climate change scenarios, are used because current climate and hydrology models cannot produce the information that is of greatest relevance to rivers, such as changes to extreme flood conditions (Dlugolecki et al., 1996; Arnell, 1996).

The general expectations are that overall warming is likely and that a warmer Earth will be a wetter Earth in many places. The consequences will include increased total precipitation in many regions, although large seasonal and regional differences are expected. Increased convective storm activity will be characteristic of many regions. Predictions of changes to cyclonic storm activity are unreliable and inconclusive but increases in intensity, frequency, and changes in pathways of major cyclonic storms are possible. The importance of snowmelt runoff will be reduced, especially in southern Canada where seasonal snow cover extent will be reduced (Houghton et al., 1996; Watson et al., 1996). These changes, superimposed on changes induced by land use, will cause changes to the river processes and morphology.

Predictions of climatic, hydrological, and fluvial change rely on a variety of evidence and arguments including generalizations from climate models, historical analogues, spatial analogues, and reasoning from general principles. The report provides a regional assessment of fluvial sensitivity to change, together with information on the likely type and direction of change, and the consequences for human activity and use of river systems.

The nature of the changes caused by climatic change depend to some extent on the size of the drainage basin in question. Drainage basin size also affects the relative impact of widespread climate change compared to local land-use change. The effects of land-use change are expected to dominate in smaller basins where a large proportion of the basin area may be affected, leading to substantial changes in runoff and erosion throughout the basin. In larger drainage basins, land use change is seldom sufficiently widespread to affect the entire basin and climatic effects will dominate. The impact of climatic change will also vary with basin size. Thus, small basins will be affected by changes in local, high-intensity storms, whereas larger basins will show a greater response to cyclonic events or basin-wide snowmelt effects. The discussion in the report concentrates on the impact on larger drainage basins, but the regional sections highlight the impact on small basins where this is a specific regional concern.

The impact and consequences of climate change

Potential consequences of climatic change for river processes include changes to the magnitude of flood flows; modification of river channel dimensions and form; changes to bank stability, bank erosion rates, and channel migration; modification of in-channel erosion and deposition; on-set of long term aggradation or degradation of river channels; changes to intensity and frequency of overbank flooding and ice-jams; and changes to the stability of valley sides. These changes in channel processes present a significant risk to structures both in and near streams including dams, bridges, water intakes, and outfalls. Structures on or near floodplains or valley margins are also at risk. Other environmental, scenic, and economic attributes of streams will also be affected, especially in-stream and riparian habitat. There is potential for significant and pervasive changes to river processes and, therefore, to the value of rivers and the associated hazards and risk.

The report is divided into two sections. Part I discusses the potential effects of climate-induced hydrological changes on the morphology and dynamics of Canadian rivers in general. This includes consideration of the climate-streamflow connection from historical data along with case studies of the effects of known flow regime changes on rivers in Canada. In Part II, the general principles are applied to specific regions of the country to highlight regions in which the hydrology is sensitive to climate change and the rivers are sensitive to hydrological change. This section also identifies responses and concerns specific to particular regions. Background review of the principles of fluvial geomorphology used in the analysis is in the Appendix.

The response of river systems to climate change may differ across the country because of regional contrasts in topography, climate, hydrology, surficial materials, permafrost conditions, and other aspects of physiography and land use. The significance of the climatic effect may also depend on the extent of existing human modification of river basins. Many aspects of the physiographic background and anticipated regional differences in sensitivity of rivers to climate change are summarized in Figure 2 (in pocket). The report, especially Part II, provides background and rationale for the anticipated effects depicted in the main map on Figure 2. The inset maps on Figure 2 provide simple summary background information on aspects of Canadian hydrology, physiography, and surficial geology that are directly relevant to the discussion in the report and the interpretation of the regional sensitivity.

PART I: CLIMATIC IMPACTS AND RIVER CHANNEL CHANGE IN CANADA

Introduction

Rivers are closely connected to the landscape and the climate. Many of the characteristics of river systems are the result of the influence of local geological and land surface conditions but rivers are also influenced by hydrological processes which are controlled by climatic conditions. Whereas river channels may be affected by a number of environmental variables (Fig. 1) the influence of climate on rivers, via its effect on streamflow hydrology, is pervasive. Climate ‘wetting’ is the dominant concern. In predicting the potential effects of climate change on rivers there are two crucial questions, 1) to what extent is streamflow sensitive to climatic change? and, 2) do river channels change in response to changes in streamflow? Particularly for northern rivers, it is also important to ask whether climate change is likely to affect river-ice processes. This part of the report seeks answers to those questions for Canadian rivers.

Climate change and response of streamflow

General considerations

The fundamental link between climate change and fluvial processes is the streamflow regime (Fig. 1). River morphology and river channel change depend to a great extent on the mean discharge, and on the magnitude and frequency of large floods. Changes to streamflow conditions may have far-reaching effects on fluvial processes and landforms.

Prediction of the impact of climatic changes on river flow remains difficult for two main reasons; first there is little known about the anticipated changes in hydroclimate, and second, even with knowledge of the likely changes in the relevant hydroclimate variables it is impossible to generalize about the likely changes to streamflow regime. It is generally assumed that a warmer Earth will increase evapotranspiration in continental climates. Without a compensating increase in precipitation this would lead to reductions in runoff and streamflow. A warmer Earth may also reduce the snow accumulation period and, thus, decrease the size and relative importance of snowmelt floods on many Canadian rivers; however, these effects may be counteracted by an increase in the incidence of warm, moist air masses over Canada, resulting in higher precipitation in many regions. There is evidence that streamflow is much more sensitive to changes in precipitation than to changes in temperature. Responses are likely to be quite different between interior and maritime regions, and between northern (permafrost) and southern regions. Similarly, the presence of glaciers will modify the anticipated response.

Quantitative estimates of impending climate change induced by human activity are currently 1–3.5°C warming of global mean annual temperature by AD 2100 (Houghton et al., 1996), based on projected changes to the atmosphere and predicted by a number of computational models of global climate. The most significant changes are expected in the northern hemisphere poleward of about 50°N in the winter season, with a warming of up to 7°C predicted for Canadian arctic winters.

Expected changes in precipitation are much less well known. The most consistent result from current modelling output (Houghton et al., 1996) is an increase in winter precipitation in high latitudes, including much of Canada. Prediction of changes in storm tracks, and of precipitation frequency, intensity, and duration are inadequate to form a basis for prediction of hydrological changes; however, current predictions do agree that a warmer Earth will have a “more vigorous hydrological cycle” (Houghton et al., 1996, p. 7).

The absence of reliable predictions of changes in precipitation presents severe problems for hydrological forecasting. Within the United States the impact on runoff of historic mean annual precipitation fluctuations (of order 10%) are much more important than changes in mean annual temperature (of order 1°C) that have occurred during the same historical period (Karl and Riebsame, 1989). A range of climate simulations yields precipitation increases due to increased atmospheric energy of about 2.8%/1°C. Changes of this magnitude are within the range of historical fluctuations found in Canada and the United States (Karl and Riebsame, 1989). In the absence of temperature change, changes in precipitation may cause significant changes in runoff, but the reverse (change in temperature with no change in precipitation) produces no consistent change in runoff. Furthermore, Karl and Riebsame (1989) conclude that in many cases the proportional change in runoff is actually greater than the associated change in precipitation. This amplification of the runoff response relative to the change in precipitation that drives it exists in the case of both increases and decreases in precipitation. The effect has now been observed in many other cases (Arnell, 1996), with the amplification greatest in drier regions (Wigley and Jones, 1985; Arnell, 1996).

Large flood events are extremely important to fluvial dynamics. In many cases significant erosion, deposition, and channel change occur on only a few days a year. Whereas the normal morphology of the stream may be adjusted to these average annual high-flow conditions, occasional very high, large flows occurring only a few times per century and lasting only a few days may cause large and persistent modifications to river processes and form. Thus, change in typical high flows, especially infrequent extreme flood events, is much more important to fluvial processes than change in the average flows. The extreme events are also the most hazardous. Engineering works are designed on the basis of historical extreme flood frequencies, but flood magnitudes and frequencies may change as a result of climatic change. Changes in flood magnitudes will depend on a variety of factors which are not easily modelled and predicted. These factors include the severity of individual storms, the amount of snowfall, rapidity of melting, and the occurrence of rain-on-snow events (*see* Church, 1988). The relative importance of these factors differs between basins of different size. Consequently, in small catchments local thunder storms may generate the largest floods, whereas in larger catchments of the same region, the seasonal snowmelt floods may dominate.

Little is known about the relation between mean climatic conditions and flood discharges. Recent analyses show that comparatively small changes in annual precipitation may cause disproportionately large increases in the magnitude of flood discharges (Knox, 1983, 1993; Arnell, 1996). Historical flood records often show systematic and persistent departures from average conditions; the most extreme floods are usually associated with years of below-average temperature and above-average precipitation. Changes in atmospheric circulation which strengthen meridional (north–south) circulation are usually associated with cooler phases in the mid-latitudes. Meridional circulation favours the development of intense, slow-moving cyclones in the mid-latitudes, from which large floods develop (Knox, 1983).

It is currently impossible to model the effect of climate change on streamflow (Arnell, 1996). Climate models do not produce the relevant parameters at a useful spatial scale. This is complicated by the fact that the effects of changes in precipitation on streamflow are mediated by land surface conditions which may also respond to climate change but can also be changed independent of climate. The alternatives to modelling for predictive purposes are a general conceptual and theoretical understanding of the climate-hydrology-fluvial process connections, and empirical relations between climate and streamflow revealed in instrumental records. These considerations show that significant changes in streamflow regime are possible as a result of climate change. Streamflow changes are likely to be driven primarily by changes in precipitation rather than temperature, and, especially in the case of large floods, comparatively small changes in precipitation may cause substantial changes to streamflow; however, contrasting responses are possible for different regions and it is important to assess these potential effects in Canada. This regional contrast arises in part because of differences in the dominant flood-generating processes and seasons. Changes to seasonal flood events are more important than any overall change in average precipitation.

Flow regimes on many southern Canadian rivers have already been substantially affected by human activity. The most obvious example is that of artificial flow regulation or diversion. In general, flow regulation by dams reduces or eliminates most flood peaks, and changes the seasonal distribution of streamflow (typically by reducing spring nival floods and increasing winter flows). The presence of large flow regulation schemes will strongly modulate any changes in flood frequency due to climate change; however, the risk of catastrophic overtopping of dams may be increased. At the same time, land-use change in drainage basins, especially urbanization of small drainage basins, may cause substantial increases in flood flows. In this case, climate change may compound the existing land-use effect.

Climate-streamflow relations: examples from the historical record in Canada

The relation between historical changes of climate and streamflow at the decade scale is a useful analogue for future conditions. Historical changes are of similar magnitude to the changes anticipated on the basis of climate modelling; however, the results of the analysis of the historical data must be treated cautiously because they provide only an indication of the likely direction of change and of the sensitivity to change, not precise predictions of future change. Future changes will not necessarily occur under the same circumstances as the historical events and in many areas, especially in settled regions of the country, land surface conditions have changed during the period of historical record.

Previous studies have shown that such climate fluctuations are coherent over substantial regions or portions of the continent indicating that future changes will be similarly widespread, but not necessarily homogeneous between regions. These analyses (e.g. Karl and Riebsame, 1989) also conclude that precipitation, rather than temperature and evapotranspiration, is the dominant influence on streamflow. This type of analysis is used in assembling the regional response information in the final sections of the report. Some examples are presented here to illustrate the observed correlations and to show some of the regional contrasts.

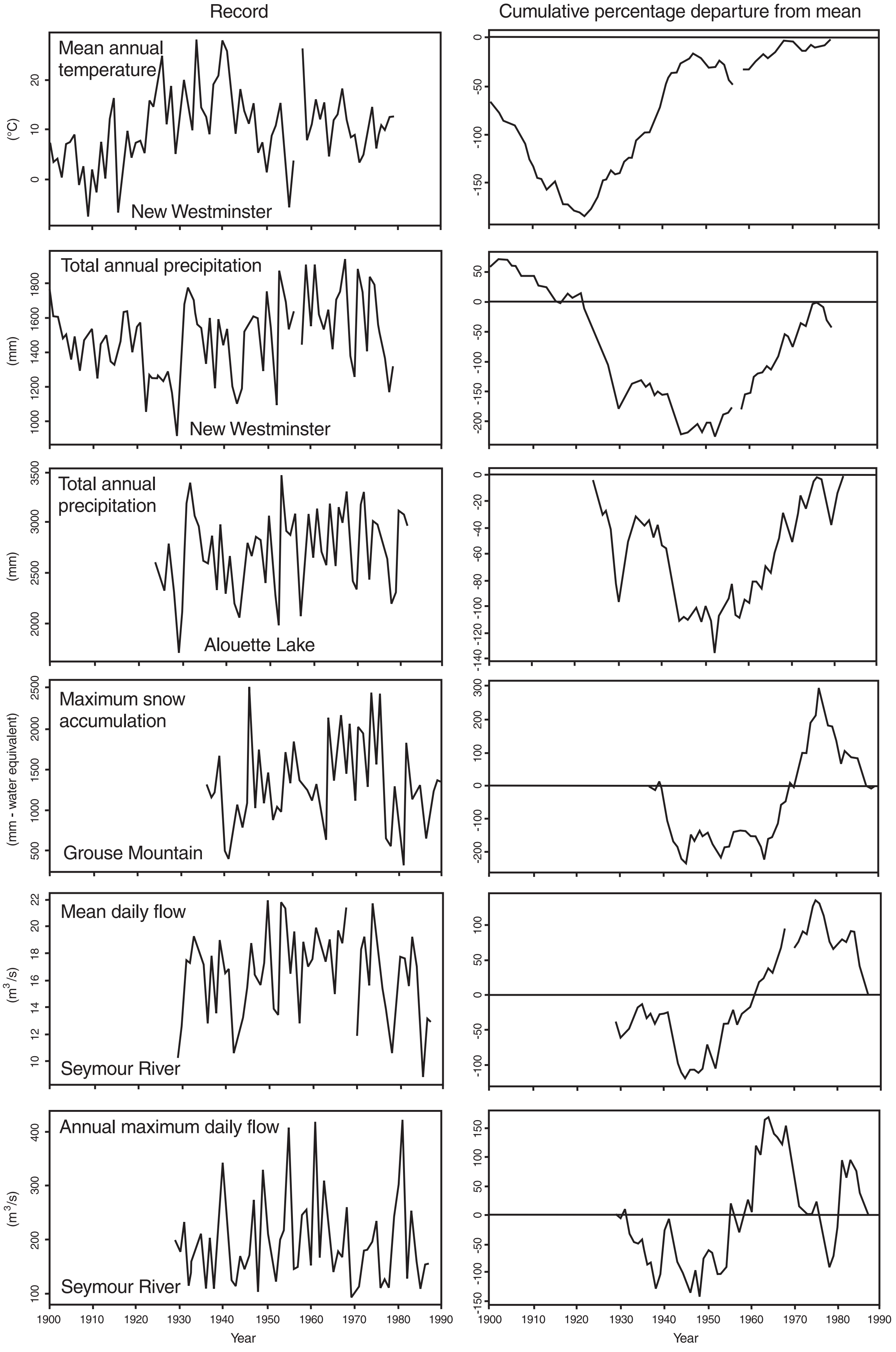


Figure 3a. *Coastal*

Figure 3.

The historical response of annual mean and daily maximum river discharge to annual variation in temperature and rainfall and snowfall accumulation for selected drainage basins from different hydrological regions in British Columbia. The left hand column shows the raw data series, and the right column shows the cumulative departure from the mean for each variable. The cumulative departure reveals the short-term trends in the data more clearly than the raw data: ***a)*** *coastal regime — Seymour River,* ***b)*** *nival regime — Columbia River,* ***c)*** *nival regime in dry interior — Okanagan River,* ***d)*** *glacial regime — Lillooet River.*

Long-term trends in highly variable data may be identified by plotting cumulative departures from the mean. The departure may be expressed as a percentage of the mean, in order to make comparisons between records. In this type of plot, a sequence of above-average years appears as an upward trend, a sequence of below-average years appears as a downward trend, and a flat plot indicates a period of average conditions. Comparison of plots from several stations in the same region can reveal the regional homogeneity of the trend and the comparison of climatic with hydrological records can display the presumed influence of the former upon the latter.

Effects of precipitation changes

Whereas precipitation changes are expected to be the dominant influence on streamflow, regional differences in variability and response are likely. These regional differences are apparent in the historical record and are expected to exist in

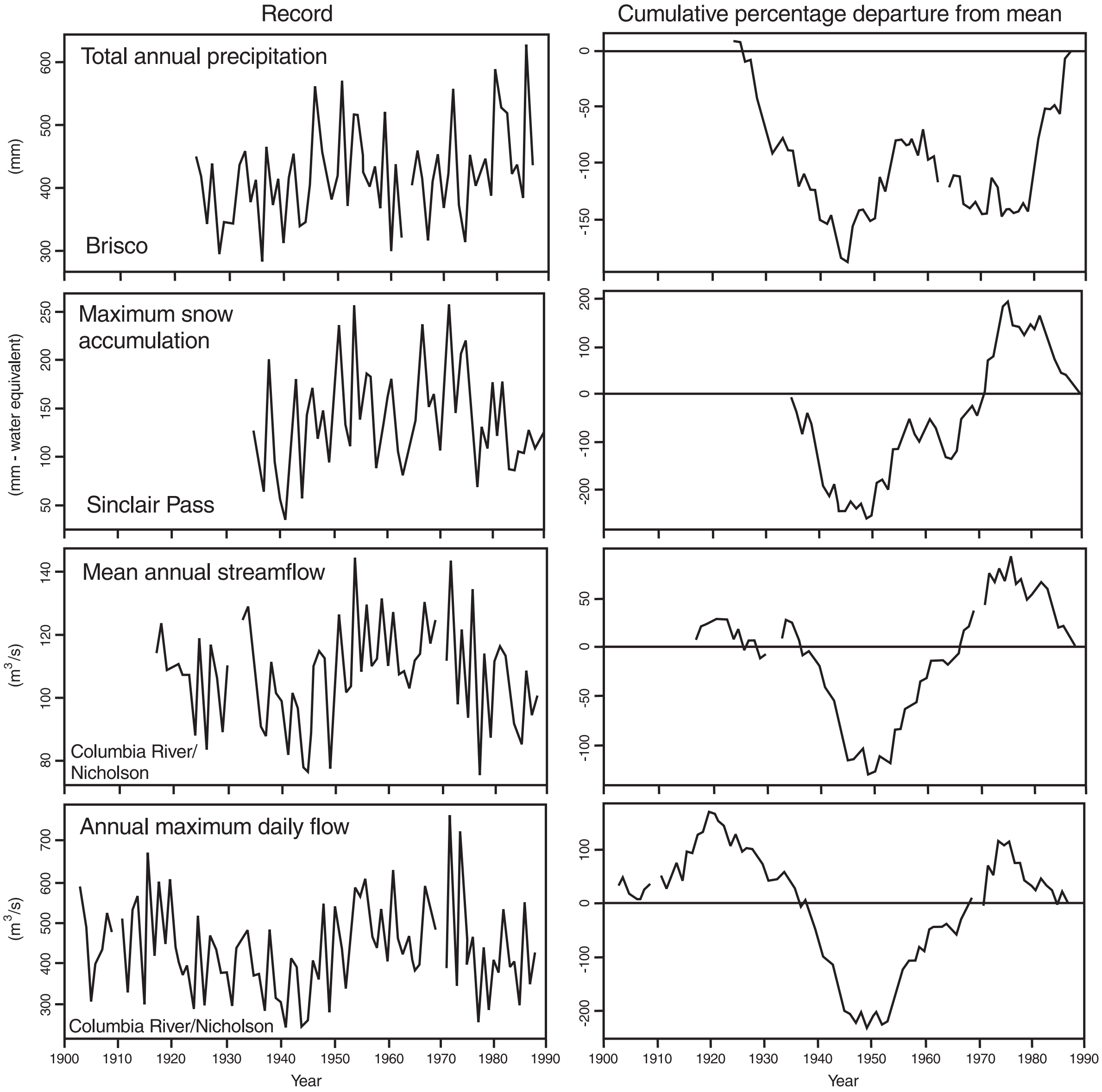


Figure 3b. *Nival*

the future. Decadal variation is present in the climate and streamflow records from all regions of Canada. The exact magnitude and timing of the variations differs between regions but is often quite consistent within a given physiographic region.

In the Cordillera, the period from 1920 until the late 1940s was dominantly a period of low runoff and relatively small floods, whereas from about 1950 until 1980, there was substantially higher runoff and floods (Fig. 3). This approximate temporal pattern is repeated in several different hydrological regions as shown by the examples in Figure 3. Precipitation

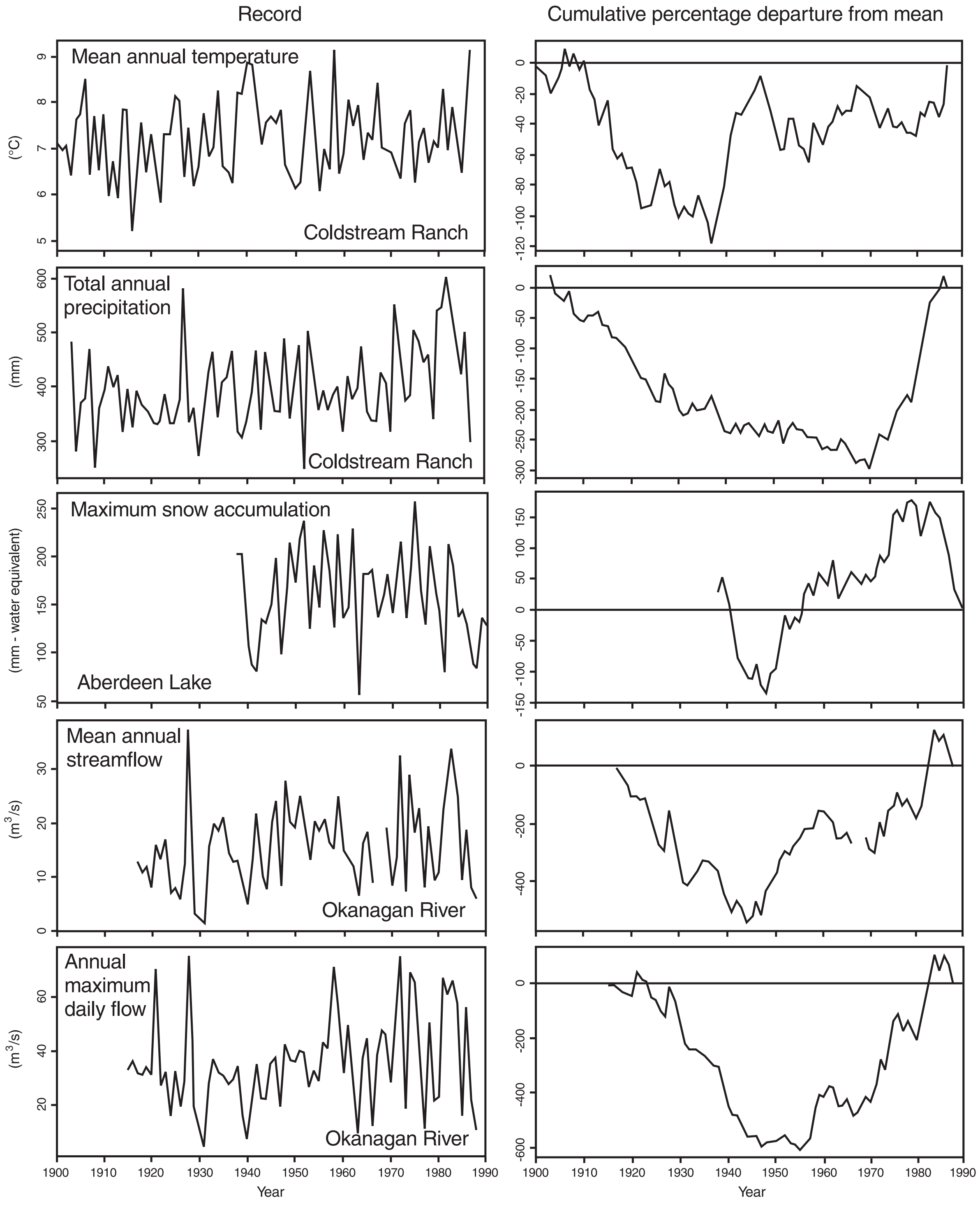


Figure 3c. *Nival – dry interior*

increased, on average 10–20%, mainly in the fall and winter. Changes in mean flow average +20% for 28 long records in southern British Columbia (Barrett, 1979). Increased winter snow accumulation made a significant contribution to increased runoff during the wetter periods (Fig. 4). The increases in streamflow are proportionally larger than those in precipitation, by a factor of about 1.5, confirming the amplification effect (Karl and Riebsame, 1989).

Precipitation trends in Figure 3 clearly relate quite closely to streamflow, especially mean annual flow, but show very little relation to temperature. Annual maximum flow also follows the trend in precipitation and mean flow, although the record is, as expected, rather more erratic. This somewhat erratic response is especially apparent in the coastal region (Fig. 3a) where the dominant flood generation mechanism is rainfall rather than snowfall. The exception to this general

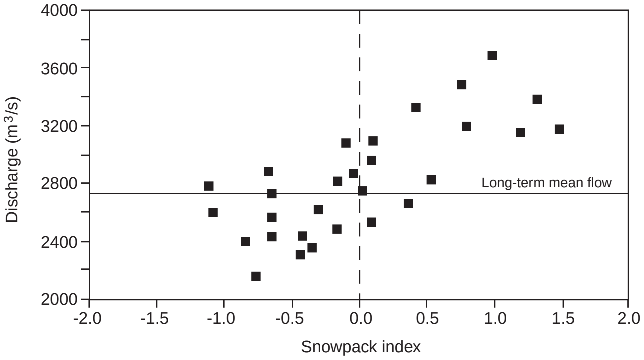


Figure 4. *Mean annual streamflow, Fraser River at Hope, versus aggregate maximum snow accumulation index for the drainage basin (*modified from *Moore, 1991, Fig. 2.14).*

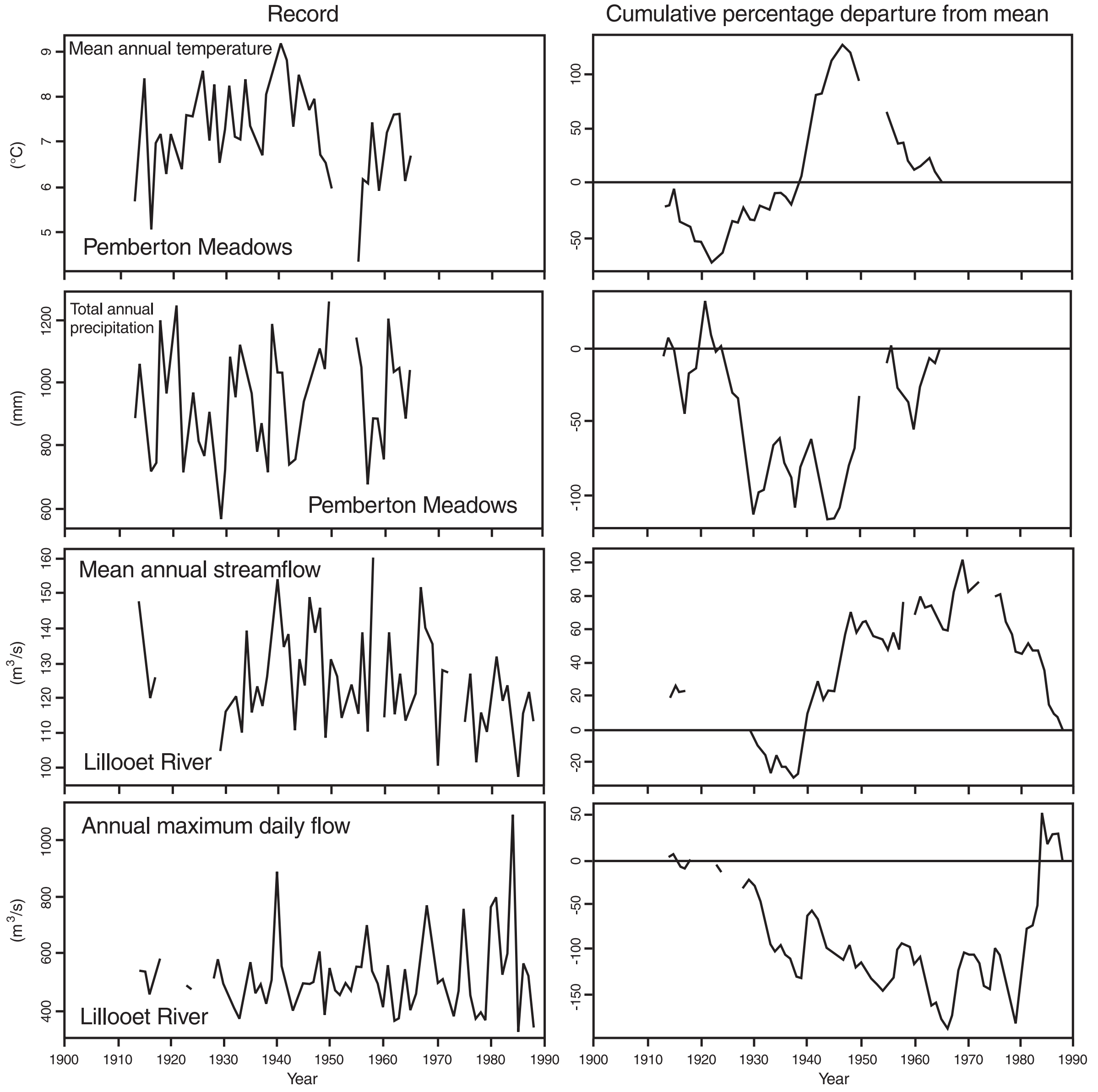
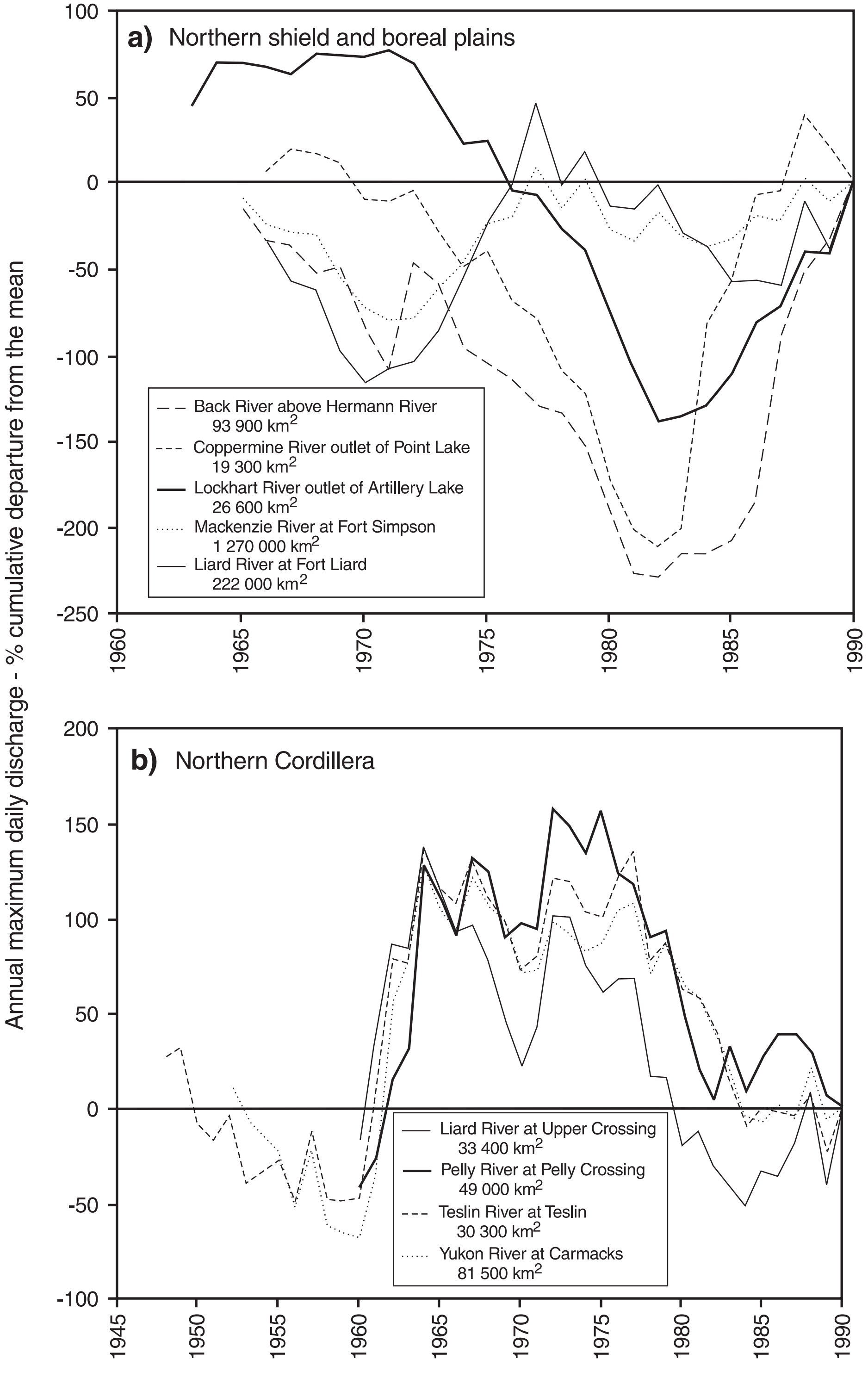


Figure 3d. *Glacial*

correlation between streamflow and precipitation history is the glacially influenced Lillooet River (Fig. 3d), where the damping of precipitation changes by ice storage results in very little change in mean flood conditions, despite substantial changes in precipitation. In this case it is also arguable that the effect of temperature is also apparent.

Decadal variation in streamflow is shown for some other regions in Figure 5. The amplification effect between runoff and precipitation is also apparent in these regions, although it varies between regions and between drainage basins. For example, in Nova Scotia, the change in precipitation between wet (1946–1975) and dry periods (1975–1990) is



comparatively low (about 4%) but the amplification factor for streamflow is between 1 and 2. Amplification factors for several large Yukon Territory rivers are about 2.

Flood frequency distributions obviously shift upward during wetter periods (Fig. 6). This means that floods of a given recurrence interval are significantly larger during wetter periods than during drier periods. Increases in annual maximum flow are often proportionally greater than those of mean flow. For example, in the Cordillera (Fig. 6a) the increases in mean annual flood are about 30%, and about 35% for the 10 year flood, compared to about 20% for the mean annual flow. The exact response is likely to depend on several additional factors including drainage basin area, the runoff generating mechanisms, and the presence of significant lake storage.

An upward shift in flood frequency curves is observed in all other regions during wetter climatic phases, albeit with some regional variability in the degree of sensitivity. In coastal regions of Nova Scotia, small decadal changes in precipitation produce large changes in flood frequency. Increases in mean annual flood of 50–60%, and in 10 year flood of over 100% are observed in some cases, despite only a 4% change in mean annual precipitation (Fig. 6b). Further inland (New Brunswick) these effects are reduced. The eastern Prairies also seem to be an area of highly sensitive flood-flow regimes. In this region mean annual flow increases between 1920–1940 and 1940–1960 were of the order of 30% in the prairie-source streams, whereas mean annual flood increases are typically 50–100% (Fig. 6c). The upward shift in flood frequencies during wetter periods is proportionally greater in the eastern Prairies than in the mountain-source rivers of the Prairies (Fig. 6d).

Changes in flood magnitude of 20–50% may very well be comparable with the changes that can be expected due to future climatic change. They indicate that the magnitude of flooding tends to be unusually sensitive to changes in climate. In the case of increasing flood magnitude there seems to be an even greater increase in magnitude of the most extreme, damaging floods. A similar conclusion has been reached by Knox (1993) from the American midwest.

The relation between precipitation changes and runoff may be confounded in more densely populated parts of Canada by progressive changes in land use. This is likely to be important in agricultural areas and even more significant in smaller drainage basins subject to extensive urbanization.

The response of drainage basins with substantial glacial water storage is different. Glaciers dampen the direct runoff response to changes in the water balance. Mass losses augment runoff during warm and dry summers, whereas mass gain may moderate flood flows in cool periods (*see* Lillooet River data in Fig. 3d, 6a). Consequently the discharge response of glacially influenced rivers is much more subdued

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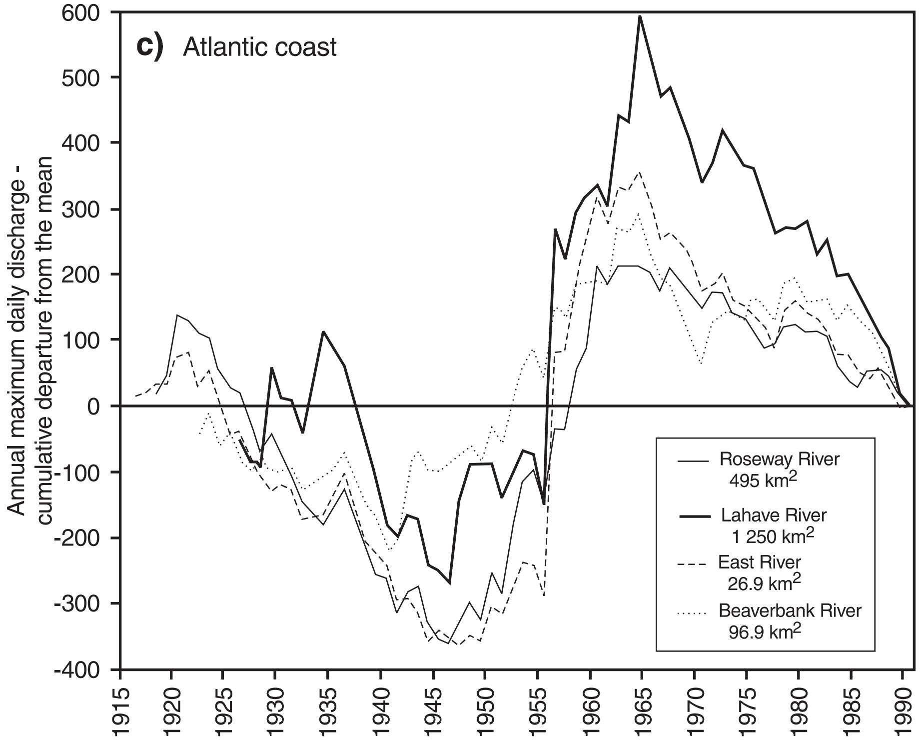
Figure 5.

Regional homogeneity, and inter-regional differences in decadal changes in streamflow. ***a)*** *Similarities in temporal pattern in streams in northern shield contrasted with those in northern Cordillera,* ***b)*** *homogeneity of temporal trends in large rivers of northern Cordillera and Yukon Territory interior,* ***c)*** *homogeneity of response in small streams on the Atlantic coast.*



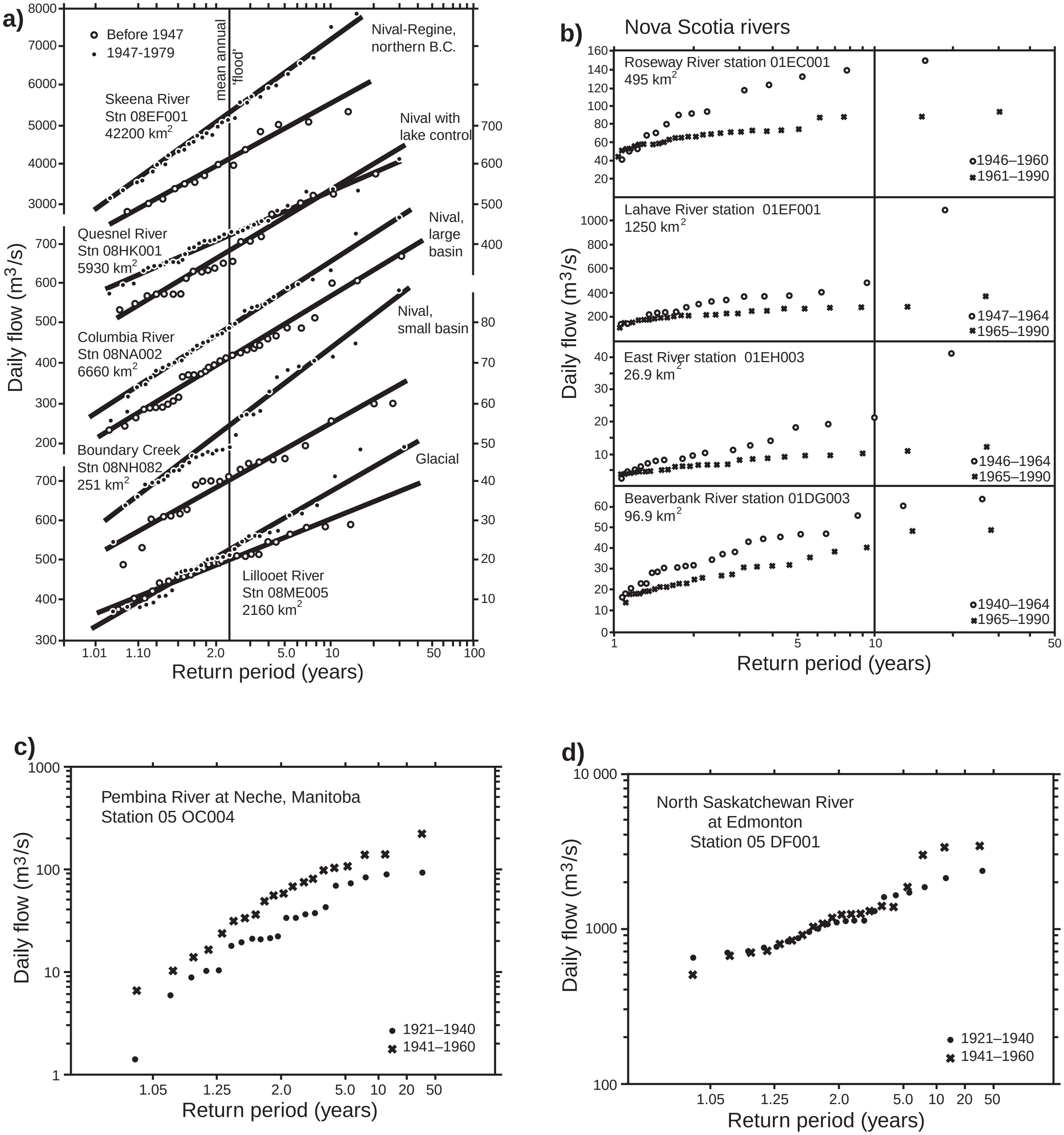


Figure 6. *Change in flood frequency distributions (annual maximum daily discharge) between decade-scale wet and dry periods in various regions of Canada.* ***a)*** *Increase in flood magnitudes in Cordilleran rivers during wet period (1947–1979) compared to preceding drier phase (pre-1947).* ***b)*** *Increase in flood magnitude in coastal Nova Scotia streams during wet phase (1940s–1960s) compared to the later (1960s–1990), drier period.* ***c)*** *Increase in flood magnitude in southeastern Prairies during wet phase (1941–1960) compared with preceding drier phase (1921–1940).* ***d)*** *Minor changes in flood frequency distribution in a large mountain-source Prairie river between wetter phase (1941–1960) and drier phase (1921–1940).*

than for the nonglacial rivers. The changes in glacier mass balance may vary regionally, for example, between the windward (western) side and leeward side of the Coast Mountains, and between the Coast Mountains and the Rocky Mountains. This effect may persist for decades.

Effects of temperature changes

The effects of regional temperature are more difficult to identify. Karl and Riebsame (1989) observed that decadal fluctuations of streamflow are much more strongly influenced by precipitation than by temperature, although temperature effects are apparent especially in relation to spring runoff. Two possible effects of temperature change on streamflow relate to increased evapotranspiration and reduced snow accumulation as temperature increases. The latter effect would reduce the magnitude of spring nival floods which is important in most regions of Canada, and paramount in some.

Historical analysis reveals some sensitivity of streamflow to decade-scale temperature fluctuations. One case of temperature sensitivity is the prairie-source rivers of Manitoba and Saskatchewan (Fig. 7), where both average and maximum daily streamflow decrease during periods of higher mean annual temperature; however, these are also periods of historically low precipitation. This sensitivity to temperature may operate through greater sensitivity in soil moisture conditions in the dry continental interior. The effect may also operate through lower snowfall accumulation in warmer years, which reduces the size of the spring nival flood event. The spring flood is often the only significant runoff event of the year in these rivers.

The role of increased precipitation in offsetting the effect of temperature on snowmelt runoff is unknown. In the case of the eastern Prairies both annual total and maximum daily discharge increase with increasing precipitation (Fig. 7), which could offset the warming effect. The net effect depends on the strength of the dependence in each case. Other complications arise in this situation. Decreased snowfall, under constant or increasing precipitation, necessarily results in increased rainfall amounts. In general, rainfall or rain-on-snow events have the potential to produce larger peak flows than pure snowmelt floods. Thus, even if nival flood magnitude is decreased, maximum daily discharges may increase. One model study (Loukas and Quick, 1996) showed that in mountainous, snowmelt-dominated basins, warming of 3.8°C and a precipitation increase of 17% will lead to a decrease in snowpack accumulation of 25–30%, a decrease in peak flow, and the occurrence of peak flow two months earlier than at present.

The effect of fluctuations in annual temperature can also be seen in flood frequency records (Fig. 8a). Again, using the eastern Prairies as an example, warmer years produce much lower (by a factor of 2–4) flood magnitudes than cooler years, for mean annual temperature ranges of 2–3°C. The effect varies, but is usually proportionally larger at low recurrence intervals than at high recurrence intervals; however, the temperature effect is negligible in other regions (Fig. 8b).

The effect of climate change on snow cover, and, hence, on nival floods can also be approached by looking at the effect of climate on the spatial extent of snow cover. The spatial extent of snow cover, and the length of the snow cover season are expected to decrease with winter warming, and a decrease in accumulated snow depth could be expected to follow. Historical data on snow cover for the past 30–40 years (Karl et al., 1993) indicate a strong inverse correlation between snow cover and temperature. In the 1980s, an unusually warm decade, snow cover area in southern Canada (south of 55°N) decreased by 7% whereas total precipitation did not change. The effect of this on streamflow is unknown. Whereas increased total precipitation may offset the effect of warming to some extent, current climate change scenarios (typically 2°C warming and 10% increase in precipitation) predict substantial reductions of snow cover despite increased precipitation (Fitzharris et al., 1996).

Historical analysis of streamflow indicates a weak inverse correlation between streamflow and hemispheric temperature (Fig. 9). This effect is observed in several Cordilleran rivers, except those that are strongly glacially influenced. This may be a consequence of reduced winter snow accumulation, but the actual mechanism connecting hemispheric temperature change to regional streamflow is indirect and unknown, and need not exist in a changed climate. In the long term, warming is expected to increase runoff from glacial sources until ice masses are substantially reduced (Houghton et al., 1996).

River channel change

Any activity or process that alters the streamflow, sediment supply, or river gradient may cause changes in river morphology and dynamics. Climatic change, through its influence on stream system hydrology, is an obvious example. This is also true of changes in secondary factors such as riparian vegetation. Any one, or a combination, of these changes may cause a change in the cross-section morphology and channel pattern, along with changes in channel dynamics (e.g. rate of meander migration).

There are also numerous examples of the impact of human activity on river systems, which serve as useful analogues and inadvertent experiments, providing insight into the likely impact on rivers of climate change. In addition they give a basis for judging the relative magnitude of human and climate impacts.

Principles

If the control of discharge and sediment supply on stream morphology and dynamics is understood, it should be possible to predict the effect on stream channels of changes in the controlling conditions such as climate. Unfortunately, this proves to be more difficult than it at first appears because of the large range of possible adjustments; because changes in several factors may occur simultaneously and their effects may be opposite to one another.

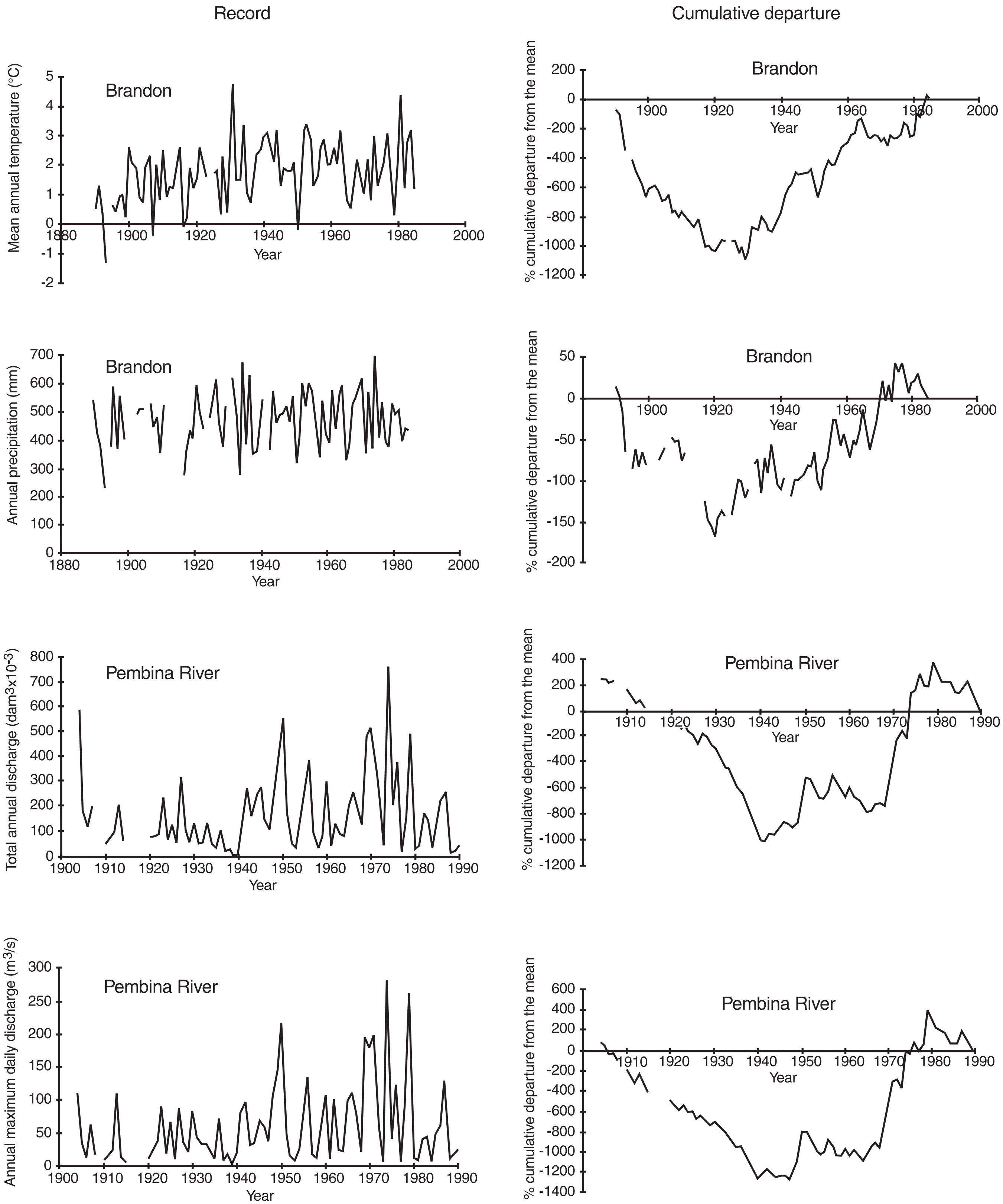


Figure 7. *Response of streamflow in a southeastern Prairies stream to decade-scale changes in temperature and precipitation.*

With a wide range of possible adjustments, and without a complete physical theory to describe the adjustments, it is possible only to predict directions and estimate relative magnitudes of change (Schumm, 1969, 1977; Hickin, 1983; Kellerhals and Church, 1989), and even these are not always reliable (Stalnaker et al., 1989). Table 1 shows the likely responses to a variety of changes. Changes involving 'imposed' increase or decrease in discharge (cases 1–6) are all plausible impacts resulting from climate change. Changes in sediment supply independent of changes in discharge are also a conceivable, but less likely, outcome of climate change (cases 7–10, Table 1), but they are very likely outcomes of land use change. In all cases, a change in discharge involves a change in the concentrations of bed material load (Q_{bm} = bed material load/discharge) and wash load (Q_w = wash load/discharge), depending on the extent to which sediment supply to the river is also altered.

The significance of the complete range of morphological responses can be interpreted in terms of channel morphology, bank erosion, degradation or aggradation of the bed, as well as in terms of stream habitat. Changes in flow conditions, substrate (bed material), cross-section dimensions, silt and/or clay content of channel sediments could all affect stream habitat. For example, increased quantities of fine sediment could indicate declining quality of spawning gravels, whereas changes in flow depth could affect water temperatures and rearing conditions for fish.

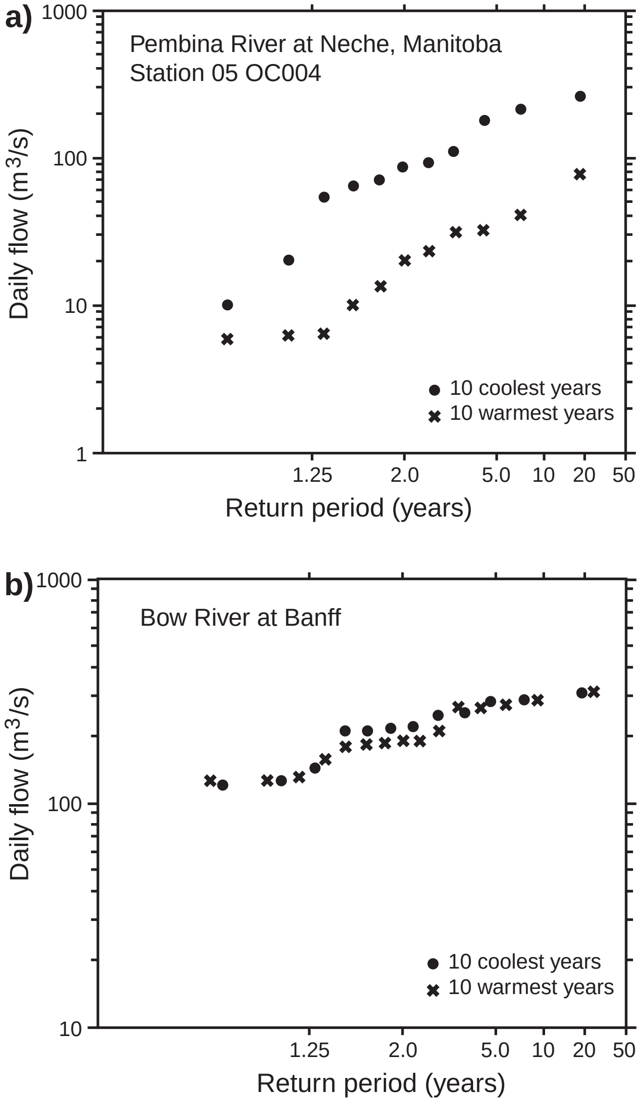


*Figure 8. Contrast in response of flood frequency distribution (annual maximum daily discharge) to annual temperature between streams in **a)** southern Prairies and **b)** eastern Cordillera.*

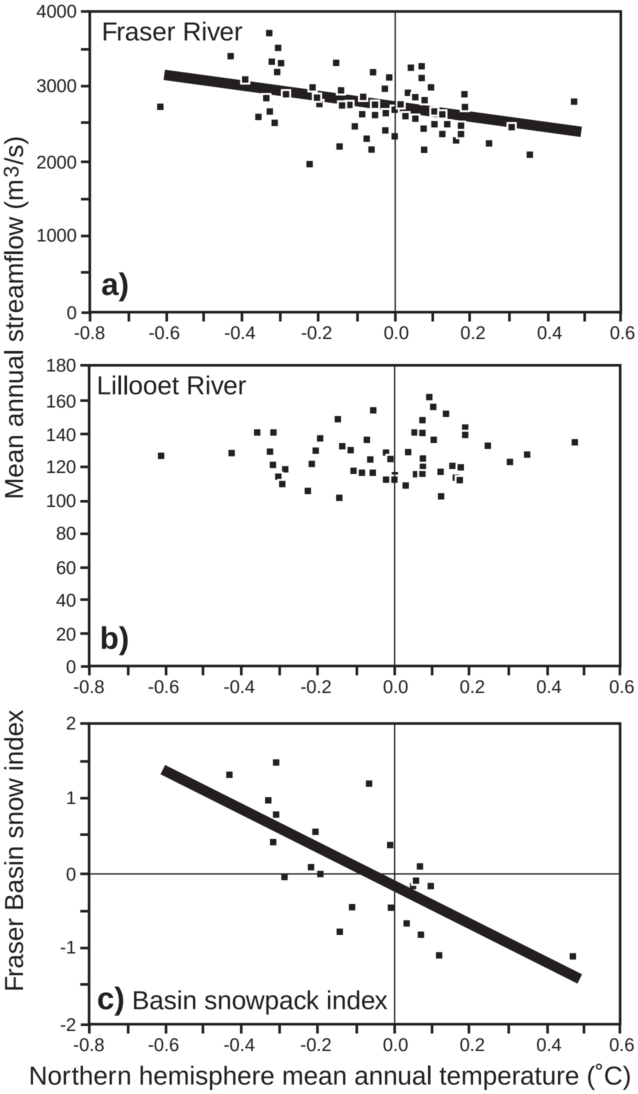


*Figure 9. Effect of mean annual northern hemisphere temperature on mean annual streamflow for **a)** snowmelt-dominated (Fraser River) and **b)** glacier-dominated (Lillooet River) flow regimes, and on **c)** Fraser basin snow accumulation index* (from *Moore, 1991, Fig. 2.15).*

Table 1. Potential morphological response of alluvial or semialluvial streams to imposed changes in discharge and sediment supply. Based on concepts originating with Schumm (1977). Table modified from Kellerhals and Church (1989).

Case	Imposed changes			Resulting changes							
	Q	Q_{bm}	Q_w	w	d	S	D	F	L	P	M
1	+	+	+	+	+	±	±	±	+	?	±
2	+	+	-	+	+	±	±	+	+	-	-
3	+	-	-	+	+	–	+	-/+	+	+	-
4	-	+	+	-	-	+	-	-/+	-	-	+
5	-	-	+	-	-	-/+	-	±	-	?	+
6	-	-	-	-	±	-	±	±	-	+	-
7		+		+	-	+	±	+	?	-	-
8		-		-	+	?	+	-	?	+	+
9			+	-	+	?	-	-	?	+	+
10			-	+	-	?	+	+	?	-	-

Abbreviations:
Q, mean annual discharge; Q_{bm}, ratio of bed material load to discharge; Q_w, ratio of wash load to discharge; w, mean channel width; d, mean channel depth, S, mean channel gradient; D, bed material particle size; F, ratio of width to depth; L, meander wavelength; P, sinuosity; M, fine sediment content of bed and bank material

Note:
1. Increases appear as '+' and decreases as '–'
2. Longterm and shortterm changes that are likely to be different are separated by a '/'
3. Changes that may occur in either direction are shown as '±'
4. Changes for which no reasonable prediction can be made appear as '?'

Not all the expected changes may occur in any particular case. In some cases, although adjustment may be expected, it does not occur because the river is not able to accomplish the required erosion or deposition. One obvious example is a river in which discharge has been reduced to the point that flows are unable to erode the river bed, making channel modification by erosion impossible. Even if the anticipated changes do occur, the rate at which the changes take place will differ between variables, reaches and rivers, and depending on whether the adjustments involve erosion or deposition. In readily eroded sediments, the texture (size) of channel and bank sediment may change in a year, whereas width and depth changes may take several years. Adjustment of slope or meander characteristics may take decades or centuries. Channels with sand-bed and unvegetated (or otherwise unprotected) sandbanks are likely to respond most rapidly.

Table 1 cannot be used predict changes in channel pattern beyond adjustments of sinuosity and meander wavelength. Figure A-4 indicates that under some circumstances alluvial channels may be poised close to the boundary between a single meandering channel and a braided channel. In this case, a comparatively small change in discharge could elicit a radical change in channel pattern—with implications for channel stability, style, and rate of channel migration, as well as hydraulic habitat conditions. Channels with very resistant bank sediments such as cohesive silt and clay are unlikely to be braided, but will respond instead to changes in discharge through a change in sinuosity.

Quantitative prediction of changes is very difficult, although for simple cases it may be possible, assuming that the change in discharge conditions is accurately known. For example, adjustment in the cross-section dimensions induced by a change in water discharge alone is readily determined by the relationship between discharge and cross-section properties. The most sensitive relation is that for channel width. On the basis of well established ‘hydraulic geometry’ relations (Fig. A-2) the proportional change in channel width is expected to follow the square root (0.5 power) of the proportional change in discharge (the ratio of the ‘before’ and ‘after’ discharges), for example, a two-fold increase in formative discharge is expected to cause channel widening by a factor of $\sqrt{2} = 1.4$.

The same proportional response to change of discharge is expected in depth, except that the depth relates to the 0.4 power of discharge. In the case of depth adjustment the exposure of resistant material in the bed may limit erosion, leading to either more frequent inundation of the floodplain or a compensating greater increase in width. In nonalluvial channels, especially those that are slightly degraded so that the floodplain is rarely inundated, the depth adjustment to increased flow may be merely the increased filling of the existing channel. This adjustment is predictable from the observed hydraulic conditions in the channel.

Decreases in discharge will simply be accommodated within the existing channel. Where sediment supply is sufficiently large, this will gradually produce channel shrinkage by deposition of channel bars, islands, and channel-side benches as well as by vegetation encroachment. The style of deposition will vary between channels. Channels in which the bulk of the sediment load is transported in suspension may shrink via deposition along the channel edges, whereas those channels transporting considerable bed load may experience substantial depth reduction and filling or abandonment of side channels. The effects of this on stream habitat are predictable from standard hydraulic equations, but are not easily generalized except to say that average depth and flow velocity are likely to decrease with a decrease in average discharge. Again, changes in channel pattern are possible following a period of sedimentation and channel shrinkage.

Changes in discharge and/or sediment supply which alter the discharge:sediment size ratio (or bed-load ratio) will, in theory, lead to an adjustment of the channel slope either by erosion of the bed (degradation) or by deposition on the bed (aggradation). The direct natural and human-induced causes of degradation are numerous (Galay, 1983). In practice, slope may be adjusted most readily by a change in channel pattern (*see* below). For example, channel gradient can be decreased through an increase in sinuosity, without the necessity for degradation. In some cases degradation may be prevented by the presence of resistant bedrock or bed sediment that the stream flows are unable to erode. Even where degradation is possible, the tendency may be counteracted to some extent by increased bank erosion which supplies extra sediment to the stream (Galay, 1983).

The analysis of the stable morphology (Table 1) does not consider changes to stream dynamics. The rate of meander migration is related to a number of factors, including the curvature of the bend (Hickin and Nanson, 1975), but is most strongly controlled by discharge and bank resistance. Meander migration rates increase with higher discharge and decrease with higher bank resistance. The highest bank resistance is associated with sediments either high in silt and clay, or with very high cobble or boulder content. In the absence of any change to the sediment type, increases in stream power will cause increase in bank erosion rates due to meander migration (in addition to the expected increase in width). Channel pattern changes may also occur as a result of changes in stream power. If the pattern changes between meandering and braided, the style of channel migration and bank erosion will change substantially.

Examples

The basic principles of river channel changes discussed above provide a guide to the nature of river responses to climate change, but are not a reliable test of whether the changes will actually occur. This review of selected Canadian case studies of river response to environmental change shows how particular rivers have actually adjusted to changes in discharge and sediment supply. These examples provide tests of the reliability of the predictive approaches. They may also be used to identify sources of deviation from the anticipated adjustment, and to assess the relative magnitudes of climate-induced changes versus human-induced changes.

Increased discharge (Table 1, cases 1–3)

The most useful natural analogues for the potential changes induced by climate change are natural fluctuations that have occurred in streamflow and river morphology during the period of recent record (up to about 80 years). The following examples are from British Columbia, where mean discharge and flood discharges were lower in the years 1920–1950 than in the years 1950–1980. The mean annual flood increased in the later period (1950–1980) by 25%, on average, and over 50% in the extreme. This is a simple case of increased discharge with, presumably, a corresponding decline in the discharge/sediment load ratios (Table 1, case 3). In alluvial rivers this should produce width adjustments of +12% for the average increase and up to about +25% in extreme cases. For example, the Bella Coola River near Burnt Bridge Creek, is a wandering, cobble-gravel river. Here, changes in width followed the trend in annual maximum daily discharge over a 40 year period (Fig. 10), with increasing annual maximum daily flow (1955–1970) being accompanied by a 20% increase in width. The predicted widths (using the established relation between width and discharge) follow the trend and predict the actual widths within a few per cent.

In other cases the results are much less straightforward. For example, the lower Skeena River, an unregulated cobble-gravel river with a wandering pattern has experienced a 52% increase in mean annual flood (Table 1, case 3), so that widths should have increased by 23%. An increase of about 9% in the mean average width was observed by 1963 but, since then, the river has narrowed so that by 1987 it was 7% narrower than in 1947. The pattern of changes does not correspond with the history of flooding and the changes are much less than would have been predicted on regime principles, which appear to be inapplicable in this case.

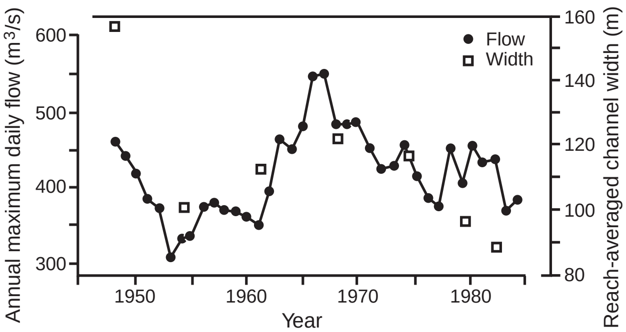


Figure 10. *Changes in channel width of Bella Coola River near Burnt Creek Bridge, British Columbia, in response to changes in discharge (data supplied by J.R. Desloges, 1990).*

Longer term historical records also give some indication of the response of Cordilleran rivers to climate change. Historical accounts and geomorphological studies indicate larger flows during the eighteenth and nineteenth centuries, perhaps from larger spring snowmelt, or from heavier autumn rainfall. Analysis of historical maps and descriptions suggest greater channel instability and channel pattern complexity (braiding or wandering versus meandering) (Gottesfeld and Gottesfeld, 1990), higher sedimentation rates (Church, 1983; Desloges and Church, 1987), and wider active floodplains at higher elevations—perhaps reflecting higher flood stages.

Interbasin diversion projects also modify stream discharge regimes. In the Kemano River the mean flow has been increased by a factor of three, but extreme floods have not increased. For the first 20 years after dam closure (1954) the river accommodated the increased flow by widening its channel, and inundating side channels. No large flood capable of moving the bed material occurred until 1974, when degradation of the bed was initiated, the channel began to narrow and to decrease its gradient. Although width adjustment occurred quite readily, only after 30 years is the channel beginning to approach the predicted values of both width and gradient. The history is interesting because it reveals that the pattern of adjustment may be complex when the channel bed is resistant to erosion. The initial response may be opposite to that which will eventually create the final stable morphology, and a single flood event may set off a train of events which is continued by subsequent moderate discharges.

In very extreme cases of flow regime modification the responses are dramatic. The Mattagami River diversion (northwestern Ontario), at the boundary of the Canadian Shield and Hudson Bay Lowlands, involved passing a large diverted flow through an existing small stream, Adam Creek, which occupied a meandering valley incised into Pleistocene deposits (Kellerhals et al., 1979). As a direct result of the much larger flows imposed on it (an extreme example of case 3), Adam Creek was scoured down to bedrock, meandering was eliminated, steep rapids formed in places, and degradation of over 10 m occurred. The extra charge of sediment flushed into the Mattagami River (Table 1, cases 7, 9) at the downstream confluence with Adam Creek formed gravel bars in the junction forcing the flow of the Mattagami River to erode the unconsolidated sediment on the opposite river bank.

A similarly dramatic impact (Table 1, case 3) is apparent on the Cheslatta River, British Columbia, also as a result of diversion of spillway flows, as part of the Kemano power project (Kellerhals et al., 1979; Kellerhals and Church, 1989). The greatly increased discharge resulted in much greater width and depth, increased meander wavelength, and decreased sinuosity. Also, as a result of degradation, bed sediment increased in size and the channel was eroded down to bedrock, leaving the former floodplain 5–15 m above current flood levels.

In small (<10 km^2) drainage basins east of Sherbrooke, Quebec, Leduc and Roy (1990) showed that land drainage was responsible for increases in width and channel capacity of small streams. The response was variable because of the local influence of bed and bank material, and vegetation cover, but width increases approached 100% on average, whereas channel capacity was increased by 150%.

Urban channels are particularly prone to large increases in flows, because of the tendency for artificial surfaces to increase the runoff quantities, and for artificial drainage systems to concentrate the increased runoff into shorter time periods. Thus, changes of the type shown in case 3 (Table 1) might be expected and have been documented. The effect becomes more obvious the larger the proportion of the drainage basin that is urbanized. Several of the streams draining south to Lake Ontario through Toronto and surrounding municipalities show these effects very clearly. Increased bank failure and erosion, channel enlargement (Fig. 11), more frequent flooding, and channel incision (reducing valley-side stability) have all been reported in many of these streams — all generally in accordance with the changes predicted for case 3 (Table 1) (Bellamy, 1994; MacRae et al., 1994).

Figure 11.

Small, confined, gravel-bed stream in an urban area (Highland Creek, Scarborough, Ontario). Increased stormflow from urban areas in the drainage basin have caused channel widening and a shift to a laterally unstable, braided channel. Photograph courtesy of K. Bellamy.

Decreased discharge (Table 1, cases 4–6)

The Peace River, in northeastern British Columbia (Fig. A-1g), has been regulated since 1968 for hydroelectric power production. It is a semialluvial, entrenched, and partly confined river with a cobble and/or gravel bed and a wandering pattern with permanent islands. The flow regulation has reduced peak discharge by about 50%, but has not affected mean flow in the river. The example most closely fits case 6 (Table 1) (Kellerhals and Church, 1989). In the first 300 km below the dam, the river is not now competent to transport its coarse-bed material and this inhibits the ability of the river to erode its bed. As a result, local channel gradient may only be altered by changes to channel sinuosity, and locally by deposition at tributary mouths; however, other changes are possible. From theory it is estimated that channel width downstream should be reduced by about 30% and depth by 20–25%. Reduction in width is achieved by vegetation succession on bars that were formerly inundated during the spring freshet, fine-sediment accretion on bar margins, and abandonment and filling of side channels. All of these changes have begun, but adjustment is continuing almost 30 years after dam closure, and is predicted to continue for decades or centuries on this large river (Church, 1995). In places sediment supply continues from the tributaries so that sedimentation is possible (Table 1, case 4). The tributaries have also responded to the drop in water level in the Peace River by degrading and entrenching their downstream reaches (Kellerhals, 1982; Galay, 1983).

Reduced flood peaks have resulted in the former floodplain of the river being abandoned as a low terrace. The bar surfaces will become the new floodplain level 2–3 m lower than the original floodplain. The abandonment and filling of side channels (reducing their total length by 50%) has significantly altered the channel pattern and reduced aquatic habitat diversity. Future changes could include increased erosion by the river of the weak valley sides, due to an increase in meandering, leading to an increase in the incidence of major landslides in the decades ahead.

The North Saskatchewan River below Big Horn Dam in Alberta is a similar case (Table 1, case 6). This unstable braided river has been subject to substantial flow regulation that has reduced the mean annual flood to 30% of its pre-dam discharge. The downstream morphology has changed radically from a braided pattern to a wandering or anastomosing pattern, by vegetation encroachment and channel abandonment. This has reduced the channel width.

In the Nechako River, British Columbia, the situation is slightly different, with an increase in fine-sediment concentration (Table 1, case 5). Vegetation has encroached on to bar tops and there has been some fine-sediment deposition downstream of tributaries, which could affect spawning gravels (Kellerhals and Church, 1989). The flow depth and width have both decreased. Again, impacts on fish are possible, especially by increasing the range of water temperature. These changes accord with those predicted in Table 1 except that the river is incompetent to adjust its gradient, and no change in meander wavelength is apparent.

The flow in many gravel and/or cobble rivers may not have sufficient force to cause bed degradation downstream of dams, but in sand-bed rivers degradation is usually readily accomplished. The Milk River in southern Alberta and northern Montana is a meandering, sand-bed stream with silty sandbanks whose flow has been depleted in Montana by Fresno Dam (Table 1, case 6) (Bradley and Smith, 1984). Pre- and postdam flood frequency curves show a halving of the 5 year flood from approximately 220 m^3/s to 110 m^3/s. Theory predicts that equilibrium channel width downstream of the dam should be approximately 0.7 times the pre-dam width, whereas the observed change was 0.75. Channel narrowing has occurred by vegetation encroachment into the channel. In sand-bed rivers, bed degradation may still be possible under reduced flows; this has occurred in Milk River, but may have been arrested by the exposure of bedrock in the channel bed. Reduced flows have also decreased the rate of bank erosion and meander migration downstream of the dam, relative to the pre-1952 rates and relative to the rates immediately upstream of the dam. There has also been a reduction in the recruitment and survival of plains cottonwood on meander lobes as a consequence of reduced flooding and sedimentation (Bradley and Smith, 1986). Similar channel shrinkage, along with a reduction in braiding and bank erosion, is observed on the sand-bed South Saskatchewan River downstream of the Gardiner Dam in southern Saskatchewan (Rasid, 1979; Galay et al., 1985) (Fig. A-1d, A-1e).

The largely human-induced changes to river morphology described in the case studies above provide useful information about river sensitivity to change but are not necessarily perfect analogues for climate-induced changes. For example, whereas dam construction generally causes a reduction in discharge and sediment load downstream (Table 1, case 6), the effects of which act in the same direction, this is not necessarily true for climate change. For example, if decreased discharge is the result of a drier, warmer climate, this may also lead to a reduction in vegetation cover, which in turn leads to increased sediment supply (Table 1, case 4) rather than a decrease (Knox, 1983).

There is an additional crucial consideration in assessing river channel response. Many Canadian rivers flow through nonalluvial material that they may be only marginally competent to erode under current flow regimes. This causes them to be stable and generally unresponsive to small changes in streamflow regime or occasional large floods; however, a long-term increase in streamflow and the magnitude of large floods could be sufficient to cross a threshold of activity which could trigger substantial adjustment and change in behaviour for only fairly small increases in streamflow. This is apparent in the case of the Kemano River, in which one substantial flood triggered subsequent adjustment in a river that had previously shown no tendency to respond to the imposed streamflow changes.

Sediment delivery to Canadian rivers

Theoretically, changes to the delivery of fine-grained (suspended load) or coarse-grained (bed load) sediment are a potential outcome of climatically induced changes to geomorphic processes in drainage basins. The consequences for river processes and morphology are included in Table 1. The impact of changes in sediment input depends on the coincident changes in discharge; in other words to the ratio of sediment load to discharge. The effects of changes in fine sediment ('wash') load (Table 1, cases 9, 10) may well differ from those caused by changes in coarse sediment ('bed material') load (Table 1, cases 7, 8).

Whereas the geomorphic literature is replete with examples of short-term impacts on sediment delivery from land-use changes and human activity, definitive data on the impact of short-term or long-term climate are scarce. The effect of climate change is expected to operate through changes in surface runoff and mass movement processes on hillslopes, the efficacy of which are strongly affected by vegetation cover. The role of climate in establishing long-term erosion rates is readily apparent, but very difficult to demonstrate in practice because of the confounding influence of several other variables.

In Canada, information on the suspended load of rivers, and hence, sediment delivery from the land surface, is restricted primarily to populated areas (Fig. 12). Recent interpretations of the available data (Ashmore and Day, 1988; Church et al., 1989; Ashmore, 1993) demonstrate that there is little climatic influence on spatial differences in sediment yield. Rather, the regional variations in sediment yield are related to differences in surficial materials, relief, glaciation, and land use. A dominant phenomenon in southern Canada is that in many river systems sediment yield increases downstream, contrary to classical expectation. This is thought to be a consequence of sediment supply being dominated by erosion of Pleistocene sand and silt deposits along degrading rivers, instead of surficial erosion derived from the entire land surface of the drainage basin.

The dominance of riparian sediment sources has important consequences for the changes in sediment delivery in changing climates. It is possible that, even if vegetation cover were to change over substantial areas, the effect on sediment delivery would be negligible. The climatic effect on valley-side stability and erosion, which may be related to channel adjustments through river widening and channel pattern changes in confined rivers, would be much more important. This dominance of riparian sources makes many Canadian river basins substantially different from those in nonglaciated landscapes to the south. Changes to land-surface conditions and processes, which are normally considered the dominant environmental causes of changing sediment delivery, become secondary to the direct connection between stream channels and their adjacent slopes. Examples of the effect of changes in valley-side stability and sediment supply are included in the regional discussions later in the report.

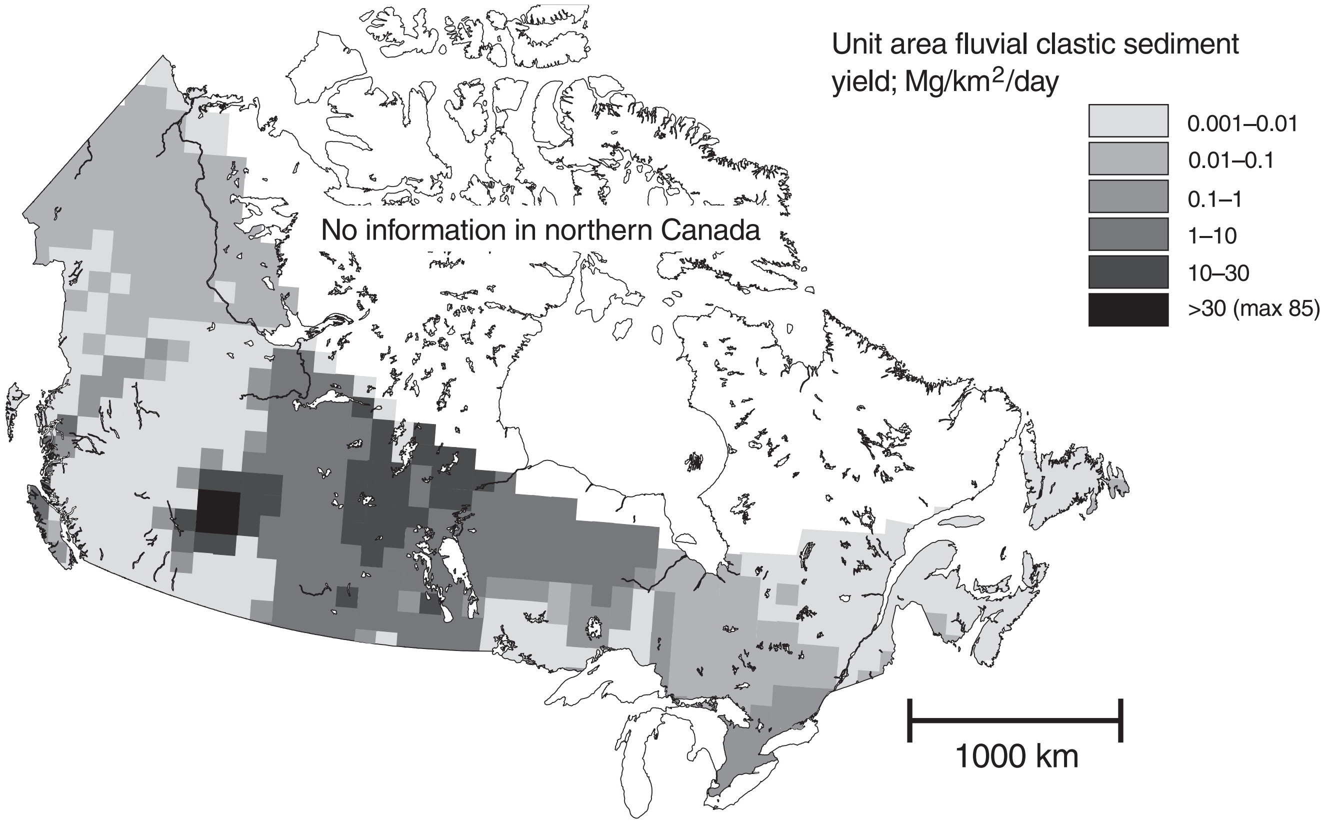


Figure 12. *Mean annual suspended sediment yield for areas of 10 x 10 km^2 in southern Canada. Values are interpolated (kriging using a 50 km grid) from widely and irregularly spaced sample points, concentrated in the Cordillera, southern Prairies, and southern Ontario. Precision of the estimates is poor in other regions, especially the Canadian Shield, coastal British Columbia, and Yukon Territory.*

A further complicating factor affecting changes in sediment loads is the effect of sediment trapping by lakes and reservoirs. The extent of natural and artificial storage along many Canadian stream systems may reduce and even negate any increases in sediment load induced by climate change. Furthermore, in general, human effects on sediment delivery may already be greater than any changes likely to follow from climatic change.

It is important to note that apart from geomorphic effects, changes in suspended sediment transport may have an important impact on environmental quality. Increased fine-sediment deposition is known to adversely affect stream habitat, and the fine sediment is the principle vector for contaminants transported through river systems.

River ice in rivers located in cold regions

The hydrological and geomorphic effects of ice jams, icings, and permafrost are unique to rivers located in cold regions (Carter et al., 1987) and, being temperature sensitive, will be influenced by climate change. In many cases these ice-related effects are assumed to be only secondary to the control of discharge and sediment load on channel processes and morphology. In some cases (for example the effects of permafrost) the effects are restricted to certain northern regions, in other cases (river ice) the effects may be greatest in the north, but are also important in other regions of the country. The processes restricted to permafrost regions are discussed in the section on ‘Northern regions’.

River-ice formation and impact

River ice has an important influence on the hydrology of cold regions, affecting flow, water levels, and storage. Moreover, many hydrological extremes, such as low flows and floods, are frequently more a function of ice effects than runoff from the land. The geomorphic effects of river ice are more controversial, but potentially significant (Church, 1988; Gatto, 1994; Scrimgeour et al., 1994). Of all river-ice processes, ice jams are the major source of economic damages, averaging approximately $20–30 million per year in Canada (Van Der Vinne et al., 1991). The growth or decline in future damages from such events depends on how climate change affects the frequency and severity of river ice freeze-up and break-up events.

The rapid hydraulic storage and release of water by river-ice jams during breakup is the most significant hydrological event of the year in cold regions. Breakup jams may be massive and destructive, causing large rises in water level, combined with the destructive effects of the moving ice. Where their occurrence persists from year to year, they are responsible for the highest water levels recorded, frequently substantially above those produced by even the most extreme open-water floods.

River-ice breakup is usually a spring event associated with spring snowmelt runoff, although mid-winter breakup is possible in maritime and temperate regions, and under artificial flow regulation. When breakup is preceded by cold weather (so that ice cover remains intact, thick and strong) and is associated with a large flood event (created by rapid snowmelt and possibly augmented by rainfall) breakup is often dynamic and violent, with ice-runs moving at several metres per second. Contrasted with these dynamic breakup events are thermal breakups characterized by gradual warming and weakening of the ice cover in place (Prowse, 1994; Fitzharris et al., 1996).

The large-scale severity and pattern of breakup is also influenced by the alignment of the river relative to major climatic influences. More dynamic events are expected where snowmelt, runoff, and breakup advance downstream with seasonal warming. In such cases, the flood wave is always advancing into a relatively cold and mechanically competent ice cover. This phenomenon is well known in the Mackenzie Basin. Much less dramatic breakups occur on rivers flowing in directions opposite to that of regional warming. In such a scenario, thermal breakup of the downstream ice cover can occur before a spring flood-wave is generated within the headwaters.

Local conditions also play a role in ice-jam effects. For example, ice jams frequently recur at the same location each year because of river features such as local constrictions, sharp bends, and division about islands. These conditions are unrelated to climate.

The geomorphic effects of river ice are disputed, but tend to be restricted to local bank and bed scour, ice pushing or rafting of sediment, destruction of riparian vegetation, and deposition of ice-rafted rocks and boulders (Dionne, 1976; Mackay and MacKay, 1977; Koutaniemi, 1984; Martini et al., 1993); however, bed scour, flow diversion, and floodplain inundation can occur during ice-related flood events. In some cases these have been observed to cause relocation of stream channels, modification of the channel pattern, enhanced bank and bed scour, as well as damage to structures and bank protection works, even on intermediate-size rivers in southern Canada (e.g. Doyle, 1988). In some local cases ice scour and ice-rafting of sediment are persistent and significant processes (King and Martini, 1983; Martini et al., 1993). Hanging ice jams formed in winter may induce local bed scour. Indirectly, ice jamming may cause cutoff of river meanders and more frequent floodplain inundation, causing accumulation of floodplain sediments to higher levels. Ice conditions, flow characteristics beneath ice cover, and breakup processes also significantly affect ecological processes (e.g. organic and nutrient inputs), physical habitat, species composition, and riparian vegetation (Prowse, 1994; Scrimgeour et al., 1994).

The role of climate on river-ice processes

Much research on river ice has concentrated on hydraulic modelling and local case studies. Research on regional-scale linkages to physiographic and climatic conditions is lacking, although it is apparent that ice formation and breakup are strongly tied to climatic conditions. The length of the ice season is the most obvious example of this connection. Historical records from North America and Europe indicate considerable decadal variation in ice-season length which correlates with trends in fall and spring mean air temperature in both continental and maritime climates. Freeze-up and breakup dates are observed to shift by 10–15 days with typical decadal temperature fluctuations of the order of 2°C. This amounts to a northward shift of isochrones of approximately 200 km (2° latitude) based on current isochrones (Prowse and Onclin, 1987). Climatic conditions also control the rate of formation, accumulation, thickness of ice cover, and the nature of the breakup processes.

If warmer conditions prevailed throughout the winter period, many rivers within the more temperate regions would remain ice-free or develop only intermittent or partial ice-cover. Even in colder regions, ice growth and thickness would be reduced. If increased winter precipitation accompanied such warming, cover thickness could be further reduced because of the added insulation provided by a deeper snowcover, although the snowcover season might be shorter. Warmer winters can also favour the formation of mid-winter breakups produced by rapid snowmelt runoff, particularly those initiated by rain-on-snow events.

Warmer conditions would delay fall freeze-up and favour earlier breakup. Warmer spring air temperatures may also affect breakup severity. On the northern Liard River, Prowse (1986) found that thermal and dynamic breakups could be separated according to the magnitude of accumulated melting degree-days in the month preceding breakup; the thermal breakups being preceded by significantly warmer conditions than the dynamic events. Given the complexity of factors controlling breakup severity, however, such results may be highly site-specific. Breakup severity is actually the result of a complex balancing between downstream resistance (ice strength and thickness) and upstream forces (flood wave). Whereas thinner ice produced by a warmer winter would tend to promote a thermal break-up, this could be counteracted to some degree by the earlier timing of the event. This is because most of the pre-break-up change in ice strength is controlled by inputs of solar radiation (Prowse et al., 1990), which is less intense earlier in the spring, particularly at high latitudes where the spring-time increase in solar radiation is most rapid.

Changes to the size of the spring flood wave depend on two climate-related factors, the rate of spring warming, and the size (water equivalent) of the accumulated winter snowpack. Greater and more rapid snowmelt runoff would favour an increase in breakup severity, whereas smaller snowpacks and more protracted melt would reduce breakup intensity. Higher rainfall associated with snowmelt would also increase severity of breakup floods; however, breakup characteristics also depend on the potentially conflicting roles of ice strength and thickness. Considering the simplest of all cases, spring breakup flooding should be less severe if winter and spring air temperatures increase and there is a decrease in the size of the snowpack available for spring runoff (Fitzharris et al., 1996). Artificial flow regulation may also contribute to a reduction in ice cover and breakup severity due to changes in water temperature and reduction of the large spring floods which normally cause severe dynamic breakup.

Summary

Climate-streamflow relations

It is clear that streamflow, the factor most influential in controlling river processes, is strongly influenced by climatic change. Whereas modelling the effect of climate on streamflow parameters such as flood frequency distributions is very difficult, historical analogues provide abundant evidence of the effect of climate change on streamflow. From analysis of selected historical climate and flow records in regions of Canada the following important potential effects of climate change on fluvial processes are anticipated.

1. In general, hydrological responses to climate change, as shown by changes in precipitation and streamflow, will be regionally homogeneous.
2. Streamflow is expected to increase during periods of increased precipitation (and vice versa), and there may be significant amplification of the streamflow response (i.e. the per cent change in streamflow will be greater than the per cent change in precipitation), which may be greater in drier regions.
3. Increases in temperature may reduce streamflow in some regions through reduced snowfall accumulation and increased evapotranspiration.
4. Changes in extreme flood flows will be proportionally greater than the changes in mean flows.
5. Changes in discharge as a result of modelled future climate changes are likely to be of the same order as those seen in the historical past as a result of natural climatic fluctuations.
6. The relation between regional or hemispheric temperatures and streamflow is weak but negative, and appears to operate by reduced snow accumulation or, in dry regions with low annual runoff, by increased evapotranspiration in warmer years.
7. Climatic warming will reduce the spatial extent and duration of snow cover, reducing the magnitude and relative significance of nival floods in some regions.
8. Sensitivity of streamflow to changes in climate and hydrology varies regionally, and depends in part on drainage basin characteristics and dominant runoff mechanism.
9. Streams deriving significant discharge from glacial sources will exhibit a damped response to climatic change, at least for some years or decades.
10. Natural and artificial lakes as well as wetlands will modulate streamflow response on many river systems, especially on the Canadian Shield.
11. There may be an increased probability of overtopping of dams, leading to catastrophic ‘Saguenay-type’ flooding.

Response of river processes

Rivers adjust to changes in the controlling variables, particularly discharge, and the response can, in some cases, be dramatic with serious consequences for the functioning of the river system. Actual examples, mainly from human manipulation of streamflow, show that the adjustments are of a type that may be predicted, at least approximately, from an existing understanding of the controls on river morphology; however, the direction, magnitude, and rapidity of change are difficult to predict and will vary between both reaches and streams, depending on the existing characteristics, dominant controls, and state of adjustment. Adjustments may take decades and the initial direction of change may not point to the final state. Factors that may influence the outcome include the alluvial/nonalluvial nature of the reach; the stream energy in relation to the material to be removed; the present-day and recent stability of the stream; the extent to which adjustment is confined by the valley sides (with consequences for slope stability), or resistant bedrock along the channel margins and beneath the stream bed; and the sequence of reaches of differing morphology along the river. This emphasises the importance of the local setting in determining how a river may respond to climatic change and the difficulty of establishing regional predictions.

Regional differences in overall response will occur because of differences in climate, physiography, and surficial materials. At the regional scale the differences in hydrology and physiography can be described by runoff intensity (annual precipitation minus annual evaporation, per unit area) and overall basin energy (the combination of runoff intensity and overall topographic relief). The inset maps on Figure 2 indicate the spatial pattern of these factors. In general, we expect areas of high basin energy and runoff intensity to be the most sensitive regions hydrologically and geomorphically.

A significant consideration under increased flood events is the erodibility of the river sediment relative to the stream energy. There is a well defined threshold above which the mobility and erodibility of sediment may increase rapidly, relative to the increase in streamflow (stream energy). Currently stable streams experiencing small but sufficient increases in streamflow to cross this threshold could undergo substantial changes with a relatively small increase in streamflow. This may be a special concern in Canada where many streams flow through nonalluvial material which they are only marginally able to erode and transport. Small changes in streamflow may be sufficient to mobilize this material.

Documented changes of morphology due to natural fluctuation in flow may involve changes in channel width of the order of 25–30%. Human activity related to dams and diversions has produced changes at least this large on the affected rivers, and in some cases the effects are much greater. In some regions of the country human impact may continue to be much more important than climatic. Similarly, for sediment delivery, the effect of human activity may well dominate any effects due to climatic change. No strong regional signal due to climatic conditions can be found for fine sediment yield in Canada. Climatic effects on local valley-side stability is likely to be a much more important factor, especially for entrenched and confined streams, than any general climatic effect on erosion of the land surface.

River ice

There is little information on the effect of river-ice on fluvial processes in general, but there are certainly significant local effects due to icing and ice jams. General climatic warming will obviously shift the geographical pattern of the extent of river-ice problems and the timing of breakup and formation; however, local conditions often determine the exact location of ice jams. The severity and frequency of ice jams is likely to be reduced overall, provided that smaller snowpacks and more gradual breakup are prevalent, but the complex inter-relations of the relevant variables leads to considerable uncertainty.

Conclusions

River morphology and processes will respond to climatic change. Changes in precipitation regimes will be especially important through their effect on streamflow and flood magnitudes. In some regions large changes in flood magnitudes are possible and consequently significant changes in river morphology and dynamics may result. Human manipulation of streamflows provides useful examples and analogues for the expected response of rivers to climatic change. These examples show that responses are predictable, but not with complete confidence in either direction or magnitude of change. Local sediment delivery conditions will be an important additional consideration affecting river response. The secondary role of changes to river-ice processes is also important, but very difficult to assess reliably.

PART II: FLUVIAL RESPONSE TO CLIMATE CHANGE IN REGIONS OF CANADA

Fluvial regions

The evaluation of the sensitivity of Canadian rivers to climate change is based on the identification of distinct fluvial regions in Canada. These are shown on Figure 2. This map is primarily intended to convey the regional characteristics of fluvial processes and morphology as determined by climate and physiography, and the consequent regional differences in sensitivity to climate change.

A number of the physical influences on streamflow and river characteristics, including geology, relief, hydro-climate, and occurrence of permafrost; have strong regional character and form the basis for identifying the corresponding fluvial regions. These are regions within which the existing streamflow characteristics, river morphology, and river dynamics are distinct, and within which the effect of climatic change and the consequent fluvial response are likely to be distinct.

The map (Fig. 2) divides Canada into a series of relatively homogeneous fluvial regions based on general physiographic, hydrological, and fluvial characteristics. These are subjectively arrived at largely from consideration of conventional regional geological, physiographic, climatic, and hydrological divisions. The major regions are identified primarily on the basis of relief and geology (although they are also climatically distinct), and the subdivisions relate primarily to differences in hydro-climate, vegetation, and permafrost conditions. The rationale for subdivision of the regions is discussed briefly at the beginning of each regional section. The end result is a series of major regions which follow, fairly closely, the conventional physiographic divisions of the country, but includes consideration of hydrological regime (cf. Bostock, 1970; Bird, 1980; Hayden, 1988; Slaymaker, 1989; Watt, 1989; Trenhaile, 1990; Wolman and Riggs, 1990; French and Slaymaker, 1993). Major boundaries were drawn from existing national maps of these variables at a common scale and projection (Douglas, 1968; Energy, Mines and Resources Canada, 1985, 1986; Energy, Mines and Resources Canada and Forestry Canada, 1993; Fulton, 1995) and from climatic and hydrological maps of Canada (Fisheries and Environment Canada, 1978; Environment Canada, 1988). Where regional boundaries are close to major drainage divides, the boundaries follow the divides.

In populated areas of the country, land-use change, due primarily to agriculture and urbanization, has already had a significant impact on fluvial processes and channel stability. An important question is the relative magnitude of these direct human effects (past and future) and the indirect effects of climate change. In addition to land-use change, in-channel flow regulation and diversions have a significant impact on channel morphology. There are few large river basins in southern Canada that are not affected to some extent by flow regulation and diversion (Fig. 13). The effects of existing human impact and their role in future responses to climate change are discussed in the relevant regional sections of this part of the report. These effects are also noted in assessing the relative sensitivity of the regions depicted on the map.

There are two important qualifications to be made that affect the way in which the map is interpreted and used. First, the division of the country into fluvial regions gives a potentially misleading impression of variation in fluvial morphology and dynamics. Variability in river morphology within regions may be as great as the variation between regions and particular river morphologies may occur in all regions. One reason for this is that the glaciation of Canada has left extensive deposits of glacial and proglacial sediments covering the bedrock. These surficial materials are the predominant source of sediment for the rivers. The distribution of these glacial sediments is complex, obscures the underlying bedrock and, therefore, produces both local variability and some inter-regional homogeneity in source materials for rivers (Fulton, 1995). For example, extensive glacial lake basin deposits occur in several regions and tend to produce a distinct fluvial morphology which is very sensitive to changes in flow regime. Regionalization tends to obscure this influence. Other effects on river processes and responses which cross regional boundaries are the presence of lakes, wetlands, and glaciers, as well as the effect of land-use and flow regulation. All of these substantially modify streamflow regime and the response to climatic change.

The second important qualification is that the fluvial regions describe the characteristics and possible responses of small and moderate size rivers contained within a single subregion; however, the drainage basins of very large river systems (Fig. 14) often cross one or more of the regional or subregional boundaries. Climatic impacts may be transmitted downstream from one fluvial region to another, causing responses that may be uncharacteristic of smaller river systems that are completely contained within the same region. One obvious instance is the contrast between large streams crossing the Prairies with their headwaters in the Rocky Mountains; and those smaller rivers originating in the Prairies. Similar effects may be seen in large Cordilleran rivers (e.g. Fraser River), and the tributaries and main stem of the Mackenzie River.

This part of the report provides more detailed interpretation and justification of the likely changes within each major region, or group of regions, on the fluvial regions map (Fig. 2), and highlights changes that are of greatest significance to each region. The map should be referred to throughout this part of the report in order to locate the relevant region(s) and for summary information on the possible changes to rivers. The prospective changes to rivers as a consequence of climate change are based on the arguments and evidence developed in the preceding parts of this report and the background information in the Appendix. In general, we have assumed that future climate change will lead to a more active hydrological cycle, with increased streamflow in many regions, and increased significance of rainfall-generated floods; especially in southern Canada.

Southern Cordillera

Regional physiography and fluvial characteristics

This region covers all of montane British Columbia and Alberta south of the extensive influence of permafrost. It is subdivided into five major subregions: ‘Exposed Coast’, Coast Mountains, ‘Dry Interior Plateaus’, ‘Central Uplands’ (Skeena, Stikine, and Omenica mountains) and ‘Interior Mountains’ (including Rocky, Columbia, and Cariboo mountains).

The Coast Mountains are tectonically active with relief approaching 3000 m, in many places. Tectonic activity, along with recovery from the effects of glaciation, continues to contribute to landscape formation, as well as to the steepness and instability of mountain slopes (Ryder, 1981; Clague and Mathews, 1987). The ‘Dry Interior Plateaus’ have relief of about 1000 m, rising to 1800 m in some ranges. The major trunk rivers, such as the Fraser River, are deeply incised into the upland surface. The interior mountains rise to 3500 m in places, but are generally lower in height further north. Forest cover is widespread but at lower elevations, in the interior plateau, the drier climate produces grassland and semiarid vegetation.

Mean annual runoff is highest on the windward side of the Coast Mountains where annual precipitation may be several metres per year and runoff may be 1000–2000 mm. The 'Exposed Coast' region is distinguished from the Coast Mountains on the basis of a larger proportion of precipitation falling as rain, more persistent summer rain, and generally low snowfall accumulations at low elevations. The 'Dry Interior Plateaus' are considerably drier, and in places semiarid. Annual runoff is generally 100–200 mm. Precipitation, snowfall, and runoff increase again in the 'Interior Mountains', but are not as great as in the coastal region. The Cordillera has the highest average annual flood discharges in the country, especially in the coastal region where discharges of 500–1000 $m^3/s/1000\ km^2$ are common. The exception is the 'Dry Interior Plateaus', where flood flows may be as low as in some areas of the 'Southern Plains'.

Flow regimes are strongly dependent on winter snowmelt, with a dominant spring peak, but in the coastal region peak flows occur in response to fall and winter rainfall, as well as to rain-on-snow. There are also large areas in the 'Exposed Coast', Coast Mountains, and 'Interior Mountains' in which flow is strongly influenced by glaciers, producing a summer peak discharge from glacier melt. Glacier-influenced stream flow regimes will respond differently to climate change because of the modulating effect of storage in the ice mass (*see* section on 'Prospective changes on Cordilleran rivers').

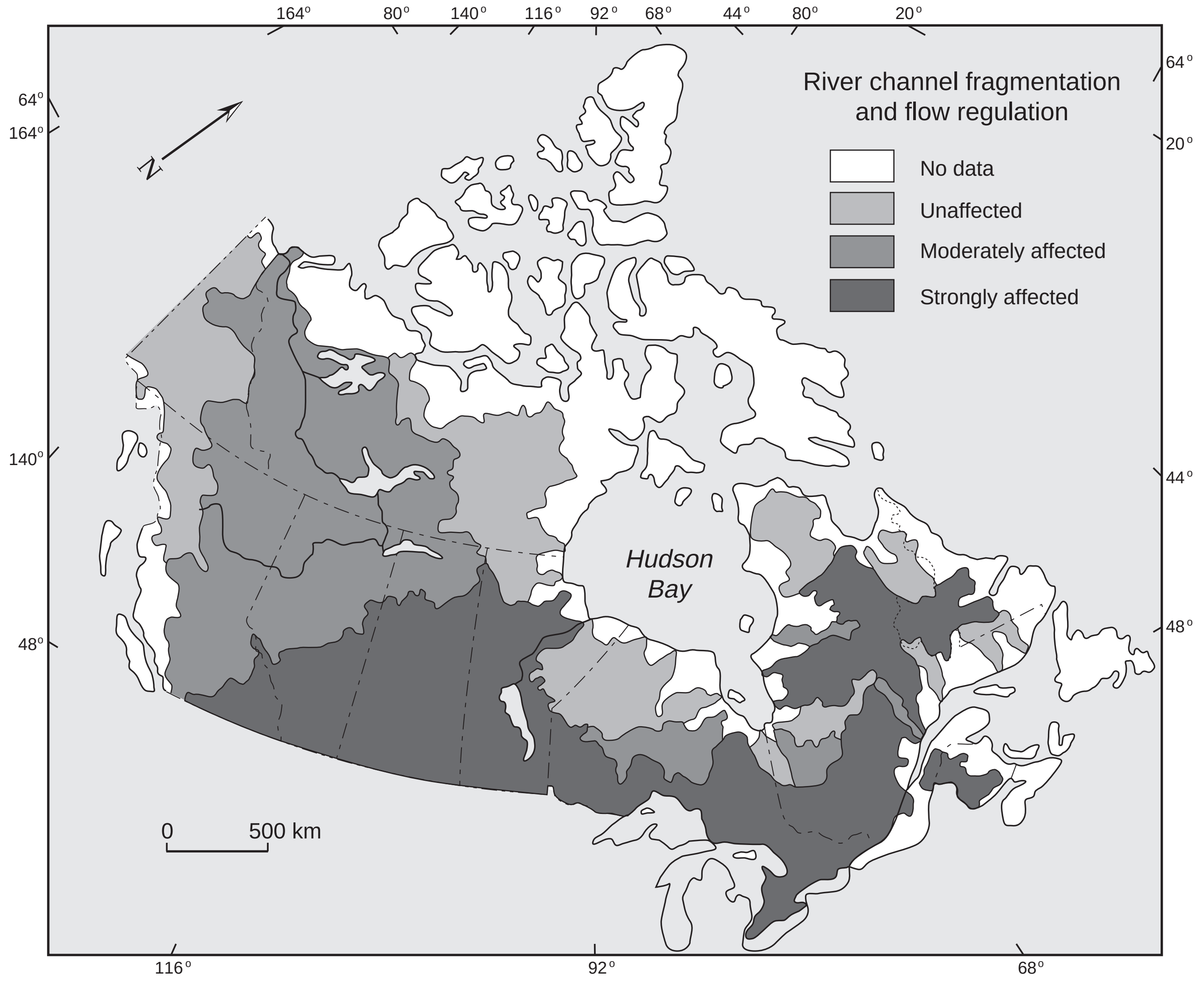


Figure 13. *Index of the effect of flow regulation and stream diversion on major river systems in Canada for rivers with mean annual discharge greater than 350* m^3/s *prior to regulation. The index estimates the relative significance of flow regulation and diversion on the annual river flow, and the impact of dams and reservoirs on fragmentation of riverine habitat (based on Fig. 1, Dynesius and Nilsson 1994).*

Fluvial morphology is highly variable, but has some distinctive regional aspects (Bovis, 1987). Most rivers are gravel or cobble bed, and channel patterns range from meandering, through wandering, to braided. Braiding is common close to glacial sources. Some low gradient, 'anastomosed' reaches also occur as seen, for example, in the upper Columbia River (Smith, 1983). Wandering streams, poised between meandering and braided are common (Desloges and Church, 1987, 1992). Rivers in the region are known to have undergone changes in morphology over the past century (Ryder, 1981; Church, 1983) in response to changes in environmental control, landslides, debris flows, and large floods (Hickin and Sichingabula, 1988). In many cases in the rivers of the Coast Mountains there is a downstream transition from braided in the upper reaches to meandering in the lower gradient downstream reaches and from gravel banks to sandy silt banks (Hickin and Sichingabula, 1988). Confinement and entrenchment in narrow valleys and canyons are also common. The major rivers in the 'Dry Interior Plateaus' region (e.g. Fraser River and its tributaries) are distinctive, being incised into bedrock within large thicknesses of glacial deposits which form confining bluffs along the length of the river (Church, 1990).

During glacial phases in the Coast Mountains ice extended over the coastal lowlands and onto the present continental shelf. Today, the lowlands and valleys contain large amounts of glacial sediments which are the primary sediment source for many rivers, floodplains, deltas, and alluvial fans. In the 'Dry Interior Plateaus' the deeply incised main valleys also receive much of their sediment supply from glacial deposits within the valleys.

In the confined valleys of the region the role of valley-side mass movement (landslides and debris flows), which may cause temporary blockage of streams, is locally significant to fluvial activity (Jordan, 1987). Likewise, catastrophic glacial

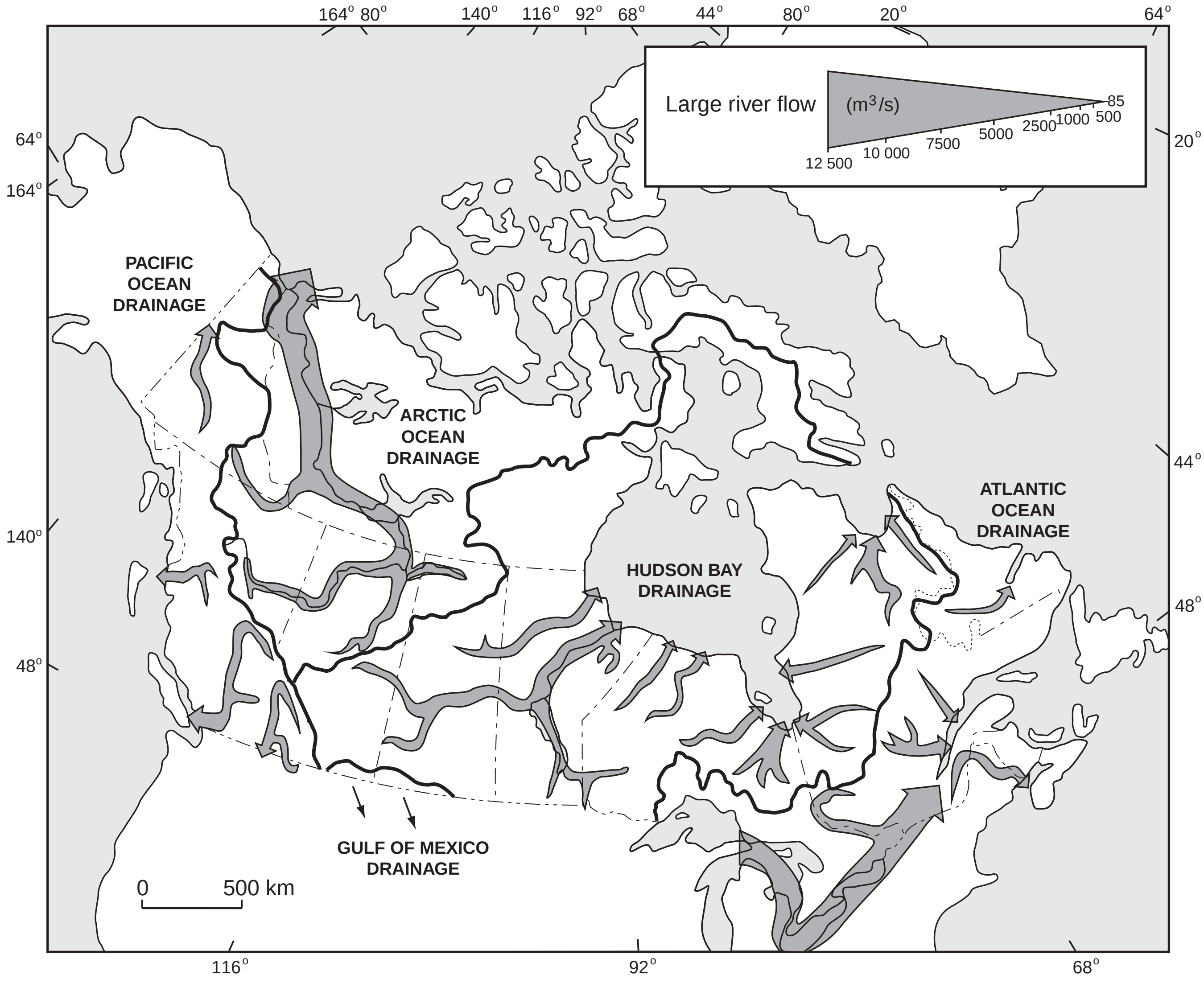


Figure 14. *Major drainage basins and annual river discharge (based on Fisheries and Environment Canada, 1978).*

lake drainage may produce flood discharges more than twice as large as those produced by rainfall or snowmelt under any climatic regime, present or future (Desloges and Church, 1992). The effects of such floods are dramatic, including large increases of channel width, channel pattern changes, floodplain destruction, and erosion of sediment which normal floods are incompetent to move.

Human activity has affected many rivers of the region, either directly, by dam construction and channellization works; or indirectly by land disturbance for resource extraction (e.g. logging and mining); however, some of the major rivers and drainage systems (e.g. Fraser, Skeena, Nass, Stikine rivers) remain comparatively unaffected by human activity (Church, 1990).

Prospective changes on Cordilleran rivers

The Canadian Climate Model predicts an increase of 4°C in winter mean temperature in British Columbia, less than 4°C in summer, an increase in winter precipitation of about 1 mm per day (90 mm for the winter season), and no change in summer. There would be little change in winter soil moisture, but a decline of 2–4 cm in characteristic summer soil moisture content (all results quoted *in* Houghton et al. (1990)). In a regional assessment which takes into account transient lag effects due to adjustment of the north Pacific Ocean, McBean et al. (1991) estimate increases of winter temperature of the order 2.5°C by 2025 and 4°C by 2050, increases of summer temperature of about 1.5°C and 2.5°C, respectively, and an increase of precipitation of about 0.5 mm per day on a year-round basis. These appear to be the best estimates for the region. The precipitation figure amounts to 180 mm per year and is consistent with the figure of Houghton et al. (1990), if the change is expected to occur mainly in the autumn and winter. The figure amounts to between 12 and 18% of current annual precipitation, the absolute total of which is not at all well known because of lack of gauging within the high mountains.

Changes in streamflow

Karl and Riebsame (1989) found that precipitation changes were typically amplified in runoff by a factor of about 2, whereas temperature changes had little consistent effect on runoff because of varying seasonal associations of change in the two effects. In southern British Columbia the amplification factor is about 1.5 between precipitation and runoff; however, a significant complication is that substantial changes in winter temperature may affect snow accumulation, hence, the timing and magnitude of snowmelt runoff, as well as the magnitude and occurrence of rain-on-snow events. In many basins in the Cordillera this represents the major annual flood and the major annual volume of runoff, so temperature may have a substantial effect on the runoff regime.

Qualitatively, the regional hydrology of the Cordillera may respond to global climate change in a number of ways:

1. an increase in autumn and winter precipitation will increase the incidence of floods in those seasons, and total runoff in the Coast Mountains and 'Interior Mountains';
2. because of warmer weather, a higher proportion of autumn and early winter precipitation will occur as rain, which may increase the size of the greatest floods in drainage basins of less than about 10 000 km^2 area;
3. in the 'Dry Interior Plateaus', the reduced winter snow accumulation will decrease the spring freshet, reducing peak flow in larger basins and causing a slight decrease in mean flow in all basins in the plateaus;
4. small basins in the 'Dry Interior Plateaus' (<1000 km^2) may experience increased flood runoff due to more vigorous summer convectional showers, although mean flow will decline somewhat with extended periods of summer low flow;
5. runoff increases in the mountains may be of order 18–27%, and the mean annual flood may increase by 20–30%, if the primary estimates of precipitation changes are reasonable;
6. where glaciers are a major source for streamflow, the effect of climate change will be moderated by the glacier storage and will reduce the likelihood of increased flood flows, but warmer temperatures and a more active hydrological cycle are expected to cause increases in average flows from glacierized basins.

Changes in fluvial processes

The projected hydrological changes are comparable with those witnessed historically. These changes should not lead to radical changes in the morphology of many rivers. Alluvial rivers may experience hydrologically determined increases in channel width of order 10–15%. In nonalluvial rivers, the changes will be small; however, in mountain valleys many of the rivers exhibit a 'wandering' habit, poised between single-thread and braided states. Some may be pushed into the braided state, with a substantial increase in bank erosion and channel zone width (cf. the Kemano River example).

General landscape sensitivity is greatest in the coastal regions where steep gradients and large annual rainfalls combine to create very high-energy geomorphic systems.

It is possible that changes in erosion of the land surface and sediment yield to the rivers may prompt more drastic changes in river channels. Such effects will be most apt to occur in the already semiarid valleys of southern interior British Columbia, but such effects will be strongly influenced by human activity including grazing of animals, agriculture, forestry, communication lines, recreation activity, and urban development. Where such circumstances dominate, it is fruitless to attempt any forecast of even an approximate nature of the anticipated effects of global climate change on fluvial processes until the magnitude of the sedimentation can be estimated.

‘Southern Plains’

Regional physiography and fluvial characteristics

The ‘Plains’ region south of the widespread permafrost zone consists of two subregions, the ‘Dry Prairies’ and the ‘Southern Boreal Plains’. It is a region of low relief glacial lake plains and hummocky glacial terrain, with extensive, deep, glacial deposits underlain by weak sedimentary bedrock. Relief increases at the western margin of the region in the eastern foothills of the Rocky Mountains. The natural vegetation cover is grassland or parkland in the south (‘Dry Prairies’), and boreal forest in the west and north (‘Southern Boreal Plains’). Agriculture has modified large areas of the ‘Dry Prairies’ and the Peace River region of the ‘Southern Boreal Plains’.

A regional trend in hydrological characteristics separates the ‘Dry Prairies’ from the ‘Southern Boreal Plains’. Annual precipitation and runoff are extremely low in the ‘Dry Prairies’, with runoff approaching zero in the driest areas and typical values around 50 mm/year. These are the lowest rates in the country, with the possible exception of the high Arctic islands. To the north runoff amounts increase, and there is an abrupt increase at the eastern margin of the Rocky Mountains, where boreal forest cover is extensive. An important feature of the runoff on the ‘Dry Prairies’ is the presence of considerable areas of internal drainage into sloughs and lakes; and the absence of a fully integrated stream system over large areas. In the ‘Southern Boreal Plains’ regions, extensive wetlands and high lake density affect flow regimes; and will moderate any changes to streamflow regimes and floods that might result from climate change.

Most of the main rivers of the Saskatchewan–Nelson River and Peace River systems have approximately 70% of their discharge supplied from the mountains. Prairie runoff is often a negligible contribution to these rivers. This contrasts strongly with streams in the eastern Prairies to which runoff is supplied locally. The result is two distinctly different flow regimes. The mountain-source rivers have a snowmelt peak in April resulting from prairie snowmelt, followed by a second, larger, peak in May or June related to snowmelt and rainfall in the mountains. Summer flows are low except for occasional large frontal or convectional rainfall floods, and winter flow is negligible. The prairie-source streams have a single snowmelt peak in April–May which may be the only significant flow for the entire year. In low snowmelt years, summer or early autumn storms (frontal or convectional) provide the peak flows. Some of the mountain-source streams, especially the Bow and North Saskatchewan rivers, have glacial sources in their headwaters which helps to sustain summer flows. These two types of flow regime will respond differently to climate change, and for many prairie streams the climate of the mountains is the significant control on streamflow.

The cause of extreme floods varies across the region. In medium to large prairie-source rivers, snowmelt, sometimes augmented by rain, is the major source of high flows. The highest floods occur when a heavy snow accumulation melts rapidly and is augmented by rain. Locally, ice jamming may raise water levels. In small basins, and in urbanized areas, summer convective storms and fall frontal storms are more likely to be responsible for extreme flood flows in the ‘Dry Prairies’ but to a lesser extent in the ‘Southern Boreal Plains’. Flooding is restricted to the floodplains of entrenched streams across the region, but is more widespread in low-relief areas such as southeast Manitoba, as shown by spring flooding in 1996 and the extensive flooding along the Red River in spring 1997. In the mountain-source streams the extreme events are likely to be associated with the May–June mountain snowmelt and rainfall. The most extreme events in this area occur when snowmelt coincides with prolonged rainstorms, such as occurred in southwest Alberta in 1995. These events are common in early summer when tropical maritime air is forced upwards against the foothills and eastern slopes of the Rocky Mountains. The result is prolonged, intense rainstorms. In these areas, summer rainfall or late spring rain-on-snow are responsible for the most extreme flows.

In both plains and foothills rivers, the flood frequency curves are often very steep. For example, the ratio of 100 year flood discharge to the mean annual flood discharge is often in the range 5 to 10 compared to, for example, 2 to 3 in the Great Lakes–St. Lawrence region. In other words, the extreme floods are very large relative to the average annual floods.

Water resource development is extensive on these rivers. Most of the large rivers flowing east from the mountains are regulated; and irrigation, industrial, and municipal abstraction are a significant influence on streamflow, to the extent that the natural flow regimes are no longer apparent on these trunk streams. Regulation of the mountain-source rivers reduces the May–June peak and increases winter low-flows. Flow regulation of the larger prairie-source streams (e.g. Assiniboine River) for flood control has also artificially reduced spring-melt discharge, but in these cases the snowmelt floods still dominate.

Rivers are typically incised and confined in valleys below the plains surface. Entrenchment of the main rivers is often 50–100 m. Some of these valleys are glacial meltwater channels whereas others were eroded postglacially by the contemporary streams. Bedrock channel sections are rare, but the valley walls are often poorly lithified bedrock. An important exception to the general entrenchment of rivers is the Red River in southern Manitoba, which occupies a very shallow valley only slightly incised into an extensive flat plain.

The large rivers flowing east from the Rocky Mountains are typically gravel or cobble streams, sometimes with a wandering pattern, in their foothills reaches. Bed material becomes progressively finer downstream, and sand-bed reaches dominate in eastern Alberta and in Saskatchewan. The confined streams are typically sinuous or meandering; and floodplain development occurs even in the confined sections. Extensive braiding occurs in some sand-bed reaches, especially along the South Saskatchewan River. The largest rivers have occasional mid-channel islands and bars, which evolve over many years (Chew, 1990). Valley-side gullying, badlands, and massive slope failures are major sources of fine-grained sediment for these rivers. The smaller prairie-source streams are also entrenched in many places. Highly sinuous, silt and/or clay channels are common in the floors of glacial meltwater valleys. Relatively high-relief drainage basins and steep streams occur on the eastern margin of the Manitoba escarpment.

Prospective changes on 'Southern Plains' rivers

Changes in flow regime are likely to differ significantly between the large rivers draining east from the Rocky Mountains and the smaller streams fed entirely from prairie runoff. The flood mechanisms and the hydrology of these two sets of rivers are quite different from each other.

Changes in streamflow

For the major rivers draining east from the Rocky Mountains the key influence on streamflow is water availability from spring snowmelt. Because at least 70% of the annual runoff in these rivers is supplied from the mountains and foothills, the change in climate conditions in the Rocky Mountains is key to predictions for these streams. The higher winter precipitation from warmer winters might be expected to counteract the effect of the shorter snow season and keep snow accumulation close to present-day values; however, spring snowmelt floods would occur earlier in the year than at present (Burn, 1994). Analysis of flow records on the Bow River at Banff indicates very little sensitivity of runoff to temperature change, but some sensitivity to precipitation (as in the Cordillera). In fact, the climatic influence on flow may be completely overridden by the artificial flow regulation by major dams on the largest rivers. In general, these reservoirs store the peak runoff events from the mountains, thus cancelling any tendency for increased precipitation to increase flood flows; however, the possibility remains that extreme flows could exceed the reservoir capacity and allow substantial flows downstream.

In the unregulated rivers of the mountains and foothills the key factor with respect to flood damage and changes to fluvial morphology is the possibility of more frequent incursions of maritime tropical air. Under current climatic conditions these occurrences produce the highest recorded floods, and these could become more frequent and larger. The period of time in which these events occur may also be extended. In a region in which flood frequency curves are already the steepest in the country, there is potential for an even greater range of flood discharges.

In the prairie-source streams the spring snowmelt flood is the major, and sometimes the only, runoff event of the year, especially in basins that are sufficiently large (1000 km^2) that convectional storms do not cover sufficient area to generate significant runoff throughout the basin. Historical records in the eastern Prairies show a marked sensitivity to climatic fluctuations; with large reductions in streamflow and maximum flow during warmer and drier years. Warmer winters will reduce snow accumulation leading to reductions in magnitude of the annual snowmelt flood. During historical warmer periods the size of the 20 year flood has decreased by a factor of 2–4 in large prairie streams, indicating considerable climatic sensitivity.

Summer low-flows are also likely to decrease because of greater evapotranspiration and lower soil moisture. An increase in temperature is likely to produce drier conditions; however, a warmer climate may also bring increased frequency of warm, moist air producing more frequent and more intense convective storms, and a greater frequency of frontal storms. This would increase the size and frequency of summer flood events in smaller drainage basins ($\leq$1000 km^2).

A significant hydrological factor on the plains, and one which is probably partially responsible for the apparent sensitivity of streamflow to climatic conditions, is the presence of extensive internal drainage areas (Fig. 2). These sloughs store much of the runoff from the ground surface and only overflow to supply streamfow during wetter periods. During drier, warmer summers water levels will drop making overflow and streamflow less likely, even though snowmelt replenishment may continue (Price, 1993). This evaporation effect will be amplified by reductions in snowmelt which currently supply the bulk of the water to these sloughs. Smaller sloughs in the southern part of the region are most susceptible to drying (Price, 1993). Lower water levels in sloughs will, in general, reduce runoff to the stream system as well as reducing the size and frequency of flood flows. In general, the likely climate change effect is an expansion of the existing areas of internal drainage, and a decrease in the frequency with which these areas overflow to the stream system. In the 'Southern Boreal Plains', wetlands and small lakes are extensive in some areas and these will moderate any streamflow response to climate change.

Changes in fluvial processes

The 'Southern Boreal Plains' is perhaps the only extensive region of the country in which vegetation change may be significant enough to affect fluvial processes and land-surface erosion. The northward extension of the grasslands belt may encourage greater agricultural disturbance on the northern fringes of the region, whereas the transition to semiarid conditions in the southwest could reduce agricultural activity. Semiarid regions are typically areas of high erosion rates, but the low relief may inhibit the effect in this case, except along the valley sides of entrenched streams where gully erosion is already widespread, or in areas of higher relief such as the Cypress Hills and Manitoba escarpment.

In the eastern Prairies lower spring freshet and lower summer flows will result in a decrease in fluvial activity; however, this may be counteracted in small drainage basins by increased frequency and intensity of summer convectional storms. The low gradient, sinuous, silt and/or clay streams which are common in this region will accommodate the reduced flows within their existing channels. Larger, sand-bed rivers will show progressive vegetation encroachment into the channel and a reduction in width. This is apparent from observing the effects of flow regulation schemes which reduce mean flows and eliminate flood peaks. The most dramatic North American example is that of the North

Platte River, Nebraska, which has undergone dramatic shrinkage in size as a result of flow extraction for irrigation (Williams, 1978). Increases in flood discharge have the potential to significantly affect stream morphology if the erosive resistance of the fine-grained sediment is overcome. Examples of such behaviour have been documented for the northern and central plains of the United States. In semiarid regimes the channel morphology may be permanently changed by a single flood event and channel morphology may become much less stable in the long term (Schumm, 1969).

Changes to valley-side stability in weak bedrock may be important in the larger Prairie streams. Changes in the water balance may alter slope stability, but the rivers themselves could affect stability by lateral undermining of slopes on the outside of meander bends. This effect is well documented and could be enhanced by either increases in meander amplitude or increases in meander migration rate.

In the mountain-source streams the increased precipitation may cause some increase in spring snowmelt floods, with the effect of causing some increases in channel width and depth, and the possibility of changes in channel pattern in streams that are already unstable. There is likely to be an increased risk of occurrence of extreme rain-on-snow floods of the type which caused extensive damage and inundation in southwestern Alberta in spring 1995.

Ice-jam flooding is also a problem in many prairie streams. Predictions of changes in severity of ice-jam flooding are problematic, but in general warmer conditions would ameliorate the hazard.

The flow of many major rivers of this region is artificially regulated. These flow-regulation schemes already have produced morphological responses larger than those expected under climate change (cf. the Milk River example discussed above (Bradley and Smith, 1984)). In the presence of continued flow regulation by reservoir storage the effect of climatic change will be small compared to the impact of flow regulation schemes.

Great Lakes–St. Lawrence Lowlands

Regional physiography and fluvial characteristics

This region is divided into two parts on the basis of differences in surficial materials and hydroclimate. The western section (Great Lakes), covering southern Ontario to the south of the Canadian Shield is a region of low relief with extensive glacial till, glacial fluvial, and lacustrine deposits, with the highest relief occurring in association with large glacial moraine complexes and the Niagara Escarpment. Originally forested, the region is now largely agricultural with large, expanding, urban areas. Pockets of native deciduous forest remain, often confined to river valleys. The eastern area (St. Lawrence Valley) is flat, apart from occasional, isolated volcanic hills, and underlain by extensive deposits of glacial marine clay, alluvium, and glaciofluvial sand. As in the Great Lakes subregion, disturbance by agriculture and urban development is extensive. Annual precipitation, annual snowfall, and proportion of precipitation falling as snow are greater in the St. Lawrence Valley subregion than in the Great Lakes subregion.

Annual precipitation and runoff increase eastward. Annual runoff is typically 200–400 mm, about 25–40% of annual precipitation. Annual flood discharges are lower than in the coastal regions of Canada but higher than those in the continental interior plains and the north, averaging about 200 m^3/s for 1000 km^2 drainage basins. There is a significant summer water deficit. Streamflow regime is typified by winter low flow, an early (March–April) nival peak, summer drought, and a secondary peak associated with cyclonic storms in the fall. The winter climate, ice regime, and nival floods increase in severity northeastward along the St. Lawrence Valley.

A variety of mechanisms contribute to flood events. Over most of the region the most common flood-generating events are spring rain-on-snow floods (Irvine and Drake, 1987), but snowmelt floods become progressively more important northward. Severe flooding is most common in the period December–May in the St. Lawrence Lowlands usually as a result of rain, or rain-on-snow. For example, in southern Ontario the median date of the annual flood is March 22 for rain-on-snow and April 5 for rain only. Flooding is controlled by the immediate weather conditions (sequence of air temperature and precipitation) rather than the total amount of snow on the ground. A deep snowpack may absorb much of the rain whereas a thinner snowpack over frozen ground may convert a larger proportion of rain into streamflow. Mid-winter thaws and floods occur in this region.

Summer convective storms and frontal storms are also important in smaller drainage basins and in urbanized areas. Extreme short duration rainfall intensities are highest in southwest Ontario, and throughout the region are, with the southern Prairies, the highest in the country; however, infiltration into dry soil, as well as interception and absorption by vegetation limit the effect of short duration rainstorms in the summer. In urbanized areas, rainfall generated floods are more significant than rain-on-snow events.

The number of rainfall-generated flood events, and the magnitude of rainfall-generated floods are greatest in southwest Ontario, decreasing northward and eastward. Conversely, the duration and relative importance of snowmelt floods increase northward and eastward (Irvine and Drake, 1987).

The highest flood discharges on streams in southern Ontario are produced by extreme rainfall events such as those associated with Hurricane Hazel in the Toronto region in October 1954 (Hare and Thomas, 1974, p. 79–80) or the storms of May 1974 in the Grand River basin (Gardner, 1977). Documentation of disastrous floods due to torrential rain in southern Quebec extends back to an extremely damaging event in June 1892 (Watt, 1989).

Ice jams may cause flood stages significantly higher than open-water floods at the same discharge (Beltaos, 1983, Fig. 11). Ice jamming is common in the region and certain sites are associated with chronic occurrence such as the lower

Thames River near Chatham, the Moira River at Belleville, and the St. Lawrence River at Montreal. In southern Quebec the greatest flood damage costs are associated with ice jams (Watt, 1989).

Streams are mainly semialluvial in character except where bedrock appears at the surface. Locally, morphology is governed by the nature of the glacial deposits through which the streams flow. Gravel and cobble stream beds are common, with occasional sand-bed reaches such as the Rouge River in Quebec and the Nottawasaga River and Big Creek in Ontario. Bed material size is usually related to local glacial outwash deposits. In Ontario, streams are commonly confined or partly confined in valleys, within which they show varying degrees of lateral stability and floodplain development. Floodplain development is most obvious on the larger rivers. Most gravel and cobble rivers have single, low sinuosity, channels that are partly restricted by entrenchment of the rivers. The larger gravel rivers and the sand-bed rivers are typically irregularly meandering. Multiple-channel reaches are very rare. The geomorphic effects of large floods appears to be limited (Gardner, 1977), partly because the rivers are confined and semialluvial.

In Quebec and eastern Ontario the exposed marine clays produce large-scale river-bank failures which in some cases have temporarily dammed the stream. The effects of damming on stream morphology persist for many years (e.g. South Nation River, Ontario). Small dams, urban development, and agriculture have all affected stream hydrology and morphology in the region. Stream-channel enlargement due to agricultural drainage has been documented (Leduc and Roy, 1990). Urban development, in particular, may have dramatic effects on streamflow and stream stability (Bellamy, 1994; MacRae et al., 1994). In small basins where a large proportion of the land area is urbanized, the consequences are increased peak discharges, decrease in groundwater contributions, and a tendency for rainstorms, especially intense summer storms, to become the dominant flood-generation event instead of snowmelt. The importance of intense summer storms is greatest in smaller drainage basins. These hydrological changes are often accompanied by artificial realignment and straightening of channels. The consequences in the short, steep rivers that are typical of the Lake Ontario drainage basin can be dramatic, including rapid degradation, incision of channels, bank erosion, and channel widening.

The St. Lawrence River is of great significance to commerce in the region. It is bedrock controlled upstream of Montreal, but becomes more alluvial in character, and comparatively shallow downstream of Montreal. The downstream section is entrenched into marine clay which also dominates the bed material. The Great Lakes, together with flow regulation structures, influence the flow so strongly that there is only slight seasonal and interannual variation. Ice jams occur at several locations on the St. Lawrence River and its tributaries. The highest water levels recorded are related to ice-jam flooding. Ice is also responsible for grooving the river bed; and the mechanical action of shore ice causes bank erosion and formation of boulder ridges (Dionne, 1969).

Prospective changes on Great Lakes–St. Lawrence Lowland rivers

Changes in streamflow

Assuming a warmer climate and increased precipitation, the important considerations for river processes in this region relate to the relative significance and absolute magnitude of rainfall, rain-on-snow, and snowmelt events. Spring rain-on-snow and snowmelt are the dominant flood-producing events at present. Snowmelt floods become progressively more important further north and east. In the future it is likely that pure snowmelt events will become less significant. Reductions in snowpack depth could actually increase the significance of rain-on-snow events by reducing snowpack water storage, and increasing the quantity of direct runoff from rain falling on frozen, snow-covered ground. This could lead to an increase in the magnitude of rain-on-snow floods and, with more frequent winter thaws, a shift of the flood season earlier in the year and the possibility of rain-on-snow events whenever there is snow on the ground. These are the events responsible for the bulk of the annual sediment transport (Dickinson and Green, 1988) and are the main influence on river morphology and dynamics. Assuming a warmer climate, increasingly ice-free Great Lakes may augment winter precipitation in areas which are currently affected by ‘lake effect’ precipitation.

In summer and early fall, increased frequency of incursion of moist, warm air masses, and of tropical storms will increase the frequency of occurrence of large rainstorms; and this represents a significant risk. A shift towards a rainfall-dominated flood regime may significantly increase the extreme flood discharges, especially in smaller drainage basins. In small, urbanized basins, this effect will be amplified by the existing tendency for increased volume and rapidity of direct runoff during rainstorms; and for rainstorm events to dominate over snowmelt. The streamflow effects of increased frequency and/or intensity of thunderstorm events is particularly important in small and urban drainage basins.

Changes in fluvial processes

There is little empirical observation of the effect of large floods on stream morphology in this region (Gardner, 1977) but it appears that the streams are relatively insensitive in this respect; however, the more permanent increases in flood flows due to urbanization have significantly affected stream channel morphology and stability. In sensitive streams an increase in width, a decrease in lateral stability, a decrease in sinuosity, and some minor degradation are likely. These changes are partly contingent on changes to the quantity and size of sediment delivered to the channels. Increased valley-side instability in entrenched and confined rivers could yield increased quantities of sediment particularly in the St. Lawrence and Ottawa valleys where ‘sensitive’ marine clay occurs (Carson and Bovis, 1989). Semialluvial streams are less likely to respond but may still undergo changes in width, depth, and channel pattern. Slope adjustment or bed degradation is unlikely; however, bed degradation is dramatic in some urbanizing streams and; locally, erodible glacial deposits and weak bedrock offer little resistance to the process once initiated. Incision would further destabilize banks and valley sides in sensitive marine clays. There are unlikely to be major changes in channel pattern as a result of the forecast flood-magnitude increases.

In many cases, especially in small drainage basins, the effects of changed streamflow regime may be small in comparison to those resulting from land-use change such as urbanization and agricultural land drainage, but they will occur in addition to the existing or future land use effects. Whereas the land-use effects are of primary concern, the additional effect of climatic change must be taken into account in planning and engineering.

Changes in streamflow in the St. Lawrence River depend very heavily on the water balance and levels of the Great Lakes. Declining lake levels would reduce flow in the St. Lawrence River but the issues of flood magnitude and generation mechanisms do not apply to the St. Lawrence River. In fact, the greatest cause for concern in the river is water quality and the deposition of contaminated sediments which are delivered from the major tributaries (Frenette et al., 1989; Frenette, 1990). Erosion and degradation of the larger tributaries could lead to increased sedimentation in the section between Montreal and Québec City.

In general, ice-jam hazards will be reduced if icecover thickness is reduced, and repeated winter breakup occurs; however, the potential for large rainstorms earlier in the season may lead to more frequent, and damaging, ice drives.

Appalachia

Regional physiography and fluvial characteristics

This region covers the Atlantic Provinces and eastern Quebec south of the St. Lawrence River. It is generally a region of low-relief plains and uplands up to about 800 m in elevation, except in the Notre Dame Mountains of Gaspésie where elevations reach 1200 m. Thin glacial deposits cover many areas but bedrock is also extensively exposed, especially in uplands. River valleys usually contain Quaternary sand and gravel deposits. Forest cover is extensive except in agricultural lowlands along the Gulf of St. Lawrence and the Bay of Fundy. The region is subdivided on the basis of relief (‘Maritime Plain’ and ‘St. Lawrence Uplands’) and climate. The ‘Atlantic Coast’ region has substantially higher annual precipitation, larger annual runoff, and a larger proportion of precipitation falling as rain.

Annual precipitation ranges from 1000–1500 mm in most of the region, with the Atlantic coast of Nova Scotia, and the southern and southeast coast of Newfoundland receiving the highest amounts (Banfield, 1981); however, observed annual runoff exceeds 2000 mm in some areas of Newfoundland (Yoxall, 1981), suggesting that measured precipitation is severely underestimated, perhaps by as much as 50% in some places (Banfield, 1981). Annual runoff is typically 60–70% of annual precipitation. Mean annual flood discharge for basins of 1000 km^2 are in the range 200–500 m^2/s, and are exceeded nationally only in coastal British Columbia.

Flow regimes in the region are characterized by winter and summer low flows, with annual maximum flows usually occurring in the spring as a result of either snowmelt or rain-on-snow events. Rainfall events in the fall also generate significant flows. In general, snowmelt or rain-on-snow events dominate in the northern areas, whereas rainfall-generated floods dominate further south, and toward the ‘Atlantic Coast’. The region is also subject to extreme flows from tropical storms, as well as summer convective storms. Prolonged cyclonic storms produce the highest discharges. Coastal Nova Scotia is most exposed to these effects and coastal areas are also more prone to mid-winter flooding. The regional subdivision reflects this effect. Timing of the spring floods varies regionally; lake and wetland storage has a significant effect on flow regimes in many rivers, especially in Newfoundland (Yoxall, 1981), and to a lesser extent in southern Nova Scotia.

Ice-jam floods are common on many rivers in the region. The St. John River, New Brunswick is notorious for ice-jam flooding. Well known events include that on the Exploits River, Newfoundland, in January 1983 in which extensive bank erosion and realignment of the river through the town of Grand Falls resulted in considerable property damage. Similarly damaging events have occurred recently on the St. John River (Beltaos et al., 1996).

Many streams are controlled by bedrock to such an extent that they have little opportunity to move laterally or vertically. Other channels have local bedrock controls that are effective in controlling the channel for some distance; however, there are reaches that can respond to changes between the major bedrock controls. Many nonbedrock channels are stable, coarse gravel or boulder channels. Sand-bed alluvial reaches exist at a few locations such as the lower Kennebecasis River in New Brunswick.

The most active channels are those that are cut into relatively thick deposits of sand and gravel in outwash plains or terraces from the last glaciation. Channels that have built their own floodplains are also laterally active if the naturally vegetated banks are disturbed. Small channels that meet large rivers with relatively wide terrace or floodplain deposits are laterally active and exhibit appreciable increase in sinuosity as the slope adjusts from the relatively steep slope of the small channel to the relatively low slope of the large river.

Prospective changes on Appalachian rivers

Dickison and Steeves (1989) have made an assessment of the potential hydrological effects of climate change for New Brunswick, based on climate model predictions for doubling CO_2. The general changes in climate by 2050, with reference to the 1951–1980 normal, are an increase in mean annual temperature of 4°C, a 10% increase in mean annual precipitation but an increase in evapotranspiration, producing no significant net change in annual runoff; however, winter snowfall is expected to decline. The result will be a shift towards rainfall or rain-on-snow floods, with an increase in size of annual flood flows.

Changes in streamflow

Although precipitation and runoff changes are predicted to be small, significant changes in river regime are possible. As in other regions, the changes in extreme runoff and flood events are the crucial concern, and these are not predictable from existing models. Flood regime in rivers of this region may be particularly sensitive to precipitation changes for several reasons:

1. There is likely to be a shift towards an increasing rainfall effect on flood flows, away from the current snowmelt dominance. This is particularly true of spring flooding. In general this will lead to greater variability in flood discharge and increased probability of very large floods because of the greater probability for rainstorms, or closely spaced sequences of rainstorms, to deliver a large amount of water in a short period of time. The occurrence of rain-on-snow events may be reduced but, provided substantial snow cover persists, these events will still occur. Under current conditions, extreme floods are usually associated with spring runoff, with the additional influence of fall and winter rainstorms in coastal Nova Scotia and New Brunswick. The likely outcome is for the role of rainstorms to become significant and to spread into interior regions currently dominated by spring snowmelt runoff. This will result in greater variability in the timing of flood events during the year and a reduction in magnitude of snowmelt floods. This is consistent with observations (Hartley and Dingman, 1993) from northern New England that maximum flood flows are more variable as rainfall-generated floods become more common.
2. There is a possibility of increased storminess bringing large regional-scale storm systems, or closely spaced sequences of storms, into the region more frequently. The particular concern is the possibility of tropical storms from the Atlantic Ocean and United States east of the Appalachians tracking further north producing a greater probability of truly extreme rainfall events (Hirchboek's (1988) "Noah Effect"). Unusually large rainfall events are present in the existing historical record. For example, in January 1956 coastal Nova Scotia experienced flood discharges two or three times the magnitude of any other flood events in 60 years of record due to persistent (6 days) heavy rain from frontal storms. In this respect the regional flood hydrology response in Appalachia may be very similar to that of the Great Lakes region because they both lie in very similar flood-climate regions (Hayden, 1988). This risk is greatest for the 'Atlantic Coast' of Nova Scotia; however, existing climate models provide very little information on possible changes to storm tracks and atmospheric circulation, making firm prediction impossible.
3. Based on analysis of historical data, streamflow in the Atlantic region appears to be extremely sensitive to precipitation variations. Whereas variation in mean annual precipitation at Halifax is remarkably conservative, with a range of a only a few per cent, streamflow variation of 50% or more occurs in the historical record. The sensitivity is asymmetrical; increases in precipitation produce much larger proportional increases in flow than the decreases in flow produced by equivalent decreases in precipitation.
4. Historical analysis of flood frequency curves shows considerable increase in the magnitude of large floods of a given recurrence interval during sequences of years with high average flow.
5. In smaller drainage basins (<1000 km^2) increasing frequency of convectional summer storms is possible, due to more frequent penetration of unstable tropical air masses.

Changes in fluvial processes

These changes in flood generating conditions, producing larger and more variable flood flows, are significant enough to cause an increase in channel dimensions as well as greater channel instability in alluvial and semialluvial reaches. If flood discharges were to double then channel widths could increase by about 40%. Bank erosion will cause problems in these reaches when the adjustment occurs. Locally, bank vegetation may restrict this adjustment. Progressive channel enlargement causes a net erosion of sediment from the river system, increasing sedimentation rates at depositional sites during the adjustment phase.

Depth is expected to increase by 30% for a doubling of flood discharge. In alluvial floodplain reaches this may cause increased frequency of overbank flows, until floodplain sedimentation and channel bed erosion are adjusted to the new flows. Where channel erosion is restricted, such as in semialluvial reaches, the adjustment will be primarily by floodplain deposition at a higher level than present, and perhaps by a larger-than-predicted width increase. In the event of extremely high flows, floodplain destruction is possible.

Adjustment of channel gradient by incision may occur locally, but will be restricted by the alternation of alluvial reaches with bedrock and semialluvial reaches. Increased discharge, assuming no significant change to sediment delivery, could eventually result in a decrease in channel gradient. Such adjustments take a very long time, and changes to channel pattern, for example, an increase in sinuosity, may occur in the meantime which will accomplish the gradient adjustment without eroding the river bed. Gradients may decrease by as much as 10% either by increasing sinuosity or by channel incision. Where bed erosion (channel incision) occurs it is a threat to in-channel structures and may cause sedimentation further downstream.

Reduced summer low flows are unlikely to affect stream morphology and dynamics, but stream habitat and water temperatures may be affected.

Ice-related flood conditions may persist during spring breakup, but more frequent thermal breakup will make truly damaging events less probable; however, high water levels from ice jams are likely to continue at sites where the hazard currently exists. Earlier breakup and occasional winter breakup are possible; where these occur during high flow, the hazard from dynamic breakup will persist.

All of these hydrologically driven changes will be less pronounced in rivers where natural or artificial storage in lakes exerts a major regulatory control on streamflow.

'Southern Shield' and 'Southern Boreal Shield'

Regional physiography and fluvial characteristics

These regions are distinguished from the 'Northern Boreal Shield' and 'Low Arctic Tundra' by the absence of permafrost; apart from this the shield regions all share similar physiography. The southern region is generally one of low relief except for the Laurentian Highlands (southern Quebec) and coastal uplands in Labrador. The terrain is bedrock with a thin, sometimes discontinuous, cover of glacial deposits, numerous lake basins, and bedrock valleys rimmed by glacial lacustrine and fluvial silt, sand, and gravel deposits. Thus, the downstream reaches of rivers, close to major lake basins, are often alluvial or semialluvial. Some parts of the 'Southern Shield' are characterized by extensive areas of glacial lake deposits overlying the bedrock (Kaszycki, 1987). Where the deposits are thickest they form extensive plains. The Ontario clay belt is the most significant from an economic and settlement standpoint, but extensive deposits also occur in the Lake Winnipeg and Nelson River basins.

Mean annual runoff increases from west to east from 100 mm to 500 mm. Flow regimes of rivers are dominated by spring (May) meltwater floods, with a secondary fall rainfall peak. The damping effects of lake and wetland storage are an important consideration throughout the region. Flood flows are the result of snowmelt runoff (e.g. the severe floods of spring 1996 in northern Ontario) often combined with ice jamming. The spring runoff event represents 50–70% of the annual runoff. Severe convectional storms may cause significant flood flows in small basins in the southern portion of the region around the northern Great Lakes.

Many rivers have extensive bedrock-controlled sections, but alluvial and semialluvial reaches occur where glacial deposits are more extensive. It is also common to find rivers entrenched into glacial or glaciolacustrine sediments with bedrock in the river bed but with erodible banks. In these rivers, channel width and sinuosity are adjustable through bank erosion, but vertical incision of the channel is precluded. Some existing diversion schemes have shown the potential for erosional modification of rivers that flow over glacial sediments.

Prospective changes on 'Southern Shield' rivers

Changes in streamflow

Flood generation is likely to remain snowmelt dominated in this region, and flow regulation by lakes and wetlands will dampen any regime changes that occur. In this respect, the response is likely to be very similar to that of the 'Northern Shield'; however, in the southern portion of the 'Shield' there will be more frequent occurrence of rain-on-snow events and possibly more frequent penetration of large-magnitude rainfall events. The result, as in other regions, is the possibility for more variable flow regimes, and hence an increased risk of unusually high flood flows.

In smaller drainage basins, especially those without significant lake control, there is a greater risk of extreme flood events increasing in magnitude, either as a result of spring rain-on-snow events, or from more intense, more frequent summer convectional storms. This risk is greater further south.

Changes in fluvial processes

Ice jamming may be alleviated by warmer winter and spring, giving thinner ice cover and greater tendency for thermal breakup; however, in general the problem will persist and in some years more extreme dynamic breakup events are possible. Flow regulation on large rivers will tend to further reduce ice effects.

Bedrock control and lake regulation will minimize the effects, but changes are still possible as demonstrated by the Mattagami Diversion, and other interbasin diversion projects. Large rivers with erodible banks may experience some widening, but smaller streams in erodible sediments are most vulnerable to channel enlargement. Formation of ice-push features, as well as bed and bank scour by ice may be reduced. In general, the changes are anticipated to be comparatively small.

Northern regions

Northern regions are separated for discussion because of the extensive occurrence of permafrost. This includes all of Nunavut and Northwest Territories, significant areas of northern Quebec, some portions of northern Ontario, northern British Columbia, and the Prairie provinces (Fig. 2b).

The presence of permafrost and the dominance of hydrology by melt processes combine to make the potential effects of climate change on river processes distinctly different in the north compared to other regions of the country; however, regional differences in relief, geology, and hydro-climate remain important to fluvial geomorphology in the north. The presence of permafrost may be a secondary factor affecting fluvial processes and climatic response, and for this reason the northern subregions are grouped with their southern counterparts, rather than as a separate northern region.

Regional physiography and fluvial characteristics

Five main fluvial regions are delineated.

Northern Cordillera

Immediately west of the 'Northern Plains' is a complex region of mountains, plateaus, and plains extending from the Mackenzie Mountains in Northwest Territories westward across Yukon Territory, and southward into British Columbia. Small glaciers occur in the Mackenzie Mountains whereas the St. Elias Mountains have many large glaciers which have a significant effect on streamflow and river morphology. Mean annual runoff is 200–600 mm, with 80% of the flow in four months of the year (spring and early summer). The dominance of the spring flood is greater in larger drainage basins than in small headwater streams. In some cases, larger floods are caused by the melting of snowpack accumulated over more than one year. Smaller, steeper streams are more susceptible to flooding from summer rainstorms. Intense rainstorms occasionally produce very large flood events, even on the larger rivers (Mackay et al., 1973).

Apart from the influence of permafrost and river icings the northern Cordilleran streams share many characteristics of the southern Cordillera. Gravel-cobble bed alluvial and semialluvial streams are common, with wandering or braided patterns. Some low-gradient alluvial reaches are meandering. Bedrock controlled, entrenched, and confined reaches are also frequent, including extensive canyons.

'Northern Plains'

This area occupies the region extending from the northern Prairies along the Mackenzie corridor to the Beaufort Sea and coastal plain. The region is subdivided into western Arctic coast to the north and the 'Northern Boreal Plains' to the south. This subdivision follows the southern limit of continuous permafrost. The whole region has surficial deposits of glacial till and glaciolacustrine silt and clay, covered by boreal forest and wetland. Mean annual runoff is 100–200 mm, with a gradual northward decline. The combined effects of low relief and poorly drained organic terrain lead to longer runoff times and more attenuated flood peaks than in the Cordillera.

The region is dominated by the Mackenzie River and its eastern tributaries. The Mackenzie River varies in morphology along its length (cf. Church et al., 1987; Carson, 1988). In general, upstream of The Ramparts (about 66°N) it is confined within a valley incised into glacial lake sediments and till. In many places the river bed is till, giving a range of size from cobbles and boulders to sand, with some bedrock exposures. There are also some fully alluvial reaches that have a wandering pattern with large islands. The alluvial reaches are associated with sediment input from the major tributaries draining the Mackenzie Mountains. Downstream of The Ramparts the river is partially entrenched and confined, with a slightly sinuous course that impinges on the till and bedrock of the valley wall in several places. The flow regime of the Mackenzie River is dominated by spring snowmelt but is strongly attenuated, relative to its major tributaries, by lake storage, especially in Great Slave Lake. The west and east bank tributaries of the Mackenzie River are susceptible to flooding from large summer rainstorms. The eastern tributaries of the Mackenzie River are generally bedrock-controlled and lake-regulated shield rivers. In contrast, the western tributaries of the Mackenzie River, which supply the bulk of the runoff and sediment, are large, active rivers originating in the Cordillera. Their plains reaches are entrenched in glacial deposits with bedrock in their upstream reaches. In most cases they become alluvial, with meandering or wandering courses further downstream. Partly entrenched and confined alluvial rivers are also common along the Yukon Territory coastal plain. In most cases these are gravel-bed rivers with braided, wandering, or meandering patterns (Galay et al., 1973; Lewis and McDonald, 1973; Forbes, 1983).

'Northern Shield'

To the east of the 'Northern Plains' lies the 'Northern Shield', a region of extensive deposits of glacial till and exposed bedrock with some glacial-lacustrine clays. The whole region is characterized by a high concentration of lakes. The regional subdivision is based on differences in vegetation cover; boreal forest dominates in the 'Northern Boreal Shield' covering the southern and western areas, whereas tundra vegetation covers the 'Low Arctic Tundra' in the north and east. Annual runoff is 100–225 mm, the dominant flow event being fed by snowmelt. Because of the dominant effects of storage on hydrological processes, these streams show very little response to rainfall events. Much of the area lies in the zone of continuous permafrost so that infiltration and percolation are inhibited.

Bedrock control of rivers is common, and many streams are effectively strings of lakes connected by short channels. The hydrological regime is dominated by lake storage resulting in reduced discharge per unit of drainage area, and low flood peaks relative to mean flow (ratio of 2:1). The large rivers have rock beds and boulder rapids but in many places are entrenched in glacial deposits (Klassen, 1986) which allows some adjustability in width (Newbury, 1990); however, there are exceptions such as the alluvial, sand-bed of the lowermost William River (Smith and Smith, 1984) and Clearwater River which drain the Athabasca Plain and the deltas of Saskatchewan, Peace–Athabasca, and Slave rivers. Ice-jam floods are important on the larger north-flowing rivers in the eastern part of the Canadian Shield.

Arctic Islands

The eastern subregions (northern and southern Innuitia) are distinctive because of their mountainous terrain, glacierized stream systems, and a pronounced oceanic influence on precipitation and storminess. Together with the Cordillera, the Innuitian regions are the only areas of the country in which glaciers are a major influence on streamflow regimes. This contrasts with the plateaus and lowlands that dominate the terrain in the western ('High Arctic') and southern ('Middle Arctic') islands and coast. The high and middle Arctic are separated by colder ground and air temperatures in the 'High

Arctic'. In addition, surficial materials in the 'Middle Arctic' are generally glacial till deposited by the Laurentide Ice Sheet, but much of the 'High Arctic' lay beyond the limit of the Laurentide Ice Sheet and here the surface is generally colluvium or weathered bedrock. Modification of flow regimes by small lakes is also much more important in the 'Middle Arctic' than in the 'High Arctic'. Surficial deposits are thin everywhere. There are extensive areas with no vegetation cover. Mean annual runoff is probably less than 100 mm (Fisheries and Environment Canada, 1978) but may be higher locally. Except in proglacial streams the snowmelt peak is the dominant flow event. Rivers are commonly alluvial or semialluvial, especially in their downstream reaches. Braiding is common in proglacial zones and elsewhere (French, 1976). Many streams are slightly entrenched and confined, with significant sediment loads, and sinuous or meandering patterns. Sediment supply is enhanced by active layer thaw slides and mass failures associated with exposure of massive ground-ice (Lewkowicz and Wolfe, 1994).

'Hudson Plain Peatlands'

This is a very low-gradient plain rimming the southern shore of Hudson Bay and James Bay. The northern subregion is distinguished by the occurrence of more extensive permafrost than the southern subregion. The major rivers are entrenched in the peat, marine clays, till, glacial sand, and gravel that cover the bedrock (Cumming, 1969; McDonald, 1969; King and Martini, 1983; Newbury, 1990; Dredge and Nixon, 1992). Many rivers are bedrock floored, and the upper reaches commonly have bedrock exposed in the banks and islands. The lower, tidal reaches may develop alluvial sections (King and Martini, 1983).

Flow regimes

Snowmelt is the major annual runoff event throughout the north; however, its significance varies and both the presence of glaciers and extensive wetlands may produce other runoff regimes (Church, 1974, 1988; Craig and McCart, 1975; Carter et al., 1987; Woo, 1990a). The 'arctic nival' regime, which is dominated by snowmelt floods, occurs in the continuous permafrost zone where winter flow is absent and spring runoff cannot infiltrate the frozen ground. Melt occurs late in the year (usually late June or July) and lasts only 2–3 weeks. Summer rain events occur but are much smaller than the nival flood except in small headwater streams (Cogley and McCann, 1976). Further south, 'subarctic nival' regimes maintain some flow in winter, and, while snowmelt remains dominant, significant summer rainstorms also occur. In some years the annual peak flow may be generated by summer frontal storms rather than by snowmelt.

There are two significant modifications of the arctic and subarctic nival regimes. In wetland areas, water storage flattens flood peaks and produces regimes with a very conservative range of discharges. Proglacial flow regimes occur in the northern Cordillera and the Innuitian mountains where extensive glacial ice persists. In proglacial regimes there is both spring snowmelt and persistent glacier melt throughout the summer. In addition, proglacial regimes may be subject to occasional very large floods, termed 'jökulhlaups', caused by the sudden release of glacially dammed water.

Runoff rates, as a percentage of precipitation, are typically very high (70–80%) because of limited infiltration and storage in the active layer, and the absence of percolation to groundwater in the presence of permafrost. Thus surface conditions and permafrost have a very important effect on stream runoff in this region. Melt processes, and storage as snow and ice, dominate the hydrology of this region.

River ice

The effects of ice jamming on flooding and erosion are discussed earlier in the report. Much of this information comes from northern rivers which are, inevitably, prone to widespread ice effects. Some of the more significant ice-jam sites in the country occur on large northern rivers. This is partly the consequence of the downstream (northward) progression of the melt, carrying ice into reaches which are still frozen. Freeze-up floods are a problem in some localities. The ecological effects of ice jamming may also be significant. For example, in northern deltas the high water levels induced by ice jams are responsible for maintaining water levels in small lake basins perched above the delta channels (Prowse and Lalonde, 1996).

Permafrost

Whereas ice jam effects occur in all regions of Canada, extensive permafrost is restricted to the north. The effects of permafrost on river morphology are debatable, but potentially significant. It is a matter of simple observation that freezing of river-bank sediments produces a set of erosion processes and bank morphologies that are unique (cf. Miles, 1976; Church and Miles, 1982; Woo and McCann, 1994). In many cases the erosion is thermally, rather than hydraulically, controlled. For example, the development of thermal erosion niches near the water surface in the spring leads to river-bank collapse. This may be aided by the presence of ice wedges in the bank. On vegetated banks the melting of the sediments may undermine the bank, allowing the organic mat to drape over the bank face and protect it from hydraulic erosion. Active-layer slides and retrogressive-thaw slides (Church and Miles, 1982) are also common modes of bank erosion.

The effect of frozen bank sediments on channel morphology and erosion rates is uncertain. It is possible that interstitial ice adds strength to unconsolidated sediments, allowing them to resist erosion (Cooper and Hollingshead, 1973), but there is little direct evidence to support this possibility. In some instances long-term rates of bank erosion appear to be no different in permafrost regions than under similar conditions in temperate regions (Lapointe, 1984, 1990). Alternatively, while frozen sediments may resist erosion, erosion rates may be increased by thermal erosion during the thaw season (Scott, 1978) producing a net increase in erosion rates.

The important issue with respect to the role of permafrost on channel morphology is its influence on the sensitivity of alluvial channels to the effects of extreme floods. In the presence of permafrost, erosion accomplished by a flood of only a few hours or days in duration may be determined by thaw rate, rather than mechanical erosion. The resistance of frozen sediment to erosion may prevent large, short-duration floods from causing rapid erosion and major channel modification that is often associated with such floods in temperate regions. This is illustrated by the floods, with an estimated recurrence interval of up to 100 years, generated by a cyclonic storm in the Mackenzie Mountains in July 1970. Despite extensive flow over the floodplain and widespread destruction of floodplain forest, morphological modification of Arctic Red River was minor (Church, 1988). This implicates the presence of permafrost as a limitation on the erosional effectiveness of large floods.

Icing

Many northern rivers freeze to their bed in the winter. Water trapped beneath the bed may be expelled to the surface, where it freezes, to produce extensive icings along the channel and floodplain. These are extensive where perennial springs occur in the river bed or valley floor, or where flow in alluvial sediments beneath the bed is pressurized by freezing from above. In spring the progressive melting of large icings may supply runoff for up to three months, thus prolonging the runoff season in the arctic nival zone in particular. In addition, the presence of icings may affect channel processes by forcing water out of the ice-filled channel onto the floodplain, or over the top of the icing. This may alter the course of the river, or cause a wider, less stable channel to persist (Van Everdingen, 1987).

Snow

Apart from supplying water for the major annual runoff event, snow may affect flow regimes and fluvial processes in other ways. The most obvious effect is that large snowdams block the channels (Woo and Sauriol, 1980). These dams often result in the development of large ponds of meltwater and dam failure may result in very large discharges downstream relative to the size of the watershed (Marsh and Woo, 1981; Heginbottom, 1984).

Prospective changes on northern rivers

Under increased atmospheric CO_2 most climate models predict slightly warmer summers, markedly warmer winters, and increased precipitation over much of the north. The increase in precipitation arises in part from predicted increases in storminess, particularly in the northern Cordillera and exposed coasts of Innuitia.

Changes in hydrology and streamflow

The effects of these changes in precipitation on runoff regime are complicated by the response of permafrost to a general warming of the climate. In general the contemporary boundaries of the discontinuous and continuous permafrost zones are expected to shift northward by several hundred kilometres; however, the shift is likely to take many years. The result is that permafrost may disappear from as much as half of the present discontinuous permafrost zone (Lewkowicz, 1992; Woo et al., 1992). Such shifts in permafrost distribution are inferred to have occurred in the past several thousand years in response to climatic fluctuations. In the continuous zone, while permafrost may persist, the active-layer depth (the depth of summer thaw) will increase.

Changes in the extent of permafrost, or depth of summer thawing, have important effects on surface hydrology and streamflow. In permafrost zones, because of frozen ground or shallow active layers, a large proportion of snowmelt or rainfall runs off over the surface directly to the stream system. If permafrost disappears or active-layer depths increase, the potential for subsurface storage of water during the summer and fall is increased. The effect is to reduce and delay surface runoff. Thus the equivalent snowmelt or rainfall event in nonpermafrost terrain will produce lower flood peaks than in permafrost terrain. The effect is likely to be most important during summer and early fall rainfall events, rather than in spring when the ground is frozen (Slaughter et al., 1983).

Groundwater hydrology may also change sufficiently to affect streamflow conditions. In areas where permafrost disappears, groundwater modulation of streamflow regimes may increase and thus prolong baseflow in channels during winter and initiate winter flow where currently none occurs. In the latter case, icings would become more prevalent in the present day continuous permafrost zone, and river-ice formation may become significant in regions which currently have no winter streamflow, and, hence, no river ice (Woo, 1990b; Woo et al., 1992).

Nival flood peaks could be lower because of a reduced snowpack due to shorter snow season, and reduction of the melt rates due to the shifting of the melt to earlier in the year when sun angles are lower and days shorter. This could be counteracted by an increase in winter precipitation (Houghton et al., 1996) which may increase snowpack accumulation. More frequent winter thaw is possible in subarctic regions. In general, especially in subarctic regions, the flow regime is likely to shift from being almost purely snowmelt dominated, to being a mixture of snowmelt and rainfall floods (Woo, 1990b). In southern areas, significant summer rainstorms already occur, and these could become more common and intense, and spread to areas currently beyond their influence. Rain-on-snow events in spring also become more likely. Streamflow will become more variable with higher peak flows, although this effect of increased storminess may be offset to some extent by the reduction in runoff ratios due to permafrost degradation or loss, especially in the summer. This increased influence of rainstorms is likely to be strongest in the larger rivers fed from the western Cordillera. Some rivers receive significant flow from outside the northern zone, and these will be affected by flow-regime changes in the headwater areas, as well as within the northern regions.

Analysis of historical flow and precipitation data for several Cordilleran streams in Yukon Territory (Yukon River, Pelly River, upper Liard River, and Teslin River) shows that these streams have flow regimes that are sensitive to changing annual precipitation. At Whitehorse, mean annual precipitation was approximately 5% higher for the period 1960–1975 than for 1975–1990. The difference in magnitude of the 10 year flood discharge for these two time periods was 20–40% on these four rivers. By comparison, the Liard and Mackenzie rivers, as well as large rivers on the northern shield, show very little consistent change in flood frequency distributions between sequences of high- and low-flow years. These Cordilleran streams, especially those further west, are predicted to experience the largest increases in storminess and annual precipitation, and are generally the most climatically and hydrologically sensitive in the north.

Glacial streamflow regimes will be affected by a warmer, wetter climate. This will affect many streams in the Innuitian mountains, along with maritime areas of the northern Cordillera. The response of the glaciers may be quite different in these two distinct regions. The exact effect depends upon the sensitivity of the glacier mass balance to changes in temperature and precipitation. In general, mass balance is most sensitive to temperature changes, and a wealth of data from various parts of the world link glacier mass-balance changes to temperature change; however, in more maritime locations precipitation may have a more significant effect than temperature on the mass balance (Fitzharris et al., 1996). An additional complication is that mass-balance change may also be sensitive to seasonal change in climate. For example, whereas a warmer summer will inevitably cause glacier retreat and increased streamflow, a warmer, wetter winter may lead to increases in glacier mass (Syvitski and Andrews, 1994). Thus, glacier retreat is not inevitable in a warmer north (Woo and McCann, 1994); however, streamflow changes are also dependent on the rate of mass turnover in the glacier. Even without a change in mass balance, increases in streamflow are possible because of more rapid mass turnover if both melt rate and accumulation rate increase.

Reduction in the glacierized area of drainage basins will increase streamflow variability by reducing the damping effect of the ice mass. This would be accompanied by an increase in average streamflow during the melt season. Most importantly, and harder to predict, are changes in catastrophic floods generated subglacially or by moraine dam failure, which affect some proglacial streams, as well as dominating the morphology and sediment transport. These are likely to occur in the event of widespread glacial retreat but will be a transient phenomenon.

Changes in fluvial processes

The sensitivity of rivers to changing flow is expected to be much greater in the ‘Northern Plains’ and Cordillera, than in the ‘Northern Shield’; however, shield rivers may still respond. For example, the Nelson River system has had raised lake levels and increased flow for about 20 years following implementation of the Churchill–Nelson diversion in the mid-1970s. The consequence has been lake shoreline erosion and increased wash load, along with channel widening and bank erosion in river sections where the channel is partially entrenched in glacial deposits (Newbury and McCullough, 1984; Kellerhals Engineering Services Ltd., 1988). The depleted Churchill River has been very slow to respond to reduced flows, but shallowing and abandonment of side channels, and gradual vegetation encroachment into the channel are now apparent. These changes have occurred despite the strong bedrock control along these streams.

The sensitivity to change depends partly on changes to the erosional resistance of stream banks due to permafrost degradation. Extensive bank thaw will cause changes in the dominant bank erosion processes, and may also lower bank resistance to erosion. In the case of the 1970 flood on the Arctic Red River, a large summer storm and extreme flooding appeared to have little effect on the river morphology, in contrast to the response of many temperate zone rivers to such events. Widespread thaw may have the effect of increasing the sensitivity of such rivers to large flood events. This is an important consideration because these events are often also the triggers for subsequent river channel change under more moderate floods. Rivers in the discontinuous permafrost zone, with subarctic nival flow regimes, or those affected by flood generation in headwaters outside the region are most vulnerable to this effect.

Permafrost degradation may also increase sediment delivery to river systems (Woo et al., 1992; Woo and McCann, 1994). Many slope processes in permafrost regions are controlled by thaw processes. A warmer climate will produce thicker active layers, and longer thaw periods potentially increasing the occurrence and rate of slope erosion by thaw slumps and active-layer slides; however, at present little is known of sediment delivery rates in this region.

Forest fires have been observed to cause permafrost degradation because of destruction of the vegetation. The consequence is an upset in the thermal conditions in the ground. This leads to thicker active (thawed) layers in the soil and increases the occurrence of shallow soil slides which may result in increased sediment delivery to headwater streams (Harry and MacInnes, 1988). If forest fire frequency increases there is the potential for increased sediment delivery, and local channel aggradation. This is likely to be significant in smaller, headwater drainage basins where burning covers a substantial proportion of the area.

Where glacial effects are important, and assuming increases in flow volume, flow variability, and occurrence of outburst floods; proglacial stream channels will enlarge, channel instability, migration rates, and sediment transport rates will increase, leading to a situation where river channels are characteristically highly dynamic.

Increased groundwater flow and winter base flow will allow formation of river-ice cover in the continuous permafrost zone. Thus, whereas ice-jam effects may ameliorate in the southern part of the region, they will spread northward to areas currently unaffected by river ice.

It is important to realize that the major rivers of the region cross the boundaries of major fluvial regions or subregions. The response of these rivers will be governed in part by effects upstream in major tributaries in other fluvial regions.

CONCLUSIONS

Climatic change is likely to cause changes to river systems in Canada. A warmer Earth will have more active hydrological processes, and the changes to precipitation and runoff patterns will affect the morphology and dynamics of rivers. Potential changes include increased precipitation, the proportion falling as rain, shifts in cyclonic storm tracks, increased intense rain, reduction in snow accumulation, reduction of glacier mass, permafrost thawing, and changes to the dominant flood-generating processes. These could all affect the dynamics and morphology of Canada's rivers, and hence river resources and hazards.

Potential changes to streamflow

Insight into the likely changes to streamflow and fluvial processes as a consequence of climate change are largely matters of qualitative inference based on historical and spatial analogues, physical principles, and summary predictions from climate models. The only assumption made here is that human activity will lead to overall warming accompanied by a more active hydrological cycle. Streamflow is much more sensitive to changes in precipitation than to changes in temperature. The effect on the frequency-magnitude distribution of flood discharges is especially important for changes in river morphology and stability.

Current projected changes to precipitation amounts are of the same order as the recorded decadal fluctuations of the past 50 years in Canada. Historical records show that periods of higher average annual precipitation in the past have also been periods of higher streamflow and flood discharges. This is true in all regions of the country, and in the extreme cases such as the southern Prairies and the Atlantic coast, the magnitude of large floods (10 year recurrence interval) increases by up to 50–100% for only 5–15% increases in annual precipitation. These proportional increases in flood discharges are larger than those for mean flows. The concern may be even greater in some parts of southern and eastern Canada if there is an accompanying shift to rainfall-dominated (or rain-on-snow) streamflow generation which is inherently a more variable and extreme process than snowmelt. This amplification of the precipitation changes in the streamflow record is a serious concern in anticipating climate change impacts, and deserves further study.

However, where snowmelt floods remain dominant there is the possibility that flood magnitudes will decrease because of higher winter temperatures causing reductions in snowpack accumulation. There is evidence of this effect in the southern Prairies.

Glaciers and ice fields will modulate the climatic effect on streamflow, but at the same time substantial reduction in ice mass due to warming will cause a prolonged period of increased average flows.

In many parts of the country, flow regimes have been artificially modified by flow-regulation and flow-diversion schemes. Where this occurs the changes to streamflow regime may be mitigated or eliminated by flow regulation. In addition, modulation by natural lake and wetland storage will reduce the effects in regions with high lake density, such as the 'Southern Shield'.

Human impact on flow regime is also the result of land-use change. This is especially significant in smaller drainage basins in which a large proportion of the land surface may be modified leading to changes in streamflow regime. The most extreme cases are small, urbanized basins. In these cases climate change effects may not be as great as those already caused by land use, but the climatic effect will add to, or compound, the existing land-use effect.

It is also important to recognize that basins of different size will respond to different effects. For example, changes to the size or frequency of small convective storms might be important to small drainage basins of less than about 1000 km^2, but will have no significant impact on larger basins in which changes to cyclonic storms or snow accumulation are more relevant.

The historical record clearly shows coherent regional responses to climate change that differ between regions. It is reasonable to assume that these regional differences in type and timing of response will persist, and this is the basis for the regional boundaries on the impact map (Fig. 2).

Impact on rivers

The effects on rivers of changes in discharge and sediment supply induced by climate change are predictable from existing knowledge of fluvial mechanics. Assuming that the likely changes in streamflow and sediment supply are known, the likely direction of change can be anticipated from basic principles and from cases in which there have been natural or artificial changes in flow regime; however, the case studies indicate that there is uncertainty in the direction and magnitude of change in some river processes and characteristics.

The potential impacts of increased discharge include channel enlargement and incision, a tendency toward either higher sinuosity single channels or braided patterns, increased bank erosion, and more rapid channel migration. Increased magnitude of large floods will result in sudden changes to channel characteristics that may trigger greater long-term instability of rivers. Increased frequency of large floods will tend to keep rivers in the modified and unstable state. Decreased discharge often results in channel shrinkage, vegetation encroachment into the channel, sedimentation in side channels, and channel pattern change toward more stable, single-channel patterns. In entrenched or confined valleys there may be reductions in the stability of the valley walls and, hence, increases in the rate of erosion caused by a greater tendency for streams to erode the valley walls. Increased valley-side erosion will increase sediment delivery to the stream with consequences for stream morphology.

Fine-grained alluvial streams are the most sensitive to flow regime changes whereas bedrock streams will be least sensitive. Many Canadian rivers fall between these extremes and are in a 'semialluvial' state in which they are sensitive to streamflow change but the response is constrained by the resistance to erosion of the glacial deposits through which they flow, and from which much of their sediment load is delivered. A significant concern in this context is that many streams are below, but close to, the threshold for mobilizing a significant proportion of their bed sediment. Small increases in typical flood discharges or even a single unusually large flood may be sufficient to push these streams across the threshold from a relatively stable condition into a condition of much greater sensitivity. There is almost no information on the nature of stream response to large floods in Canada, especially for these 'semialluvial' stream types.

Stream morphology, as well as the nature, rapidity, and magnitude of the change, are often strongly influenced by local conditions. Most regions have examples of just about every river type. Nevertheless, climate and hydrology do vary regionally; and regional geological and topographic influences are still apparent, so it is possible to recognize regional fluvial characteristics, responses, and sensitivity. This is the basis for the national picture presented in the report and map (Fig. 2).

The regions of greatest concern are those that combine a greater sensitivity (i.e. greater propensity for climatic change to effect changes to rivers) and high vulnerability due to denser population and greater infrastructure investment. This amounts to large parts of the Atlantic provinces (Appalachia), southern Ontario and Quebec (Great Lakes–St. Lawrence Lowlands), southern parts of the Prairie provinces ('Southern Plains'), and British Columbia (southern Cordillera, especially coastal regions). These are the regions that are at greatest risk to increased flood magnitude through a shift towards rainfall-dominated flow regimes. Moderately sized drainage basins (10 000 km^2) will be affected by changes in frequency, intensity, and duration of cyclonic storms, whereas smaller basins will also be affected by changes in convectional storm activity. Small, urban basins and steep coastal mountain basins are especially sensitive. Stream-channel enlargement, degradation, increased bank erosion, and migration are possible. Some Cordilleran streams could change towards unstable, braided patterns. There is the possibility of the reverse effect, channel shrinkage, in the southern plains. Increased valley-side instability along entrenched streams is a significant risk in the 'Southern Plains' and the St. Lawrence Lowlands.

Less sensitive and vulnerable regions cover much of the shield, the 'Northern Plains', northern Cordillera, and the Arctic Islands. Rivers are generally less sensitive to change because of extensive bedrock influence and the modulating effect of lakes on streamflow changes. Snowmelt will remain the dominant flood-generating process so that no significant change in flow regime and flood magnitudes is anticipated in many areas; however, in the southern 'arctic subnival' zone there is an increased risk of large summer rainstorms.

Substantial changes to the extent of permafrost may result in the loss of permafrost in the contemporary discontinuous permafrost zone, and a northward retreat of the continuous permafrost zone of the order of hundreds of kilometres. This will create a zone in which existing continuous permafrost will become discontinuous. The consequences of permafrost thaw include a damping of flow peaks in summer, more active slope erosion processes increasing sediment delivery to streams, greater groundwater flow resulting in maintenance of baseflow conditions in winter, and development of river-ice in rivers which currently have no winter baseflow. The effects of icing formation will shift northward.

The geomorphological role of ice and ice jams is not well known, but is a very important consideration throughout Canada. Ice-jam and breakup effects will spread northward. In the south, more frequent thermal breakup and thinner ice cover may reduce the occurrence of damaging floods. Dynamic breakup flood events are still likely and when they do occur may be enhanced by greater runoff volumes from rain-on-snow.

Time scale of change

The time-scale for response for river processes and morphology will vary from years to centuries. This partly depends on the time scale of climatic change and of the secondary responses such as permafrost degradation. In cases of artificial flow regulation, in which the river is subjected to an almost instantaneous change in flow regime, river adjustment is progressive and incremental. In large rivers there is evidence that adjustments take centuries (Church, 1995). In contrast, small urbanizing streams are known to undergo rapid adjustment over a few years, or even during a single flood event. Channel shrinkage effects requiring sediment deposition and vegetation encroachment will be slower than erosional adjustments causing channel enlargement. In some cases, adjustments may await the occurrence of a flood event sufficiently large to effect the latent changes.

Understanding of future changes to fluvial processes from climate change in Canada can be enhanced by further hydrology and geomorphology research in a number of areas. Among the most important are 1) the role of river-ice in fluvial processes; 2) the sensitivity and response of Canadian rivers to large floods; 3) the role of permafrost in affecting fluvial processes and the effect of large floods; 4) the morphology and dynamics of 'semialluvial' streams; and 5) the response of streamflow to changes in precipitation regime and flood generation processes.

Concluding remarks

Climate change can and does cause changes to river processes. Future climate change is likely to cause changes to streamflow hydrology sufficient to induce measurable changes in the morphology and dynamics of alluvial and semialluvial rivers and streams in many parts of Canada. These in turn will affect the use that we can make of floodplains, and the mitigative measures required to maintain structures and transportation routes which cross or follow stream channels. The effects on river form and dynamics may only become apparent gradually, but there will be immediate effects on stream habitat and water quality resulting from changes to streamflow and sediment concentrations. Catastrophic changes from large floods are possible. In many cases the changes are likely to be no larger than those seen this century during natural fluctuations in climate, but there is the potential for more radical change. Climatic impacts may well be less significant than the existing human impacts on streams, but the climatic impacts will be ubiquitous and, in populated regions, may add to or compound the human effects.

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APPENDIX A

Fluvial morphology and dynamics

INTRODUCTION

River morphology and dynamics vary widely and different types of rivers will show different sensitivity and responses to climatic change. It is important to summarize the basic characteristics of river channels in order to understand the various factors, including climatic conditions, which cause geographical and temporal variation in river forms and processes. This in turn provides the basis on which the sensitivity and response of rivers to climate change can be predicted. The descriptions of regional fluvial characteristics and sensitivity presented in Part II, and the interpretation of the Figure 2, rely on a basic knowledge of the characteristics of rivers and the environmental controls on river processes.

RIVER CHANNEL TYPES

From the point of view of the response of rivers to climate change, it is essential to make a fundamental distinction between three general classes of river; alluvial, bedrock, and semialluvial (Kellerhals and Church, 1989). These three types of river show quite different morphologies and will respond quite differently to climatic change.

Alluvial streams flow across materials that they have deposited. The downstream reaches of large rivers, such as the Fraser River, that flow across alluvial plains, and those rivers flowing across alluvial fans and deltas, are typical of this type of stream. The morphology of the river, including the gradient of the alluvial surface, is determined by the present day river in adjustment with the prevailing water discharge, sediment characteristics, and imposed valley gradient. Alluvial rivers change readily, adjusting their morphology to changing flow and sediment conditions, by migrating across the floor of their valley. They are adjusted to the current conditions and are, therefore, sensitive to change in those conditions. The most reliable predictions of response to climate change can be made for alluvial rivers, mainly because they are the class of rivers on which much of the existing knowledge of river mechanics is based; however, no major Canadian rivers are extensively alluvial.

Bedrock streams, while affected by streamflow characteristics, are heavily constrained by the resistant rock that bounds their channels. Adjustment to altered streamflow conditions is slow and difficult to detect. There is considerable variability within this group depending on the nature of the rock and its structure. Bedrock streams may contain small areas of alluvial deposition but their overall morphology and dynamics are bedrock controlled, and they are unlikely to show any large, short-term response to climate change; however, not all bedrock streams are resistant to erosion. Rapid adjustment is possible in less resistant lithologies.

Semialluvial streams are not strictly alluvial, but neither are they constrained in their adjustment to the same extent as bedrock streams. These rivers flow through erodible material and show many of the characteristics of alluvial rivers (development of depositional landforms and channel pattern) but the rapidity and completeness of their adjustment to external variables is restricted. This category is extremely important in Canada where many rivers flow through, and are incised into, a variety of Quaternary deposits (till, lake sediments, and glacial outwash) which are erodible but which the river may not readily transport under the prevailing flow conditions. This may limit the adjustment of channel width, depth, pattern, and gradient; and inhibit rapid response to changing flow regime. Thus, whereas an alluvial channel may respond to large flood flows by widening and deepening, semialluvial channels may not adjust quickly and so cause more extensive overbank flooding; however, sufficiently large changes in flow may trigger dramatic adjustment if the bed material becomes erodible.

SEDIMENT TYPE

Fluvial morphology, processes, and sensitivity to change are strongly influenced by the character of the sediment supplied to, carried by, and deposited along the river. It is useful to subdivide alluvial and semialluvial streams according to the dominant grain size of sediment in the bed and banks. These are *silt and/or clay; sand; gravel; and cobble and/or boulder*. The mechanics, hydraulics, morphology, and response to climate change may differ among these sediment types. As a rule of thumb, channels with silt and/or clay bank sediments are relatively narrow and deep, and often have sinuous, meandering channel patterns (Fig. A-1a, A-1b), whereas gravel and sand channels tend to be wider and shallower with lower sinousity, and the potential to develop wandering or braided

Figure A-1a. *Low sinuosity, partially confined, sand-bed river in southern Prairies (Red Deer River near Drumheller, Alberta). Increased flows may cause increased meandering, channel widening, and more frequent impingement on valley sides. Climate change may also increase sediment delivery from valley-side gullies. Photograph by P. Ashmore. GSC 2000-013A*

***Figure A-1b.** Meandering, sand-bed river (Riviére Rouge, near La Conception, Quebec). Point bars and submerged sand bars are visible in the channel, and erosion is active on the outside bank of the meander bends. Active erosion and migration is evident from the scars of former channel positions visible in the floodplain. Sand-bed, alluvial reaches of this type may be very sensitive to increases in flood discharge. Government of Quebec photo number Q78821-63*

***Figure A-1c.** Anastamosed channel pattern in fine-grained sediment (upper Columbia River near Golden, British Columbia). Photograph courtesy of D. Smith.*

Figure A1-d, (above) e, (below). *Braided sand-bed river (South Saskatchewan River near Saskatoon). Upstream flow regulation has caused vegetation encroachment on bars, reduction in channel width, and reduced sediment transport rates. Increased flows due to climate change would reactivate the river, but the existing flow regulation may prevent this.* ***d)*** *Governments of Canada and Saskatchewan photo no. C.S.M.A. 78004-14-L7 123,* ***e)*** *Photograph by P. Ashmore; GSC 2000-013B*

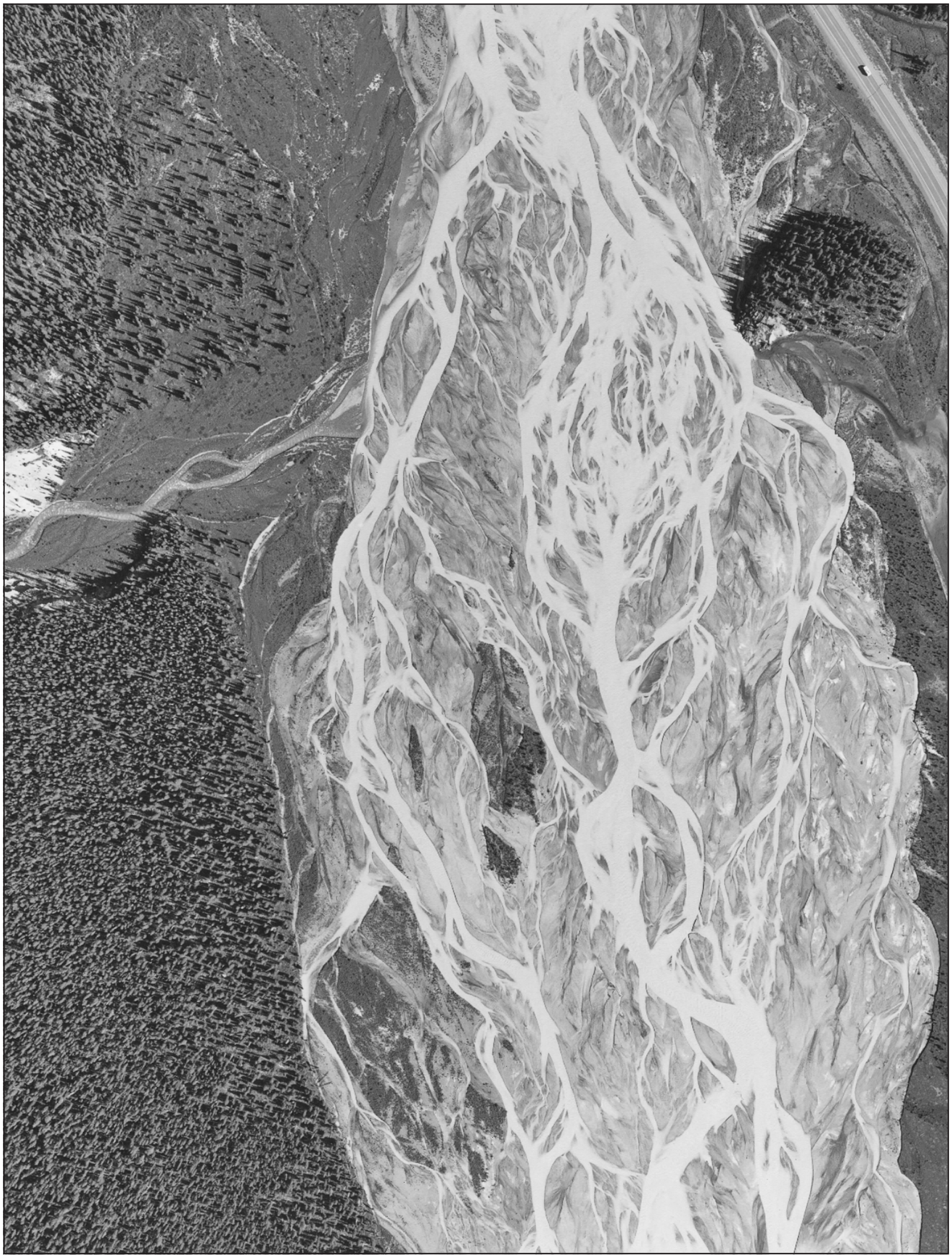

Figure A-1f. *Braided gravel-bed (Sunwapta River, Alberta). Rivers of this type are inherently unstable. Increased flows or delivery of coarse sediment would increase activity and lateral instability, whereas decreased discharge would tend to reduce the river into a single, more stable, channel. NAPL A31610-37.*

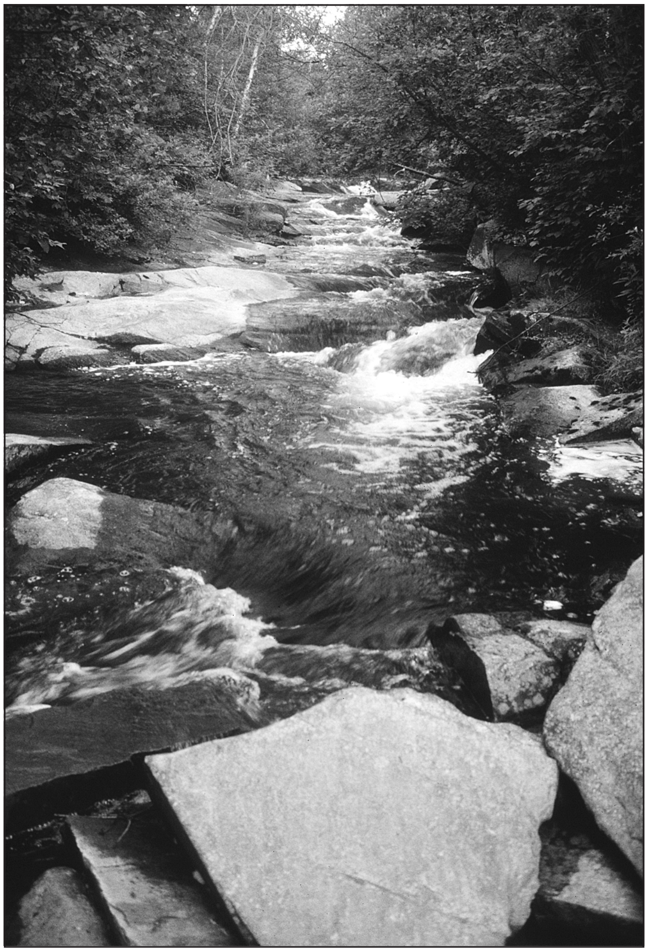

Figure A-1g. *Wandering, partly confined, gravel-bed river (Peace River, British Columbia). Upstream flow regulation has stabilized the channel, caused vegetation encroachment on bars and abandonment of side channels. Unregulated tributaries still supply sediment to the river and cause local sedimentation at confluences. Photograph by M. Church. GSC 2000-014A*

Figure A-1h. *Small, bedrock-controlled and boulder-bed channel in the southern shield (Four Mile Creek near North Bay, Ontario). Bedrock rivers are generally insensitive to changes in streamflow, although some streams in weak bedrock, such as shale, can respond quickly to changes in streamflow regime. Photograph by P. Ashmore. GSC 2000-013C*

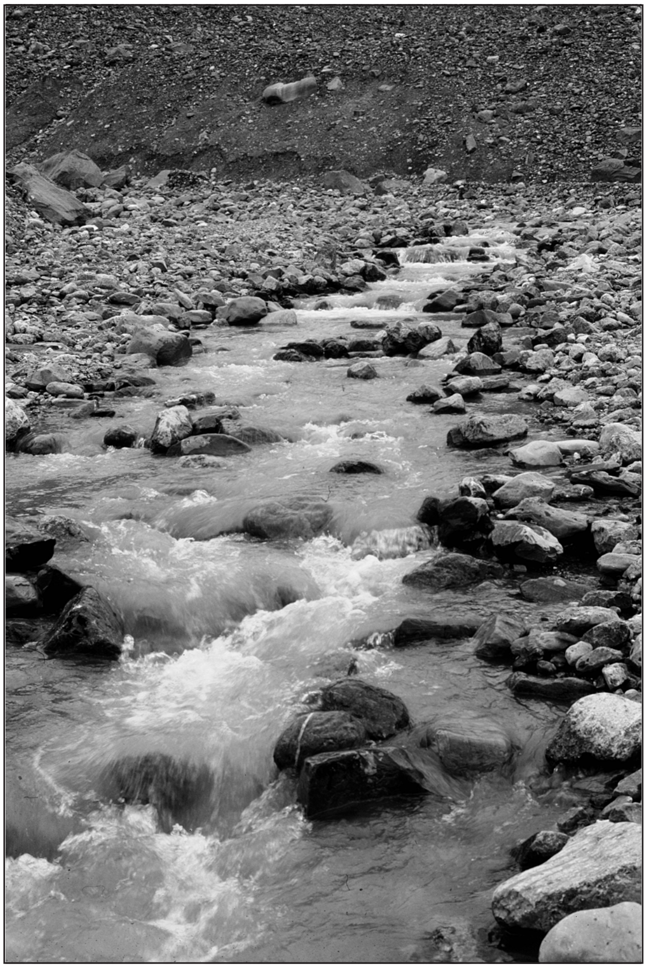

Figure A-1i. *Small, boulder cascade-type river (outlet stream from Athabasca Glacier, Alberta). This type of stream is laterally stable but small, steep creeks of this type can be subject to sudden high flood flows, especially in mountain landscapes, causing rapid modification of channel form. Photograph by P. Ashmore. GSC 2000-013D*

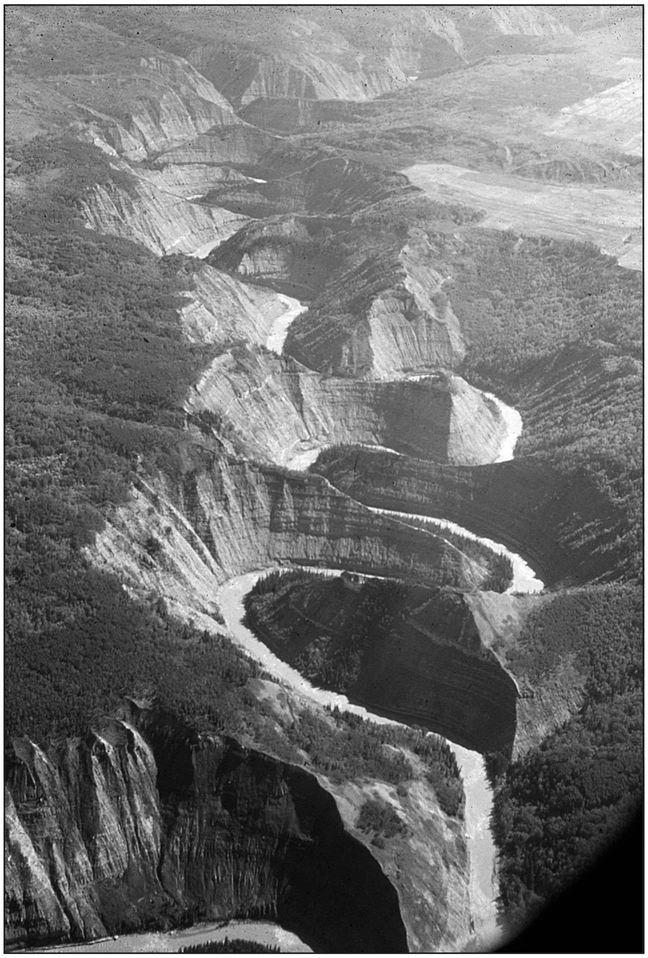

Figure A1-j. *Meandering river, incised (entrenched) into bedrock and fully confined by valley walls (Pembina River, Alberta). Valley sides are unstable and supply much of the sediment to the river. Increased flows may increase valley-side instability, but the river is so tightly constrained that other adjustments are unlikely. Photograph by P. Ashmore. GSC 2000-013E*

patterns (Fig. A-1c–A-1g). Boulder streams are often small and steep, and have a morphology that is controlled by individual boulders that may be as big as the channel is deep (Fig. A-1h, A-1i). In general, sand channels are the most sensitive to changes in the controlling variables. This is because, unlike silt, sand is not cohesive, but remains small enough to be moved relatively easily by water currents.

RIVER MORPHOLOGY

River reaches

The lengths of river channels are often classified into homogeneous segments called reaches, which may also be expected to show a uniform response to changes in the controlling variables. Alluvial and semialluvial rivers adopt a relatively stable morphology in response to the prevailing sediment supply and discharge. Morphology is characterized primarily by channel cross-section size, shape, gradient, and the river channel planform (‘channel pattern’). The variables controlling channel size, pattern, and gradient change along a river. The general trend is for discharge to increase downstream as the drainage area increases, while bed-sediment grain size decreases downstream. The consequence is that river morphology changes downstream also. For example, river channel width and depth usually increase progressively downstream as a result of the increased discharge. The transitions may be abrupt, such as at the confluence of a river and a large tributary. The reach concept emphasises the importance of variations in morphology along the river in response to local conditions, and downstream trends. An important consequence is that there may be large differences in river morphology and response to climate change at the scale of individual reaches. These differences may be greater than those generally occurring at the regional scale.

The specific responses of rivers to climate change can be described in terms of a series of variables that are widely used to describe the major elements of the morphology and processes in rivers. These are briefly reviewed here to provide the basic terminology and concepts that are used in the subsequent predictions of sensitivity and change. The bulk of the discussion in this section relates to alluvial and semialluvial streams, and to relatively large streams in which stream morphology is determined by fluvial processes and geological constraints (Church, 1992).

Width and depth

Width and depth are fundamental characteristics of a river, and are demonstrably sensitive to water discharge and, hence, to climatic change. Both channel width and mean depth (and, therefore, cross-section area) increase directly with the stream discharge (Fig. A-2), with width increasing rather more rapidly than depth. These 'hydraulic geometry' relations may be used to describe changes in channel form that occur downstream along a river as its discharge increases, or to compare the morphology of streams with different channel-forming discharges.

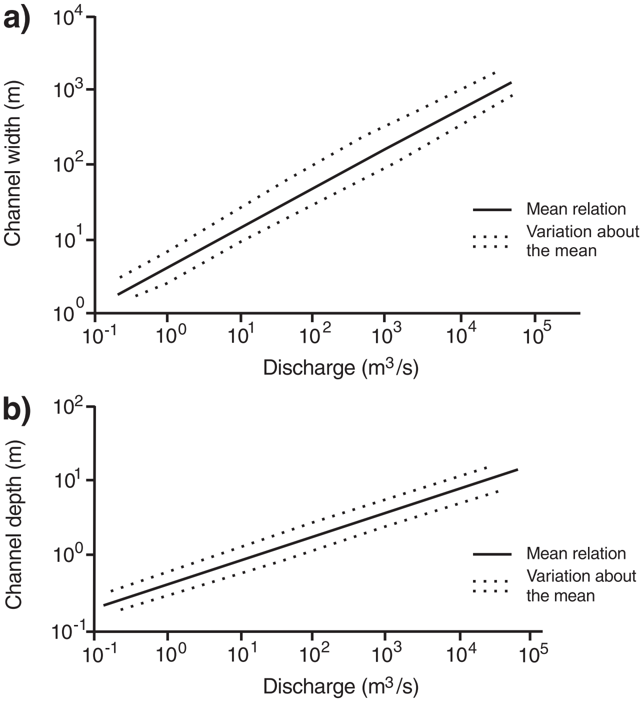

Figure A-2. *Relation between* ***a)*** *mean channel width,* ***b)*** *mean channel depth, and stream discharge. The solid line indicates the main trend of the data. Sediment and channel pattern exert a secondary influence on width and depth, causing the scatter around the main trend line, indicated by the dashed lines. Sand-bed rivers, and braided rivers tend to be wider and shallower than silt and/or clay and gravel and/or boulder single channels at a given discharge. (Based on graphs in Ferguson (1986); Kellerhals and Church (1989); Church (1992)).*

The stable cross-section dimensions are also influenced by the nature of the bed and bank sediment, and by the presence of river-bank vegetation. In general, any factor which increases the resistance of the banks to erosion will result in a narrower and deeper channel. For example, for a particular discharge, channels transporting sand tend to be wider and shallower than those flowing through cohesive, finer grained sediment. Bank vegetation may also be very influential in protecting against erosion.

Gradient

The average gradient of a river reach is primarily a function of discharge and sediment size (or bed material load) (Lane, 1955; Bray, 1982). Coarser bed sediment, or a larger load of bed material causes gradient to increase, whereas gradient will decrease with increasing discharge. These relations reflect the necessary rate of expenditure of energy to move the load of water and sediment introduced into the channel. Thus, gradient depends on the ratio discharge:sediment size (or bed load), and decreases as this ratio gets larger. Empirical relations between slope, discharge, and grain size for alluvial rivers indicate that slope declines more rapidly with increasing discharge in gravel-bed streams than in sand-bed streams (Blench, 1969; Bray, 1982).

Channel pattern

Rivers show a wide variety of channel pattern characteristics, which are governed by the valley gradient, the discharge, and the sediment type. Figure A-3 summarizes some common types of pattern, their characteristics, and the conditions which influence their occurrence. The exact values of discharge, gradient, and sediment characteristics for each type of channel pattern are difficult to specify, but for the obvious distinction between braided and single channel rivers it is possible to show at least approximate limits of these factors (Fig. A-4). Figure A-1a–A-1g illustrate the characteristics of a number of different channel patterns.

Braiding is unlikely in silt and/or clay channels. In general, the greater the stream discharge and gradient relative to the sediment size, the greater is the propensity for the river to develop either high sinuosity meanders (in the case of cohesive, silt and/or clay sediment), or to split into multiple channels (in the case of sand or gravel sediments). It is apparent from Figure A-4 that if average discharge conditions were to change as a result of climate, it is possible that some rivers would undergo a substantial change in channel pattern with consequences for channel width, lateral stability, and other aspects of river dynamics.

Apart from differences among pattern types, other significant aspects of channel pattern can be quantified. Meander morphology may be characterized by the average down-valley spacing of bends — the meander wavelength. Meander wavelength increases with both river discharge and channel width. Channel sinuosity (the degree of wiggliness of the channel) varies considerably with discharge, and also is greater in streams with a large wash load or high silt and/or high clay content in bank sediments. Thus, meander bend characteristics are potentially sensitive to changes in flow regime and hence to changes in climate.

Channel migration and bank erosion

The lateral migration of stream channels is a natural process related to the passage of the sediment load which has important consequences for human structures on the river banks and the habitation of floodplains. The pattern of migration differs between river types. Meandering streams (Fig. A-3) migrate systematically across their floodplain and downvalley. Occasionally channels may be abruptly abandoned when a meander bend is cut off, but usually migration is rather slow (it is unusual to find rates of migration exceeding 1 m per year, except in very large rivers). Because of this systematic and slow migration it is possible to establish the average direction and migration of the channel from historical maps and aerial photographs covering several decades. Nanson and Hickin (1986) show that maximum absolute rates of bank erosion and channel migration in meandering streams in western Canada, while influenced by the bank sediments, are largely controlled by stream power (discharge multiplied by channel gradient).

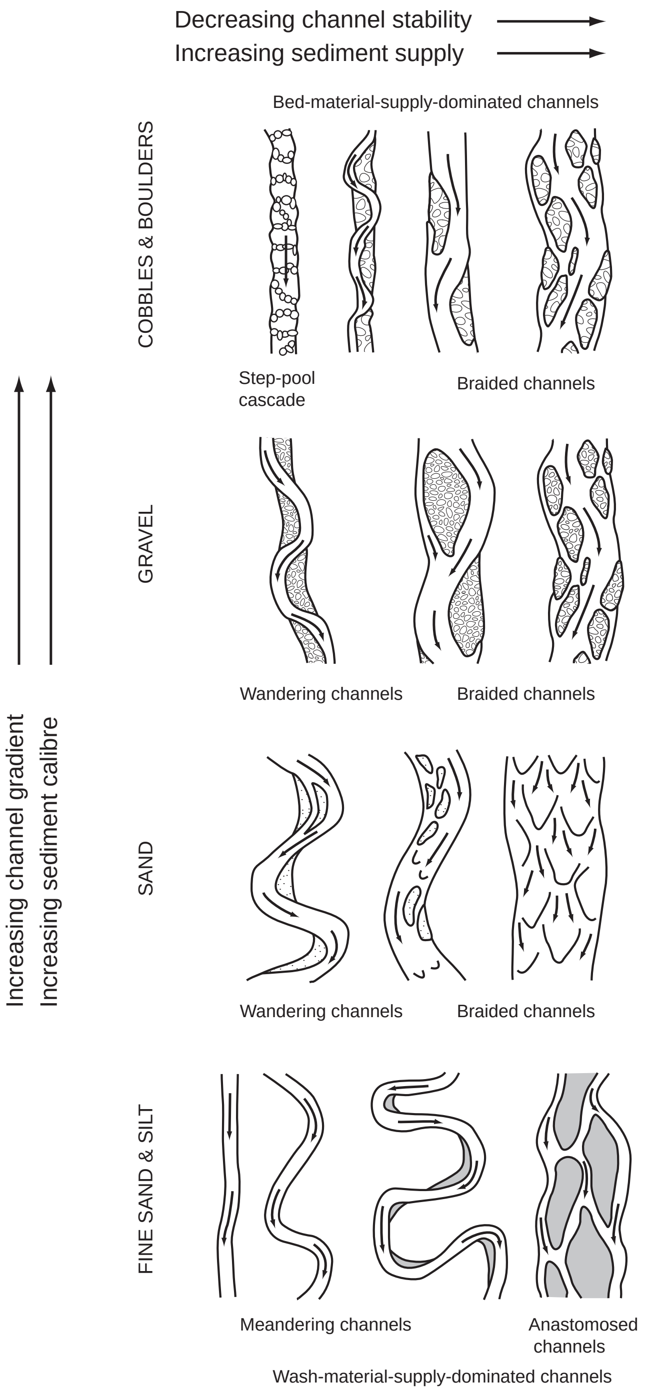

Figure A-3. *River channel pattern morphology characteristics and controls (*modified from *Church, 1992).*

In contrast, in braided rivers (Fig. A-3) individual channels may shift at rates of metres per day, and much of the shifting occurs in an unpredictable and episodic fashion. Lateral migration rates and bank retreat rates may be as rapid as several metres per hour. Furthermore, channel shifting occurs by 'avulsion' as well as by systematic lateral migration. Avulsion is the abrupt switching of flow from one channel to another. Lateral migration rates in braided streams are likely to increase with increasing ratios of stream power and/or sediment size, but the controls on frequency of avulsion are not known.

Lateral instability is especially problematic in streams where rapid aggradation is occurring, such as on alluvial fans. Commonly the streams flowing across alluvial fans are braided, but even if they are not, abrupt, unpredictable channel shifting is normal.

Channel entrenchment and confinement

The preceding morphological characteristics relate to the stream channel. The morphology of the stream valley may also play a significant role in controlling river activity and morphology, and the river response to climate change. The following categories are modified from Galay et al. (1973):

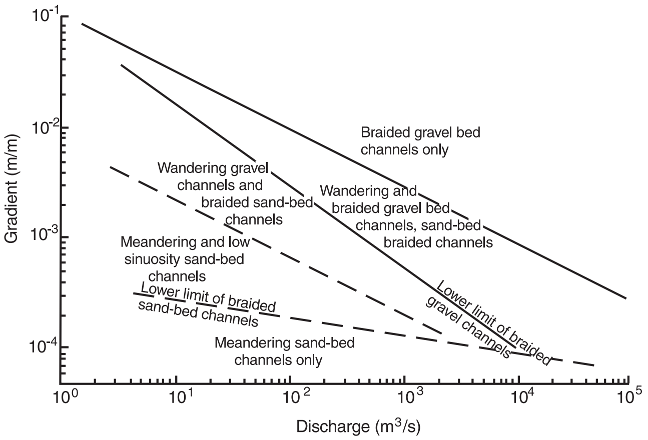

Figure A-4. *River channel pattern as a function of discharge and valley gradient.*

Confined channel: the channel is bordered on either side by banks that are higher than the highest flood level, or by valley sides. The narrowness of the valley restricts floodplain formation to small, isolated pockets. The channel frequently impinges on the valley sides for long distances. If the channel is tightly confined as a result of incision it is 'entrenched' or 'incised' (Fig. A-1j).

Partly confined channel: the river is confined by valley walls in short reaches, but the channel impinges on the valley walls only occasionally. River planform and floodplain may be well developed (Fig. A-1a, A-1g).

Unconfined channel: rivers flowing on an alluvial plain or fan. Neither planform nor floodplain development are restricted by valley sides (Fig. A-1b, A1-d, A-1f).

The changes in hydrology and sediment supply, together with changes in base level and crustal rebound following deglaciation have, in general, produced entrenchment and/or confinement of many rivers in Canada. In some cases the present streams occupy valleys that were formed by large, entrenched rivers. These rivers are 'underfit'.

CONTROLS OF RIVER MORPHOLOGY AND DYNAMICS

Variation in river morphology and dynamics is controlled by a number of physiographic variables. To understand and predict the response of rivers to climate change it is necessary to review both the influence of these physiographic variables on river morphology and the effect of climatic conditions on these variables. It is also important to understand the particular aspects of the linkages between climate, physiography, and river morphology that are most critical in assessing the effects of climatic change on river systems. Not all these physiographic variables will change over the relevant time scale for assessing climate change impacts. A further complication is that, in some cases, these variables can, and have, responded to events related to human activity independent of climatic change.

Discharge and flood flows

The discharge of water in a river has a pervasive influence on all aspects of river hydraulics, dynamics, and morphology; but discharge is highly variable in time at a particular place and not all discharges experienced are effective in controlling or modifying channel morphology. The relevant 'channel-forming' discharge, or range of discharges, occur during flows near or, in excess of, 'bankfull' (bankfull is when the water flow just fills the channel but does not spill onto the floodplain). These are usually flows with an average frequency of occurrence of once every 2–5 years. At any particular time the morphology depends on the size of the channel-forming discharge and the recent history of extreme floods. Thus river channel form is the result of a sequence of flood events.

Many rivers exhibit a more or less stable form that is adjusted to the dominant flood flows. In unusual cases, very large floods may occur with effects on river morphology that persist for decades, or which trigger a new phase of instability or morphological change that can be maintained by subsequent 'normal' floods. Rivers in which the flow regime includes frequent large floods may never achieve a stable form. These large events may result from unusually large or intense rainfalls, or be due to some unusual mechanisms such as catastrophic drainage of glacier-dammed lakes. Assessment of the effect of climate change on fluvial processes must focus on the occurrence of these typical and extreme flood flows, rather than on the average daily flows, and, hence, on the variability of discharge rather than mean values. It is also these extreme high flows which represent the greatest threat to structures and habitation near rivers (Fig. A-5); however, in the context of water resources and river habitat, the full range of flows is relevant.

The discharge regime of rivers is determined by the combined effects of the water input to the drainage basin and by the surface properties of the drainage basin, which influence runoff formation and timing of flood peaks (cf. Watt, 1989; Wolman and Riggs, 1990). Runoff is normally the result of rainfall, snowmelt, rain-on-snow, or glacier melt. Occasionally unusual events such as glacial outburst flows and bursting of natural or artificial dams produce 'catastrophic' flows. The discharge regime (the flow rates and timing of flow peaks) depends in part on the nature of the water input. Input from rainfall or rain-on-snow events have the potential to produce more extreme runoff events than snowmelt mainly because snowmelt is limited by variable solar energy, but the discharge regime is also affected by the dominant pathways along which water is transferred to the channels. Water moving across the ground surface reaches the stream channel quickly, causing rapid, large increases in streamflow in comparison to the water which infiltrates into the soil and reaches the channel by percolating through the soil. Therefore, the partitioning of runoff among these pathways directly controls the quantity and timing of runoff reaching the stream, and consequently, the magnitude of variation of stream discharge.

The surface conditions relevant to runoff processes include soil characteristics and vegetation cover. Human activity, such as agriculture or urbanization, may substantially change the surface conditions (by clearing and ploughing or paving surfaces) and the flow paths (by installation of storm sewers). In Canada the widespread presence of permafrost in northern regions, which prevents infiltration and through which there is effectively no groundwater movement, is also an important factor affecting runoff characteristics.

Sediment supply

The quantity and grain size of sediment supplied to rivers is a major influence on morphology and dynamics. The sediment comes from the erosion of the hillslopes of the drainage basin and erosion of the river bed and banks. The grain size and supply rate from the hillslopes are independent of the river channel system, being controlled by hillslope gradient, soil and

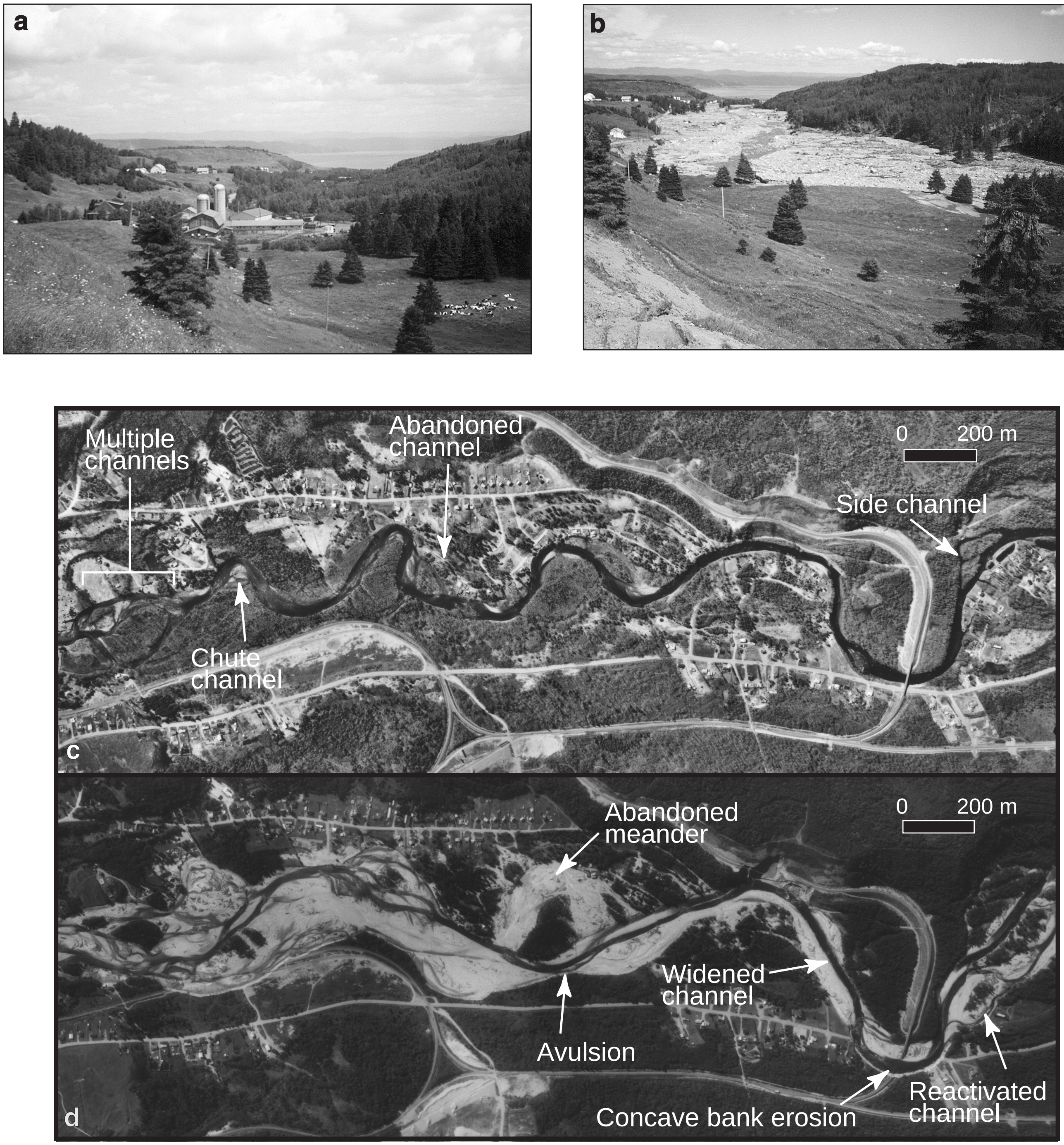

Figure A-5. *Geomorphic effects of catastrophic flooding on the Ha!Ha! River (**a** and **b**) and à Mars River (**c** and **d**) in the Saguenay region of Quebec, July 1996. Figures **a)** and **c)** show the rivers prior to the flood and **b)** and **d)** show the after effects that include erosion of large areas of the floodplain, rapid channel widening, change from a single channel to braided pattern, and valley side erosion. Photographs **a)** and **b)** courtesy of R. Tremblay. Photograph **c)** courtesy of Hauts-Monts Inc. HMQ 94-119 May 24, 1994; **d)** courtesy of Photocartothèque Québécoise, Ministère des Ressources naturelles, Québec Q96304-48, July 30, 1996.*

rock properties, vegetation cover, land use, and climate. Hillslope erosion rates and sediment supply vary over several orders of magnitude worldwide. The supply of sediment from the channel bed and banks is influenced by the streamflow and by the properties of the sediment (e.g. grain size) which control the propensity of the sediment to be eroded. Where a floodplain is present, bank erosion is part of the continuing exchange of sediment that occurs between the river and the floodplain.

The sediment load of the stream may be divided into two components. The wash load is that portion of the load finer in size than the sediment on the stream bed. It is transported in suspension and its quantity is determined solely by the supply from the land surface, not by the stream-flow conditions. The bed-material load is eroded directly from the stream channel and may be carried either in suspension, or as bed load. Its quantity depends upon the power of the stream and the erodibility of the sediment in the bed and banks of the channel.

Valley gradient

Over the time scale of a few years or decades the valley gradient is an important independent control on stream morphology because it sets the rate at which the energy of the water is expended as it flows downslope. Valley gradient is the outcome of the regional geomorphic history, including the influence of recent glaciation, sea-level change, crustal isostatic recovery, and tectonic tilting or uplift.

Secondary factors

Whereas discharge, sediment type, and valley gradient are the major influences on channel morphology, a number of secondary factors may be influential, especially locally. For example, riparian vegetation may affect local bank resistance and erosion rates, as may the occurrence of river ice and ice-rich (permafrost) sediments. There may be local topographic constraints on river morphology and activity, such as the entrenchment or confinement of a stream within a narrow valley. There are also a large number of channels with local morphology that is the direct result of human interference through channellization works.

The role of climate

From the discussion above of the major influences on river morphology and dynamics it is apparent that climatic conditions are, indirectly, a major control on river systems through:

1. *runoff quantity*, climate characteristics of a region control the total quantity of water discharged from a drainage basin by controlling the average balance of precipitation and evapotranspiration;
2. *stream flow (discharge)*, climate affects the timing of seasonal streamflow as well as the magnitude and frequency of individual flood events, determining the range of discharges in the stream channel;
3. *surface conditions*, streamflow characteristics are affected by movement of water over the land surface, and this is influenced by vegetation, which is partly climate-controlled; and
4. *sediment yield*, the quantity and calibre of sediment supplied to the river is also important to river morphology, and again climate plays a significant role in driving the hillslope erosion processes, whereas local geology, physiography, glacial history, and land condition affect erodibility and the dominant erosion processes.