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Newsletter / Bulletin

LIMNOLOGY

The Publicly Unknown Science of Inland Waters:
Overviews on Some of Its Important Topics

LIMNOLOGY

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Webmaster: Shawn Martin • Email: smartin@gartnerlee.com

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The Canadian Society of Environmental Biologists Newsletter is a quarterly publication. The Newsletter keeps members informed of the Society's activities and updates members on the current affairs and advances in the field of environmental biology. This publication draws together the widely diverse group of Canadian environmental biologists through a national exchange of ideas. Members are invited to contribute papers, photos or announcements that are of a national biological and environmental interest. Letters to the editor are welcome. This is a volunteer non-profit organization and we rely on your participation to make the newsletter a productive forum for ideas and discussion.

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LE BULLETIN de la SCBE 2007

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Le Bulletin de la SCBE est une publication trimestriel de la Société Canadienne des Biologistes de l'Environnement. Le Bulletin informe les membres des activité de la Société sur événements courant ainsi que les progrès qui font en sciences de l'environnement. Par un échange d'idées au niveau national, cette publication intéresse un groupe très diverssifié d'environmentalistes Canadien. Les membres sont invités a contribuer des articles, photos (noir et blanc) ou des messages qui sont d'intérêt nationale en sciences biologiques et envrionmentales. Les lettres à l'editeur sont bienvenues.

Tout la correspondence d'affaires, y compris les abonnements, les changements d'adresse, les exemplaires retournés et les formulaires: CSEB National Office, **P.O.Box 962, Station F, Toronto, ON, M4Y 2N9. Les lettres à l'editeur: Gary Ash, Editor, courriel: gash@golder.com**

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The Canadian Society of Environmental Biologists

CSEB OBJECTIVES

The Canadian Society of Environmental Biologists (CSEB) is a national non-profit organization. Its primary objectives are:

- to further the conservation of Canadian natural resources.
- to ensure the prudent management of these resources so as to minimize environmental effects.
- to maintain high professional standards in education, research and management related to natural resources and the environment.

OBJECTIFS de la SOCIÉTÉ

La Société Candienne des Biologistes de l'Environnement (SCBE) est une organisation nationale sans but lucratif. Ses objectifs premiers sont:

- de conserve les ressources naturelles candiennes.
- d'assurer l'aménagement rationnel de ces ressources tout en minimisant les effets sur l'environnement.
- de maintenir des normes professionnels élevés en enseignement, recherche, et aménagement en relation avec la notion de durabilité des ressources naturelles et de l'environnement, et cela pour le bénéfice de la communauté.

LIMNOLOGY

THE PUBLICLY UNKNOWN SCIENCE OF INLAND WATERS: OVERVIEWS ON SOME OF ITS IMPORTANT TOPICS

Volume 64, Number 1, Spring 2007

Guest Editor: ***Dr. Tom Northcote***

Canadian Society of Environmental Biologists
National Office
P.O. Box 962, Station F
Toronto, ON
Canada M4Y 2N9

Preface

I have been concerned for decades that inland waters, and especially those that serve in several key ways as one of the most important commodities supporting human populations, are so poorly recognized by the general public - especially its field of science, limnology, that deals with the physics, chemistry, and biology of such waters.

Consequently, I quickly accepted the suggestion by the CSEB executive to serve as a Guest Editor in organizing a series of contributions on this subject for the Spring 2007 issue of the Bulletin, and began to canvass colleagues who might prepare short but stimulating papers on limnological subjects of relevance to the inland waters of Canada, around an overall focus "Limnology - the publicly unknown science of inland waters with overviews on some of its important topics."

Soon it became apparent that subject limitation and sequencing would be a major difficulty in this broad area, especially within the limits of a single issue of the Bulletin. Furthermore, there was the problem pointed out sharply by David Schindler, Canada's best known and most effective limnologist, in reviewing my contribution, that "to publicize limnology, papers in the CSEB Bulletin certainly will not do it - we need to get to the pagans, not the converted!" Of course in many ways he is correct, even with the CSEB membership from across the country. But it is my hopes that this set of contributions, and perhaps with others later, could be put into a follow-up publication that could be distributed much more generally to the public, along with strong oral and television presentations geared effectively to "conversion of the pagans"!

As a start for the present set, it seemed best to put the paper by Judy Isaac-Renton and her colleagues next after my opener, with the thought that the subject of health for the general public would surely demand their most immediate and effective attention, as well as hopefully appropriate action. Then would follow working across Canada from west to east, a series of five other papers, one on an endangered marsh-pond complex on B.C's Okanagan Lake, one on the heating up topic of climate warming focussed on freshwaters of Canada's western prairies, one on small community drinking water treatment in central Canada, one on mining impacts on waters of the Canadian north, and one on forestry effects on freshwaters across Canada.

Originally I had planned to have a short closing overview for this sequence of contributions but have decided against doing so in order not to divert attention from Gordon Hartman's strong six point call for research action at the close of his paper on forestry effects.

T.G. Northcote
Guest Editor

Causes For The Little Public Recognition Of Limnological Science And Needs For Improvement

T.G. Northcote – Professor Emeritus
UBC Departments of Zoology and of Forest Sciences
c/o 10193 Morrison Close, Summerland, B.C., CANADA V0H 1Z7
E-mail: tnorthcote@vip.net

Abstract

Although a main cause for general non-recognition of the science of limnology is its somewhat esoteric name of Greek origin and given over a century ago, there now seems little to be gained in trying to change it. Limnologists throughout the world must intensify efforts very soon to make both its name and its importance much better known among those of all walks of life, but especially to teachers at all levels, administrators, and politicians, and by using more powerful and effective approaches than in the past. Otherwise, inland potable water will take over oil's present role of importance, and could then become a major cause of serious international confrontation.

General Non-Recognition of Limnology

For nearly half a century I have been giving presentations most years at a series of lower and upper level schools in British Columbia, often working with the Science World program initiated in part by the Canadian limnologist Dr. Peter Larkin. Almost invariably the teachers encountered have never heard anything about the science of limnology, and certainly not their students. At each school session, with frequent use of the word limnology and getting it repeated by the students, by demonstration of simple limnological equipment, a pictorial presentation showing some large lakes and rivers of the world with their fascinating flora and fauna, I conclude with a hands-on session in which student groups sort out as many locally collected but different live organisms that they can find with small "limnonets" and "limnosuckers" from "limnoponds" putting the "critters" into "limnodishes" for projection onto a large screen where I point out what they are, what they "do," and why they are important. After such localized exposure of limnology as an important field of science, and no doubt followed in various ways by other limnologists throughout the world, one might expect to meet a few of the general public occasionally who at least know what limnology is, what a limnologist does, and why it is important. Rarely does this happen. When introduced as a limnologist, a very common response is – "Oh how interesting; do you study tree limbs or human limbs?"

That clearly demonstrates what a serious problem limnologists face, the name given to our science – "limnology", coming from the Greek word for swamp / marsh / pond / lake, first coined in the late 1800s, and now including all inland waters, be they fresh or saline, standing or running, surface or ground waters, polluted or unpolluted. So we have identified one problem – it is the name given to the science of inland waters. Recently this name and subject has been recognized in a few of the large dictionaries, but try typing "limnology" into any computer driven text and up it comes in blaring red underline indicating a non-word! In large part this is our fault as limnologists for not rectifying such nonsense. I tried several times to get limnology or at least inland waters or freshwaters (at times and places not so fresh) included in the list of subjects which "Science World" sends out to schools for teachers to select subject areas for specialists to visit their schools. No luck. I was told that the teachers wouldn't recognize what this subject was, so they stuck with "oceans"! But I tell each class I visit that few people anywhere in the world drink seawater, without suffering from the "trots" or the high cost of desalination.

Yes, the problem in part is our name, but it is also us as limnologists! We just haven't been forceful enough to get better and broader recognition of our science. Some have tried as outlined above, and by making note of the problem at in-house scientific meetings such as those of the International Association of Theoretical and Applied Limnology (SIL) or the American Society of Limnology and Oceanography (ASLO). I had a lead article in the September 2002 SIL News entitled "Limnologists in Schools – SIL Possibilities" (Northcote 2002) but got virtually no comments – good, bad, or indifferent on it.

Is the Science of Limnology Important?

Perhaps before attempting to answer that question, it would be prudent first to consider the broader fields of science generally, where one would think there could be little doubt of not having an affirmative answer. Yet a recent viewpoint in BioScience (Wertheim 2006) starts with the comment that "We all know the dismal statistics:", and goes on to bemoan the plummeting science literacy of both younger and older fractions of the American population. In her concluding two sentences, Margaret Wertheim, a top science journalist, says "In short, those of us who love science are called upon to be missionaries. It is time to get off our high horses and go out to the people."

Limnology, the umbrella science of inland waters, surely should be a focal point for addressing world issues and public problems concerning such water over the globe, where nearly one billion people lack access to potable water as noted in the UN 2006 *World Water Development Report* according to Holden (2006a). One of the most serious regions for agricultural land degradation is in Africa, where now only 4% of the 950 thousand square kilometres of arable land is irrigated, making water supply problems all the more critical (Holden 2006b). But even in the United States, those relying on groundwater to drink should be concerned that volatile organic compounds (VOCs) from gasoline, cleaning products, and paint occur in 90% of aquifers and wells tested in a 17 year period by the U.S. Geological Survey (Unger 2006). Apparently these VOCs are at present considered safe for human consumption, but so have a rather long list of contaminants later found not to be so safe! Furthermore human population growth, thought to have ceased in developed nations, has not in the U.S., now third in the world after China and India, and with the U.S. total reaching 300 million by autumn 2006 (Holden 2006c). And where water diversion for agriculture and urban use of the large U.S. Colorado River now results in it no longer reaching its mouth in the Gulf of California (Pearce 2006). Neither does the Rio Grande on some years, despite its name and salt laden content from over-use for agricultural irrigation.

But surely here in Canada, often thought to be the land of water, snow and ice, there surely can be no problems with water supply. Perhaps so in major parts of the Arctic and Hudson watersheds (Peterson et al. 2006), but most certainly not so in the Okanagan Basin of British Columbia (Northcote 1996), one of the driest regions of Canada, where water supply demands from rapidly increasing population growth are over-taxing supply, and show little promise of decreasing over the next several decades.

Much of the whole 25 August 2006 issue of Science was focused on freshwater resources from its cover, to its Editorial (Kennedy and Hanson), on to its Newsfocus (Stone and Jia), its major book review (Postel), its general review (Peterson et al.), its Special section covering two more reviews (Oki and Kanae; Scharzenbach et al.), two perspectives (Fenwick; Tal), and two news articles (Bohannon; Service). Nowhere in this impressive focus was there a single mention of the science of limnology! To me this powerfully signifies that we as limnologists have missed far more than the boat – we seem also to have missed top scientific as well as public interest!!

Possibilities for Improved Recognition of Limnology

1. Should we continue pointing out the problem?

Well, yes but not just as we have been. For the last 25 years or more, limnologists have been noting parts of the overall problem, as did Jack Vallentyne at a SIL Presidential Address (Vallentyne 1981), as have others there (Löffler 1988), and elsewhere (Jumars 1990; Kalff 1991; Wetzel 1991; 1992). Even earlier David Schindler, then heavily involved running a multifaceted research program in the Experimental Lakes Area of the Manitoba-Ontario region, was in high demand to inform Canadian and American governments on the looming acid precipitation problems, arising in large part from industrial activities in both countries. Other limnologists have been reaching out to the young as I have outlined – especially in Brazil (Tundisi et al. 1998; Campos and Tundisi 1998) and in Japan (Kawashima et al. 1998). In 1988, Environment Canada put out three inland water fact sheets, the first on “Water – Natures Magician” (four pages), the second on “Water – here, there and everywhere” (six pages), and the third “Clean water – a priceless asset” (twelve pages), but nowhere in any of these can you find any reference to limnology or limnologists! More recently, SIL President Carolyn Burns from New Zealand has been actively noting these problems facing limnologists (Burns 2000, 2002), as has the Canadian limnologist, David Schindler, elsewhere. In the opening sentence of his perspective to commemorate the 100th Anniversary of the Canadian Journal of Fisheries and Aquatic Sciences, he said “Considering its importance to all life on earth, it is strange that freshwater has been our most mistreated and ignored natural resource” (Schindler 2001) – very strong and true words indeed! Yes, there has been considerable talk and writing about the need to bring limnology to the fore in public knowledge and concern, but too little of it broadly and effectively reaching the voting general public and their politicians in attempts to popularize limnology as a key science having vital links to the maintenance of human survival on earth. Even the *World Water Development Report* from the United Nations, published in late March 2006, and noting the fact that close to 1 billion people lack access to fresh water, apparently contains no direct comment on the need to get limnologists into its panoramic view of world inland water problems (Holden 2006a). Certainly there has been no lack of pointing out inland water problems here in Canada and abroad for decades, but far too little of it directly promoting the pressing need for limnology and limnologists, per se, to politicians and the general public. The 4th year and graduate limnology courses that I taught in the Department of Zoology at the University of British Columbia have not been continued since shortly after I retired in 1992, and these were well subscribed and attended from 1968 on.

2. Should we coin a new, more easily and widely understood name for our science?

Make only a quick mention of the word for the science of marine waters – oceanography – and almost immediately a bell rings in the minds of the young and old alike, rather than their blank look usually following mention of limnology. Should the name limnology be replaced by "inland aquology," if the latter is etymologically correct? I think not. For one thing computer systems don't recognize "aquology," or even "aquatology," but more seriously there are now many long-term associations, societies, and organizations that have had "limnology" for decades in their names, awards, and so on. They are unlikely to change their names. Just coining a different name for limnology, no matter how much more readily it may be grasped by the general public, will not be enough.

3. Then what should we, as limnologists, do?

In my view we must now become far more active in promoting the name of our science – limnology – but also what it encompasses, how it covers such a breadth in science and technology, and most importantly what will be needed from it now and in the very near future if we are serious about trying to reduce the enormous problems facing the many "developing" areas of the world for safe and adequate supplies of drinking water, along with inland water's many other essential human uses in most regions of the globe (this shouldn't include lawn or even golf course sprinkling!). Water will quickly become the most vital fluid on earth, far more so than oil, as human populations continue to grow and their demands for water continue to escalate overall. National and international confrontations, if not wars, may soon arise over inland water not land, political orientations, oil, and focuses such as religions or ethnic divisions that in part have been causal up to now. Limnologists keenly need to make their science far better known broadly throughout mankind in order to reach all of its levels and divisions.

Perhaps, as Wertheim (2006) suggested for science in general, limnologists should be pushing as missionaries to have limnology move towards becoming a religion!

In nearly a decade of work on high elevation Lake Titicaca in the Peruvian/Bolivian Altiplano that is what we in the now forgotten Westwater Research Centre at UBC in some ways tried to do, not all that successfully, with a long but under-funded CIDA project (see Dorcey and Northcote 1988; Northcote et al. 1989; Northcote et al. 1991; Cruz et al. 2006). Major reorientations will be needed in what limnologists (and most other scientists) now strive for – publication numbers strongly tied into promotions; increasing the numbers belonging to their various societies and associations; personal recognition at the local, national and international level; grant support and so – in other words, a large shift in what now seems most important. This surely will not be easy but if it doesn't happen, far more than just a branch of science vital to mankind may be lost!

So in summary, here is a short four point "do-list" not only for limnologists but also for those in the many other related branches of inland water supply problems, corrections, and general understanding:

- Intensify efforts to reach out to the young whose minds are not yet so locked into television violence and war games. Thereby the messages not only are taken back to parents, but also are given for continuing amplification to teachers.
- With appropriate modifications and local example details, continue to bring relevant information on inland water problems requiring limnological inputs to service clubs, water management boards, and other such bodies whose key interests often seem to focus largely on further "development" issues and human population growth.
- Get water issue problems and publications tied in with limnology posted in the several suitable websites, such as that of the Safe Drinking Water Foundation, as suggested by Hans Peterson (see his contribution in this issue of the Bulletin).
- Submit notice of the focus for this series "Limnology – the publicly unknown science of inland waters with overviews on some of its important topics," perhaps along with its preface, to a set of top publications read by a Canada-wide audience.

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Microbial Source Tracking of Fecal Pollution in Inland Waters: How Does It Help Protect Public Health?

J. Isaac-Renton[1,2], C.S. Ong[1,2], N. Prystajecky[2], S. Shay[1], T. Edge[3], V.Gannon[4]
[1]BC Centre for Disease Control, BCCDC Laboratory Services, Vancouver, BC
[2]Department of Pathology and Laboratory Medicine,
University of British Columbia, Vancouver, BC
[3]National Water Research Institute, Environment Canada, Burlington, Ontario
[4]Public Health Agency of Canada, University of Lethbridge, Lethbridge, Alberta

Introduction

Microbial Source Tracking (MST) may be described as the application of laboratory techniques to compare the similarity of microorganisms collected from aquatic ecosystems (including drinking water sources) to microorganisms collected from possible fecal pollution sources. This comparison is done in order to make inferences about the likely source of fecal contamination, hence the source of point or non-point contamination that may be a risk to human health. The collection of MST techniques has often been referred to as a toolbox.

Some techniques appear to be more relevant than others in certain circumstances. Some investigators prefer the term Fecal Source Tracking, recognizing non-microbial markers (human mitochondrial DNA, caffeine) left in feces have also been used to identify human sources of contamination.

MST is a relatively new area of investigation. It was developed in response to the recognized need to protect watersheds, which provide source water for drinking, recreation, food processing and irrigation and to maintain healthy aquatic ecosystems. While point sources of fecal contamination (such as municipal outflows) can usually be identified in watersheds and corrected, non-point sources (such as run-off of animal wastes, leaking sewage pipes and septic systems) may be much more difficult to identify. Is MST a tool that may help identify public health threats resulting from fecal contamination of inland waters? Recent MST workshops in Canada and the US (National Water Research Institute, March, 2005 (www.nwri.ca/microbialsourcetracking/intro-e.html), Water Environment Research Foundation, February, 2005) were held to address these questions. Experts concluded that expectations that arose in the 1990s around MST have now been tempered by the recognition of the need for additional research to better understand the strength as well as the limitations of MST techniques.

Microbial contamination of drinking water is a major concern world-wide. To better protect the public health, multiple barriers from Source (Watershed) to Tap are now recommended. This best practice requires new partnerships from Source to Tap, including enhanced collaboration between watershed managers/Ministry of Environment and medical and environmental health officers/Ministry of Health. This paper attempts to answer the question—how useful is the current MST toolbox, particularly as it relates to protecting drinking water?

Current Approaches

Fecal contamination of drinking water is currently monitored using "indicator" or "surrogate" bacteria such as *Escherichia coli*. *E. coli* (one of the fecal coliforms from the intestines of man and animals) is relatively easy to grow in microbiology laboratories and detect in water samples. Indicator bacteria are used around the world by public health agencies to monitor drinking water for fecal contamination at the water distribution system level. While public health interventions (such as boil water advisories) follow identification of potential risk (*E. coli* detected in water) and are invoked to prevent disease, they do nothing to prevent the circumstances that lead to the contamination of the drinking water.

In a Source (Watershed) to Tap model, MST is helpful to watershed managers and also to public health partners in identifying these sources of fecal pollution in water, and in focusing efforts to prevent this contamination and waterborne diseases.

Sources of fecal contamination can be determined using a variety of molecular and microbiological methods—the tool box. Most MST tools are based on the characterization of individual microbial strains by genotypic profiles or phenotypic traits. These methods are generally classified as being library dependent or library independent. Library dependent methods rely on the compilation into a database of profiles/traits of microbial strains from known host origins relevant to a specific geographic area. In contrast, library independent methods rely on characterizing host-specific markers without requiring information from a database.

Both library dependent and library independent approaches rely on two important assumptions. The first is that of homogeneity and the stability of the intestinal microflora within a species (i.e., the gastrointestinal microbial flora) will be more similar from one individual to another (independent of diet, age and sex etc.), over time, place (such as from one farm to another), for a given animal species than to the microbial flora of another animal species. The second assumption is that unique features or "signatures" of microbes will be maintained, detectable or measurable, in deposited feces, and that these signatures will also be maintained by microbes in water.

The level of fecal source discrimination that can be achieved depends on the method used. Some methods can only discriminate human fecal sources from all other sources, whereas some methods might be able to discriminate between different individual forms from the same type of host group under certain circumstances. This is an important factor when selecting a method for an MST study. What is the required level of resolution in order to meet project objectives? From a watershed protection, and hence a public health perspective, at a minimum, resolution should be able to identify sources of contamination as being from humans or from animals. To date, no MST method has been identified as being generically applicable to all watershed systems and to all types of projects. Tables 1 and 2 summarize the three most commonly used library independent and library dependent MST methods, along with some of their advantages/disadvantages.

In selecting the appropriate MST method, it is important to realize that to date no single method is capable of identifying all types of fecal contamination. As such, it may be necessary to use several methods in combination to achieve the appropriate level of resolution. Furthermore, it may be possible in the future that best MST practices will be to combine the aforementioned microbiological methods with other non-microbial methods.

Table 1. Library Dependent MST Method

METHOD	DESCRIPTION	ADVANTAGES	DISADVANTAGES	RESOLUTION
ANTIBIOTIC RESISTANCE	• Most common phenotypic method used for MST • Method relies on the assumption that levels and patterns of antibiotic resistance differ between humans, livestock and wildlife • Isolate patterns are compared to antibiotic resistance patterns library • Cultivation dependent • Targets include *E. coli*, *Enterococcus* spp.	• Low cost • Rapid • No specialized equipment required • Requires only basic microbiology training	• Assumes that all hosts will have been exposed to some level of antibiotics • Possible that wildlife living in close proximity to livestock may be exposed to antibiotics through livestock feed • No standard suite of antibiotics and concentrations used for testing • Instability of plasmid-mediated antibiotic resistance	• Discriminates between different host groups (Humans vs. Livestock vs. Wildlife) • Not useful for differentiating between different wildlife hosts • Resolution from mixed samples is unknown and further research is required
RIBOTYPING	• Analysis of DNA fragment patterns generated from restriction enzyme digestion of genes encoding 16s rRNA compared to database with known patterns • Method works on premise that bacteria are adapted to digestive system of host species. These differences can identify host origins • Cultivation dependent • Targets include *E. coli*, *Enterococcus* spp.	• Highly reproducible • Specific	• Expensive and labour intensive • Specialized equipment and training • Long turn-around time • Large database required; isolates from broad geographic region or must be designed for a specific watershed	• Dependent on data base size and geographic representation • Resolution to the individual host level (i.e., individual farms or herds)
REPETITIVE ELEMENT (REP) PCR	• Cultivation dependent • Targets *E. coli* • Amplification of multi-copy, conserved repetitive elements common in bacterial genomes • Resulting banding pattern (fingerprint) are compared to fingerprints in a library • Identical pattern suggests that it is the same strain of bacteria • Similar patterns indicate that the isolates are related	• Requires basic molecular biology training • Low cost • Compatible with high throughput platforms	• Large database required • Geographical and temporal variability limit the transferability of reference libraries	• Dependent on database size and geographic representation

Some pathogenic microbes including bacteria (*E. coli* 0157), viruses (Norovirus) and parasites (such as *Giardia* and *Cryptosporidium*) can be very host specific but are not easily manipulated in most microbiology laboratories. Although these agents are rarely shed in the feces of healthy human and animal populations, infected animals may serve as amplification hosts. Therefore, their potential to cause zoonotic infections and the impact of their waterborne spread on human health, especially for some of their species that are not as host specific, should be considered. Development of special procedures to detect and to characterize new approaches for these pathogens (Pathogen Source Tracking) is underway. Recently McQuaig et al. (2006) have reported detection of the wide spread and human-specific polyomaviruses (which is voided in the urine of approximately 50% of the population). This abundant and widespread group of viruses may serve as a specific marker for contamination of water by human sewage.

Table 2. Library Independent MST Method

METHOD	DESCRIPTION	ADVANTAGES	DISADVANTAGES	RESOLUTION
BACTEROIDES-PREVOTELLA	• Due to its abundance in feces, is a potential noncoliform indicator organism • Does not replicate in the environment, therefore provides quantitative assessment of contamination levels • Culture independent • 16s rRNA specific primers are most commonly used in host species-specific PCR assays • Analysis by sequencing or restriction fragment length polymorphism (RFLP) • Commonly applied genotypic method	• Requires basic molecular biology training. • Can be performed in standard molecular laboratory. • Low cost • Can be applied, used as simple multiplex and quantitative PCR formats	• Marker tests not available for all species (e.g., avian and beaver markers have not been identified) • Influenced by PCR inhibitors in water • Standardization and quality control is very important • Little is known about the survival times for these anaerobic bacteria in the environment	• Distinguishes between human and animal sources • Potential for greater resolution, dependent on the identification of species specific markers
VIRUS SPECIFIC PCR	• Monitoring directly for human enteric viruses by Reverse Transcriptase PCR (RT-PCR). • Targets include Entero-virus, Adenovirus, Noro-virus, Rotavirus	• Rapid • Requires basic molecular biology training • Can be performed in standard molecular laboratory.	• Has not been widely applied • RT-PCR might detect non-viable viruses which have no impact on public health • Not always present even when humans present • Present in low numbers in environment. • Method should be used in combination with one or more methods for predicting presence of fecal pollution and enteric pathogens.	• Discriminates between human and livestock sources • Future potential to identify viruses specific to wildlife species.
F+ COLIPHAGE	• Targets a virus that infects *E.coli* • Culture dependent • Indicator of fecal, sewage and enteric viral contamination • Classification into four groups (I-IV) using genetic or serological approaches • Groups II and III are highly associated with human waste • Groups I and IV are associated with animal waste	• Requires basic training • Low cost • USEPA developed protocols available	• Low numbers in the environment • Contradictions to the groupings have been reported (i.e., Group I phage has been documented in human wastewater)	• Distinguishes between human and animal sources • At present time, additional resolution (i.e., animal host) is not achievable.

Safe Drinking Water: Role of MST?

Current water quality monitoring at Tap is focused on detecting indicator organisms such as *E. coli* in drinking water distribution systems. Results are often available only after the water is consumed by residents. No information as to the source of the fecal contamination is provided by this testing. All contamination events that actually have occurred are also not detected by the current approach to monitoring, due to small test sample size or limited sampling in time and place. A more comprehensive approach to safe water is needed.

Even within this comprehensive framework, with Medical Health Officers working in partnerships with aquatic ecosystem experts and watershed managers, there is a growing need for an improved evidence-base to accurately and reliably determine the source of fecal contamination of source waters used for drinking. At present, MST is still under development, and there is no universally accepted “best” technique. Some methods will see limited use, while others will see continued use and refinement. At the moment, MST tools need to be combined with historical, geographical or other lines of evidence, and are all needed to convincingly identify the non-point source of water contamination. There are no standardized methods, and there have been few field studies to test the reliability of MST results. Research efforts to evaluate existing MST techniques and develop new ones are urgently needed for many stakeholders, including public health agencies. MST, with an armamentarium that continues to evolve, will become part of the public health toolbox of the future.

Since safe drinking water is a major public health issue, in BC and around the world, MST programs could be a useful meeting place to connect key partners, particularly the Ministry of Health and the Ministry of the Environment, in the Source to Tap model.

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Preservation (for the Present) of an Endangered Small, but Biotically Rich Marsh-Pond Complex, Near Summerland, BC on Okanagan Lake Shoreline

Sue P. Salter
Cordillera Consulting
7311 Huddleston Rd. Summerland, B.C. V0H 1Z6
Email: suesalter@shaw.ca

T.G. Northcote
10193 Morrison Close, Summerland, B.C. V0H 1Z4
Email: tnorthcote@vip.net

Abstract

A small, distinct marsh on the shoreline of a large British Columbia lake has been under development threat. Extensive benthic invertebrate sampling was done in 50 day intervals over the course of a year, along with testing of physical and chemical parameters before a large hotel complex was built or groundwater interruptions took place. The invertebrate sampling results showed that diversity within the small marsh was high compared to adjacent lake littoral sites. High nutrient levels in spring inflows may in part account for high diversity in the marsh-pond, as well as the high abundance of benthic invertebrates in the adjacent lake shoreline sites. The impact of the hotel complex, including possible lower nutrient supply on the diversity and abundance of the invertebrate community, should be followed.

Introduction

Shorelines of lakes, whether large or small, are usually the regions of highest biodiversity and productivity. But a wide range of human activities also are focused on lake shorelines, and can result in severe habitat alterations. Indeed, in many large lakes of Europe, North America, and elsewhere in the world, shoreline marshes of lakes with their associated wetlands and ponds have suffered very heavy alteration, if not complete losses. An outstanding example is that of Okanagan Lake, not heavily endowed with shoreline marshes (Clemens et al. 1939), where various human activities (park and beach recreational development, lakeshore cottage and suburban development, and shoreline road and harbour construction) have resulted in considerable loss of shoreline marsh habitat (Northcote 1997).

Along the southwestern side of Okanagan Lake, where a 42 km section of shoreline has been drastically altered by the above means, there is now virtually only one small piece of lakeshore marsh remaining – that of the Lower Summerland marsh-pond about 100 m in length (Fig.1). It was critical to document fully its nutrient sources, biological diversity, and abundance of its pond and marsh complex, only a part of which had been summarized previously (Northcote and Northcote 1996; Northcote 1997).

This compilation characterizes the community structure of aquatic invertebrates in the marsh-pond and nearby lake-front to establish baseline criteria prior to the construction of a hotel complex only a few metres away. We examine two aspects of benthic community structure, its overall total taxonomic richness, abundance and functional feeding groups, and then compare its seasonal diversity and abundance.

Study Area

The shoreline of Okanagan Lake at Lower Summerland, British Columbia, is a narrow strip of land (50-100 m in width) at the base of a 100 m clay cliff. The marsh pond is a small (0.4 hectare) discrete shallow waterbody, separated from the lake by a 3 m wide sandy berm and elevated ~1 m above the lake. The water level of the pond rises and falls with lake level. There is water in the pond year-round, supplied by two distinct spring inflows (Fig.1) along with a number of smaller spring upwellings, which are common in the lake shoreline area. The pond occasionally forms a partial ice cover in the winter, but rarely freezes over. There are steep, heavily shrubbed banks to the north, south and west of the pond, and its emergent vegetation is comprised of *Scirpus lacustris*, *Pavonia typhalaea*, *Cornus stolonifera* and *Lythrum salicaria* L. The aquatic macrophytes in the pond are mainly dense patches of *Potomogeton crispus* and *Lemma minor* combined with areas of open water. The substrate of the pond is mainly black organic mud, with considerable amounts of fine blackened wood particles. Over the years, the pond has been the dumping ground for a cherry processing plant, and the substrate has been heavily supplied with cherry pits.

The marsh front and lake front sites (Fig.1) are shallow littoral zones, with a sandy substrate and a moderate density of mainly *Potomogeton crispus* macrophyte growth. Both areas are sheltered on the north side by a 50 m rip-rap berm constructed for the local yacht club.

Methods

On each occasion (usually mid-morning) that sampling was done on the Lower Summerland marsh pond, marsh and associated lake front sites, near-surface water temperatures were recorded and 250 mL water samples collected and stored briefly under refrigeration for laboratory analysis a few hours later. Invertebrates dwelling near the shoreline bottom were sampled by sweeping a 15 x 19.5 cm dip net (1 mm mesh) along a 2 m transect parallel to the shore and then back again over the same strip of bottom, thereby covering an area of 0.39 m^2. Triplicate samples were taken a few metres

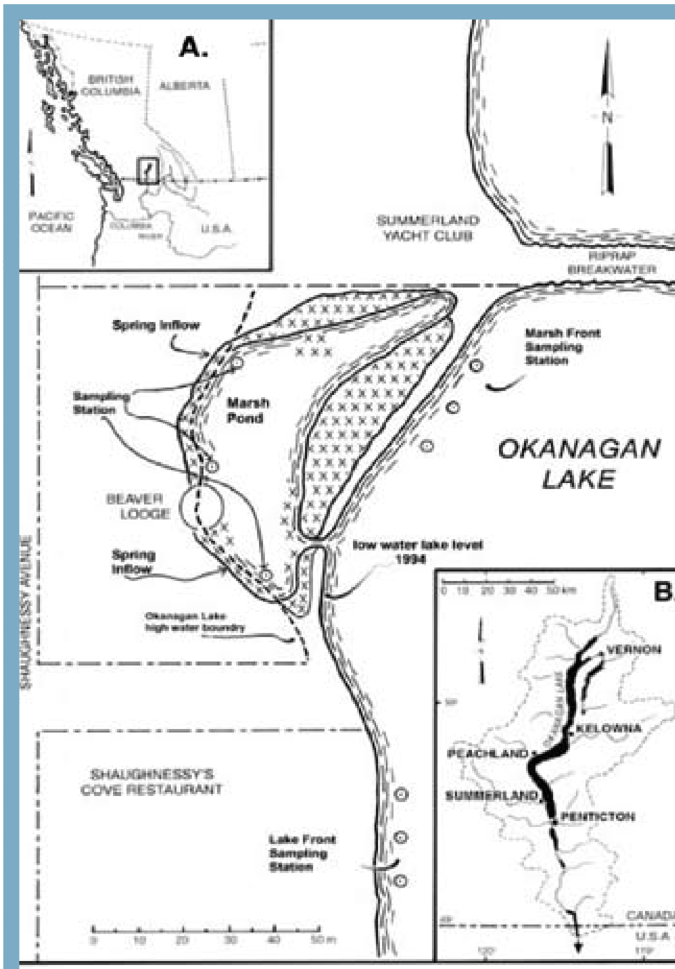

Fig. 1. Map of study area showing A. general location in British Columbia, B. location of Summerland, marsh pond, marsh front, lake front sampling sites and spring inflows.

apart, gently washing out fines through the net, and preserving the remaining organisms along with debris in 5% formalin. The invertebrates were sorted and identified under a dissecting microscope at 10 - 50x magnification to the lowest practical taxa. After sorting and identification, the invertebrates were stored in 80% ethanol.

Statistical Analysis

The Shannon-Wiener and the Simpson diversity indices were calculated. The Shannon-Wiener index will indicate greater diversity with larger values, and the Simpson's index will range from 0 to 1.0 to indicate low to high diversity. The Jaccard Coefficient of Community Similarity was calculated, which ranges from 0 to 1.0 to indicate low or high similarity between two sites. This index is useful when comparing collections with similar taxa (http://lakes.chebucto.org/E/E-1/diversity.pfd). Taxa richness and taxa abundance were tallied over the whole study period, between winter and summer seasons, and organized into functional feeding group charts to show differences and similarities between the sampling sites.

Results

Water Temperature Characteristics

Throughout the sampling period of the study, surface water temperatures were taken at the three sites (Fig. 2). Temperatures at the marsh pond were lower than at marsh front and lake front sites during the summer and autumn periods, but slightly higher during winter and spring. During cold spells in winter, much of the pond froze over except for an area near the northwestern side (Fig. 1) where warmer spring water entered.

During high water periods in Okanagan Lake, especially when combined with strong wind, it was possible for lake water to intrude into the pond through its southern outlet (Fig. 1).

Water Chemistry Characteristics

There were marked differences in water chemistry between the marsh pond and the marsh front along the nearby shoreline of Okanagan Lake over the 1994 to 1996 study period (Fig. 3). Conductivity of the marsh pond water was high, ranging seasonally from nearly 700 to over 800 µS/cm, with highest values near the northern portion of the pond where spring water inflow

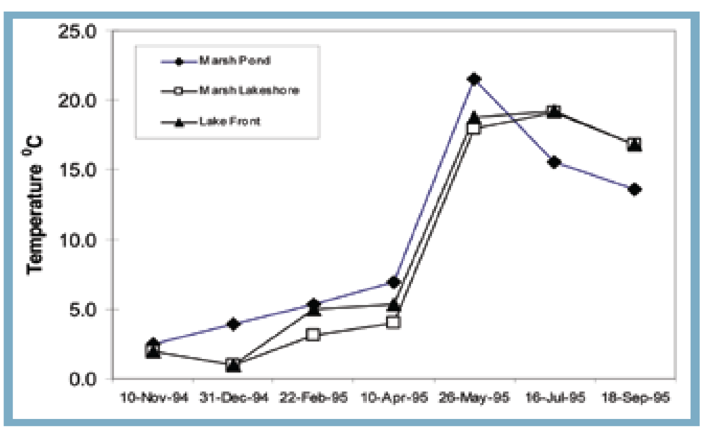

Fig. 2. Water temperatures at the three sampling sites from November 1994 to September 1995.

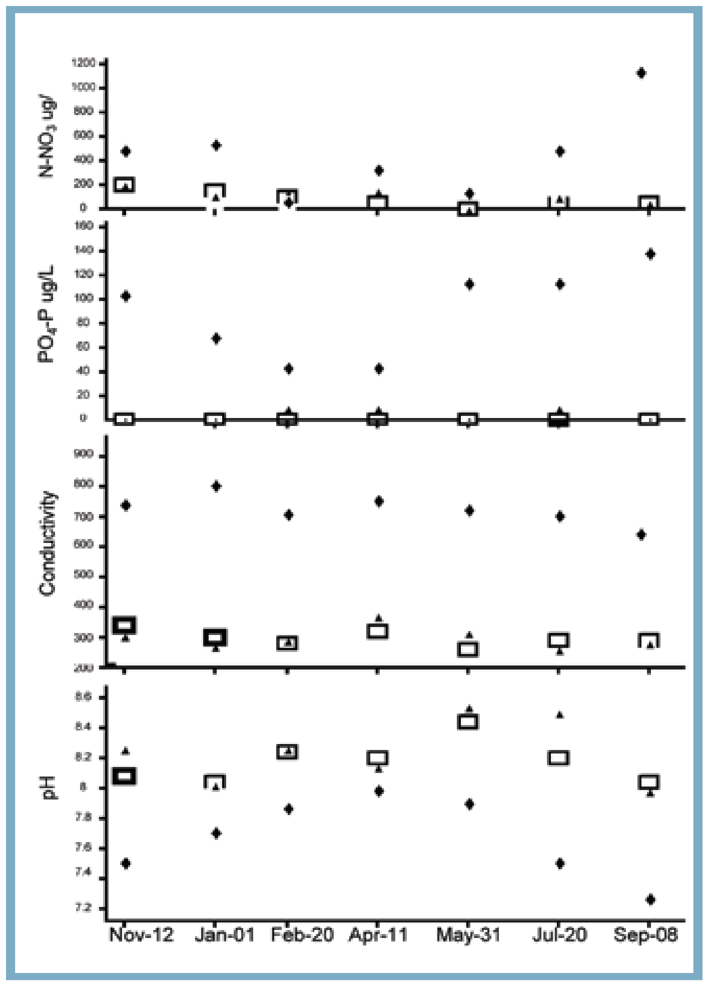

Fig. 3. Four water chemistry characteristics of the three sites. □ - Marsh Front, ▲ - Lake Front, ♦ - Marsh Pond.

was evident. At all sites sampled, water conductivity ranged from the mid 200 to mid 300 µS/cm. Total dissolved solid content (mg/L) of the pond and lakeshore waters (data not shown) were always about half of those for conductivity. Marsh pond water pH ranged from low to high 7 values over the study period, consistently lower than that of the adjacent marsh front and lake front waters, which were in the low to mid 8 levels (Fig. 3 lower). Levels of dissolved reactive phosphorus in marsh pond water were high, always above 10 µg/L and often approaching 100 µg/L or more (Table 1). Frequently it was highest towards the northern portion of the pond, but not always so. In contrast, phosphorus levels at the marsh front and lake front sites were either at 10 µg/L, or often below our standard detection level (<10 µg/L).

Table 1. Values for Nitrogen-Nitrate and Reactive Phosphorus levels at all sites, with average values for each site over the study period calculated.

Date	Marsh Pond		Marsh Front		Lake Front	
	NO_3-N	PO_4-P	NO_3-N	PO_4-P	NO_3-N	PO_4-P
12-Nov-94	450	190	200	10	170	<10
1-Jan-95	55	35	130	<10	150	10
20-Feb-95	114	43	100	<10	160	10
11-Apr-95	77	137	30	<10	50	<10
31-May-95	186	77	30	<10	60	10
20-Jul-95	450	110	25	<10	40	<10
18-Sep-95	396	100	50	<10	50	<10
Average	213	97	90	<10	107	<10

At six of the seven sampling periods, dissolved nitrate-N levels in marsh pond water near the spring water inflow area towards the northern end were much higher than that towards the marsh pond outflow, as well as for the lakeshore waters nearby (data not shown), the one exception being in late February 1995 when the pond was ice covered except for a small area near its northern end. There may have been mixing then with low nutrient melt water, though that was not evident for phosphate.

Epibenthic Invertebrate Diversity and Abundance

In total, 58 invertebrate taxa were collected in the three sites. Taxa richness (Fig. 4) and abundance (Fig. 5) were greatest in the marsh pond (see also Appendix 1). The marsh front and lake front sites had similar taxa richness, but the taxa abundance in the marsh front was almost double that of the lake front. In general all sites showed a decrease in abundance and richness during the months of November, December and February, while showing an increase in numbers during the rest of the year, with a large increase in numbers between February and April. The marsh front and lake front sites showed decreased numbers in July.

Of the taxa collected in the study, the most abundant were the crustacea in the marsh pond, followed by oligochaetes and diptera. Coleoptera were well represented in the pond (six species), but had only half that number of taxa in the two shoreline sites. In the marsh front, the oligochaetes were most abundant, followed by diptera and then crustacea. The lake front was similar to the marsh front, but with lower total numbers.

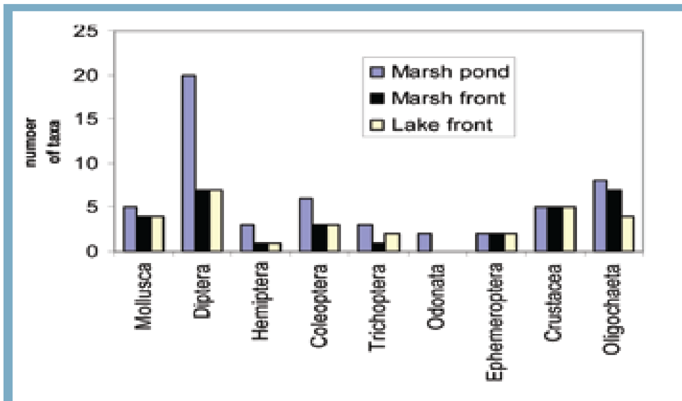

Fig. 4. Taxa Richness for major taxa found at three sampling sites at Lower Summerland marsh.

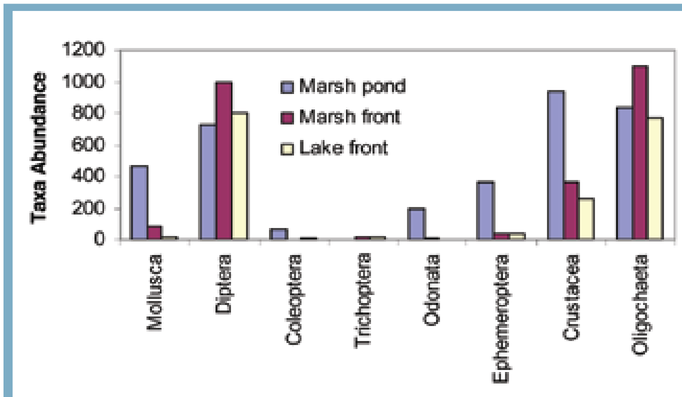

Fig. 5. Taxa abundance for major benthic taxa found at three sampling site of Lower Summerland marsh.

The taxa showing the most diversity in the marsh pond were diptera by more than double those of any other group at any other site. The second most diverse group in the marsh pond were oligochaetes, followed closely by Coleoptera and Crustacea. The other sites showed similar levels of diversity in Diptera, Oligochaeta and Crustacea (5-10 taxa). The marsh pond was the only site with high numbers of Odonata (Fig. 4).

Calculations of diversity using the Simpson's Diversity index and the Shannon-Wiener index (Table 2) showed diversity being greatest in the marsh pond, and at similar levels in the marsh front and lake front. The Jaccard coefficient showed the two most similar sites were the marsh front and lake front sites. Its value comparing marsh front to marsh pond (Table 2) was less than half (0.41).

Table 2. Statistical results for all taxa found at three sampling sites at Lower Summerland marsh.

	Marsh Pond	Marsh Front	Lake Front
Simpson's diversity index	0.93	0.83	0.86
Shannon-Weiner diversity index	4.7	3.353	3.363
Jaccard coefficient of community similarity	R***	0.4074	0.6316
Taxa abundance (Total)	3619	3463	1923
Taxa abundance (Summer)*	1840	959	998
Taxa abundance (Winter)**	637	277	340
Taxa richness (Total)	45	35	35
Taxa richness (Summer)*	36	23	28
Taxa richness (Winter)**	31	21	17

** April, May and July data were used for this calculation*

*** November, December and February data were used of this calculation*

**** R indicates use as reference site*

When taxa were placed in functional feeding groups (Fig. 6), other patterns emerged. All sites had half or more taxa represented in the collector group. The marsh pond had the largest proportion of predators (36%) than any other sites, whereas the marsh front and lake front had similar predator proportions of 15 and 17%, respectively. Scrapers were not represented in the marsh pond, whereas the marsh-front and lake front had 15% and 18% of the taxa as scrapers.

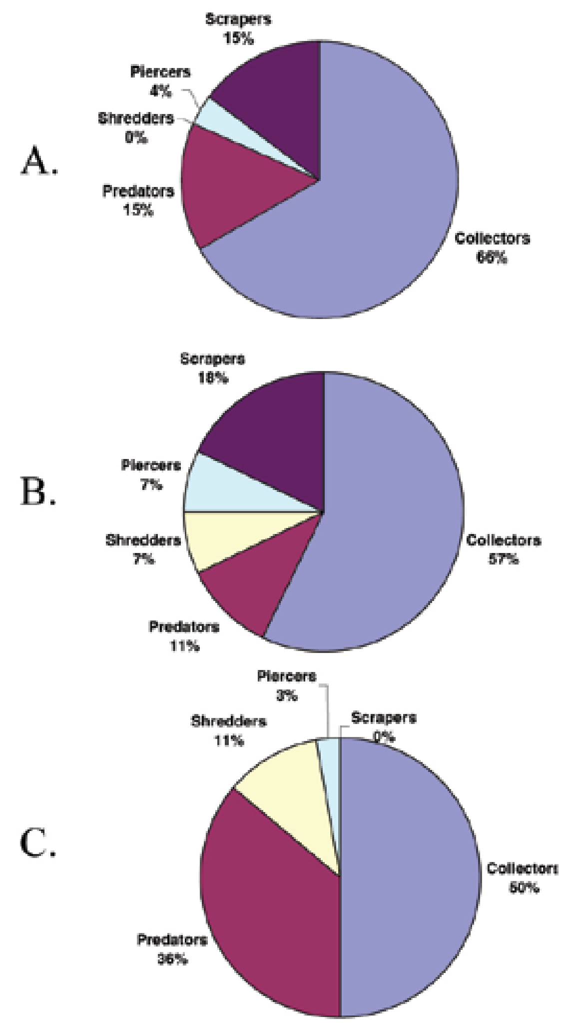

Fig. 6. Functional Feeding Groups. A – Marsh Front, B – Lake Front, C – Marsh Pond.

Discussion

The nitrate and phosphate levels from the spring outflows into the marsh pond site provided a rich supply of nutrients, thereby enhancing periphyton and macrophyte growth. Wetlands enriched by nitrogen or phosphorus from geomorphic or anthropomorphic sources can increase the algal growth and, with it, the numbers of invertebrates (Gabour et al. 1994; Rader and Richardson 1994). More recently, it has been shown that the qualitative and quantitative differences in groundwater regimes will alter benthic algal species richness and biomass (Hagerthey and Kerfoot 2005). Algae as a food supply may become a limiting factor in the food web of a perennial marsh (Hann 1989), although excessive nutrient loading has been shown to have a negative effect due to the high oxygen demand of the algal community (Spiels and Mitsch 2000). At the time of this study the marsh-pond was not known to have experienced any significant disturbances to its inflow regime.

The outflow of the marsh pond feeds directly into the marsh front site, and its nutrients, though diluted, should be slightly higher than general shoreline levels a hundred or more metres away. The littoral zone of the marsh front and lake front appear similar in some aspects to the marsh pond (elevation, aspect, substrate, depth), but very different from the marsh pond in terms of soil type, wave action, temperature, nutrient levels, effects from precipitation, transpiration and breadth of the fish fauna. These differences preclude easy comparisons using indices developed for wetland systems (Wilcox et al. 2002). The diversity of coleopterans is lowered in the shoreline sites either by limitation of food sources or by wave action causing limitation of refugia, by temperature differences and variations, or by a combination of all of these factors.

Since this study started in autumn 1994, there have been many changes taking place that could profoundly affect the marsh pond ecosystem. The most obvious was the building (2003-2006) of a large hotel complex between Shaughnessy Avenue and the western shore of the marsh pond (Fig. 1). The hotel has built an underground parking area, which at one point during construction, caused the flow of groundwater to the pond to be cut off completely. The pond was dewatered for a period of several weeks in midsummer (June 2003) until the water was rerouted back to the pond.

Another major, though less obvious, event is the changeover from septic tanks to sewers in the municipality of Summerland. The infrastructure for sewers was installed in 1994-5, and since that time households have been changing over to the new system. The fish hatchery (located 75 m north of the marsh pond) has measured water quality regularly in their spring water supply, and have noted a drop in total nitrogen of 7.9 mg/L in 1995 to 5.9 mg/L in 2003, and a drop in specific conductance of 651 µS/cm to 453 µS/cm in 2006. The sewage of Summerland is now given secondary treatment, and the effluent flows into a deeper area of Okanagan Lake 3 km south of the marsh-pond. The effects of these lower rates of dissolved nutrients flowing into the pond, as well as to the lake littoral zones in Summerland municipality, also need to be assessed.

Nevertheless, it should be noted that had not our study of the small but biotically rich marsh-pond been actively underway in the mid 1990s, demonstrating its local importance as one of the very few such habitats left along over 40 km of the western Okanagan Lake shore-line north of Penticton, it might well have been filled in, as has happened to similar habitat to its north and south. The municipality of Summerland, its mayors and councils, as well as the developer, deserve commendation for reacting positively to the information presented to them on this vital marsh-pond complex, thereby providing it with strong and sincere protection. With continuing pressures, however, from other developers to push for ever increasing population growth in the region, much of it focused along the lake shore-line, there is a strong need to continue regular monitoring of conditions in and around this very special marsh pond complex.

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Appendix 1

List of invertebrates from the Marsh Pond, Marsh Front, and Lake Front. Numbers are relative abundance.

Class	Order	Family	Genus	Trophic Level	Habitat Group	Marsh Pond	Marsh Front	Lake Front
Hydrozoa	Hydroida	Hydridae	*Hydra*	C, F	Cng	0.38	0.42	0.29
Planaria	Tricladida		*Dugesia tigrina*	Sp	Sp	0.00	0.04	0.29
Gastropoda	Basommatophora	Physidae	*Physa*	Sp	Cb	6.33	0.17	0.08
		Lymnaeidae	*Stagnicola*	Sp	Cb	7.04	0.46	0.17
		Lymnaeidae	*Lymnaea stagnalis*	Sp	Cb	0.29	0.00	0.00
		Planorbidae	*UID*	Sp	Cb	5.25	1.71	0.33
Pelecypoda		Sphyaeriidae	*Pisidium*	C, F	Sp	0.42	1.04	0.25
Arachnida	Hydrachnidia	UID	*UID*	P	Cb	0.00	0.30	0.30
Clitellata	Oligochaeta	Tubificidae	*UID*	C,G	B	4.42	0.00	0.00
		Naididae	*UID*	C, G	B	8.04	13.38	21.25
		Naididae	*Stylaria*	C, G	B	0.04	3.58	8.21
		Lumbriculidae	*Lumbriculus/Stylodrilus*	C, G	B	16.83	23.79	0.17
Hirudinea	Rhynchobdellida	Glossophoniidae	*Placobdella*	C, G	B	0.92	0.17	0.25
Crustacea	Ostracoda		*UID*	C, F	P	2.75	8.79	2.29
	Cladocera	Daphniidae	*Ceriodaphnia reticulata*	C, F	P	10.54	1.50	1.50
		Chydoridae	*UID*	C, F	P	5.21	2.75	3.63
	Copepoda		*Orthocyclops*	C, F	P	6.67	0.25	0.17
	Amphipoda		*Hyalella azteca*	Sp	Ss	13.92	2.00	3.25
Insecta	Ephemeroptera	Baetidae	*Callibaetis americanus*	C, G	Ss,Cbs,Cng	14.92	1.17	1.17
			Procleon	C, G	Sw, clin	0.29	0.00	0.00
		Tricorythidae	*Tricorythoides minutus*	C, G	Sp,Cng	0.00	0.50	0.33
	Odonota	Coenagrionidae	*Ishnura*	P	Cb	8.17	0.33	0.00
		Aeshnidae	*Aeshna*	P	Cb	0.17	0.00	0.00
	Trichoptera	Hydroptilidae	*Agraylea*	Pr	Cb	0.00	0.92	0.50
			Hydroptila	Pr	Cng	0.00	0.00	0.46
		Rhyacophilidae	*Rhyacophila*	P	Cng	0.00	0.04	0.00
	Coleoptera	Haliplidae	*Haliplus(larvae)*	Sd, H	Cb	0.54	0.00	0.00
			Haliplus(adult)	Sd, H	S,Cb	0.17	0.00	0.00
			Brychius(larvae)	Sp	Cng	0.00	0.00	0.04
		Dydiscidae	*Agabus*	P	Ss,D	0.58	0.00	0.00
			Ilybius	P	Ss,D	0.08	0.00	0.00
			Oreodytes	P	Ss, Cbs	0.75	0.00	0.00
			Hydaticus	P	Ss,D,Cbs	0.13	0.00	0.00
		Hydrophilidae	*Laccobius*	P	Cbs	0.33	0.00	0.00
		Elmidae	*Dubiraphia*	C, G	Cng,Cbs	0.00	0.08	0.08
		Gyrinidae	*Gyrinus*	P	Cbs,Ss	0.00	0.00	0.04
	Megaloptera	Corydalidae	*Corydalus*	P	Cng,Cbs	0.04	0.00	0.00
	Hemiptera	Corixidae	*Corisella*	Sp	Ss	0.83	0.00	0.00
		Notonectidae	*UID*	P	Ss	0.04	0.00	0.00
	Diptera	Chironomidae	*Chironomus*	C, G	B	16.54	10.58	0.00
			Krenopelopia	P	Sp	4.08	0.08	0.00
			Crictopus trifascia	Sd, H	Cng,B	1.63	0.00	13.92
			Psectrocladius	C, G	Sp, B	5.63	3.75	8.17
			Orthocladius	C, G	Sp, B	0.00	48.92	0.00
			Paratanytarsus	C, G	Sp	0.00	1.67	9.75
			Kiefferulus	C, G	B	0.00	7.50	0.00
			Dicrotenpides	C, G	B	0.00	2.96	0.00
			Ablabesmyia	P	Sp	0.00	0.00	0.79
			Procladius	P	Sp	0.00	0.00	0.67
		Ceratopogonidae	*Bezzia*	P	B	1.13	0.00	0.00
			Culicoides	P	B	0.25	0.00	0.00
		Chaeoboridae	*Chaoborus*	P	Sp,P	0.25	0.00	0.00
		Culicidae	*Culex*	C, F	P	0.21	0.00	0.00
		Tipulidae	*UID*	Sds, CPOM	B	0.08	0.04	0.00
			Antocha	C, G	B	0.08	0.00	0.00
			Prinocera	Sd,CPOM	B	0.04	0.00	0.00
		Stratiomyidae	*UID*	C, G	Sp	0.04	0.00	0.00
		Empididae	*Hemerodromia*	P	Sp,B	0.04	0.00	0.00

Trophic levels are C-Collector, F-Filtering, Sp-Scraper, P-Predator, G-Gatherer, Sd-Shredder, H-Herbivore, CPOM – course particulate organic matter.
Habitat categories are Cng-Clingers, Sp-Sprawlers, Ss-Swimmers, B-Burrowers, C-Climbers, D-Divers, P-Planktonic.

The Cumulative Effects of Climate Warming and Human Demands on the Freshwaters of Canada's Western Prairies

D. W. Schindler
Dept. of Biological Sciences
University of Alberta
Edmonton AB
T6G 2E9

Introduction

Several years ago I predicted that climate warming would have great effects on Canadian freshwater, both as the result of the direct effects of warmer temperatures and increased evaporation, but also by its influence on bio-geochemical cycles and other human-caused problems such as eutrophication and declining fisheries (Schindler 2001).

Since that time, a number of studies during a period of increased warming have shed more light on the subject. It is now clear that "ground zero" for Canadian water will be in the western prairies, where a combination of factors will place additional demands on already scarce water supplies, including rapidly increasing air temperatures, expanding populations of humans and livestock, and irrigated agriculture.

The 21st century is also likely to be drier than the 20th (Schindler and Donahue 2006). In the remainder of this paper, I give details on several factors that contribute to the looming problem with freshwater shortage on the prairies.

Historic Drought: A Wild Card in Prediction of Water Scarcity

Studies using tree rings (Sauchyn and Skinner 2001) and salinity sensitive diatoms (Laird et al. 2003) have shown that the 20th century was the wettest in the past several hundred years in the western prairies. In earlier centuries, droughts lasting a decade or longer were common. The same proxy indicators show that even the "Dirty 30s," which most regard as a tragic drought, were rather puny by long-term prairie standards. The arrival of European settlers corresponded with an unusually wet period. We only have instrumental measurements of climate, water levels and river flows for the 20th century, which makes us believe that this period was "normal," whereas the above studies indicate that it was much wetter than average. It seems unlikely that the western prairies will escape a major drought for a second century in a row.

The Problem of Scale

Journalists and politicians constantly reassure us that Canada has a lot of water. The abundance of our water is often compared to that of other countries. The implication is that if we have water shortages somewhere, we will simply move the water to that region. Some also talk of selling water to the USA. But in size, Canada is more comparable to all of Europe or Australia than to a European country, or for that matter to most countries of the world. At least six of the Canadian provinces are larger than the largest European countries. The distribution of water in Canada is also as variable as it is in Europe, with the Maritimes being equivalent to the Scandinavian countries, but Alberta more comparable to Spain in available water. Much of western prairies and northern Canada has runoff of less than 100 mm per year. Larger rivers of these regions originate in the mountains, where they derive most of their water. Diversion of water from areas of abundance to areas of demand would require moving it great distances, involving very costly infrastructure, as well as enormous ecological damage. Both economically and ecologically, it makes more sense to move people and industry to the water than vice-versa.

While the many glacial basins in northern and eastern Canada do indeed contain a large quantity of water, the water is renewed only very slowly. Typically, large lakes have water renewal times on the order of 100 years or more. Runoff per unit land area in Canada, as represented by river flow, is the true measure of water that can be used sustainably. In sustainable water supply, we rank only 6th among the world's countries, with about half the supply of Brazil and $^{2}/_{3}$ that of the Soviet Union (Sprague 2006). In average sustainable water supply, we are equal to the USA or China, two countries that are generally regarded as short of water, as a result of high populations, industrial use, and widespread water mismanagement. It is clear that we should not squander our freshwater supplies by exporting them to other countries, especially those that have already sacrificed or befouled their own supplies. We will need the water here, for both ecosystem health and human demand.

The Effects of Climate Warming on Prairie Hydrology

Most parts of the western prairies have already warmed by 2-3 C°, mostly since 1970. Depending on society's will to cut greenhouse gases, the prairies may be 4-6 C° warmer than they are now by 2100 (Schindler and Donahue 2006). This is well outside the range of climate that occurred in the prairies during the mid-Holocene, a time when there was little surface water on the prairies (Schindler 2001).

Climate warming affects several aspects of available water on the prairies. While most Global Climate Models suggest that slight increases in precipitation will occur, the increased temperature is likely to cause increased evaporation and potential evapotranspiration to more than offset the additional precipitation (Schindler and Donahue 2006).

In addition, a higher proportion of winter precipitation is likely to fall as rain as climate warms. This seeps away slowly, rather than accumulating on the ground like snow, which may be regarded as a free "reservoir" that is available just when we want the water for planting crops. Snowpacks are expected to dwindle in the future as climate continues to warm (Lapp et al. 2005).

While glaciers generally provide only a small part of annual flow to the major prairie rivers, they can be an important part of late summer flow, particularly in dry summers. For example, the Bow River can contain 50% glacial melt at Banff in a hot, dry July-August (Young 1996; Hopkinson and Young 1998). This cold water can also be important for the maintenance of cold water fisheries, such as those of the Bow River. Unfortunately, glaciers are dwindling rapidly as climate warms. Large glaciers have lost about 25% of the mass that they had in the early 20th century (Watson and Luckman 2004). Small glaciers have lost as much as 50% of their mass since then.

While prairie groundwater aquifers are less studied, many are also recharged by precipitation in the mountains and foothills. It is critical that we begin a more comprehensive study of groundwater systems of the prairies.

Removing Our Catchments' "Armor"

Most people don't realize that wetlands and riparian zones provide vital protection for prairie waters from a wide variety of hydrological irregularities. Wetlands act much like the capacitors in an electrical circuit, retaining water during storms and snowmelt, and releasing it slowly to rivers, lakes and aquifers over a period of months to years. As a result of this regulation, they help prevent both droughts and floods. Ironically, it is possible to have both lower average river flows and more floods as the combined result of climate warming and human modifications to catchments.

Wetlands also retain water so that silt, nutrients and pathogens remain behind, and are less likely to reach our main water courses. Unfortunately, in much of the southern prairies, 70% of the wetlands have been drained or filled by people who were unaware of these values (Ducks Unlimited at http://www.ducks.ca/aboutduc/news/archives/2000/000201.html).

Riparian zones are also compromised by removing native vegetation, alien invasive species, plowing, fertilizing, applying herbicides and pesticides, or pasturing animals right to a river's edge. As a result, major precipitation events carry pathogens, silt and chemicals directly into the rivers.

Dams and Reservoirs

Engineers usually prescribe dams and reservoirs as an antidote to water shortages. While these are wonderful for people who can benefit from the stored water, they are of no benefit to those downstream. There are well-known and numerous types of environmental impacts of dam building. The river channel below a dam usually shrinks, forming a new channel within the old as a result of lost hydraulic energy (Newbury 2003). Above and below the dam, bank erosion, siltation of spawning areas, formation of new beaches and high turbidity are common (Valdez et al. 2001). Flooding reservoirs produces a significant quantity of greenhouse gases from rotting flooded vegetation (St Louis et al. 2000) and causes fishes to accumulate large amounts of methyl mercury (Bodaly et al. 1984), or to dwindle in abundance (Valdez et al. 2001). Aboriginal or rural people are displaced (Rosenberg et al. 1997). In overall damage to the environment, hydroelectric power is probably the least desirable power source. It is certainly not the "good clean power" promoted by hydroelectric companies or uninformed politicians. In the words of Daniel P. Beard, retired Commissioner of the U.S. Bureau of Reclamation, reflecting on the 20th Century dam building in the U.S.A. in the September, 1996 issue of World Rivers Review: "... the most important lesson we have learned from our water-development experience: we reaped great benefits, but very great costs. For some the jury is still out on whether the benefits outweigh the costs. But for many, the answer is simple "we have paid too dearly for 'cheap' power and water." Later, he characterizes dam promoters as "Like high pressure salesmen, dam boosters paint an ideal world: Cheap power, cheap water, increased agricultural production, economic development and an end to hunger! The reality is somewhat less rosy."

Unfortunately, as water supplies dwindle, so will hydroelectric power generation. Engineers and hydroelectric company officials are already calling for damming more rivers to compensate.

Human Withdrawals

In the prairie provinces, irrigation of crops is the main use of freshwater. In Alberta, irrigation permits are about 70% of licensed water withdrawals, mostly from the Bow, Oldman and South Saskatchewan rivers. Little of the irrigation water is returned to the river, and the water that is returned is often polluted with nutrients, pesticides and pathogens.

Withdrawal for municipal use is also growing. For example, Calgary has one million people and is still growing rapidly. Considerable effort is being put to improving water conservation. Pipes, which leaked about 30% of treated water, have been repaired to where leakage is now about 12 percent. The cost was $500,000,000 (Paul Fesko, City of Calgary, pers. comm.). Typically, about 70% of water treated for municipal use is returned to a river after sewage treatment. Thirty percent leakage is probably about average for most western cities. Calgary has also started requiring water meters in new housing. These efforts will certainly extend their water supplies, but they will not be enough if the city continues to grow at its present rate.

Typical European households use about half the water of North American ones, with no apparent compromises in sanitation. We must strive to reduce municipal water consumption throughout Canada, but especially in the western prairies.

Seasonal Effects on River Flows

Typically, hydrologists have examined trends in annual flows or so-called natural flows, where water withdrawn for various purposes is added to river flows (Gan 2000; Peterson et al. 2002; Rood et al. 2005). But these numbers do not tell the whole story of impacts on the rivers. The biota of many prairie rivers is most vulnerable during late summer, when temperatures are warmest, the solubility of oxygen is lowest, and decomposition is at its highest. Fish kills have been recorded from the southern prairies both as the result of high temperatures and diurnal oxygen sags. During this period, evaporation is greatest, snowmelt is gone, and human demands for irrigation and municipal use are highest. Summer is also when most reservoirs in Canada are filling, because the water is most needed in winter.

As a result, less water is released to downstream reaches. As mentioned earlier, the removal of wetlands has also stripped away features of the catchments that once spread flows more evenly through the summer. As a result of the combined effects of all of these factors, summer (May-August) flows in prairie rivers have declined from 30 to 85% during the 20th century (Schindler and Donahue 2006).

Effects of Climate Warming on Water Quality

Unfortunately, for most waters the solution to pollution is still dilution. Less water flow in our rivers translates into higher pollutant loads. In lakes, it translates into slower water renewal, which is known to increase nutrient concentrations and thus eutrophication. In general, a halving of the rate of outflow from a lake is equivalent to at least doubling the nutrient load (Schindler et al. 1978). In lakes where hypolimnetic anoxia and a shortage of iron allow nutrients to return from sediments, the effect of increased nutrient inputs can be much greater, requiring more complicated models (Vollenweider 1976).

There are other effects on water quality, complicating the interactions between land and water. For example, Schindler et al. (1996) showed that lower stream flows reduced the amount of phosphorus and silica transferred from catchments to lakes. Many lakes, especially those receiving excessive amounts of phosphorus and nitrogen, already use up their reserves of silica early in the ice free season. If the N:P ratio is low, the result of declining silica is an earlier switch to nitrogen-fixing Cyanobacteria, which often accumulate as blue-green surface scums (Schelske 1999).

Perhaps the most obvious effect of reducing flows is that salts must build up, causing increases in salinity and conductivity. This is the very phenomenon that causes the shifts in diatoms that have been exploited by paleoecologists in deducing the frequency of past droughts (Laird et al. 2003). At present, many of the lakes of the western prairies show long-term decreases in level and increases in salinity. Some are becoming closed basins. For example, Lake Wabamun, a popular recreational lake west of Edmonton, which is also the site of power plants that produce some of the highest emissions of CO_2 and mercury in Canada, has not had outflow since 1992. Total Dissolved Solids have increased about 21%, in part as the result of evaporation but also because of salts used in a water treatment plant on the lake (Schindler et al. 2004). If closed basin conditions persist, calcium carbonate eventually precipitates, and lakes begin to be dominated by other dissolved salts (Rawson and Moore 1944; Hammer 1984). In the later stages of evaporation, lake biodiversity decreases greatly.

In addition to the effects of reduced flow on eutrophication and salinity, climate change will increase the mercury burden in many montane and boreal lakes. Methyl mercury accumulation in fish is currently a widespread problem for humans and piscivorous wildlife in the world (Wiener et al. 2003). Mercury deposition has increased over broad regions of the earth as a result of human emissions to the atmosphere (Fitzgerald and Lamborg 2003). Most of this mercury is sequestered in soils and wetlands, and only that falling directly on lake surfaces is moved rapidly into food chains (J. W.M. Rudd, pers. comm.). However, climate warming is predicted to increase forest fires, as a result of more extreme fire weather (Westerling et al. 2006). Insect outbreaks such as mountain pine beetle (Potter et al. 2005), also contribute by increasing fuel loading. Burned catchments release nutrients to streams and lakes for several years after fire (Bayley et al. 1992). We have observed substantial increases in both mercury and nutrients in lakes and streams where catchments were burned. Most of the increase of mercury in fishes was caused by changes in trophic structure of the lake's food web from increased productivity (Kelly et al. 2006). There will probably be more nasty chemical surprises that result from climate warming, once we study its impact on other bio-geochemical cycles and food chains.

What Must Be Done?

Given the slow pace at which governments are acting to reduce emissions of greenhouse gases, it is almost inevitable that the prairies will suffer serious shortages of fresh water. It is essential that strong actions be taken now to minimize damage to prairie water supplies.

Firstly, we must move rapidly to protect our remaining wetlands and riparian areas. Restoration of damaged wetlands and riparian areas is also a priority. In the current financial climate, we cannot expect farmers to undertake these activities without financial assistance.

Municipalities must regulate water supplies to minimize water consumption. Metering water supplies, repairing of leaky distribution systems, mandating low flow shower heads and low volume toilets, limiting use of water for lawns and gardens, and other standard methods will help. Most municipalities should probably have pricing structures that are the reverse of what they are now, where enough water for drinking and sanitation costs very little, but the price of water increases rapidly with increasing use. This would encourage people to return to an age old practice of catching rainwater runoff from their roofs for gardening and watering lawns. This inexpensive practice has a second benefit: reducing the amount of storm runoff after large rainfalls, which often otherwise overwhelms sewage treatment plants.

In the driest parts of the prairies, industries should be selected that use little water. It makes little sense to undertake costly and ecologically damaging water diversion schemes, just so that every municipality can "develop" without regard for water supplies.

Public education is an important part of the process. The value of protecting wetlands, riparian areas and other natural features of catchments is important. Many still regard groundwater aquifers as totally separate systems, envisioning huge underground rivers bringing them endless supplies of water. The intimate connections between ground and surface waters that are so obvious to water professionals are unknown to most farmers or village planners. Often, the connections are only realized when wells begin to run dry, or when Walkerton-like contamination of groundwater supplies results. Disruption of aquifers by mining gravel or coal, or drilling for oil and gas are very common.

Agriculture, too, must adapt. Unfortunately, the reaction of big agribusiness to drought is to call for more dams and reservoirs, at the expense of all taxpayers. The resulting ecological damage has been mentioned above. It would make more sense to grow crops that require less water. Large livestock operations need particularly careful scrutiny. The most water-efficient ones often use less than 20% of the water that the average ones do. Some have substituted composting schemes for lagoons, even generating heat or electrical power in the process. But large livestock operations are also an increasing source of nutrients and pathogens to many prairie waters (Anderson et al. 1998; Chambers et al. 2001).

Irrigation must increase in efficiency. The day when it was sustainable to irrigate hay to feed to cattle is over. In order to use water efficiently as well as to minimize fossil fuel use, we will most certainly find the farmers of the future using large irrigated greenhouses, perhaps heated and powered by geothermal sources, wind or compost, raising vegetables and fruits for local consumption, especially considering the rate of growth in cities like Calgary and Edmonton. It makes little sense to keep importing these commodities from the southern USA, where water shortages and contamination with pathogens, pesticides, and other chemicals is already causing irreversible ecological damage. Fossil fuel needs to move the produce north would also be eliminated.

Using valuable freshwaters to carry away the wastes of people and their livestock made sense in the 19th and early 20th century, when we lived lightly on the land, water was plentiful, and waterborne disease was a major problem in population centers. With the increased populations and other demands of the 20th and 21st centuries, it is probably time that we reconsidered this traditional practice. Populations of humans and livestock have increased manyfold in the past century. In the words of J.R. Vallentyne, we live in "pathological togetherness," where water discharged as sewage often does not reside for long in a river or lake, before entering the next water intake. At present, huge water treatment plants rely on sheer technical muscle to treat all of their intake water to a standard where we can drink it. While they are able to make the water pathogen free, treatment plants cannot efficiently remove the host of antibiotics, hormones and pharmaceuticals that are released with modern human sewage and livestock effluent. Typically, almost all of our expensively treated water is used for flushing toilets or watering lawns, clearly one of the more frivolous of modern human practices. It is time to reconsider how we use water, and how we treat it for different uses. Perhaps only a few liters per day should be treated to a standard suitable for drinking and sanitation, so that the other several hundred liters per day that each North American typically uses could be treated to a lower standard.

Even with the best of improvement in human practices, it is clear that water scarcity will eventually limit human populations and human endeavors in the western prairies. There are important social decisions to be made about emissions of greenhouse gases, the integrity of catchments, population and industrial growth, and water conservation, which will have important bearing on the scarcity of water that we are willing to tolerate. We should remember that many of the most water-impoverished areas of the Middle East today were once vast networks of wetlands and rivers, including the fabled Garden of Eden in the Tigris-Euphrates river basin.

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Development of Effective Drinking Water Treatment Processes for Small Communities with Extremely Poor Quality Water on the Canadian Prairie

Hans Peterson
Safe Drinking Water Foundation, 912 Idylwyld Drive, Saskatoon, SK S7L OZ6, Canada, Email: hans.peterson@yahoo.com
Robert Pratt
George Gordon First Nation, Box 443, Punnichy, SK SOA 3CO, Canada, Email: gordonwaterkeeper@yahoo.com
Roberta Neapetung
Yellow Quill First Nation, Box 37, Yellow Quill, SK SOA 3AO, Canada, Email: yellowquill@xplornet.com
Anthony Steinhauer
Saddle Lake Cree Nation, Box 97, Saddle Lake, AB TOA 3TO, Canada, Email: projheal@hotmail.com

Abstract

Microbially and chemically poor quality surface and ground water sources are frequently used for the production of drinking water by rural communities across Canada and indeed internationally. Canadian cities, in contrast, generally obtain drinking water from high quality source waters yet provide far more extensive treatment than rural water treatment plants when the opposite needs to be true. This realization has prompted the development of drinking water treatment processes based on biological removal of compounds that can either be energy or nutrient sources for bacteria, which are followed by reverse osmosis treatment of the water. This process is allowing small water treatment plants to cost-effectively produce superior quality drinking water from marginal water sources that previously could not be used for drinking water.

Introduction

The Canadian prairie is semi-arid, and while cities are located near large rivers, most rural communities rely on local surface and groundwater supplies. Some communities, for example, Saddle Lake Cree Nation, have been developed around natural lakes, while others have excavated holes in the ground (dugouts) to trap mainly water from the snowmelt in the spring. There are more than 100,000 dugouts on the Canadian prairie. The drainage basins for these dugouts and hypereutrophic lakes are generally >80% agricultural, with high levels of nutrients and other agricultural compounds ending up in the water. With evaporation losses of around one metre every summer, compounds in the water, such as dissolved organics, concentrate making it a challenge to treat in the water plant. Associated with these shallow reservoirs are heavy algal and weed growth further degrading the quality of the stored water. Is then ground water any better?

Unfortunately, a large part of the Canadian prairie in pre-historic times was an inland sea, and when the sea retracted it left vast deposits of salt behind resulting in brackish well water. One province, Saskatchewan, has indeed increased its Drinking Water Quality Guideline Value for Total Dissolved Solids (TDS) to 1,500 mg TDS/L in contrast to everywhere else in the world where this number is 500 mg/L. While TDS is an aesthetic objective, accompanying these high levels of TDS are frequently high levels of organics, iron, manganese, ammonium, and arsenic, also presenting water treatment challenges. It is especially troubling that the guideline level for arsenic has gone from 50 micrograms/L to 25 and now to 10 when it actually needs to be below 5 (Kapaj et al. 2006).

Here we show examples of rural surface and ground water, as well as their treatment. We then describe a project that has successfully tackled the poor quality by developing an integrated biological and Reverse Osmosis (RO) treatment system that produces exceptionally high quality drinking water. The continued development of this process in several aboriginal communities has resulted in improved treatment efficiencies, while at the same time, costs have decreased to make the process less expensive (while producing better quality water) than conventional + RO treatment.

There are hundreds of rural communities facing huge challenges to make their drinking water safe. We use Yellow Quill First Nation as an example of one such community, located about 300 km northeast of Saskatoon. Yellow Quill has had one of the longest boil-water-advisories in Canada, put in place in 1995, and it could not be lifted with the existing surface water source and water treatment equipment.

Yellow Quill and Other Water Treatments

The quality of Yellow Quill's raw water source is compared with Saskatoon's and also bottles of the waters themselves (Fig. 1).

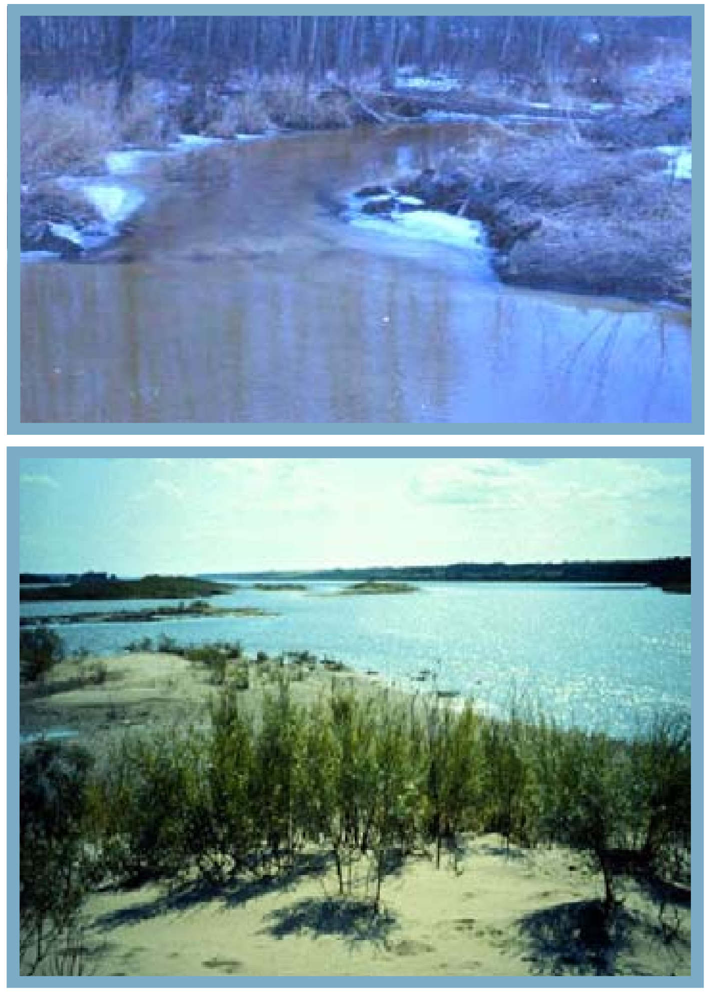

Fig. 1. *Yellow Quill raw water source (upper horizontal) contaminated by wastewater lagoon discharge; Saskatoon raw water source. South Saskatchewan River (lower horizontal) originating from the Rocky Mountains.*

The small Yellow Quill Water Treatment Plant housed one direct filtration unit (addition of coagulant, upflow clarifier, and a downflow rapid sand filter), which was incapable of producing water safe for human consumption. High levels of organics produced unacceptably high levels of trihalomethanes (THMs), and the package treatment plant was also incapable

Yellow Quill raw water (left bottle) and Saskatoon raw water (right bottle).

Saskatoon City water

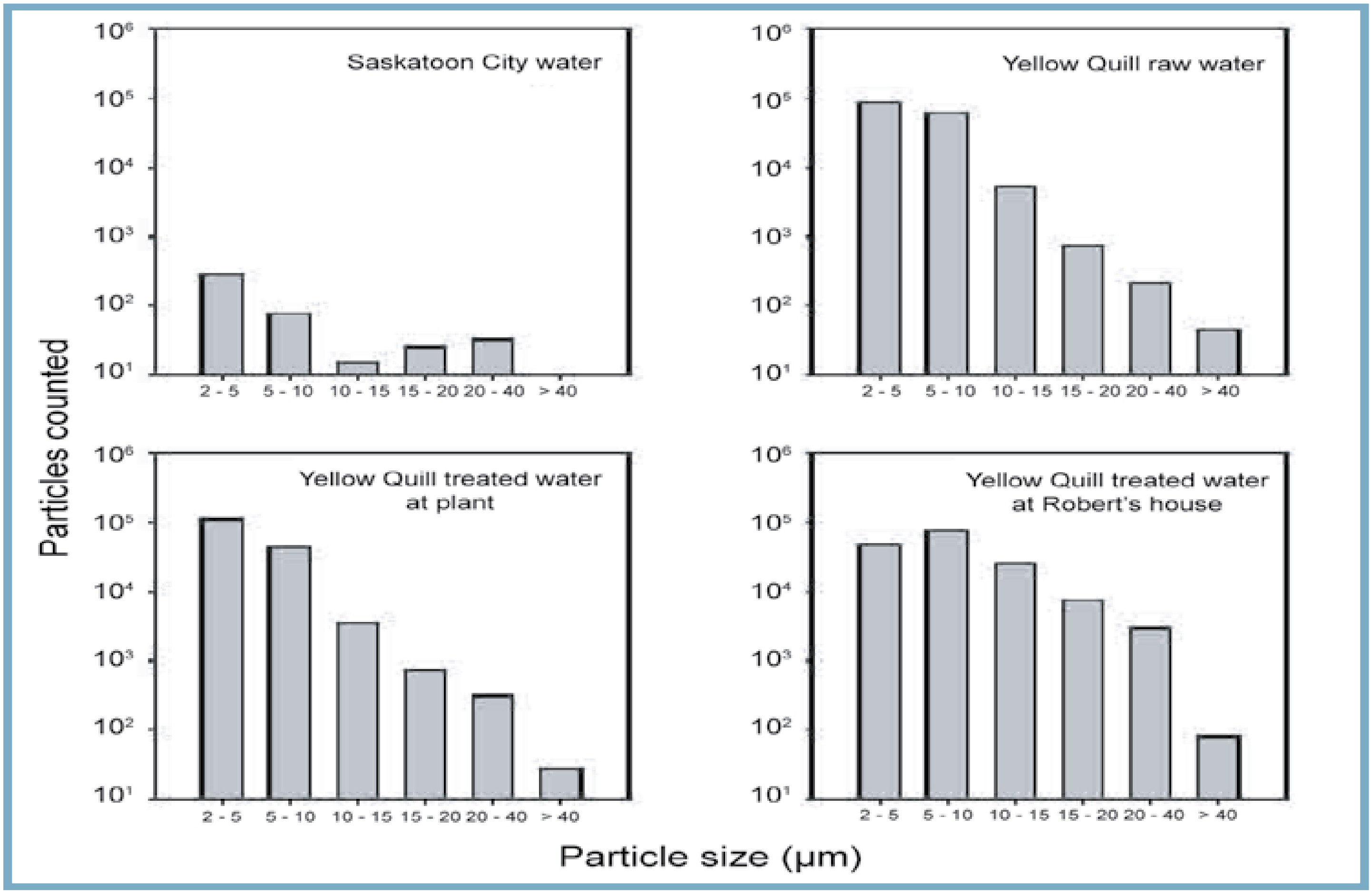

***Fig. 2**. Particle size distributions for Saskatoon city water and that of Yellow Quill First Nation.*

of removing the heavy particle load it experienced most of the time.

Water quality in terms of particle size and abundance of treated water at Yellow Quill is compared with that for the city of Saskatoon (Fig. 2). While Saskatoon's distributed water has a total particle count of less than 50 particles/mL, Yellow Quill treated water values both at the treatment plant and in the distribution system were in excess of 20,000 particles/mL. Particle count is not regularly used to determine acceptability of drinking water in aboriginal communities, but where it is used by larger cities, the requirement is to produce particle levels <50 or <100 per mL.

The problem for Yellow Quill and many other rural communities is the exceedingly poor water quality sources that they have to treat. This is combined with fewer resources to treat the water in terms of treatment equipment, people, and financial support. Simple water treatment processes are frequently used, such as at Yellow Quill, treating water within minutes, while cities using far superior quality raw water have many more processes that are continually optimized. While Yellow Quill was supposed to treat its water within five minutes, Saskatoon takes up to two hours, and Calgary (treating even better water than Saskatoon) takes up to six hours to complete its treatment. Only by using small subsets of the Canadian Drinking Water Quality Guidelines can regulatory authorities claim that the treated water is "safe." Perception, unfortunately, is not reality. There is a great need to address the use of inferior quality water sources for human consumption as many communities simply don't have the luxury to pick and choose their water source. Limnologists trained in water quality areas are needed to better help manage and protect water sources that are going to be used for drinking water.

A search for better quality source waters around Yellow Quill was not successful, as the only source that could be used was nearly a hundred kilometres from the community. Improving the treatment of the surface water supply was considered, but the small creek from which Yellow Quill pumped its water to a constructed reservoir was highly unreliable, with years of no flow. Discharge of an upstream sewage lagoon into the small creek was also of great concern. Calls for the upstream community to discontinue discharging its effluents into the watershed of the creek (the wastewater could have been used for irrigation) were unsuccessful, leaving Yellow Quill's Water Project Team to look at other alternatives.

When the original surface water treatment plant was constructed, ground water had been discounted because of its poor quality. However, in contrast to the surface water, it was available in ample quantity. Yellow Quill's ground water is similar to many other such sources on the Canadian prairie, being naturally contaminated with arsenic, high levels of sulphate, ammonium or nitrate, calcium, magnesium, as well as organic matter (Peterson et al. 2006; Peterson and Sketchell 2003). These typically brackish water sources (TDS levels >1000 mg/L) are supplying both potable (with Saskatchewan's altered guideline for TDS) and non-potable water requirements for many rural communities.

Unfortunately, rural communities frequently use treatment methods that simply cannot render these poor quality water sources safe for human consumption from either a chemical or microbial standpoint. Indeed, it is possible that >90% of native drinking water treatment plants may not be able to produce drinking water that meets the current Canadian Drinking Water Quality Guidelines. The federal government and engineering companies providing water treatment equipment and drinking water treatment advice need to implement more effective water treatment processes and testing must be carried out to ensure that safe drinking water is actually produced. The treatment methods applied to these exceedingly poor quality water sources have even failed on better quality water sources in large communities, where also the technical and financial constraints were not as limited as in most rural communities (Mouchet 1992).

The federal government agency responsible for aboriginal people in Canada, Department of Indian and Northern Affairs Canada (INAC), is relying on engineering companies to design and construct water treatment systems. However, the dilemma for Canada's aboriginal communities is that INAC is not requiring that the treated water meets all of the Canadian Drinking Water Quality Guidelines. Instead INAC relies on Health Canada's bare bones assessments of drinking water safety (10% of the total guidelines) total and free chlorine, *Escherichia coli*, coliforms and nitrate. To meet four of these five parameters, water treatment plants are not necessary, only chlorine is. While Health Canada every two years or so make more extensive analyses, these are generally not used by INAC to assess treatment plant efficiencies and, indeed, this information is not always communicated to INAC.

Currently, it therefore is feasible for engineering companies to design inadequate treatment systems and INAC simply has no ability to make the appropriate drinking water safety assessments. If this does not change soon, there is an urgent need to establish a different mechanism to ensure the full implementation of the Canadian Drinking Water Quality Guidelines in every aboriginal community in Canada. One also needs to remember that current European and U.S. regulations are considerably more stringent than the Canadian Drinking Water Quality Guidelines and as more is learned about chemical and microbial contaminants, drinking water guidelines around the world are becoming more stringent.

There are INAC people, however, that have realized the extent of the problems and are trying to put things right. The Saskatchewan regional office of INAC has pioneered advances in drinking water treatment processes for several years, with some failing and others succeeding. INAC officers realized that both chemical and microbial issues need to be addressed before the drinking water supply can be considered safe, and started in 2001 to apply RO membrane treatment to render brackish ground water suitable for human consumption. This also included a few misguided attempts to just get the chemistry right, forgetting about microbial threats and constructing water treatment plants where RO water is "blended" with pre-treated water. This practice is enabling the construction of inferior treatment plants as the fall-back of simply adding more "blend water" can disguise RO treatment problems and provides no microbial protection. While frequently ignored by the federal government, viral and bacterial issues pertaining to ground water must be addressed in the future (Peterson 2001).

George Gordon First Nation, with arsenic levels above 70 micrograms/L in its raw water, was not able to decrease those concentrations to safe levels with the manganese greensand filtration process it was using. In 2001, RO membranes were installed. However, both chemical and microbial fouling became apparent, and despite frequent cleanings, the membranes became permanently fouled after just over one year. The next set was fouled within eight months. Microbial and chemical analysis of the fouled membrane showed that extensive biofouling was accompanied by the accumulation of a string of different compounds covering the white membrane with a brown layer of fouling material (Fig. 3). Microorganisms, including manganese oxidizing bacteria, were present in the biofilms that covered the membranes.

Fig. 3. *A cut open reverse osmosis membrane fouled by manganese oxidizing bacteria leaving a brown coating on top of a bright white membrane sheet. From the George Gordon First Nation water treatment system.*

One alternative to solving the above problems with treating challenging water supplies is to obtain better quality water through supply pipelines, but the scarcity of good quality water and long transport distances can make this very expensive. For example, bringing better quality water to Yellow Quill required the construction of 100 km of pipelines, with its associated $8 million in construction and material costs. The realization that many communities were struggling to produce good quality drinking water sparked the development of water treatment processes that could effectively deal with existing water sources.

The Yellow Quill Pilot Study

A 20 month pilot study was initiated at Yellow Quill First Nation. Conventional water treatment technologies, such as manganese greensand, were tested along with advanced technologies, such as ozone and biological filtration. A test water supply of 200 L/min was supplied directly from the well into the pilot study trailer (Fig. 4). Inside this trailer, raw water was distributed to several different treatment processes. Different combinations of treatment were tested using both pressurized and gravity filtration systems. Conventional water treatment processes, including manganese greensand, failed to remove both iron and manganese. While ozone removed some contaminants, the filtration run lengths were short and the floc difficult to contain. Better success was obtained

Fig. 4. *The pilot water quality trailer (outside top and inside bottom) used by Yellow Quill First Nation to test raw water treatment processes.*

with the biological filtration trials, and the work started centering on using different types of material including granular activated carbon and expanded clay for the attachment of bacteria. In the end, we were able to develop a highly effective biological treatment process integrated with RO membranes.

The Full-Scale Yellow Quill Treatment Plant

The material used for the attachment of microbes in the full-scale water treatment plant was Filtralite expanded clay supplied by the Maxit Group from Norway (Fig. 5).

Fig. 5. *Upper: Expanded clay material (Filtralite) with size similar to coarse coffee grounds. Lower: Electron microscope photograph showing bacterial clusters on the expanded clay material.*

Operational data for the full-scale plant are shown for biological treatment and membrane treatment (Table 1). These data were collected before a series of design modifications were carried out, resulting in complete ammonium oxidation and greater arsenic removal by the biological process. In addition, the RO treated water is currently running through a calcium and magnesium mineral bed raising treated water calcium and magnesium levels to produce a healthy as well as a safe drinking water. The distributed water has no detectable trihalmethanes or heterotrophic bacteria, and chlorine residuals at the treatment plant do not deteriorate in the distribution system.

Table 1. Operational Data from the Yellow Quill Water Treatment Plant

Mainly Biological Removal (full-scale plant)

Substance	Raw	BioTreated	Membrane Treated
Iron (mg/L)	9.0	0.03	0.007
Arsenic (μg/L)	21	6	<0.4
Ammonium-N (mg/L)	3.7	1.9	0.05
Phosphorus (mg/L)	0.17	<0.01	<0.01
Turbidity (NTU)	100	0.19	0.09

Mainly Membrane Removal (full-scale plant)

Substance	Raw	BioTreated	Membrane Treated
TDS (mg/L)	1858	1850	17
Calcium (mg/L)	280	250	0.2
Magnesium (mg/L)	120	98	<0.1
Silicon (mg/L)	12.7	12.2	0.16
DOC (mg/L)	10.0	8.1	<0.2
Manganese (mg/L)	0.25	0.24	<0.001
Nitrate-N (mg/L)	<0.01	2.0	0.36

Compared with conventional treatment of groundwater, mainly manganese greensand for similar types of water, the amount of backwash water required for the fully developed biological treatment system is 20 times less. Even ahead of the membranes, all of the ammonium is oxidized to nitrate (after modifications to the original plant), and most of the arsenic and other bio-available material (bio-available-DOC, etc.) are also removed. After biological filtration, the water is biologically stable resulting in low biological fouling, of the reverse osmosis membranes. The Yellow Quill water treatment plant has been providing high quality drinking water for three years (Fig. 6). Our experience with membrane cleaning is quite limited as there is very little fouling/scaling and only one membrane cleaning has been carried out so far. The developed process has now been implemented in two other water treatment plants, George Gordon and Pasqua First Nations.

Fig. 6. *Upper: full scale biological filters; lower: reverse osmosis treatment unit at the Yellow Quill First Nation water treatment plant.*

This process is dealing not only with poor quality water but also with water temperatures for ground water sources as low as 6 °C. The process is robust, requiring few operator interventions. It is also highly cost-effective due to extremely low chemical use (no chemical additions for the biological treatment process and low levels of antiscalant for the membrane process with final disinfection carried out with low levels of chlorine). The process uses inexpensive and long-lasting filtration material. In addition, the plants operate 24 hours per day for weeks before backwashing or any other direct operator intervention is required. Switching from manganese greensand + RO to the Integrated Biological and RO Process has been estimated to save the George Gordon First Nation $100,000 per year mainly in decreased RO membrane replacements, decreased use of chemicals and process water. A similar integrated biological and reverse osmosis treatment process is currently being developed for the exceedingly poor quality surface water (DOC, 25 mg/L) at Saddle Lake Cree Nation in Alberta. It is simply not feasible to allow large levels of DOC in the distributed drinking water when chlorine is used as a disinfectant (Peterson et al. 1993). It is also not possible to use pre-oxidation strategies to produce high quality drinking water from poor quality surface water sources (Peterson et al. 1995).

Concluding Remarks

The Integrated Biological and RO Membrane Process was developed in pilot form and then scaled up to deal with the communities' entire water needs. Engineers took the pilot data and did the necessary magnifications. When government agencies finally realize that the production of truly safe drinking water is less expensive than allowing small rural drinking water treatment plants to become "Centers for Disease Creation," then biological limnologists must become involved to ensure that we can take advantage of microbial green power and limit the use of chemistry. Understanding and implementing biological drinking water treatment solutions are areas where engineers are often uncomfortable, and need additional scientific support; such support also improves the comfort level of both the community and the federal government. These developments are, of course, not limited to aboriginal communities, but also are suited to other rural drinking water treatment plants. They also offer an economic and better quality alternative to rural drinking water pipelines, which can suffer from slime problems caused by bacterial growth in long distribution system pipes.

Indeed, water to be distributed in long pipelines should be biologically stable (microbial nutrient and energy sources removed) to reduce this problem. The removal philosophy used in the developed process, therefore, is quite different from that used in conventional water treatment plants. Conventional treatment removes some compounds, but leaves many microbial nutrient and energy sources intact. Indeed, any oxidative treatments, such as ozonation, chlorination, etc., increase the quantity of biologically available organic material. Also, conventional treatment relies on inactivation of disease-causing microbes, as bacteria and viruses cannot be effectively removed. This means that conventionally treated water is prone to build-up of microbial slimes in the distribution system and when drinking conventionally treated water, we also consume large quantities of "inactivated" microbes. The realization, however, is growing that many microbes cannot be effectively inactivated, and their removal is desired.

The removal of microbes as well as microbial nutrients and energy sources, therefore, may become a future requirement to produce truly safe drinking water. It, therefore, is quite likely that biological filtration will become not only a future "nicety" in drinking water treatment, but an essential part of advanced water treatment technologies in Canada and around the world.

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Mining Development and Impacts on Aquatic Resources in the Canadian North

Ken J. Hall
Professor Emeritus
Department of Civil Engineering
The University of British Columbia
Vancouver, B.C., CANADA, V6T 1Z4
(kjhall@civil.ubc.ca)

Introduction

Anyone who flies over the Canadian North will certainly be impressed with the mosaic of lakes and rivers, of all sizes and shapes, that drain these northern watersheds. In this last Canadian frontier, the rush is on to stake claims and exploit the mineral resources at an accelerated rate, with the potential to threaten the integrity of our northern watersheds and the aquatic ecosystems that they support. The discovery of diamonds has led to a claim staking frenzy that we have not seen since gold was discovered in the Klondike (Anon. 1). At the end of 2003, with the Ekati and Diavik mines in operation, Canada was the world's third largest diamond producer after Botswana and Russia (Anon. 2). The magnitude of the rush for diamonds in the Canadian North is very evident, with the number of prospecting permits increasing from 190 in 2003 to 1518 in 2004, and with the exploration companies having laid claim to more than 28 million hectares in the Canadian North (Anon. 2). The rapid rise in the price of uranium, considered one of the only viable energy replacements for dwindling hydrocarbon resources, has also pushed exploration further into the northern frontier, to develop and exploit this hazardous mineral. Canada's Athabasca region in northern Saskatchewan is presently producing 30 percent of the world's uranium (Anon. 3). Also, the high price for gold has made exploitation of lower grade deposits and those at greater distances more feasible. With the price of oil at \$60-\$70/barrel, a more rapid expansion of the Athabasca oil sands is set to take place.

With a northern environment, which is in some areas 30 percent surface water, it is obvious that mineral exploration and development will create impacts on the aquatic environment that will be difficult or expensive to manage.

This paper will summarize recent exploration and mining activities for diamonds, gold and uranium in the Canadian North (Figure 1), and explore the potential impacts that these activities can have on the sensitive aquatic resources of this region. No attempt will be

Fig. 1. *Base map of Northern Canada for location of detailed maps on mineral extraction and exploration that follow: 1- diamonds, 2-uranium, 3-placer gold.*

made to investigate the extraction of hydrocarbons (natural gas and oil sands), since this is an extensive area and would require further research. Recent documentation of the impacts of diamonds, placer gold and tar sands development in the Canadian North and the management issues faced have been reviewed by Fisheries and Oceans, and is used to provide the information presented in this paper (Birtwell et al. 2005).

Diamonds: Exploration and Development

Diamonds are found in kimberlite pipes, and are formed deep in the earth under very high temperatures and pressures. Fipke and Blusson, two prospectors, first found diamonds in 1991 when they learned to follow the kimberlite minerals of garnet and olivine scattered by the glaciers until they led to the pipes (Anon. 4). They joined forces with BHP Minerals to develop the Ekati diamond mine site located in the headwaters area of the Coppermine River, 300 km NE of Yellowknife. This exploration and development has been the mining success story north of latitude 60. The company has found dozens of kimberlite pipes in their 344,000 ha claim area around Ekati (Anon.1). The potential for conflict with water resources becomes evident when a terrain analysis shows that 30 percent of this claim area is water.

The 2005 statistics indicate that 12.3 million carats of diamonds were extracted in 2005 (Anon. 5), which are coming from the Ekati mine and the Diavik mine on Lac de Gras (Table 1). There is a third producing mine in Nunavut, the Jericho Diamond Mine (an open pit mine), as well as an underground mine currently under construction at Snap Lake. The Gahcho Kué diamond property at Kennady Lake is currently undergoing environmental assessment. These activities will secure Canada as one of the top diamond producers in the world (Anon. 1,2,4).

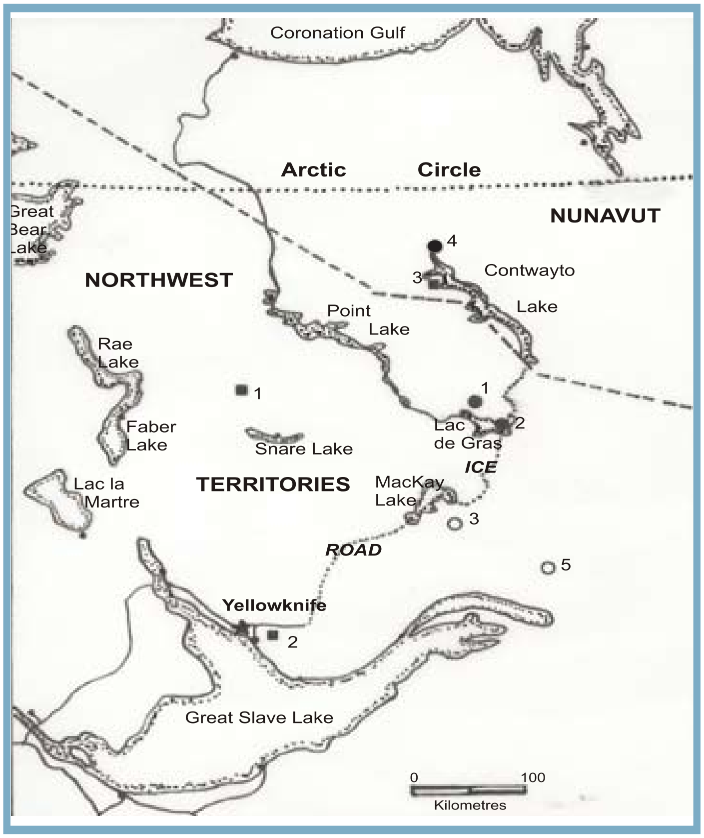

Fig. 2. Areas of diamond mining and selected gold mine locations in Northern Canada: Operating diamond mines: [●] 1-Ekati, 2-Diavik, 4-Jericho. Diamond mines under development or review: [○] 3-Snap Lake, 5-Gahcho Kué (see Table 1 for more details). Closed gold mines: [■] 1-Colomac, 2-Con/Miramar (Yellowknife), 3-Lupin. Dotted line from Yellowknife to Contwoyto Lake shows ice road (adapted from Anon. 1).

Diamond Mining Impacts on Water Resources

Often the kimberlite pipes are found under lakes, as the kimberlite is relatively soft and the moving glaciers scoured out these areas and left depressions, which were filled with water. Once a pipe is discovered, drilling equipment must be flown to the site to evaluate the diamond content and quality. If the pipe is considered valuable enough to mine, then it is necessary to get road access into the area to bring in materials, energy, supplies and heavy equipment to develop the site. In the case of Ekati, this required the construction of an ice road, 350 km in length, from Yellowknife to move several thousand transport trucks between February and April when the ice road can be used. Seventy-five percent of this road, which must be constructed every winter, is over frozen lakes. The

Table 1. Diamond mines in the Canadian north and their limnological impacts

Mine	Location[s]	Production	Lakes Affected	Limnological Impacts
Ekati (BHP/ DiaMet)	300 km NE of Yellowknife, NT	3-5x10^6 ct/y	12 lakes lost (6 open pits)	Stream diversion Any restored pit lakes much deeper. Tailings lakes lost
Diavik (Aber Resources /Rio Tinto)	30 km SE Ekati Lac de Gras, NT	8x10^6 ct/y	Dyke into Lac de Gras (Open pit)	Loss of littoral area Tailings will be land based; only small ponds affected
Snap Lake (De Beers)	220 km NE of Yellowknife, NT	Projected 1.6x10^6 ct/y (2006)	Underground mine/	Tailings will be land based; only small ponds affected
Jericho 3 (Tahera Diamond Corp.)	Nunavut	Production (2005-2006)	Tailings disposal (lake and 2 ponds)	Tailings will destroy lake and 2 ponds
Gahcho Kué (De Beers)	100 km SE of Snap Lake	Planning Stage	Kennady Lake	Extensive limnological impacts in Kennady Lake

[s] see Fig. 2

Diavik mine uses the same ice road as Ekati, with an extension to Lac de Gras, and requires 2000 truck loads of supplies annually (Anon. 4). The same ice road supplies Snap Lake and Tahera.

The impacts of ice road construction on the aquatic environment include the potential for spills of liquids and leaking of lubricants and fuel from the large transportation armada. The rapid warming that is being experienced in the Canadian North due to recent climate change could shorten the seasonal use of an ice road, with the potential upset or loss of vehicles when ice melts as the drivers try to push the season for safe transportation.

At the mine site, all facilities must be developed, including fuel storage tanks, personnel housing, water supply and wastewater treatment, processing plant, runway for aircraft, and tailings storage facilities. The impact of the ore extraction and processing on the aquatic environment will depend upon the site characteristics and the location of the kimberlite pipes to be excavated. If the kimberlite pipe is under a lake, the drainage pattern must be changed and then the lake pumped out to get access to the kimberlite. In the case of Ekati, site development and operation has directly impacted twelve lakes within the claim block

(Birtwell et al. 2005). Six lakes have been dewatered to get at the underlying kimberlite pipes, four lakes are being filled with tailings, one lake is covered by a waste rock dump, and one lake disappeared due to gravel extraction for the aircraft runway. A restoration plan has to be in place when the diamond deposits are exhausted, but there are obvious losses of lakes without replacement. Reflooding of deep open pits with possible influx of groundwater, some of which could be saline, will create different aquatic environments. Some lakes could develop meromixis (i.e., the lake will only partially mix due to a more saline deep layer of water), and there would be considerable loss in the littoral areas of the new lakes, unless benched to create shallow shoreline areas at closure.

The Diavik diamond mine development involved the construction of a rock dyke to isolate the kimberlite pipe in Lac de Gras. Large volumes of tailings have to be stored and dewatered, which will be stored on land and will affect some small fishless ponds in the area. The Snap Lake development will involve underground diamond extraction, so there will be no open pit mine, but tailings must be stored. The Jericho site in Nunavut involves an open pit mine, but does not require the draining of a lake. However, the tailings are discharged to Long Lake (9 ha) and two ponds. Thus the direct impacts of diamond mine development can be variable, and the impacts on the drainage patterns and water quality conditions in the regions lakes will reflect these differences (Anon. 1).

Fortunately the kimberlite ore extracted from the pipes does not have a high sulphur content, so acid rock drainage problems, which plague the extraction of many elements from their sulphides (zinc, lead, etc.), is not a big environmental issue. In the processing plants, the isolation of the diamonds makes use of density separation, where ferrosilicate minerals are used, and the fluorescence of the diamonds under x-rays makes the isolation procedure relatively free of corrosive and dangerous extraction chemicals.

Uranium: Exploration and Mining

With the pending shortages of hydrocarbon resources, nuclear power is considered the main replacement energy resource. World leaders are planning to triple the number of nuclear power plants in the world, which has spurred on the exploration for new uranium resources. The price of uranium has gone from $22/kg in 2003 to $125/kg, an increase of 450 percent in three years (Anon. 6).

In Canada, uranium is found in the Northwest Territories (Great Bear Lake, Rayrock), in northern Saskatchewan, in the Athabasca Basin with mines at Cluff, Key, Rabbit, and Wollaston lakes and Uranium City (Figure 3). In the past 15 years, northern Saskatchewan has become the uranium capital of the world, with some of the richest uranium ores (20% U_3O_8) ever discovered (Anon. 7).

In 2005, over 12,000 tonnes of uranium were produced in northern Saskatchewan (Anon. 5). In Ontario, uranium has been mined at Elliot and Bancroft lakes.

Fig. 3. Areas of Northern Canada with known uranium deposits (adapted from Anon. 8)

Due to the higher prices and demand, exploration for uranium has moved farther north and accelerated considerably. In addition to further exploration in the Athabasca River basin, the Thelon and Hornby River basins in the Northwest Territories and the Baker Lake area in Nunavut are key exploration sites (Figure 3, Anon. 8).

In the mining process, the ore is crushed and made into a slurry. The uranium oxide is leached with sulphuric acid. After solids settling, the acid solution passes through an ion-exchange medium to trap the uranium. The uranium is extracted and precipitated as uranium oxide (99%, U_3O_8). The tailings, which contain most of the original ore as well as acid and radioactivity, are pumped as a slurry and stored behind a tailings dam. The tailings are usually covered with water to reduce surface radioactivity emission and eliminate dust problems. For some underground deposits, the uranium can be solublized by pumping in a highly oxygenated weak acid solution which is then pumped to the surface for further processing.

Uranium Mining Impacts on Water Resources

The risks of uranium mining on the environment and human health are great, if adequate safeguards are not taken in extracting the ore and handling the waste materials. As new deposits are found and developed, the impacts are similar to the exploitation of diamonds or other minerals, with effects from access roads and mine development on the physical integrity of the watershed. There is the potential for radioactive materials to contaminate surface and ground water in the watershed. In addition to the radioactivity of the tailings, they can also contain heavy metals, acids (sulphuric acid used in the extraction process), ammonia and salts, which must be properly managed to prevent environmental contamination (Anon. 9). Failure of containment dams used to store tailings can result in extensive downstream contamination. In the Elliot Lake area of Ontario, there have been over 30 tailings dam failures, and the entire Serpent River system, with more than a dozen lakes, is badly contaminated with radioactivity (Anon. 7). If the tailings deposits are allowed to dry out, radioactive dust can be distributed widely, with potential impacts on both the terrestrial and aquatic ecosystems. As the ore is processed, the release of radioactive radon gas to the atmosphere is both an environmental and human health problem.

Gold Exploration and Development

With the price of gold deregulated in the 1970s, exploration has intensified and the present price >$600 US/oz. makes the exploitation of lower grade ores feasible. Gold production in 2005 in Canada was 120,000 kg, with most of that production (80%) coming from the Precambrian shield area of Ontario and Quebec (Anon. 5). The Yukon is well known for placer gold mining (Birtwell et al. 2005), but this area only contributes <2% of annual production (Anon. 5). However, the negative impacts upon the environment of placer gold mining far exceed its contribution to production.

Placer Gold Mining

Most of the placer gold mining in the Yukon River basin comes from the unglaciated areas of the Yukon plateau between Dawson and Whitehorse. The main placer mining activities are along the Indian (38.7%), Klondike (20.6%), Sixtymile (14.4%), and Lower Stewart (10.4%) rivers (Figure 4, Anon. 1989). Overall in the Yukon River basin, when all of the sediment generated and released is considered, up to 17 percent of the water courses have been impacted by these land disruption activities (Birtwell et al. 2005).

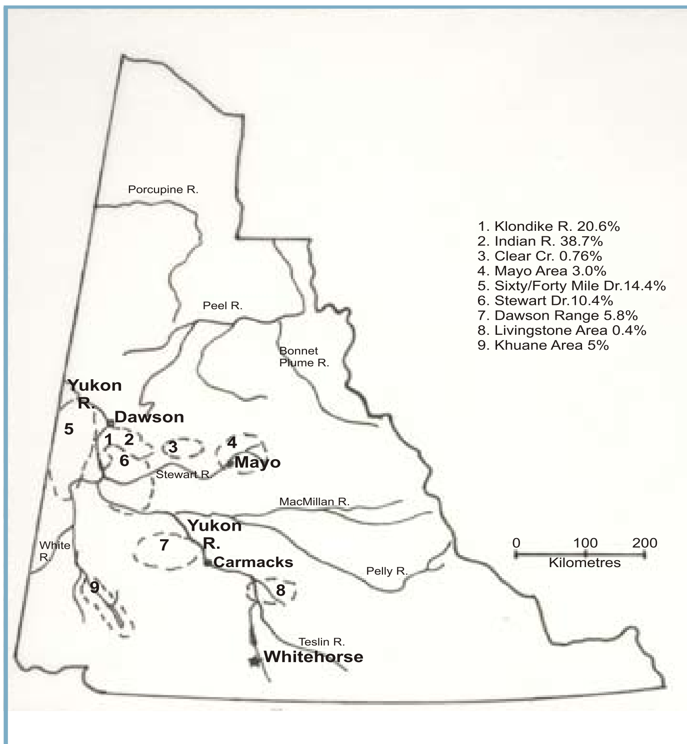

Fig. 4. Placer gold mining activity in the Yukon River basin. Percent values in legend show relative importance of the total 385,800 oz. of gold recovered from the basin (adapted from Birtwell et al. 2005)

Aquatic Impacts of Placer Gold Mining

Road construction is necessary to transport heavy earth moving equipment to a mining site. This can result in stream flow disruption and severe erosion problems as well as sediment generation even before the processing of the gold deposit begins. The site development first involves removing and storing the overburden material. Then the gold bearing materials are excavated, slurried with water and the heavier material subjected to gravity separation to recover the dense minerals. For example, in 1988 there were 6-8 million m^3 of material sluiced for gold, with 2-3 times that material removed to expose the gold bearing gravel and sand - overall a total of 30 million m^3 of material. In 2003, there were 324 water licenses for placer gold recovery, although not all of these were active (Birtwell et al. 2005).

Direct habitat destruction is one of the obvious impacts of placer gold mining, as whole streams are diverted to get at the gold bearing deposits. It is important in regulating these activities, to do a full stream assessment and classification to determine the degree of protection required to preserve the aquatic resources. The washing of gold bearing material generates large volumes of suspended sediment, which must be treated in settling basins prior to any discharge to a fish bearing stream. As long as the suspended sediment remains below 25 mg/L, the sediment risk to fish and their habitat is relatively low. This risk increases to highly unacceptable as concentrations reach 400 mg/ L and higher (Birtwell et al. 2005). Suspended sediment can have many impacts on aquatic organisms (Langer 1980; Berg and Northcote 1985). High turbidity reduces water transparency and light penetration, reducing photosynthetic processes. Predator/prey interactions are significantly impacted due to poor visibility. Gills of fish and invertebrates can be coated with silt, and along with physical abrasion ,affect respiration. Eggs deposited in stream gravels can be covered with silt and smothered. Benthic invertebrates can also be displaced and smothered by sediment.

Aquatic Impacts of Pit and Underground Mining

Where the gold occurs in bedrock materials, it is mined by open pits or underground excavation activities. In remote northern areas, ice roads are being used to get access to the mineral deposits, and impacts are the same as discussed under diamond mining. Again at the mine site, overburden materials must be removed and stored in a watershed, with the potential for negative effects on the hydrologic regime of the area. In these hardrock mineralized areas, there is concern for contamination from other elements, such as arsenic, which has been an ongoing contamination problem at the former gold mine in Yellowknife (Bright et al. 1994). Also, gold is often found with other metals of economic interest, and the occurrence of metal sulphides and iron pyrites (fools gold) creates problems with acid rock drainage (ARD) from the waste rock and tailings storage site. This strong acidity, often with pHs of 1-2, is directly toxic to aquatic organisms. Furthermore, it can also dissolve other toxic metals, such as copper and zinc.

Recovery of the gold concentrate, especially in low grade deposits, often uses techniques such as cyanide leaching and complexation. The gold complex is then adsorbed to carbon to recover the gold, but the tailings are contaminated with cyanide, which is highly lethal to most aquatic organisms. A case in point is the Colomac gold mine, which operated from 1990 to 1997, and mined 16.7 tonnes of gold from an open pit mine in the Northwest Territories, 220 km north of Yellowknife. When the mining company went bankrupt, the Contaminants Division of Indian and Northern Affairs was left with site monitoring and the cleanup. The tailings from the mine (11.2 million tonnes of ore milled) were deposited in two lakes behind a dam where water quality would hopefully stabilize before runoff from the watershed would breach the tailings dam and move downstream. The lake receiving the tailings contained high levels of cyanide, which was oxidized to thiocyanate and finally ammonia. To manage the water in the area and prevent the Tailings Lake from filling too fast, water was pumped to the open pit mine (Pit Lake), degrading its water quality as well. To correct the water quality problem in both lakes, it was decided to add phosphorus to the lakes to balance the N:P ratio and encourage primary production to sequester the ammonia, which was between 30-40 mg/L NH_3-N. This was done, which stimulated algal production and reduced the thiocyanate in the lakes to 0.5 mg/L (Chapman et al. 2003). However, high levels of ammonia still remained in the lake, attributable to decomposition of cyanide compounds and internal cycling when anoxic conditions developed below the thermocline. Also, the heavy biological production reduced water transparency considerably so that N and P removal was only occurring in the upper few metres of water. Lake aeration is now being used as a mitigative measure to improve the water quality (oxidize the remaining thiocyanate and nitrify the ammonia) before the tailings lake water fills the impoundment and escapes downstream.

Summary

The information provided indicates that there is an accelerated growth in the exploration for, and development of, mineral resources in the Canadian North. Access to these remote northern areas by ice roads is largely over frozen lakes, which creates concerns for watershed drainage patterns, erosion, and spills and leaks from vehicles. Mining of the diamond bearing kimberlite pipes often requires the drainage of a lake to access the ore. With uranium mining, the release of radioactive material is a main concern. Placer gold mining causes direct habitat destruction, and high sediment concentrations are a management problem. Mining activities create tailings, some of which are contaminated with chemicals, that are usually stored in a depression or lake.

With the extensive water resources in this region, there will be impacts upon the aquatic environment that will be difficult to prevent. Thirty-one of the 50 lakes approved for elimination for industrial development in the North have occurred over the past 10 years (Birtwell et al. 2005). Although compensatory and restorative measures are required to be in compliance with the *Fisheries Act*, our lack of limnological knowledge hampers this process. Knowledge is gradually being developed on the freshwater limnology of our northern waters, but research in the Canadian North is expensive due to the large distances and long winters. The ecological information and literature available in such publications as that of McCowan and Martin (2006) is a good start. There is still the need to obtain more basic limnological information in the Canadian North, and to make sure it is available, as well as used, by all government agencies and industrial operations in that large area.

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Forestry and Fresh Water in Canada: Transitions To an Unknown Future

G.F. Hartman
1217 Rose Ann drive,Nanaimo
Nanaimo, B.C., V9T 3Z4
E-mail: gordon_hartman@telus.net

Introduction

To date, our approach and much of our understanding of forestry effects on Fresh Water environments and fish has been based on studies, which are usually set in a dual context. By dual, I mean, study forestry activities within a lake region or a watershed versus environmental or fish responses within the system. In the future, progressively more forestry activities and the consequent responses of Fresh Water environments (plus fish within them) will be set in a complex and difficult context. Conditions will be driven by environmental and social processes, which are already being influenced far beyond the watershed scale.

Some such processes, which 're-set the clock' on aquatic conditions in Canada and particularly in British Columbia, are occurring now, and require research response followed by quick, positive and appropriate action.

Here I will indicate briefly some of the differences between stream and lake responses to forestry activities, and will direct readers to useful sources of such information. Following these comments, I will briefly examine some aspects of a more complex situation in which forestry and Fresh Water interactions in Canada will be played out.

Forestry Effects on Streams and Lakes: Interconnected But Different Kinds of Environments

Streams

There is a vast number of publications on the effects of forestry activities on stream conditions and watershed processes. These can not be reviewed here. A major part of the literature that is published focuses on forestry impacts on fish habitat and fish in stream environments, rather than on limnological effects on stream or lakes. Stream and lake environments are closely connected, but are different in important ways. These differences results in different responses to forestry.

Three important dissimilarities between stream and lake environments, which cause forestry effects to be different between them, are:

- Streams systems are linearly connected environments that change from headwaters downward (Vannote et al. 1980). Lakes, although usually connected to the stream-river system, function partially as distinct ecological units.
- Streams have a high ratio of 'shoreline' length relative to surface area. Marginal connection to the forest is high. Although the ratio of 'shoreline' length to surface area may be high in small lakes, it becomes very low, relative to streams, in large bodies of water.
- Stream channel bottoms are, relative to that of lakes, unstable. Stream channels may shift over time and their beds may change on an annual basis. Streambed studies may provide a short-term record of in-channel changes (Toews and Moore 1982; Tschaplinski et al. 2004). They do not, however, reflect patterns of sediment loading over decades. Lake bed studies may, however, provide histories that indicate land use effects over hundreds of years (Scully et al. 2000; Laird et al. 2001; Laird and Cumming 2001). Histories of stream channels, available from long-term aerial photograph series, reveal that location and dimension may change naturally over time. Forestry activities may increase the rate and amount of such changes.

Logging within watershed and forest removal at the margins of streams affects, at the very least, three limnological characteristics:

- Turbidity;
- Thermal; and
- Chemical.

Changes in these characteristics result from structural alterations in or by the channel: loss of riparian vegetation, loss of bank and bottom stability, destabilization and loss of large woody material in the channel.

Because the literature on effects of forestry on streams and fishes is so extensive, I offer four principles that should be kept in mind regarding forest impacts. For more consideration of these, see Hartman and Scrivener (1990) in which the principles are tabulated and illustrated:

- Forestry programs within a watershed involve different activities, such as road construction, road use, falling, yarding, and silvicultural work. The different activities, and ranging scales in their intensities, have different effects on the various elements of stream habitat (see Hartman 2004; and Hartman and Scrivener 1980, Figure 79).
- Watershed systems, depending on climate, topography, and soils, may exhibit different responses to forestry work. Different fish species, and different age groups within them, will not necessarily show the same responses to environmental changes associated with various forestry activities.
- Hydrological, fluvial geomorphological, thermal, and trophic processes are complex and interconnected (see models in Hartman and Scrivener 1990; Hartman 2004). Although many fish-forestry managers indicate that they recognize the complexity, many of them do not read the scientific literature and do not fully understand the nature and the complexity of processes within the systems with which they work.
- Responses to forestry activities may be manifest over decades. Carnation Creek is still undergoing changes due to forestry activities carried out from 1975 to 1985. This is so because watershed and stream responses to logging occur in a sequence of different changes that may occur over many decades (Hartman and Scrivener 1990; Tschaplinski et al. 2004).

Lakes

Until recently, there has been much less study of the wide range of forestry impacts on lakes than on streams. This was regarded as surprising, because limnological research on flowing waters was largely ignored in the early development of the science (Northcote et al. 2004). Some discussion of forestry effects on lakes, referred to below, provide for a fuller review. For a start, readers should refer to Northcote (2004) and Northcote et al. (2004). Several studies on lakes, particularly in the Canadian Shield region, are included in the volume edited by Carignan and Steedman (2000). These studies provided clear indications that various lakes may respond differently to logging around them. There are a number of important lake responses to forestry.

Northcote et al. (2004) considered the effects of forestry on lakes in three major contexts:

Spatial – from 'airshed', watersheds, internal (lake basin) including shoreline, surface, mid-water, and benthic areas. Airshed effects may include fall-in of dry ash from fires and waste-wood burners, decreased near-shore zone litter-fall with forest removal, and chemical changes in rain. Watershed-generated effects include turbidity increase in open water (Parkinson et al. 1977), and sediment deposition on the lake bottom from road construction and harvesting activities (Northcote et al. 2004).

Temporal – seasonal, annual, decadal, or over the centuries. Logging produced 2-10 year long increases in dissolved organic material, mercury and mineral matter in a Michigan lake (Scully et al. 2000). These authors suggested that forestry activities may affect physical structure and autotrophic food web composition for 100 years. Lamination in the lake bottom from forestry activities about 1885 indicated that forestry activities affected sediment deposition patterns over long periods (Scully et al. 2000).

Functionally – effects on physical, chemical, and biological processes. Removal of shoreline forest may change windspeed over a lake, and hence the degree of mixing (Steedman and Kushneruik 2000). It may, as well, alter water clarity (Steedman 2000; Steedman and Kushneruik 2000; Carignan and Steedman 2000). Effects of forestry on dissolved constituents may vary among lakes depending on morphometry, drainage basin features, and water replacement time in the lake. They may also depend upon the ratio between harvested area (proportion of basin) and lake volume (Carignan and Steedman 2000).

Four 'principles' were listed in regard to forestry effects on stream-watershed systems. In many respects these apply equally well to lakes. One important difference is that lake basins may preserve histories of land use activities (Scully et al. 2000; Laird et al. 2001; Laird and Cumming 2001) that are longer than those that can be detected in stream channels. Lake basins, over long periods of time, remain in the same location. River and stream channels, even those with no history of human disturbance, alter and may change location dramatically.

Intricacy of Fresh Water Environments

Fresh-water resources, however, exist in an inter-connected complex of environments beyond streams and lakes. These include glaciers, permafrost zones, soil moisture, groundwater, atmosphere, lakes, rivers, estuaries, and wetlands. These environments may all be affected, one way or another, by activities such as logging, log transport and storage, forest regeneration, and wood processing (Northcote and Hartman 2004). They are affected, however, by a host of other human influences ranging from broad-scale climate effects driven by global-scale processes, to local (small-scale) marshland loss or groundwater depletion caused by construction of a single subdivision. To date, there is little research on effects of forestry on fresh-water environments such as ground water, wetlands, or permafrost.

Forestry Effects Beyond the Watershed Scale

At present, there are two major situations that have a large potential to complicate the relationship between forestry activities and limnological conditions in Canadian inland waters.

These both have impacts beyond the watershed scale:

1. The cumulative scale of forest removal, in parts of Canada, is enormous. This observation applies directly to the geographic extent of cutting and the density of clearcuts across the wide areas of operation.
2. The complex combination of climate change effects on forests, i.e., altered forest distribution, insect outbreaks, permafrost melting, and increased forest harvest rates, will have important implications to forestry-related fresh-water conditions. The following section examines these issues.

Cumulative Scale of Forest Removal

The perception that one gets regarding forest removal, when viewed through satellite imagery, is quite different than that obtained by a cross country drive or even an air flight. In British Columbia, forest removal is intense and widespread, covering almost all landscapes where forests exist or existed. Satellite

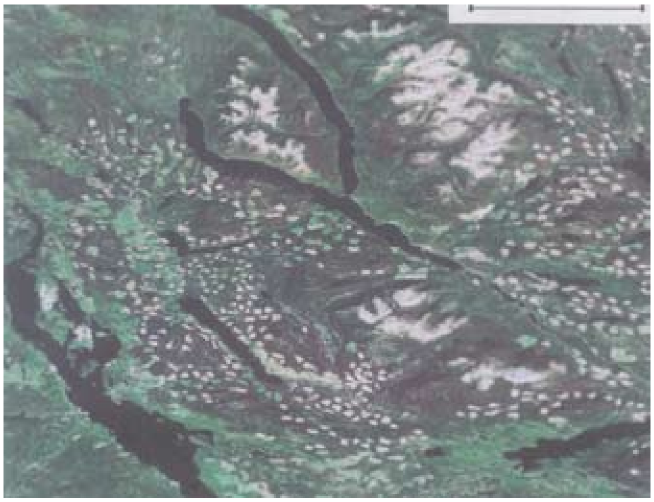

***Fig. 1**. Intensity and distribution of clearcuts in the Babine, Takla, and Stuart lakes area of central British Columbia. Most recent clearcuts appear white, older ones are pale green in this and the next three figures. The line in the white panel, upper right, indicates 20 km in this and the next three figures. The center of the image is at about 125º,40' west longitude x 55º north latitude. (Figures 1-4 are used with permission of TerraMetrics Inc., http://www.truearth.com).*

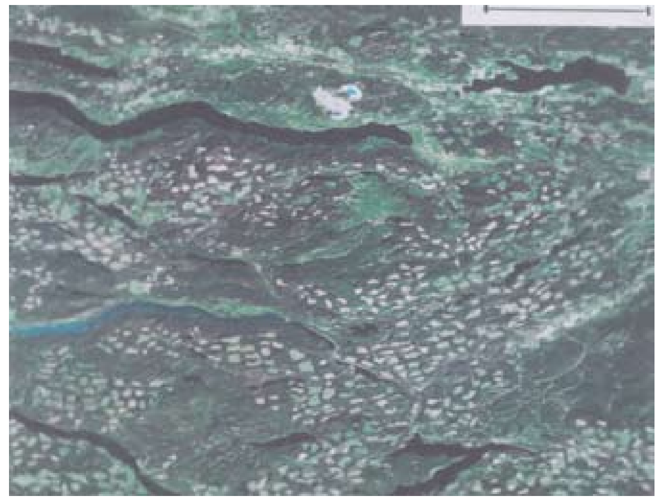

***Fig. 2.** Intensity and distribution of clearcuts in the area south of Francois Lake, near upper left, and Fraser Lake, upper right, central British Columbia. The north-east end of the Nechako Reservoir and Kenney Dam are near the lower right corner of the figure. The center of the figure is at about 125º west longitude x 53º, 40' north latitude.*

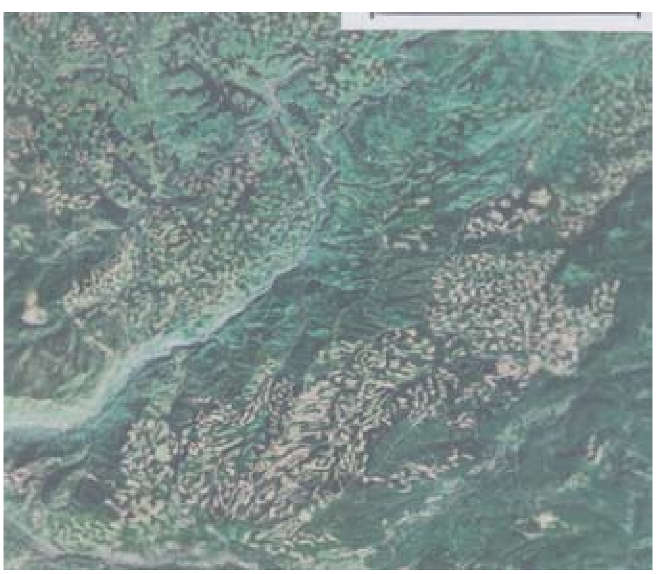

***Fig. 3.** Intensity and distribution of clearcuts in western Alberta. Center of the image is at about 118º, 45' west longitude x 54º, 14' north latitude, about 40 km north-east of Grande Cache.*

***Fig. 4**. Density and distribution of clearcuts in New Brunswick. Center of the image is at about 66º, 40' west longitude x 47º, 20' north latitude, about 160 km north of Fredericton. There is almost no original forest left in New Brunswick.*

images centered on an area bounded, in Figure 1, by Babine Lake (lower left). Takla Lake (upper), and Stuart Lake (lower right), and a second area located south of Francois and Fraser lakes, and north of the Ootsa Lake (Kenney Dam) complex (Figure 2), illustrate the scale of forest removal. These images are representative of the intensity of forest removal from the Rocky Mountains, in the east, to the Coastal mountains in the west. That imagery in Figure 3, shows the extent and intensity of forest removal in western-central Alberta, north-east of Grande Cache. Figure 4 illustrates the almost complete coverage of forest cutting activities in north-central New Brunswick.

These images are not presented as an attack on the forest industry. They are used to indicate that, at landscape levels greater than a single watershed, forestry activities may have impacts on air-shed conditions, soil water temperatures, stream hydrology, or regional climate. Such aquatic impacts would develop slowly over the course of forest removal occurring at landscape scales even wider than the limited areas shown in Figure 1-4. Forestry impacts could also be confounded by effects of other human activities, such as agriculture. These points are made to support the case that we should begin to consider potential effects of forestry, on aquatic conditions, at far wider landscape scales over longer time periods.

Forestry Effects in the Context of Wider-scale Processes

The effects of forestry on freshwater environments may develop concurrently with effects of other human activities in the same region, e.g., agriculture, urbanization, utility corridor development, or hydroelectric expansion. In this regard, management moves beyond the dual consideration of forestry and fresh water. Forestry effects on aquatic habitats and fishes become part of a configuration of impacts, largely driven by population increase and economic growth. Such cumulative effects on fresh-water environments are usually negative. The use of forest lands for well managed logging can be the least damaging of an array of land uses. The maintenance of well managed forestry, rather than urbanization and agriculture, can be a better option for sustaining fresh-water environments within a watershed or regional area.

Impacts may be increased under the influence of changes that are beyond the regional scale and are driven by human activities at a continental or world-wide level. We may deal locally with effects or symptoms of these latter processes, but they will not be resolved in the restricted context of forestry-related fresh-water management measures. I give two examples in which global processes exert a dominant and changing influence over forested landscapes and may alter the nature of forestry effects. One of these involves the effects of climate change on the Boreal forest and the potential to exacerbate logging impacts. The second involves the effects of climate change and fire suppression on Lodgepole pine forests of British Columbia and their potential to increase forestry impacts.

Boreal Forests: The Push to the North

Canada contains over one third of the world's Boreal forest. It stretches from Newfoundland-Labrador, across the Hudson Bay lowlands, along the Canadian Shield, and northwest to Yukon and Alaska in an arc of approximately five million km^2. The Boreal forest zone includes the Churchill-Nelson and Peace-Athabasca river systems and about one half million lakes (Anonymous 1999). In these Canadian provinces, essentially all of the Boreal forest lies south of the northern limit of discontinuous and continuous permafrost. However, the range of sporadic permafrost extends one half to one third down into the Boreal forest (Figure 5).

Forestry activity is pushing into the Boreal forest. Since about 1990, over 30% of the Boreal forest has been allocated for industry (Saskatchewan Environmental Society Forestry Fact Sheet <saskenv@link.ca>. Cutting is extensive in some areas. In Quebec, in a single 628,000 ha watershed, 132,000 ha were cut during an 11 year period (Global Forest Watch Canada, 780-451-9260). In the Muskwa-Kechika Management Area, one quarter of a 6.3 million ha area is "protected"; and three quarters are listed as "management" zone (www.bcforestinformation.com).

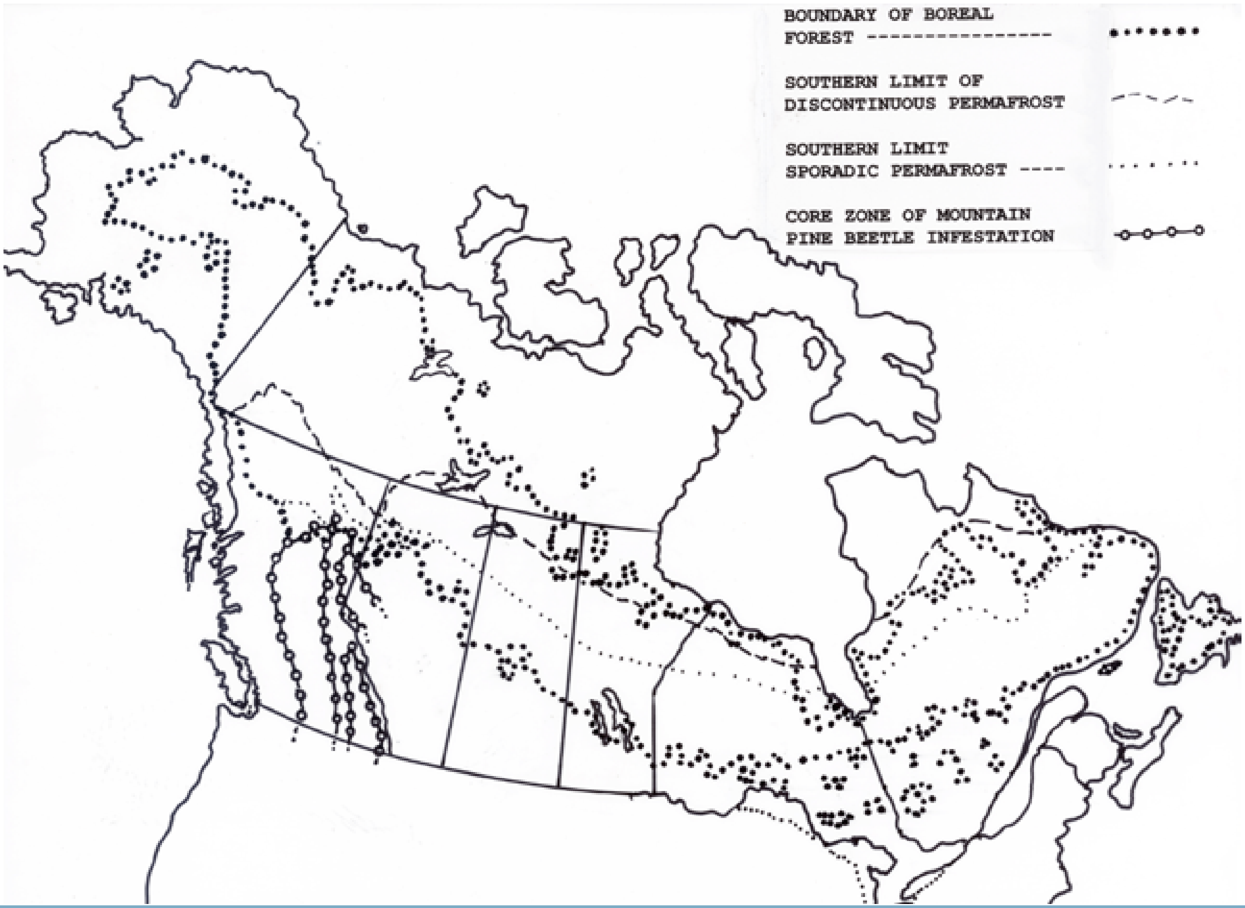

***Fig. 5**. Distribution of Boreal forest in Canada. Approximate boundaries for the Boreal forest, and southern limits of discontinuous and sporadic permafrost are indicated. The core zone of the Mountain pine beetle infestation is put in only to indicate the scale of the outbreak. The Boreal forest contains the northern ranges of Lodgepole and Jack pine.*

Such forest activities are occurring in areas of fragile soils and slow growing forests. The effects of forestry on fresh-water environments in these areas will be coupled with impacts from linear disturbances, such as those in the oil and gas exploitation industry.

Forestry operations on patches of sporadic permafrost or on melting permafrost zones are not well researched, and effects are problematic for aquatic environments. We are not dealing well with such matters because the management approach in Canada has been to allocate opportunities for industry, and deal with forthcoming environmental problems with the limited benefits of hindsight.

Pine Beetles and Fire Suppression: Fresh Water Challenges

A current high profile and major crisis issue involves Mountain pine beetle *(Dendroctonus ponderosae)* outbreaks that are occurring presently in Lodgepole pine forests in British Columbia. However, these infestations have the potential to extend, albeit more slowly, across the Jack pine pine forests of Canada (B. Wilson, Canadian Forest Service, Victoria, to CBC, August 25, 2006). Mountain pine beetle eruption in British Columbia has been driven by climate changes, but aided by programs of fire suppression that have increased the amount of mature lodgepole pine threefold over the past ninety years (http://www.for.gov.bc.ca/hfp/mountain_pine_beetle/facts.htm).

By 2006, mountain pine beetle kill of Lodgepole pine is projected to be 377 million m^3 plus 33 million m^3 salvaged. By 2016 only about 10% of the pine that existed in 2006 may be alive. Of this volume, nearly 40% will be standing dead (Eng et al. 2006). Areas of projected beetle kill, with subsequent massive salvage and potential fire, will include almost all of the Fraser River basin, parts of the upper Skeena River drainage and valleys in the Kootenay region. By 2016, the projected cumulative volume of trees killed will be about 80% of the total, or 850 million m^3 (British Columbia Ministry of Forests, Research Branch, Information Leaflet). The infestation of Mountain pine beetle is anticipated to move eastward and spread, albeit more slowly, through the Jack pine forests across the Boreal zone of Canada (Bill Wilson, Canadian Forest Service, Victoria, B.C., to CBC, August 2006).

I believe that it is unlikely that anyone can accurately project the impacts of this sequence of events starting with the extensive clear-cutting indicated, followed by the beetle infestation and logging salvage impacts, and followed yet further with potential massive wildfire. The nature and scale of primary effects on lake and river limnology, hydrology, sediment loading, lake and stream temperature regimes, and water chemistry and temperature, can only be guessed at. The secondary effects on fish resources and the esthetic quality of lakes and streams are also difficult to project. The scale of potential changes is so great that massive, integrated, long-term research-based evaluation of processes of forest change and concurrent physical limnological and biological responses is urgently needed. This is required along with appropriate and quick follow-up action. The scope of such a project may be well beyond the kinds of present monitoring and beyond the capacity of competent and committed people within the B.C. Ministry of Forests.

A Call for Research Action:

New Scales of Complexity

I offer the following recommendations:

- The governments of Canada and the Provinces should establish now, a research program that is long-term, cooperative, integrated, and multi-disciplinary. This should be done to track and understand, as much as possible, the environmental effects that are occurring primarily as a result of climate effects and insect outbreaks, and secondarily because of rapid and large-scale management responses to the outbreaks.
- This program should be designed to monitor, analyze, and understand the processes of change on a very large scale. There are programs, of much smaller scale, that have many of the needed types of research attributes, e.g., Experimental Lakes Area project and the Carnation Creek Watershed project. Because they are so much smaller, these projects are not specific research models for the current insect outbreak situation. However, they do demonstrate organizational attributes and benefits from such integrated studies.
- The program should have the capacity for expansion if or when beetle outbreaks and emergency logging expands across Canada.
- The program should be built with dedicated budgets and staffing that is beyond the reach of administrators with short-term agency agendas. The ecological and socio-economic implications of the sequence of events threatening the pine forests of the Boreal Zone are enormously important. They are so important that research and management program responses to them must be designed to avoid being captive to any particular political agenda.
- These ideas are offered as ‘seeds’ for consideration, perhaps by the Canadian Society of Environmental Biologists. There is urgency for action because, even now, the ecological conditions in much of central British Columbia are under enormous impacts from climate change, insect outbreaks, and the rapid wholesale emergency logging that is going on.
- A final observation — if invaders from another nation were doing as much damage to our environment and economy, with a potential to do even more, governments would respond at once!

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LIMNOLOGY

THE PUBLICLY UNKNOWN SCIENCE OF INLAND WATERS: OVERVIEWS ON SOME OF ITS IMPORTANT TOPICS

A 20 cm diameter Secchi disc (with light meter attached), probably the most widely used limnological instrument for measuring water transparency in lakes and slow moving rivers.

Dr. K.J. Hall and limnology student preparing to measure water transparency of Loon Lake, Malcolm Knapp UBC Research Forest.

Lake Okarai, New Zealand with a very heavy planktonic algal bloom that would reduce water transparency readings to a few centimetres on both sides of a top to bottom curtain.

The same lake location a few months after introduction of a heavily algal grazing fish, silver carp (Hypophthalmichthys molitrix) to the right portion of the lake where water transparency measured by a Secchi disc would be several metres.

See Carruthers (1986) N.Z. Ministry of. Agriculture. Fisheries Research Division Environmental Report #68 for this Lake Okarai study; Northcote (1988) Canadian Journal of Fisheries and Aquatic Science 45(2): 361-379 for "top-down" views on fish in freshwater ecosystems generally.