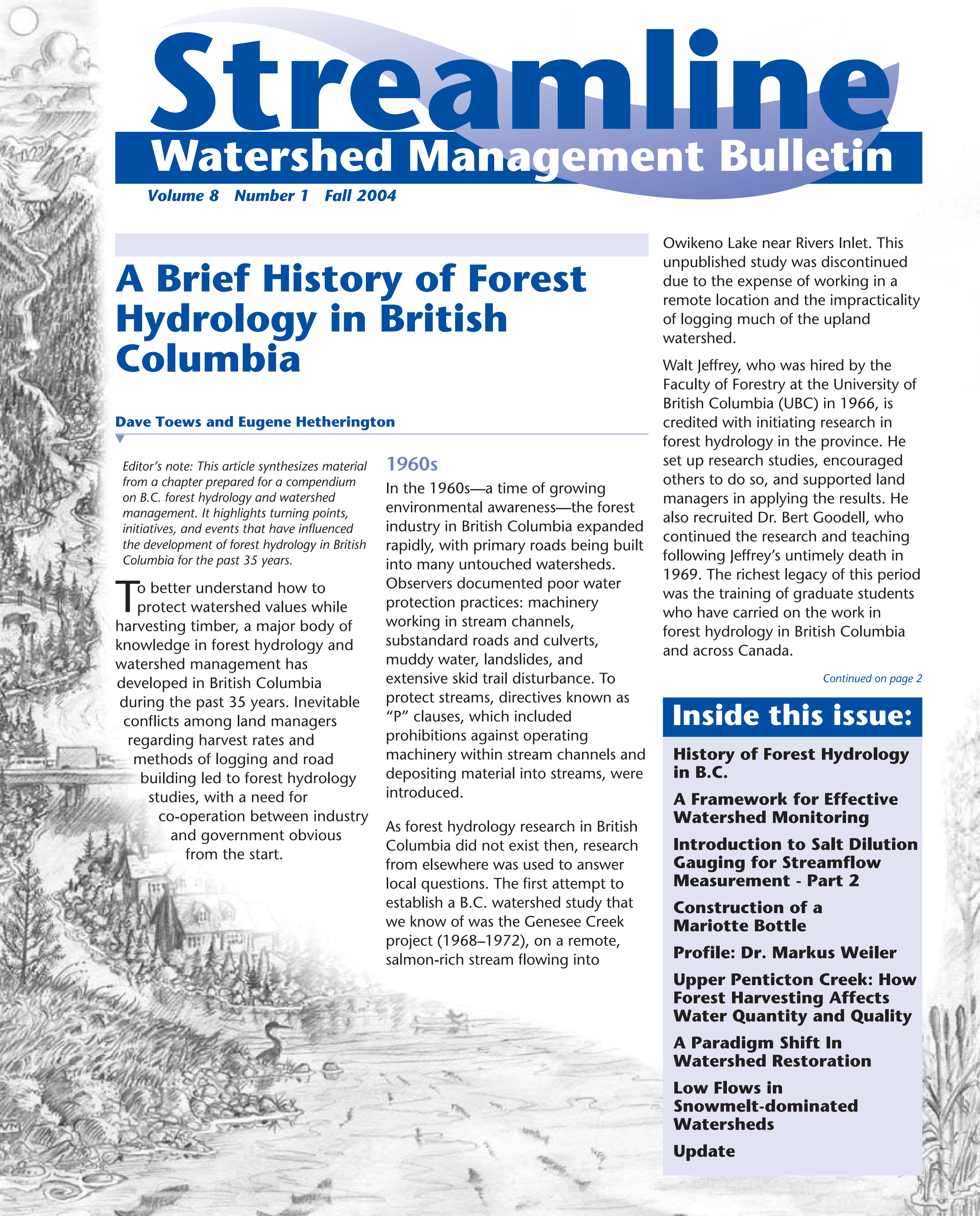
Streamline
Watershed Management Bulletin
Volume 8 Number 1 Fall 2004



A Brief History of Forest Hydrology in British Columbia

Dave Toews and Eugene Hetherington

Editor's note: This article synthesizes material from a chapter prepared for a compendium on B.C. forest hydrology and watershed management. It highlights turning points, initiatives, and events that have influenced the development of forest hydrology in British Columbia for the past 35 years.

To better understand how to protect watershed values while harvesting timber, a major body of knowledge in forest hydrology and watershed management has developed in British Columbia during the past 35 years. Inevitable conflicts among land managers regarding harvest rates and methods of logging and road building led to forest hydrology studies, with a need for co-operation between industry and government obvious from the start.

1960s

In the 1960s—a time of growing environmental awareness—the forest industry in British Columbia expanded rapidly, with primary roads being built into many untouched watersheds. Observers documented poor water protection practices: machinery working in stream channels, substandard roads and culverts, muddy water, landslides, and extensive skid trail disturbance. To protect streams, directives known as "P" clauses, which included prohibitions against operating machinery within stream channels and depositing material into streams, were introduced.

As forest hydrology research in British Columbia did not exist then, research from elsewhere was used to answer local questions. The first attempt to establish a B.C. watershed study that we know of was the Genesee Creek project (1968–1972), on a remote, salmon-rich stream flowing into Owikeno Lake near Rivers Inlet. This unpublished study was discontinued due to the expense of working in a remote location and the impracticality of logging much of the upland watershed.

Walt Jeffrey, who was hired by the Faculty of Forestry at the University of British Columbia (UBC) in 1966, is credited with initiating research in forest hydrology in the province. He set up research studies, encouraged others to do so, and supported land managers in applying the results. He also recruited Dr. Bert Goodell, who continued the research and teaching following Jeffrey's untimely death in 1969. The richest legacy of this period was the training of graduate students who have carried on the work in forest hydrology in British Columbia and across Canada.

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Inside this issue:

Published by:

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Content and Article Submission Information:

Information in this publication is presented to increase communication and understanding of innovative knowledge and current research results in watershed management. Articles on technical information, research results, perspectives, news releases, conference / workshop highlights, and other relevant submissions are welcomed. All material published reflects the opinions and conclusions of the contributing author(s), not those of FORREX, our editorial staff, or our funding partners. We welcome your feedback on ideas or opinions that have appeared in past issues of Streamline. We reserve the right to edit all submissions for content, style, and relevance to Streamline.

This publication is funded in part by the British Columbia Ministry of Forests through the Forest Investment Account, Forest Science Program and by the USDA Forest Service.

ISSN 1705-5989

Printed in Canada

Printed on recycled paper

http://www.forrex.org/streamline

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1970s

The first major watershed study in British Columbia began in 1970. The Carnation Creek project on Vancouver Island is the longest term and most highly published watershed study in the province (155 citations listed in Hartman and Scrivener [1990], and at least 50 since then).

A second important study, started in 1972, was the Slim–Tumuch project east of Prince George. One of the main findings of this study was that most of the logging-related sediment that entered streams came from a single source of lacustrine material—a result that may have been avoided by locating the road elsewhere (Brownlee *et al.* 1988).

A historic conflict in 1979 arose in the Queen Charlotte Islands in association with the approval of logging in the Riley Creek watershed, an area particularly prone to landslides (Donnelly and Martin 1980). At first, the federal Department of Fisheries and Oceans did not object and the B.C. Forest Service issued a cutting permit. Fisheries reconsidered its stance following a significant storm in the fall of 1978 that resulted in landslides. Fisheries personnel notified the forest licensee that unless logging was suspended, the forest company would be charged under the *Fisheries Act*. When the company continued to log after notification, a company official was charged with obstruction of justice and fallers were arrested. A major impasse resulted and senior politicians including the premier, the federal Minister of Fisheries, and the prime minister became involved. Finally, all parties agreed that the area could be logged if it could be done safely. A steep portion of the block directly above a tributary stream was deleted from the cutting permit and the road system was deactivated immediately after logging.

The incident at Riley Creek shaped forest hydrology and fish/forestry research in British Columbia. It led to the formation of the Fish/Forestry Interaction Program (FFIP) that culminated in a final symposium 15 years later, as well as the associated publication of the influential *Carnation Creek and Queen Charlotte Islands Fish/Forestry Workshop: Applying 20 years of Coastal Research to Management Solutions* (Land Management Handbook 41; Hogan *et al.* [editors] 1998).


E. Hetherington

Logging on Carnation Creek floodplain, 1976.

Also in the 1970s, awareness of the effects of large woody debris in streams and the importance of the structure of stream channels increased. Scientists learned that, in addition to the traditional forest hydrology topics of quantity, regime, and quality of water, there was a need to consider channel and debris stability. It became apparent that forest harvesting adjacent to channels could affect the long-term stability of streams, even when there was no instream activity.

Another intense topic of discussion was the effect of logging on rain-on-snow events on the Coast. A study in the Queen Charlotte Islands outlined the theoretical impacts of logging on peak flow (Toews and Wilford 1978); its recommendation that harvesting be limited to one-third of a watershed within a 25-year period was controversial. The debate led to related studies in the Queen Charlotte Islands, as well as a study by Beaudry and Golding (1987) in the Vancouver area.

1980s

By the 1980s, projects established earlier were producing results and science-based watershed management policies were evolving. Carnation Creek started yielding significant findings, which were presented at major workshops in 1981 (Hartman [editor] 1982) and 1987 (Chamberlin [editor] 1988). In Carnation Creek, complex relationships between biological and hydrologic parameters such as stream temperature, streamwater nutrients, and channel stability came to be better understood. A workshop in 1983 led to the development and implementation of the *Coastal Fisheries Forestry Guidelines* that were subsequently refined in a second edition (B.C. Ministry of Forests *et al.* 1988). The guidelines were agreed to by both industry and government, and implemented with an intensive training program.


E. Hetherington

Gordon Hartman leading a tour along the upper Carnation Creek channel.

By the mid-1980s, the B.C. Forest Service had hired research hydrologists in five of six forest regions; the Ministry of Environment and forest companies were also hiring specialized staff with interests in hydrology. New programs were set up to broaden the geographical scope of research in the province. Common concerns included mass wasting, surface erosion and sediment from roads, snow hydrology and rate-of-cut, fish/forestry interactions, and the effectiveness of constraints on forest management. Hetherington (1987) published a useful synthesis of the Canadian literature on many of these issues.

For most of these technical problems, it has been possible to translate research findings into practice. The rate-of-cut issue has been an exception. Is it necessary to regulate the rate-of-cut on a watershed basis? A workbook for coastal watersheds (Wilford 1987) illustrated some of the difficulties of combining various impacts in a watershed into a single analysis. The trials of this method were useful in promoting further discussion regarding the appropriate nature of a cumulative effects model.

Meanwhile, the FFIP in the Queen Charlotte Islands presented initial findings in a workshop in 1986, including an overall emphasis on slope and channel stability and associated fish habitat impacts in a geomorphologically active environment. Results expanded the forest hydrology knowledge base and were used to revise the *Coastal Fisheries Forestry Guidelines*.


E. Hetherington

Charles Scrivener sampling gravel. Carnation Creek, February 1984.

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1990s

To reflect a sub-boreal environment, the Department of Fisheries and Oceans established another fish/forestry/hydrology watershed study in the Stuart–Takla area north of Prince George (MacDonald [editor] 1994). As the use of technology grew, various attempts were made to develop or calibrate computer simulation models that could assess the effects of forest management scenarios on streamflow, including the HSPF model at Carnation Creek, the UBC Watershed Model at Upper Penticton Creek, and the WRENSS model in the Okanagan. The UBC Forestry Faculty has recently calibrated the Distributed Hydrology Soil Vegetation Model (DHSVM) using data from three southern B.C. watersheds.

> *While a great deal has been accomplished in British Columbia since the mid-1960s in forest hydrology and watershed management, much remains to be learned.*

A crucial event in the development of logging guidelines in British Columbia occurred in the early 1990s when an alliance of environmental groups, First Nations, and private individuals came together to protest continued logging in the Clayoquot Sound area on the outer coast. In response, the government selected a group of independent scientists to study the issue. In 1995, the Scientific Panel for Sustainable Forestry in Clayoquot Sound recommended that logging continue, but on a very limited scale and under stringent guidelines. The transferability of these report recommendations to other regions of the province has not been tested.

Of major importance in forest policy was the introduction in 1994 of the B.C. government *Forest Practices Code* and of Forest Renewal BC (FRBC), an initiative aimed at rehabilitating B.C. watersheds. Previous decades of research paved the way for the preparation of *Forest Practices Code* guidebooks and the development of procedures for the Watershed Renewal Program of FRBC. An additional legacy of FRBC was the establishment of two endowed chairs in forest hydrology at UBC and two at Okanagan University College.

The *Forest Practices Code* was intended to specify precisely how activities were to take place in the forest. The coastal and interior watershed assessment guidebooks (B.C. Ministry of Forests 1999; B.C. Ministry of Forests and BC Environment 1995a, 1995b) were prepared and hundreds of watersheds throughout the province analyzed (Carver and Teti 1998).

2000s

The forestry professionals who produced the guidebooks clearly saw the many gaps and shortcomings in applied forest hydrology and geomorphology research in British Columbia. With the need to verify information in the guidebooks, a number of procedures were begun in the late 1990s. A workshop in the Interior brought together people conducting assessments with those applying the results. The proceedings *Watershed Assessment in the Southern Interior of British Columbia* were published in 2001 (Toews and Chatwin [editors] 2001).

In 2001, the B.C. government replaced the *Forest Practices Code* with a new results-based approach that specifies broad overall results for the forest industry. It allows licensees considerable latitude in achieving those results, provided environmental standards are maintained. The research question is: What measurements can be used reliably to determine watershed condition on an operational scale? Basic to implementing the new strategy will be a sound understanding of watershed science in a geographically diverse province.

In summary, while a great deal has been accomplished in British Columbia since the mid-1960s through research, practice, education, and policy development in forest hydrology and watershed management, much remains to be learned.

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A Framework for Effective Watershed Monitoring

Dave Wilford and Richard Lalonde

The Bulkley Land and Resource Management Plan (LRMP) requires that monitoring be undertaken to ensure that water and fish habitat objectives are met (Bulkley Valley Community Resources Board and Interagency Planning Team 1998). An interagency/licensee committee (see Acknowledgements) was asked to develop a monitoring plan. This was a major task, given 68 watersheds with diverse hydrology, geomorphology, and aquatic resources within a 7620 km^2 timber supply area (TSA). The committee recognized that each watershed needed to be reviewed individually to identify values that would be sensitive to forestry-induced watershed changes. Also, the committee reviewed existing approaches, such as watershed assessments (B.C. Ministry of Forests and BC Environment 1999) and watershed classification (Cheong 1996), and discussed the challenge with hydrologists and geomorphologists. The conclusion was that we needed to create a process-based, watershed overview approach to identify appropriate parameters. The committee also recognized that it would be impossible to individually examine each watershed, so a simple approach to ranking watersheds, based on past/proposed forest harvesting and aquatic values was adopted. We ranked all 68 watersheds and identified appropriate monitoring approaches in 29 watersheds over five weeks. This article details our approach to watershed monitoring.

> *We ranked all 68 watersheds and identified appropriate monitoring approaches in 29 watersheds over five weeks.*

The Framework

Our approach had two components: ranking the watersheds and identifying suitable parameters and appropriate spatial sampling scale (e.g., site, tributary stream, multiple locations on main stream).

Ranking the Watersheds

Given time and financial constraints, we developed a ranking system to ensure watersheds with high aquatic values were examined and received monitoring decisions. Community watersheds, key fish-producing watersheds, and watersheds with red- or blue-listed fish species were rated as having high aquatic values. Watersheds rated moderate had limited fish species and numbers of fish in a regional context. Watersheds with low aquatic values had few or no fish present. All watersheds were then ranked according to the percentage of watershed area with past and proposed forest harvesting: low potential of risk to aquatic resources was less than 20%, moderate risk was 20–30%, and high risk was greater than 30%. The values and potential risks were numerically ranked (Table 1) to produce an overall priority ranking for each watershed. The controlling factor in the numerical

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ranking is forest harvesting (as opposed to aquatic values), because the focus is on the potential risk of past and proposed forestry activities to aquatic resources. All watersheds with a rank of five or less were examined. Watersheds with a rank greater than five were slated for potential examination in the future, subject to funding.

Table 1. Matrix of aquatic values and potential watershed impacts

		Potential impact		
		L	M	H
Values	L	7	5	3
	M	6	4	2
	H	5	3	1

Examining the Watersheds

Physical processes and aquatic resources in the highest ranked watersheds were analyzed using geographic information system (GIS) software. High priority watersheds were delineated and a series of overlays were prepared including: topography, ortho-photographs, terrain stability or environmentally sensitive areas for soils (ESAs), surface erosion hazard, past forest harvesting, proposed forest harvesting, roads, natural disturbances (primarily wildfires), stream classes, fish inventory, water intakes for community watersheds, and past studies (e.g., research, watershed assessments, fisheries studies). The GIS data, in combination with the group's experience and supplemental background studies, were used to answer questions regarding geomorphology, hydrology, aquatic resources, and forest harvesting (Table 2). These questions were selected to develop a clear picture of a watershed, which is central to the selection of both appropriate indicators and spatial scale for monitoring.

> *The GIS data, the group's experience, and background studies were used to answer questions regarding geomorphology, hydrology, aquatic resources, and forest harvesting.*

Developing the Questions

Geomorphology

Geomorphology questions focus on the availability of sediment to the stream channel, characteristics of the stream channel, and selected physical watershed features. In reviewing the high ranked watersheds, several key points/assumptions emerged. In watersheds with high natural sediment source levels, we considered that it would most likely be difficult to detect changes due to forest management at the watershed (main stream) level. We understood that stream channels with high bedload transport most likely have a low population of aquatic invertebrates (due to substrate instability); therefore using the Benthic Index of Biological Integrity alone would be inappropriate for detecting land use impacts (Karr and Chu 1999; Bennett and Rysavy 2003a, 2003b; Weigel 2003). We recognized that channel morphology changes over time can be determined from aerial photographs. However, it is necessary for the channel to be visible on aerial photographs (at least 20 m wide) and for there to be an adequate time series (e.g., two sets of photos taken before forestry activities and two sets after forestry activities—work that can be undertaken as monitoring for proposed harvesting).

Hydrology

Hydrology-related questions focus on streamflow characteristics, potential for water temperature issues, and watershed physiography. Several cautions/challenges were encountered in collecting/interpreting the data. Because watershed-specific hydrometric data were not available for most of our watersheds, it was necessary to consider relief and size/location of lakes to determine streamflow characteristics. These estimates were balanced against our combined local knowledge to address seasonal and long-term streamflow characteristics. These characteristics are a central factor with regards to channel and benthic stability (Lamberti *et al.* 1991; Knighton 1998). With several exceptions, specific water temperature data were not available, so we identified watersheds with potential high-temperature issues based on the size and location of lakes and wetlands, and the nature of riparian zones (e.g., watersheds with extensive lakes and wetlands, and shrubby riparian zones were identified as having potential high-temperature issues). We wanted to know if large peak flows (e.g., 25-year return-period flood) had recently destabilized a stream channel. Destabilized channels characteristically carry high bedload levels and may have high suspended-sediment loads. We recognized that watersheds with these channel qualities may present challenges for separating forest management effects from natural levels at the upper end of the range of natural conditions. Watersheds that have major tributaries with significantly different characteristics will most likely require different approaches in monitoring each tributary. Several watershed assessments offered useful guidance for monitoring.

Fish

Fish-related questions focus on the fish species present, location in a watershed, habitat requirements, instream enhancement or restoration

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Table 2. Watershed-specific questions

1. Geomorphology

- Do natural landslides run into streams?
- What is the extent of naturally unstable terrain (e.g., using environmentally sensitive areas [ESA], terrain stability or sediment source maps, or aerial photos)?
- Does the watershed have “gentle-over-steep” terrain?
- Is surface erosion likely to be an issue (e.g., lacustrine deposits)?
- Are glaciers present in the watershed?
- Does the stream channel carry a high bedload?
- Are there multiple channels or back/side channels?
- What is the relative relief of the watershed?
- Is the stream channel visible on aerial photographs?
- Are historic aerial photographs available?

2. Hydrology

- Are lakes or wetlands present in the watershed?
- Location of lakes/wetlands: upper, middle, lower watershed?
- Aspect of the watershed (for snowmelt)?
- Runoff characteristics: rapid, moderate, slow?
- Are there major tributaries with significantly different characteristics (e.g., relief, erosion, stream channels)?
- Are gauging stations present in the watershed or adjacent watersheds?
- Have there been recent, large destabilizing peak flows?
- Have natural disturbances influenced the forest cover (e.g., wildfires, insect epidemics, windthrow)?
- Are natural disturbances expected to influence the forest cover (e.g., mountain pine beetle)?
- Are there past hydrologic studies (e.g., professional reports, inventories, monitoring)?

3. Fish

- Where are fish located in the watershed?
- What are the key habitat requirements of the species present (e.g., spawning and rearing)?
- Are red- or blue-listed species present?
- Have critical habitats been identified?
- Are there any known fish barriers (e.g., natural or related to land use)?
- Have habitat investments been planned or implemented in the watershed?
- Do natural factors limit or threaten fisheries (e.g., low or high flows, high temperatures, winter icing of spawning areas)?
- Are there past studies (e.g., professional reports, inventories, monitoring)?
- What is the level of detail of current inventories and have they been repeated?
- Has there been a history of issues with the fish species present (e.g., related to land use in the watershed, escapement)? Specify the issues.

4. Other Aquatic Resources

- What other aquatic resources are present in the watersheds (e.g., domestic water, blue- or red-listed aquatic life forms)?
- Location of the resources within the watershed?
- Are there past studies (e.g., professional reports, inventories, monitoring)?
- Has there been a history of issues regarding other aquatic resources (e.g., low flows, land use, over-commitment of resources through licensing or use)?

5. Past Forest Harvesting

- What are the extent and location of past logging (e.g., factors calculated for watershed assessments - % watershed logged, current equivalent clearcut area, road density, extent of riparian logging, site preparation methods)?
- Have non-status and inactive roads been deactivated?
- Have there been stream quality crossing or similar assessments?
- Are roads contributing sediment to streams (e.g., observed or monitoring data)?
- Have there been landslides from roads or logged areas?
- Have there been water resource issues associated with past logging?

6. Proposed Forest Harvesting

- Will unstable terrain be logged or roaded?
- What special measures or prescriptions are planned?
- Will “gentle-over-steep” terrain be logged?
- What are the extent and rate of proposed harvesting?
- Will special measures be taken for logging or road building?

7. First Approximation Monitoring Decisions

- Given the natural hydrologic and geomorphic processes in the watershed, issues associated with aquatic resources, and effects of past forest harvesting, what is the potential for the planned forestry activities to affect aquatic resources?
- What specific water or aquatic habitat values could be influenced by the planned forestry activities?
- Given the natural processes in this watershed, is it possible to measure changes in these values (which parameters)?
- What is the appropriate spatial scale for monitoring?
- What techniques or equipment could be used to measure the parameters?

8. Development of a Monitoring Plan

- It is necessary to follow a series of steps in developing an effective and successful plan (refer to Wilford 2003)?

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investments, research and assessments, natural factors limiting or threatening populations, and past issues related to forestry activities. Some species such as bull trout require cool water temperatures and thus highlighted a key monitoring parameter for us. In reviewing our watersheds, we found that some required monitoring at the watershed scale if past forest harvesting removed riparian forests in the lower watershed and forest harvesting is proposed in the upper watershed. In other cases, we found it appropriate to monitor temperatures at a site level if past forest harvesting had a limited effect on riparian forests and glacial melt water dominated the main stream temperature. Information about past issues related to forestry activities such as landslides, impassable drainage structures, sediment from road running surfaces, and elevated stream temperatures was important when we selected monitoring parameters.

Other Aquatic Resources

Questions about other aquatic resources (values) highlight domestic water consumption, the presence of blue- or red-listed aquatic life forms (e.g., tailed frogs), the spatial location of these resources, past issues relating to forestry activities, and information derived from past assessments, research, and/or monitoring. We found that, aside from information about domestic and community watershed licences, it was uncommon to find watershed-specific information about other aquatic resources. However, we recognized the value of any available baseline work and recommended repeat inventories for monitoring.

Past and Future Effects of Forest Harvesting

Our methodology uses a series of questions to explore the effect of past forest harvesting. Where watersheds had been assessed using the Watershed Assessment Procedures (WAPs) (B.C. Ministry of Forests and BC Environment 1999), information on the extent of past logging was readily available. Where WAPs had not been undertaken, this information was generated using GIS. Having past and proposed forest harvesting as a GIS layer (using a computer projector) was very useful for group discussions on potential impacts and monitoring opportunities. Information from the Watershed Restoration Program and the local forest licensees helped to answer questions about road deactivation, status of drainage structures, sediment production from surface erosion, forestry-related landslides, and water resources issues associated with past logging.

Questions about the potential effects of proposed logging focused on the types of terrain to be logged, the extent and rate of harvesting, and planned special measures. In a few cases, logging or road building was proposed on unstable terrain. We examined the potential for sediment transport to streams in these areas, and requested information on special measures or prescriptions proposed to prevent detrimental effects. In several watersheds, logging was proposed on gentle terrain upslope of steep terrain. This "gentle-over-steep" terrain (Grainger 2002) has been identified in the Bulkley TSA as a potentially hazardous situation unless special attention is paid to maintaining water routing. Even with careful attention, accelerated snowmelt has reduced slope stability in the steep terrain. The extent of proposed harvesting in a watershed can be a significant factor in selecting monitoring parameters. Specifically, if only limited harvesting is proposed (e.g., < 1% of the watershed), it may not be possible to detect an effect on aquatic resources. The rate of harvesting can also be significant. A rapid rate of harvest, particularly if unstable terrain has been identified, may not allow much time for monitoring feedback to adjust practices (e.g., a delay in the occurrence of landslides due to lack of sufficient precipitation may result in extensive logging on unstable terrain). Fortunately, this was not the case in our watersheds. We considered that it was important to know what special measures would be undertaken with regard to logging or road building. The focus was not only on unstable terrain, but also on stream crossings, logging and silvicultural systems, site preparation, and deactivation. Explicit rationale for these special measures was also considered important (e.g., feedback from adaptive management or application of research results to reduce effects to aquatic resources). Our committee considered monitoring an important feedback mechanism for evaluating these special measures.

The "gentle-over-steep" terrain has been identified in the Bulkley TSA as a potentially hazardous situation.

Developing Watershed-specific Monitoring Strategies

The data collected by answering the questions regarding the physical, biological, and harvesting history of a specific watershed allow for a cumulative watershed analysis: "What is the potential effect of past and planned forestry activities on aquatic resources?" Central to this question is the specific water or aquatic habitat value that could be influenced. However, the sensitivity to changes must be considered in light of the natural processes in each watershed. Once parameters for the values are identified, it is prudent to determine the spatial scale (site, tributary stream, main stream) at which any potential changes might be detected. Several examples from the

Bulkley TSA illustrate this stage of the decision-making process. In our review, some watersheds had little new logging planned. However, in some cases, extensive riparian logging placed watersheds at what was considered by the fisheries agencies to be a threshold for temperature-sensitive fish (Table 3). In such cases, it was determined that the proposed logging in headwater areas may further elevate stream temperatures, even with best management practices. Thus, a monitoring need was identified at the watershed scale (i.e., monitoring throughout the watershed). In other watersheds we examined, past logging was limited and the proposed logging was on terrain with limited potential to affect aquatic resources (i.e., low erosion potential and no streams in the proposed harvesting areas). Monitoring in these cases could be costly and may not provide any substantial information related to achieving the goals of monitoring (i.e., the effects of forest management on aquatic resources would be below the detection limit or may not occur). We also encountered several "gentle-over-steep" situations, with the steep sections actively failing into stream channels. In these cases, the natural sediment loads in the streams were too high to detect forest management influences at the watershed scale and monitoring was therefore most appropriate at the site level. We used repeat sediment source surveys of the slopes directly below the logging to detect incremental changes.

Once the appropriate parameters and the spatial scale for each specific watershed value have been determined for a watershed, we recommend following a series of steps (Wilford 2003) in developing effective and successful monitoring plans.

Limitations of the Framework

The two main elements in the framework were prioritization and watershed-specific questions. Our prioritization allowed us to quickly rate the watersheds based on the criteria outlined previously. Using the extent of harvesting without regard to location of harvesting resulted in several watersheds with extensive riparian logging being rated incorrectly as "low potential risks" because they had limited overall logging. We also recognized that our approach would not capture

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Table 3. Summary of monitoring decisions for three watersheds

Name	Watershed Attributes	Past–proposed Forest Harvesting	Monitoring Decision
Arnett	50.3 km^2 – upper watershed is a wide basin with the slopes disconnected and a low-power stream. The mid to lower channel reaches are incised with naturally failing banks. There is high bedload transport and rapid runoff.	There has been no past logging. Proposed logging is 6% of the watershed, with some class IV terrain and gentle-over-steep situation with 2 blocks.	Monitoring at the site level – repeat sediment source mapping of the steep terrain below the 2 blocks – pre-harvest and annually for 5 years. Then assess the situation.
Goathorn	187 km^2 – extensive, naturally unstable terrain along stream channels, high bedload transport, north aspect with cold water temperatures. One major tributary has low relief, moderate runoff, and a stable channel. Thirty years of hydrologic and biologic studies associated with a proposed coal mine. High aquatic values (bull trout) and the need to maintain low water temperatures.	Past logging is 17% of the watershed with riparian logging in one reach. Roads have been deactivated and there have been no issues with past logging. Proposed logging is 2% of the watershed over the next 5 years.	Monitor stream temperatures at the site level – small streams in the proposed harvesting area.
IR#5 Nilkitkwa	16.8 km^2 – low relief with slow runoff and generally stable channels. Beaver dams and wetlands in the lower watershed. An IWAP was done in 2000. Coho and rainbow trout are present.	Past logging is 38.9% of the watershed with an equivalent clearcut area of 31.3%. The peak flow index is high. There has been 3 km of clearcut riparian logging. One channel reach is currently unstable as a result of harvesting-related sediment sources. Lack of large woody debris recruitment could lead to channel instability in 3 reaches. Some roads have been deactivated but there have been no road-related sediment issues. Proposed logging is 1.2% of the watershed.	Monitor stream temperatures at the watershed level. Establish benchmark channel reaches – impacted and potentially unstable. Repeat descriptions after major runoff events or every 5 years.

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watersheds with significant issues related to past forest harvesting. As a result, after watersheds were prioritized using percentage of harvested area as the leading factor, we reviewed the list to identify obvious ranking errors. In addition, the rankings were reviewed following the watershed-specific examinations. During the examinations we noted two situations where the ranking was too low: one due to agricultural clearing that was not accounted for, and the other due to incomplete forest harvesting data.

Our committee found that addressing the presented watershed questions resulted in a significant exchange of information. Presenting GIS data visually (using a computer projector) allowed the group to appreciate the watersheds in a short time. To effectively address the questions, at least one person needed to compile information on watersheds (we hired a consultant for five weeks). We were fortunate in the Bulkley TSA because a significant amount of information had been compiled for the LRMP.

> *We are satisfied that our prioritization and assessment process produced defensible monitoring strategies for the key watersheds in a TSA.*

Conclusions

We are satisfied that our prioritization and assessment process produced defensible monitoring strategies for the key watersheds in a TSA. We consider that having the strategies in place will help to ensure that limited funds for monitoring aquatic resources are invested efficiently and effectively in the Bulkley TSA. Monitoring parameters that may change will provide the necessary feedback to ensure that forest management maintains aquatic resources as specified in the Bulkley LRMP.

Acknowledgements

This article was written with support from the members of the Bulkley Aquatic Resources Committee: Gary Quanstrom and Kent Coish (West Fraser Mills Ltd.); Bob Mitchell, Dave Duncan, Steve Willis, Glen Buhr, and Dave Wilford (B.C. Ministry of Forests); Tom Pendray (Fisheries and Oceans Canada); Sean Sharpe and Ian Sharpe (B.C. Ministry of Water, Land and Air Protection); Boyd Brown and James Cuell (B.C. Ministry of Sustainable Resources Management); Jay Baker (Silvicon Services Inc.); and Dave Bustard (D. Bustard and Associates). The Forest Investment Account (Province of BC) through Pacific Inland Resources, a division of West Fraser Mills Ltd., and the B.C. Ministry of Forests, Skeena Stikine Forest District provided funding for our project.

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Introduction to Salt Dilution Gauging for Streamflow Measurement Part 2: Constant-rate Injection

R.D. (Dan) Moore

Introduction

Stream gauging by salt injection is a technique that will work in many streams in which current-meter measurements are unreliable. This extension note builds upon a previous Streamline article (Moore 2004b) and describes field and computational procedures for stream gauging by constant-rate salt injection. The emphasis is on small streams (less than about 2 m in wetted width) under low flow conditions (discharge less than about 100 L/s). A future article will introduce slug injection, which is better suited to gauging higher flows. Users are encouraged to experiment with the following procedure to suit individual circumstances.

The Concept

A tracer solution injected into a stream at a defined rate, q (L/s), will become uniformly mixed across the stream at some distance below the injection point as a result of turbulent flow. After enough time has elapsed, a steady state (equilibrium) will develop, where the relative concentration of the tracer in the stream is

$$RC_{ss} = \frac{q}{q+Q} \approx \frac{q}{Q} (q << Q) \quad (1)$$

where Q is the stream discharge (L/s) and RC_{ss} is the relative concentration at steady state (L/L). From Equation (1), the discharge can be computed as:

$$Q = \frac{q}{RC_{ss}} \quad (2)$$

Because electrical conductivity (*EC*) is linearly related to *RC* for dilute solutions, RC_{ss} can be determined from *EC* measurements as follows:

$$RC_{ss} = k(EC_{ss} - EC_{bg}) \quad (3)$$

where k is the slope of the relation between *RC* and *EC*, and EC_{bg} and EC_{ss} are the electrical conductivities of streamwater at background (i.e., prior to injection) and at steady state (i.e., *EC* remains constant in time).

An ideal reach begins upstream of a flow constriction and contains no pools or backwater areas below.

Combining Equations (2) and (3), discharge can be computed as:

$$Q = \frac{q}{k(EC_{ss} - EC_{bg})} \quad (4)$$

To apply Equation (4), we need to measure the injection rate of salt solution, q, and the background and steady state values of *EC*, and to construct a calibration curve of *RC* versus *EC* to derive k. Table 1 lists the equipment required.

Choice of a Measurement Reach

To apply the technique successfully, find a stream reach that features complete lateral mixing in a short distance (Moore 2004b). Longer reaches require a longer injection duration (and thus volume of salt solution) to achieve steady state. Selected reaches should have as little pool volume as possible, because the slow exchange of tracer within the pool volume will greatly increase the time to achieve steady state. An ideal reach begins upstream of a flow constriction (e.g., where the flow narrows around a boulder, promoting rapid lateral mixing) and contains no pools or backwater areas below. A rough guideline is that the mixing length should be at least 25 stream widths, but complete mixing may require much longer or shorter distances, depending on stream morphology. Culverts can be convenient measurement locations if large cobbles are positioned in the flow just below the upstream (input) end to promote lateral mixing within the culvert.

Methods of Injection

Several methods are available for injecting solution at a constant rate, including siphons (Johnstone 1988), battery-powered pumps (Elder *et al.* 1990), and Mariotte bottles (Mellina *et al.* 2002; Story *et al.* 2003). For small streams, a Mariotte bottle constructed from a 10-L carboy with spigot works well for injecting the tracer (Figure 1). The 10-L carboy holds an adequate volume of solution appropriate for small streams, and fits into a large backpack for hiking to remote sites. Also, it does not require batteries and has no mechanical parts. A companion article (Moore 2004a, this publication) describes the

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construction and application of a Mariotte bottle.

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Figure 1. Mariotte bottle injecting into culvert.

Mixing the Injection Solution

We use NaCl (table salt) because it is inexpensive, readily available, and environmentally benign for the concentrations and durations normally involved in discharge measurement. The salt concentration in the injection solution should be high enough to produce a measurable increase in electrical conductivity while remaining less than the solubility. It should also be low enough to avoid raising the salt concentration in the streamwater above any thresholds associated with negative ecological impacts (Moore 2004b).

If C_s represents the maximum desired salt concentration in the stream (g/L), the corresponding concentration in the injection solution (C_{is}; g/L) can be estimated as

$$C_{is} = (Q_{est} / q)C_s \tag{5}$$

where Q_{est} is an estimate of stream discharge based on the product of estimated width, depth, and velocity. The change in electrical conductivity from background to steady state (ΔEC; S/cm) will be, to a close approximation, proportional to the concentration of added salt:

$$\Delta EC = \beta C_s \tag{6}$$

where β is a proportionality factor, approximately equal to 2100 (µS/cm)/(g/L) at 25°C; the precise value depends on background electrical conductivity (Hongve 1987). For example, a steady-state concentration of $C_s = 20$ mg/L ($= 2 \times 10^{-2}$ g/L) should produce a change in EC of about 42 µS/cm. Combining Equations (5) and (6), we can estimate the salt concentration in the injection solution that would be required to generate a desired change in EC:

$$C_{is} = (Q_{est} / q)\Delta EC / \beta \tag{7}$$

The injection solution does not need to be made with local streamwater. If site access is easy, it is often useful to premix the solution to allow generous time for dissolution. The accuracy of the method critically depends on the *complete* dissolution of the salt. For strong solutions, decanting is advised to minimize the presence of undissolved salt.

When mixing the injection solution in the field, we use pre-weighed bags of salt (typically 10 to 100 g per bag, depending on the flows to be gauged) to allow for flexibility in the volumes and concentrations. The concentration of salt need not be precisely controlled, since calibration is expressed as the volumetric concentration of tracer solution in streamwater, not the mass concentration of salt in the streamwater.

Determining *k* by Calibration

Steps:

1. Create a secondary solution by mixing X mL (typically 5 or 10 mL) of injection solution with a measured volume V_0 of streamwater (typically 1000 mL, but different volumes can be used). Use of streamwater for mixing the calibration solution is necessary. This solution will have a relative concentration, RC_{sec}, given by

$$RC_{\mathrm{sec}} = \frac{X}{V_o + X} \tag{8}$$

for $X = 10$ mL, $V_0 = 1000$ mL, $RC_{sec} = 9.90 \times 10^3$.

2. Measure a volume V_c of streamwater (typically 1000 mL, but greater volumes allow for greater dilution) into a "calibration tank," a beaker or pail dedicated for this use. The calibration tank must be clean, and have never carried a strong salt solution because residual salt will bias the calibration. Even though most electrical conductivity probes will adjust EC to a standard value of 25°C, the calibration tank should be immersed in streamwater (e.g., in a shallow pool at the stream's edge), to minimize temperature changes during the calibration. A "corral" constructed from cobbles helps to hold the calibration tank in place.

3. Measure the initial conductivity, EC_0, in the calibration tank. This EC will correspond to $RC = 0$.

4. Use a pipette to add a known amount of the secondary solution to the calibration tank (e.g., 2 mL). Separate pipettes for the injection and secondary solutions must be used to avoid contamination. Mix thoroughly and record the EC and water temperature.

5. Repeat step 4 until the mixed EC in the calibration tank exceeds EC_{ss}. At each step, compute the relative concentration as

$$RC = \frac{RC_{\mathrm{sec}}\ \Sigma y}{(V_c + \Sigma y)} \tag{9}$$

where Σy = the cumulative amount of secondary solution added to the calibration tank (mL).

Use at least three additions of secondary solution, even if EC_{ss} is exceeded on the first or second addition, to allow a check on the linearity of the calibration and to protect against errors that could occur undetected if only one addition were used (as in the calibration procedure described by Elder *et al.* 1990).

Start out using additions of 2 mL of secondary solution. If the resulting change in *EC* is small relative to the difference $EC_{ss} - EC_{bg}$ (i.e., it would take many additions to cover the range), then the volume of additions can be increased to 5 or 10 mL.

6. Using the *RC* – *EC* data from steps 3 to 5, fit a straight line to the points and find its slope, *k*. Alternatively, for field computation, the slope can be estimated as

$$k = \frac{RC_f}{EC_f - EC_o} \qquad (10)$$

where RC_f is the relative concentration for the final calibration mixture, and EC_f is the corresponding electrical conductivity.

Summary of Field Procedures

Table 1 lists the equipment required. Steps in conducting a measurement are as follows.

1. Select the reach to be measured.
2. Record the background *EC* and water temperature at the downstream end of the mixing reach, as well as upstream of the injection point.
3. Measure a volume V_o of water using the volumetric flask and pour into the secondary solution bottle.
4. Measure a volume V_c of water using the volumetric flask and pour into the calibration tank.
5. Immerse the calibration tank in a shallow pool at the stream's edge, downstream of the measurement point.
6. If using a Mariotte bottle set up on a tripod within the stream to inject the salt solution, set up the tripod at the injection point, then remeasure *EC* at the downstream end of the reach to ensure that setting up the tripod has not altered the background conductivity.
7. Begin constant-rate injection, and observe *EC* at the downstream end of the mixing reach. When *EC* appears to level out, measure it across the section to check for lateral mixing. If *EC* varies across the stream, try moving farther downstream. If there are large pools downstream, and it appears unlikely that complete lateral mixing will occur, note the highest and lowest *EC* values across the stream. You can use these values to estimate a "most likely" value for EC_{ss}, as well as to estimate error bounds.
8. After you have recorded EC_{ss} and the water temperature, measure the injection rate using a graduated cylinder and stopwatch.
9. Retain some of the injection solution in a 60-mL Nalgene bottle, then turn off the Mariotte bottle.
10. Determine *k* using the procedure described previously, then compute the discharge by Equation (4).

Table 1. Equipment list

Item	Purpose
Siphon, pump, or Mariotte bottle	injecting at a constant rate
1-L volumetric flask	measuring streamwater
1-L plastic graduated cylinder	providing backup in case volumetric flask breaks
Plastic measuring cup with handle	pouring streamwater into volumetric flask
Squirt bottle	topping up streamwater in volumetric flask
60-mL Nalgene bottle	taking a sample of injection solution for pipetting
5- and 10-mL pipettes[1,2]	measuring injection solution to mix secondary solution
Pipette filler (rubber squeeze bulb)	drawing water into pipettes
2-L wide-mouth plastic water bottle	mixing the secondary solution
2-L plastic beaker or pail	calibrating tank
2-, 5-, and 10-mL pipette[1,2]	measuring secondary solution
Plexiglas rod or tubing, 30 cm long	stirring in calibration tank
100-mL graduated cylinder	measuring injection rate
Stopwatch	measuring injection rate

[1] Separate sets of pipettes need to be used for measuring the injection and secondary solutions.

[2] Spare pipettes should be carried in case of breakage in the field. Alternatively, 10-mL plastic graduated cylinders or graduated pipettes could be carried as a backup.

Example

The following example is from measurements made on a stream near Takla Lake, B.C. The injection solution was mixed using approximately 300 g of NaCl in 6 L of water. The secondary solution was mixed from 10 mL of injection solution and 1 L of streamwater. The injection rate was $q = 1.53$ mL/s.

The calibration data are summarized in Table 2. The volumes V_o and V_c were both 1000 mL. From a regression of *RC* against *EC*, the slope of the *RC* – *EC* relation was $k = 1.23 \times 10^{-5}$ cm/µS.

$$Q = \frac{q}{k(EC_{ss} - EC_{bg})} = \frac{1.53 \cdot 10^{-3}\, L/s}{(1.23 \cdot 10^{-5}\, cm/\mu S)(221\, \mu S/cm - 206\, \mu S/cm)} = 8.3\ L/s$$

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Table 2. Calibration data for example

Vol. of secondary added (mL)	Cumulative vol. of secondary added ($\Sigma\gamma$) (mL)	Electrical conductivity (*EC*) (µS/cm)	Relative concentration (*RC*) (L/L)	T (°C)
0	0	206	0.0	14.7
5	5	210	4.93×10^{-5}	14.6
5	10	214	9.80×10^{-5}	14.6
5	15	218	1.46×10^{-4}	14.6
5	20	222	1.94×10^{-4}	14.6
5	25	226	2.41×10^{-4}	14.6
5	30	229	2.88×10^{-4}	14.5

Errors and Limitations

Two key requirements for accurate measurements are that (1) the salt in the injection solution be completely dissolved, and (2) the injection solution be fully mixed across the channel. In addition, discharge should not change appreciably during the injection trial.

Errors may arise through inaccuracies in measuring the volumes of streamwater, injection solution, and secondary solution. These errors can be effectively minimized if a volumetric flask is used to measure streamwater and if glass pipettes are used to measure the injection and secondary solutions. However, take plastic ware into the field as a backup in case of breakage. The accuracy of the calculated discharge is directly related to the accuracy of the injection rate. To reduce the magnitude of this source of uncertainty, conduct several measurements and average them.

> *Errors may arise through inaccuracies in measuring the volumes of streamwater, injection solution, and secondary solution.*

Another source of uncertainty is in measuring the difference in *EC* between background and steady state. In the previous example, the uncertainty in the difference will be ±1 µS/cm relative to a difference of 15 µS/cm, or about ±7%. This error could be reduced by injecting at a higher rate or using a more concentrated injection solution to effect a greater *EC* at steady state. Equation (7) could be used to estimate the desired concentration (assuming a fixed injection rate).

We have used constant-rate salt injection to measure flows from 1 to 100 L/s. For higher flows, the main limitation is the ability to inject tracer at a sufficient rate and duration to achieve steady state with a measurable change in *EC*. Higher flows may be gauged by using a larger carboy, floating siphon, or pump equipment, or alternative methods such as slug injection. For example, Johnstone (1988) measured flows up to 100 m^3/s using a floating siphon. However, that approach is not feasible for remote sites accessed by foot.

At low flows, hyporheic exchange may complicate measurements through the infiltration of streamwater into the bed or banks and re-emergence some distance downstream. Consequently, streamflow gauged by salt injection would measure not only flow within the channel, but also an additional component flowing in the subsurface. Thus, salt dilution measurements may not be comparable to methods that gauge surface flow in the channel such as a current meter or other volumetric method.

Rainfall can influence the measurements in two ways. First, unless the calibration tank is sheltered, rain falling into it may dilute the concentrations below the calculated values, producing biased calibrations. Second, rain may generate stormflow, resulting in altered discharge and background *EC*. Subsequently, *EC* may not achieve a clear plateau, resulting in uncertainty. The hydrologic response, however, will depend greatly on characteristics such as soil depths, textures, and moisture content, so generalizations cannot be made.

Acknowledgements

Solvej Patschke, Anthony Story, Eric Mellina, and Matt Gellis helped me experiment with variations on the constant-rate salt injection method. Michael Church, Greg Henderson, Robin Pike, and an anonymous reviewer provided constructive comments on earlier drafts. However, any errors remain the sole responsibility of the author.

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Construction of a Mariotte Bottle for Constant-rate Tracer Injection into Small Streams

R.D. (Dan) Moore

Liquid tracers are commonly injected into streams to measure streamflow, hydraulic characteristics, and rates of nutrient uptake (e.g., Webster and Ehrman 1996; Story *et al.* 2003). A Mariotte bottle, based on a device developed by the French physicist Edme Mariotte in the 17th century, provides a simple method for injecting tracer at a constant rate. This article describes the construction and application of a Mariotte bottle appropriate for injecting tracer into small streams.

Construction

A simple Mariotte bottle can be constructed from a carboy fitted with a spigot (Figures 1 and 2; Table 1). A 10-L carboy holds a sufficient volume of tracer for gauging small streams at low flow, and fits into a large backpack for transport to remote field sites. We have measured flows as low as 1 L/s and as high as 100 L/s using a Mariotte bottle (e.g., Mellina *et al.* 2002; Story *et al.* 2003).

D. Moore

Figure 1. Materials required to construct Mariotte bottle. From left to right: 10-L carboy, pipette tip, Quick Disconnect Connector, rubber stopper with Plexiglas tube inserted.

To construct the Mariotte bottle, the screw-on cap is replaced by a size 13½ one-hole rubber stopper with a length of Plexiglas tube inserted to a level about 10 cm higher than the spigot level. The tube should be inserted such that it remains below the surface of the tracer fluid (as shown in Figure 2) throughout the measurement period; otherwise, tracer solution will not discharge at a constant rate. The tube allows air to enter as water drains, thereby maintaining a constant water pressure at the spigot, resulting in a constant outflow rate. The lower end of the tubing should be cut on a bevel, to facilitate bubbling.

The spigot is fitted with a tubing connector and pipette tip with the end cut off. The non-tapered end of the tubing connector fits snugly into the spout of the carboy, and the pipette tip is slid over the tapered end of the connector. This set-up "steps down" the outflow rate, and allows the spigot to be opened fully for delivery of tracer while controlling the injection rate. Several pipette tips with a range of hole diameters allow for a range of injection rates. It is important that the outflow be a continuous stream rather than discrete drips. If the water drips out, air will enter and create an inconsistent outflow rate.

Application

The Mariotte bottle can be set up on a square of plywood fixed to the top of a tripod, to provide a stable base for the bottle. If the stream is narrow, it may be possible to have the tripod legs span the stream.

After setting up the Mariotte bottle, open the spigot to begin injection. When the spigot is first opened, the

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Table 1. Equipment list

Item
10-L carboy (Nalgene no. 2318-0020)[1]
Quick Disconnect Connector (Nalgene no. 6150-0010)[1]
Pipette tip (100- to 1000-L volume)
13½ one-hole rubber stopper
40 cm length of Plexiglas tubing (5 mm outside diam.)
Tripod with plywood square

[1] Nalgene part numbers provided purely for reference. No specific endorsement of Nalgene parts relative to alternative manufacturers is intended or should be implied.

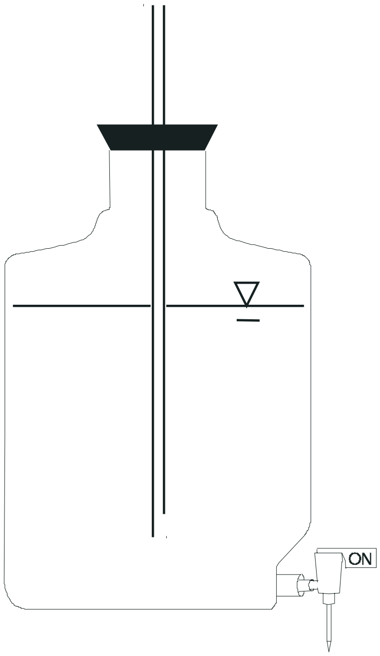

Figure 2. Schematic of assembled Mariotte bottle.

injection rate will be higher than the ultimate steady-state rate until air begins bubbling through the air entry tube. Once “bubbling” begins, the injection rate will be constant. Bubbling can be detected by listening for the distinctive “gurgling” sound that occurs every few seconds. Because the Mariotte bottle will initially drain at a rate higher than the steady-state constant rate, the measured tracer concentration in the stream (e.g., as measured by electrical conductivity for salt injection) may initially overshoot and then settle down to the steady-state value. To avoid this, a bucket can be used to catch the injection solution until constant flow is established.

The injection rate (q) can be measured using a 100-mL graduated cylinder and a stopwatch. It is important to measure q in the field, since the injection rate via the pipette tip varies with temperature. In addition, the outflow rate is influenced by the orientation of the pipette tip, which depends on the inclination of the support base for the Mariotte bottle, and on the height of the lower end of the bubbler tube. Several trials should be conducted to obtain an average outflow rate. Repeated measurements also allow estimation of the uncertainty for use in error analysis.

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Profile

Dr. Markus Weiler: A New Face in B.C. Hydrology

How and when do hillslopes contribute to streamflow in watersheds? How does residence time of water draining a watershed affect flow pathways and storage as well as water quality? How do natural and human disturbances in forested watersheds change the properties of soils and hence infiltration characteristics and flow paths of water? These are some of the questions that Dr. Markus Weiler, Assistant Professor in the Departments of Forest Resources Management and Geography at the University of British Columbia (UBC), and FRBC Chair in Hydrology since January 2004, is currently investigating.

Dr. Weiler completed his Ph.D. at the Swiss Federal Institute of Technology (ETH) in Zurich, Switzerland in 2001. His dissertation dealt with the experimental identification and numerical modelling of flow in natural soils, to evaluate the effects of macropore flow on runoff generation and to predict flow pathways in watersheds. While at ETH, Markus also collaborated on various consulting projects related to stochastic hydrology, flood hydrology, and impacts of environmental changes on surface and subsurface hydrology.

Weiler spent the last two years in the United States as a postdoctoral researcher in the Department of Forest Engineering at Oregon State

University (OSU). There he worked with Jeff McDonnell on projects dealing with runoff generation in forested catchments, hydrologic processes at the hillslope and plot scales, and impacts of forest management and forest fire on runoff and nutrient dynamics in the Pacific Northwest (PNW). Working at OSU has provided him with valuable insights into the issues and conflicts related to forestry activities in the PNW. “In Europe, I was taught to work in a completely human-influenced environment,” he observes. “Working in the PNW is different—it’s much like researching a natural environment and dealing with the conflicts between humans and nature.”

> *“A constructive dialogue between field hydrologists and the hydrologic modelling community will be a key element to better understand the complexity of water flow and solute transport in watersheds.”*

M. Weiler

M. Weiler transporting flume.

As FRBC Chair in Hydrology, Weiler has started to develop a research program collaborating with both government and industry. He is now working on a project with Dr. Younes Alila, several partners from the forest industry, and the B.C. Ministry of Forests regarding how to move beyond the equivalent cut area approach in the B.C. Interior. He is also actively pursuing funding from NSERC for a project to better understand water and solute response in different runoff generation processes. In addition, he is participating in a USDA-funded research project addressing the topographic, hydrologic, and soil biogeochemical controls on CO_2 generation and efflux in watersheds.

A challenge for Weiler is to combine knowledge of detailed hydrologic process at the plot and hillslope scales with the apparently simpler, integrated responses at the watershed scale. Most hydrologists agree that understanding hydrologic processes on all scales is a prerequisite for prediction, especially in ungauged basins. However, the dilemma is how to link detailed process knowledge and observed non-linear behaviour in small-scale hillslopes to the myriad of simultaneously occurring hydrologic processes within large-scale watersheds. To answer these questions, he is following a parallel approach, where obtaining a detailed understanding of small-scale processes guides the development of distributed hillslope models that integrate the complexity of the plot scale (e.g., preferential flow), and large-scale observations. Depending on the temporal and spatial scales, Markus incorporates isotope techniques, artificial tracing techniques, nutrient dynamics, and temperature variation studies. Weiler comments that “a constructive dialogue between field hydrologists collecting data and process information and the hydrologic modelling community will be a key element to better understand the complexity of water flow and solute transport in watersheds.”

In addition to research, Weiler lectures on hydrology and watershed processes at UBC. He is also developing a graduate course on tracer methods in hydrology. This course will address how natural and artificial tracers can be used to better grasp processes in soils, hillslopes, watersheds, and streams. Dr. Weiler is incorporating both field experiences and up-to-date computer simulation and modelling into his teaching. “I am fascinated by field observation, where we can conceptualize how hydrology really works,” he notes. Weiler also hopes to revitalize and extend the graduate program of Interdisciplinary Hydrology at UBC. “The water cycle sustains life and a habitable environment by transporting mass, energy, and substances,” he argues. “Thus hydrology should be one of the key elements connecting geo- and biosciences with engineering and social science.”

M. Weiler

M. Weiler installing v-notch weir in culvert.

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Upper Penticton Creek: How Forest Harvesting Affects Water Quantity and Quality

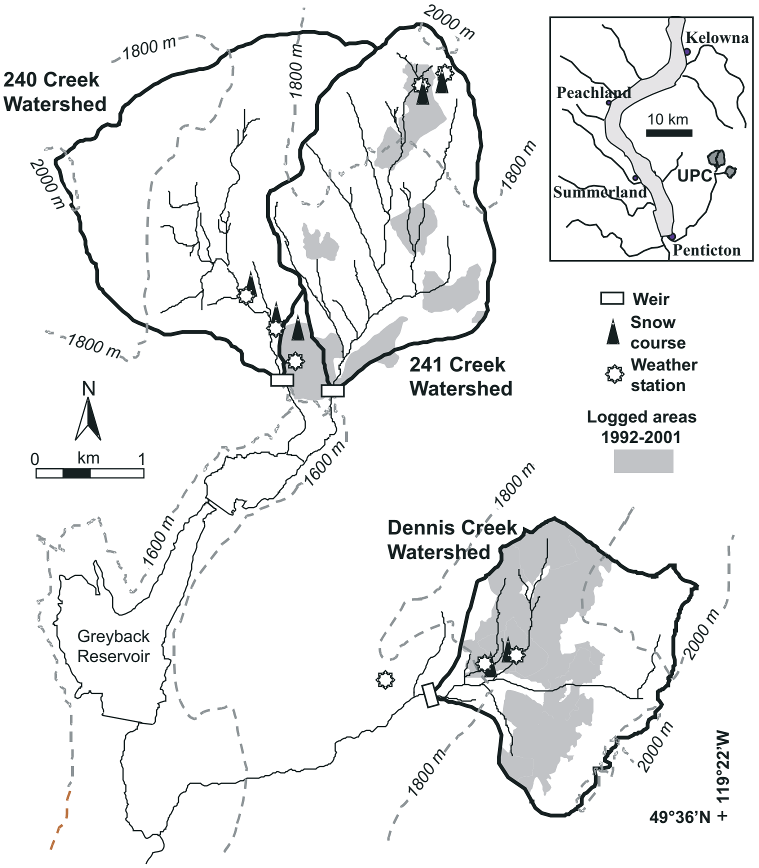
Rita Winkler, Dave Spittlehouse, Tim Giles, Brian Heise, Graeme Hope, and Markus Schnorbus

A continuous supply of high quality water is essential for domestic use, agriculture, industry, recreation, and aquatic life. Concerns about the sustainability of water supplies in the dry south-central Interior and the potential effects of forest land use on aquatic resources led to the establishment of the Upper Penticton Creek Watershed Experiment in 1984. From the initial streamflow and summer weather measurements, the experiment has grown to include a network of all-season weather stations, snow survey sites, channel monitoring sections, water balance installations, aquatic habitat surveys, and water quality measurements. Now an inter-disciplinary, multi-agency experiment with both control and treatment watersheds and pre- and post-logging measurements, it is the only experiment of its kind in the B.C. Interior and one of eight in Canada (Buttle *et al.* 2000).

At Upper Penticton Creek, researchers investigate the long-term effects of logging and forest regrowth on water quality and quantity, and on aquatic habitat. As well, they examine immediate operational questions related to changes in snow accumulation and melt with forest harvesting and regrowth, the effects of forest clearing on stream temperature, and modelling to predict potential changes in peak flows with increasing clearcut area. This article outlines the experiment and summarizes research results that were presented at a February 2004 workshop in Kelowna.

Upper Penticton Creek

The Upper Penticton Creek Watershed Experiment includes the watersheds of 240, 241, and Dennis creeks, three small headwater tributaries to Penticton Creek approximately 26 km northeast of Penticton, B.C. The watersheds are gently sloping, approximately 5 km^2 in size, and range in elevation from 1600 to 2150 m. The 240 and 241 Creek watersheds are oriented to the south while Dennis Creek flows to the west. The watersheds are forested with lodgepole pine (*Pinus contorta* Dougl.), and mixed Engelmann spruce (*Picea engelmannii* Parry) and subalpine fir (*Abies lasiocarpa* [Hook.] Nutt). During the last decade, annual precipitation has varied from 580 to 840 mm, of which approximately half fell as snow. Winter air temperatures occasionally drop to –20°C while summertime high temperatures can reach the upper 20s. From 0.8 to 3 million m^3 of water flow from each watershed annually, amounting to between 30 and 60% of the annual precipitation. The highest peak flows, which occur in May during mid- to high-elevation snowmelt, can reach



Upper Penticton Creek: Stream network, monitoring stations, and harvested areas in the 240, 241 and Dennis Creek watersheds.

Map Source: MoF Southern Interior Forest Region, D. Spittlehouse


R. Winkler

Surveys of snow depth and water content in forest and clearcuts occur regularly during late winter and early spring.

1.5 m^3/s, about 0.1 million m^3 of water in a day.

The experiment follows a paired watershed design that includes pre-disturbance environmental monitoring in all study basins. Under this experimental design, one (or more) watershed is logged while another remains undisturbed as a control. Environmental monitoring continues in all watersheds throughout the experiment. This design enables researchers to separate post-disturbance changes related to the weather from those caused by logging. At Upper Penticton Creek, the 241 and Dennis Creek watersheds were logged in several passes, beginning in the winter of 1995, with four years between passes. Approximately 10% of the area in each watershed has been harvested in each logging pass, totalling 20% overall. Conventional feller-buncher and skidder logging techniques have been used throughout the experiment. The 240 Creek watershed has remained unharvested, as the control. By late 1999, a spruce beetle outbreak had killed many trees in the Dennis Creek watershed. These trees were subsequently logged in the winter of 1999 to 2000. At present, 30% and 53% of the 241 and Dennis Creek watersheds, respectively, have been logged. The effects of this level of cut will be measured for at least five years.

Water Quantity

Four years of post-20% logging streamflow measurements in 240 and 241 Creeks were completed in 2002. We have found that the 20% harvest in the 241 Creek watershed has had a minimal effect on peak streamflow and annual water yield. However, streamflow response to fall rains appears to have increased even at this low harvest level. Changes in daily peak flows as predicted by the Distributed Hydrology Soil-Vegetation Model (DHSVM) at 20% harvest were less than 5% for frequent events (i.e., those having a recurrence interval of 10 years or less for model output). Modelling results further suggest that increases in peak flows of up to 10% can be expected for infrequent events (i.e., those having a 50-year recurrence interval). Modelling of peak flow for more extensive harvesting indicates that the maximum increase expected is less than 50% regardless of the extent of forest cover removal. This result is thought to reflect hydrologic processes in gently sloping topography such as that in the 241 Creek watershed. The field measurements and analysis of streamflows post-30% and post-53% logging are continuing.


R. Winkler

Visitors discuss forest hydrology during a tour stop at the 240 Creek weir.

Water Quality and Aquatic Habitat

Water quality in our study streams remains high. Small increases in stream nitrate-nitrogen were measured during peak flows after the extensive spruce beetle salvage in the Dennis Creek watershed. All stream nitrogen concentrations were low (<0.5 mg/L) in comparison to the drinking water standard (10 mg/L). No significant change was measured in stream nitrogen in 241 Creek at the 20% harvest level. Other chemical water quality data are also being analyzed.

Elevated concentrations of suspended sediment are observed each year when streamflow increases in spring. These sediments largely originate at road–stream crossings and from ditches. However, because of limited supply in the experimental watersheds, sediment concentrations peak well before maximum spring streamflows. Elevated sediment concentrations were also observed during fall rains, during and immediately after the extensive spruce beetle salvage in the Dennis Creek watershed. At no time did sediment concentrations exceed 20 mg/L and

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were most frequently lower than 5 mg/L.

Maximum, minimum, and mean 241 Creek stream temperatures in the clearcut reach were approximately 9, 2, and 6°C higher, respectively, than in the forest above the clearcut. Current research is comparing stream temperatures over a similar elevation gradient in the unlogged 240 Creek and downstream of the openings along 241 Creek.

The aquatic invertebrate communities of 240, 241, and Dennis creeks are dominated by Diptera (primarily chironomids). Following logging, aquatic biodiversity stayed constant or increased. Primary feeding groups changed from shedders to scrapers as the food supply changed from leaves to algae.

Interception and Evaporation

From 20 to 30% of the rainfall is intercepted by trees and evaporates, the percentage decreasing with increasing storm size. About 30% of the total summer evaporative water loss from the forest is by interception whereas 70% is by transpiration. Daily transpiration on sunny days during the summer varies from 5 to 50 L per day depending on tree size. There is about 30% less evaporation from recent clearcuts than from the forest. In the winter, forest interception of snowfall results in 15–30% greater accumulations of snow in the clearcuts relative to lodgepole pine and mixed spruce–fir stands, respectively. Snow in the open melts 1.3–1.5 times faster than in the forest. Snow surveys at high, mid, and low elevations have shown that clearcutting has synchronized melt runoff from high-elevation openings with melt from low-elevation forests. Once this change occurs over a large enough proportion of the watershed, changes in the pattern of spring runoff are expected.

R. Winkler

Weather station near the top of 241 Creek watershed.

Summary

The post-20% harvest data for Upper Penticton Creek demonstrate that any changes in water quantity and quality related to the treatment were small at the watershed scale. However, our results also illustrate that changes in forest cover at the stand scale can affect individual hydrologic processes and highlight the importance of protective riparian zones around small headwater streams. Maintaining riparian vegetation will reduce the potential for elevated stream temperatures and sediment delivery to stream channels. Locating roads away from channels and minimizing the number of stream crossings can further reduce sediment delivery to streams.

Post-20% harvest data for Upper Penticton Creek demonstrate that any changes in water quantity and quality related to the treatment were small at the watershed scale.

Although in its 20th year, the Upper Penticton Creek Watershed Experiment continues to evolve as more is learned about how Interior snowmelt-dominated watersheds function. Future work at Upper Penticton Creek includes assessment of 30%- and 50%-cut effects on streamflow and water quality. Other new studies will focus on hillslope processes and flow routing, hydrologic modelling, and the development of operational guidelines. More information about our research can be obtained from the lead author or at:

http://www.for.gov.bc.ca/rsi/research/Penticton/index.htm

Acknowledgements

The Upper Penticton Creek Watershed Experiment involves many agencies and individuals, including: Weyerhaeuser Co. Ltd.; Gorman Bros. Lumber Ltd.; the B.C. Ministries of Forests, Sustainable Resource Management, and Water, Land and Air Protection; the B.C. Forest Science Program; Water Survey of Canada; the City of Penticton; Caro Environmental Services; Dobson Engineering Ltd.; Skyline Forestry; ALO-Resources; FORREX; Okanagan University College; the University College of the Cariboo; and the University of British Columbia.

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A Paradigm Shift in Watershed Restoration

Dave Heller

Editor's Note: The following paper was presented as part of SER 2004, the International Society for Ecological Restoration's 16th annual conference, held in Victoria B.C., Canada, Aug 24-26, 2004. For further information on this event, see http://www.serbc.info/public/ser_seminar

Watershed and stream restoration on National Forest System (NFS) lands of the Pacific Northwest have changed dramatically in the past decade. A new paradigm for the restoration of riparian and aquatic ecosystems has quietly emerged. It reflects substantial improvements in the understanding of ecosystem- and watershed-scale dynamics and involves the development and implementation of new management strategies for riparian and aquatic resources.

The primary driver for many changes has been the implementation of a comprehensive Aquatic Conservation Strategy (ACS). The ACS, which is part of the Northwest Forest Plan (Plan) (USDA *et al.* 1994), emphasizes ecosystem management at the landscape scale. It is science-based and provides for comprehensive and consistent protection and restoration across more than 24 million acres (about 10 million hectares) of NFS land in Oregon, Washington, and northern California. The ACS replaces 20 individual forest plans that varied substantially in their content, approach, and quality of management direction for riparian and aquatic resources.

Aquatic Conservation Strategy (ACS)

The ACS has four components that are implemented in a co-ordinated manner to achieve aquatic and riparian ecosystem health described by nine ACS objectives. These objectives address a variety of physical and biological processes including: timing and duration of streamflow; physical and biological connectivity; and introduction/routing/storage of large wood and sediment, plant/animal species, and habitat diversity. The four ACS components are as follows:

1. Riparian Reserves

Land and water areas are managed to emphasize the sustained production of riparian-dependent resources (fish, water, certain species of plants and animals, etc.). Riparian reserves apply to lands adjacent to all streams (perennial and intermittent/ fish and non-fish bearing), lakes, reservoirs, springs, wetlands, and unstable slope areas likely to affect riparian and aquatic ecosystems.

2. Key Watersheds

A network of watersheds are managed as refugia for fish stocks at risk, and for the continued production of high quality water critical to downstream habitat. These watersheds represent the best remaining, or most readily restorable, aquatic habitat in the plan area.

3. Watershed Analysis

Ecosystem conditions are examined at the watershed scale (20,000–200,000 acres or 8,000–80,000 hectares). The mid-level analysis offers an interdisciplinary diagnosis of watershed health comparing current resource conditions to reference conditions and identifying key processes likely responsible for major gaps between the two. The analysis gives watershed-scale context for future management and an initial strategy for the restoration of watershed conditions to benefit aquatic- and riparian-dependent resources.

4. Watershed Restoration

A comprehensive, long-term program guides watershed-scale restoration of aquatic resources. Restoration activities focus on those watersheds most likely to positively respond to treatment. Identification and completion of high priority work are emphasized. Watershed analysis is completed before any restoration activity is begun.

The Restoration Strategy focused activities on a few high priority watersheds and "secured" or "stormproofed" them by removing risk factors.

The Restoration Strategy changed the approach to aquatic restoration. First, it focused activities on a few high priority watersheds and "secured" or "stormproofed" them by removing risk factors (e.g., unstable roads, areas of severe erosion). Second, before the implementation of any restoration activity, a watershed-scale analysis is required to identify key processes and watershed areas needing attention, and prioritize timing of future treatments. The requirements for Watershed Analysis broadened the scale of analysis and planning for restoration. Interdisciplinary teams were forced to identify key processes controlling conditions and to design treatments for root causes of altered conditions.

Finally, the Strategy provided the framework to treat whole watersheds with an integrated set of watershed-scale restoration treatments (roads: drainage and/or

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stabilization, decommissioning, fish passage, upslope-surface erosion, and slope stabilization; riparian areas: fencing, planting, silvicultural treatments, large wood introduction and instream creation and complexing of habitats, bank stabilization, nutrient supplementation, etc.). Although these and other changes may seem trivial today, they reflected a cutting-edge approach when they were introduced. These changes fostered lively debate and dramatically shifted organization and delivery of the restoration program. Table 1 summarizes changes to aquatic restoration since the Plan was implemented in 1994.

Major road fill before removal. Road restoration activities, especially decommissioning, stabilization, and fish passage, are a major element of the Restoration Program and account for nearly 60% of annual restoration funding.

D. Heller

Major road fill after removal as part of decommissioning project. Fill removal allows reconnection of streams and significantly reduces future risk of wash and maintenance costs tied to major storm events.

In the 10 years of implementing the Restoration Strategy, much has been accomplished. Annual funding has averaged about $15 million per year. Roughly 60% of these funds have gone into road-related treatments, particularly decommissioning, stabilization, and fish passage improvement with a focus on "stormproofing." Riparian and instream works have accounted for about 30% of the funding. Much of this work is centred on increasing the complexity of aquatic habitats and floodplains by adding large wood. The remainder of the funding has been used for upslope treatments (slope stabilization, soil decompaction, reforestation, etc.). To date, high priority work for 21 watersheds, each having an area of 25,000–50,000 acres (10,000–20,000 hectares), has been "completed." This accomplishment, although appearing simple, represents a major shift in the focus and delivery of the restoration program.

Table 1. New versus old paradigms for restoration of aquatic- and riparian-dependent resources

New	Old
1. The "best" watersheds are treated first. Highest priority treatments remove risk factors that may threaten the integrity of the watershed.	1. The "worst" watersheds are treated first. Highest priority is to create desired habitat conditions for stream segments/sites in the worst condition.
2. Efforts focus on a few priority watersheds.	2. Treatments tend to focus on stream segments or sites. They are scattered over several watersheds.
3. Watershed analysis precedes project work, identifies key processes, and prioritizes areas and associated treatment approaches that address "causes."	3. Analysis is generally limited to the project scale, and to addressing site-scale conditions. Treatments address "symptoms."
4. A wide range of treatments are generally integrated at a watershed scale and sequenced based on an overall work plan.	4. A narrow range of treatments usually focus on individual sites. They are not integrated at the watershed scale.
5. Highest priority work is completed in a watershed before work emphasis shifts to the next priority watershed.	5. Highest priority work is completed on individual areas or sites located in a number different watersheds.
6. Partnerships are an essential part of restoration. Skills and resources are strongly leveraged.	6. Partnerships are limited in number and scope. There is some leveraging of skills and resources.

Partnerships

Key to the watershed restoration paradigm shift have been partnerships with a wide variety of groups including: federal, state, and local agencies; tribal governments; non-governmental organizations; foundations; local communities; and landowners. The diversity of partners often allows consideration and treatment of priority sites throughout a watershed regardless of land ownership. Partnerships also provide for significant leveraging of skills and resources. On average, two to three dollars of partner funding are available for every one dollar of USDA Forest Service funding. Partners also frequently assist with/conduct monitoring and maintenance of completed work.

> *There is also a growing focus on setting up the conditions for stream processes to create the desired conditions rather than directly engineering them.*

In the last few years, instream restoration protocols have also changed, with a more strategic approach to the selection of treatment sites at the watershed scale. Currently, more attention goes into locating low-gradient, unconstrained areas with complex aquatic and riparian habitats, ensuring longitudinal connection to other areas of the stream channel, and lateral connection to the active floodplain and off-channel habitats. Treatments that once emphasized neat, engineered, well-ballasted, and/or anchored structures are now being replaced by the unanchored complexes of whole trees and large wood. As a result current instream work often appears "messy." These treatments are generally located strategically in the stream (geologic "nick" points, old jam locations, alluvial "hot spots" for fish production). There is also a growing focus on setting up the conditions for stream processes to create the desired conditions rather than directly engineering them. This often entails treating areas outside the low-flow (wetted perimeter) channel, including large areas of the active floodplain.

Changes to instream restoration philosophies have demanded improved understanding of watershed and stream channel processes. Better analytical skills in various subjects such as hydrology, fluvial geomorphology, silviculture, and hydraulic engineering are prerequisites for most projects. Interdisciplinary planning teams are now critical. As confidence in analytical and operational capabilities has grown, projects have become larger and more demanding. Increasingly these involve reconstruction of severely altered channel/floodplain sections and removal/replacement of road fills and crossings. Table 2 summarizes the paradigm shifts for instream restoration treatments.

Table 2. New versus old paradigms for instream restoration treatments

New	Old
1. Treatments generally consider the full stream channel and include the active floodplain.	1. Treatments are generally limited to the low-flow or summer stream channel.
2. Treatments appear "messy" and are designed to mimic conditions created by natural processes.	2. Treatments are often "neat" and engineered. They are designed to create a specific hydraulic or habitat condition at a site.
3. Treatment materials, such as large wood and boulders, are not anchored or ballasted. Some downstream movement and re-complexing are expected.	3. Treatment materials are generally well ballasted and anchored. Movement from the site of placement is viewed as a "failure."
4. Reconnecting vertical (up and downstream) and lateral (stream channel/off channel/floodplain) access for adult and juvenile fish and other aquatic species is increasingly a priority.	4. Reconnecting access is generally limited to improving vertical (up and downstream) access for adult salmon only.

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Stream before treatment with large woody debris (LWD) to increase habitat complexity and improve stream connectivity with the floodplain.

Stream after treatment. Groupings of LWD pieces are placed at natural collection points. Often they are not anchored and will move short distances, creating complexes that provide excellent habitat.

Conclusion

The current U.S. Watershed Restoration Program is a major improvement from previous efforts on public lands in the Pacific Northwest. The process is more strategic, better integrated, and more likely to contribute to long-term change in watershed and aquatic habitat conditions. The program is part of the ACS, which is based on the premise that active restoration only occurs when linked to a larger set of strategic actions that ensure the protection and passive restoration of watersheds at a broad scale.

Today we are just beginning to see priority restoration work completed for individual watersheds. Although project effectiveness, as well as the overall ACS, is still being monitored, it will likely be some time until the long-term success of the new paradigm shift can be determined.

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Reference

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Low Flows in Snowmelt-dominated Watersheds

Robin Pike and Rob Scherer

Conflicts between water withdrawals and instream uses occur in many watersheds in the southern B.C. Interior. During water shortages, public concerns about forest harvesting and low stream water levels often heighten. A common perception is that timber harvesting causes streams to dry up. This article examines the potential effects of forest management on low flows in snowmelt-dominated regions, and summarizes information presented in a detailed report by Pike and Scherer (2003).

What Are Low Flows?

Low flows are the minimum flow or absence of flow in a stream during the dry season. Low flows are continuous and often characterized by lowest average flow over a defined time interval (i.e., 7-day period each year). Though sometimes confused with drought, low flows are a normal part of the yearly water cycle. Drought is distinct in that it is an unusually long period of minimal to no precipitation sufficient to produce hydrologic imbalances and economic and (or) ecological effects. In snowmelt-dominated regions, the low flow period typically extends from late summer through the winter until spring snowmelt (Figure 1). The low flow period ceases with the melting of the winter snowpack leading to the spring freshet.

Low flows are important for many reasons. Water levels can be critical to fish passage in the late summer and can dramatically alter aquatic habitat especially when streams run dry. Low water levels also limit the amount of water that can be withdrawn for agriculture or human consumption, affect recreation, and ultimately affect urban development and commercial activity.

extent of aquifers, the rate, frequency and amount of recharge, the evapotranspiration rates from the basin, distribution of vegetation types, topography and climate" (Smakhtin 2001, p. 149).

Drought and climate change are critical influences on streamflow. Few studies, however, have been able to isolate the direct influence of climate change on low flows. Leith and Whitfield (1998) studied streamflow and climate trends in six watersheds in the B.C. Interior. Their research demonstrated an "earlier onset of snowmelt runoff followed by an increasingly long and dry summer, with the possibility of water shortages in late summer" (Leith and Whitfield 1998, p. 230). Increases in winter streamflows observed were attributed to a greater percentage of precipitation falling as rain versus snow.

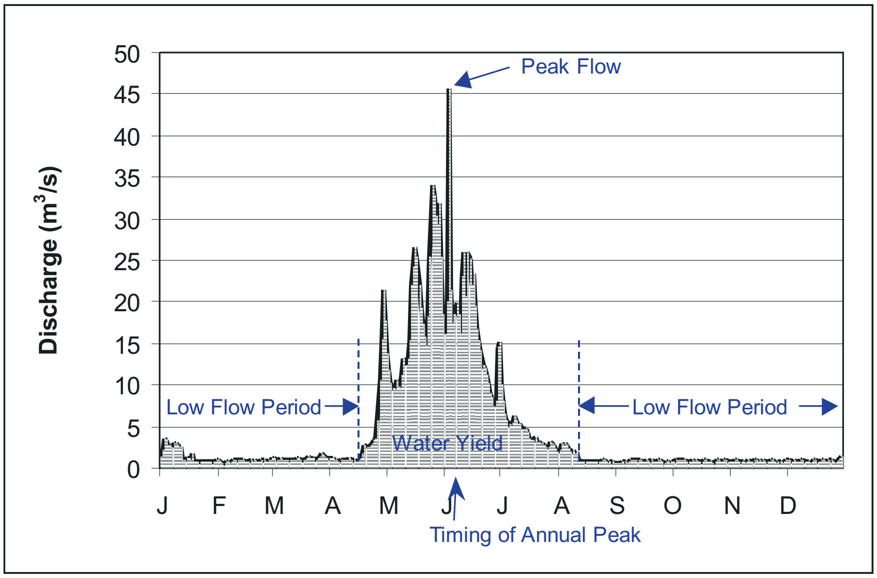

Figure 1. Typical annual snowmelt-dominated hydrograph. Water yield denoted by shaded area under hydrograph. Data source: Environment Canada, Mission Creek, B.C.

What Factors Influence Low Flows?

Low flows are maintained through the release of water from groundwater storage, flow from channel banks, and (or) surface water discharge from lakes and wetlands. In catchments with glaciers, dry-weather flow in late summer and early autumn can be augmented by glacier melt. Factors controlling the magnitude of low flows include "the distribution and infiltration characteristics of the soils, the hydraulic characteristics and

Natural disturbances such as beetle epidemics and wildfires can also influence streamflow, although few studies have examined the sole influence of these change agents. Three studies that address low flow changes associated with beetle epidemics and (or) wildfire

(Bethlahmy 1975; Cheng and Bondar 1984; Potts 1984) all report increases in water levels after disturbance.

Land use and human activities also influence streamflow. Smakhtin (2001) noted that human activities that both increase and decrease low flows in a watershed include:

- groundwater withdrawals;
- drainage of valley-bottom soils for agriculture or construction;
- changes to vegetation communities through clearing or planting leading to modification of evapotranspiration loss;
- urbanization through the creation of impervious surfaces;
- direct river withdrawals;
- irrigation return flow;
- industrial discharge;
- importation of water from outside of the watershed; and
- dams and impoundments.

In southern British Columbia, agriculture, mining, hydroelectric generation, reservoirs, water diversions, and forestry are the major activities that influence streamflow. Multiple factors affecting low flows must therefore be considered when determining the incremental influence of human activities on water levels beyond the natural background state.

Which Hydrologic Processes Does Forestry Affect?

Timber harvesting affects interception, evapotranspiration, snowmelt and accumulation, infiltration, soil moisture, and runoff generation in a watershed.

Interception, Evaporation, and Transpiration

Depending on forest characteristics, a portion of rain and (or) snow will be held in temporary storage on the vegetation surfaces. Interception loss is the portion of precipitation that is returned to the atmosphere by evaporation or sublimation. Numerous studies have shown that coniferous forests can intercept one-quarter of the annual precipitation but that this amount varies by storm size, intensity, duration, and weather conditions (Spittlehouse 1998). In one study in the southern B.C. Interior, Spittlehouse (1998) calculated interception losses (May–October, total precipitation 454 mm) in lodgepole pine and Engelmann spruce–subalpine fir forests to be 24%. Timber harvesting therefore decreases water losses at the site level by reducing the leaf area of a stand, leading to increased amounts of precipitation reaching the forest floor.

Timber harvesting also affects transpiration and evaporation. Transpiration is the movement of water from the ground through plant leaves (stomata) into the atmosphere. In a forested watershed, evaporation commonly occurs from plant surfaces, the ground surface, and open water. Evapotranspiration is a term frequently used to denote the combined "loss" (return) of water to the atmosphere through evaporation, transpiration, and interception. Timber harvesting modifies these processes by removing transpiring trees and by reducing interception losses (evaporation) related to the forest canopy. Overall, "reductions in evapotranspiration increase the amount of water during low flow by: (1) increasing the amount of stormflow during low flow periods; (2) reducing the extraction of soil water that is moving into the channel system; and (3) increasing the amount of water available for deep percolation to recharge soil moisture and groundwater that moves through the mantle to provide baseflow" (Satterlund and Adams 1992, p. 264).

Within a watershed, it is thought that management activities that occur within low flow source areas (i.e., riparian areas) will have a greater influence than those occurring in non-source areas. We use three studies to demonstrate the influence of riparian vegetation on streamflow (low flows), though none of these studies were conducted in snow-dominated catchments. Hicks *et al.* (1991) identified reductions in low flows in two basins, 8 and 15 years after timber harvesting. Reductions were attributed to changes in riparian vegetation to species that used more water. In another study, Berndt (1971) documented the effects of a wildfire on streamflow in three research watersheds in the east Cascade Mountains. Prior to wildfire, streamflow oscillated daily due to transpiration from vegetation rooted in the streamside capillary fringe. After the wildfire, only minor daily oscillations were observed. Berndt found that vegetation removal through wildfire lead to "general elevation of flow rates above extended normal depletion curves" (1971, p. 7). In South Africa, Scott (1999) found that clearing riparian vegetation caused a disproportionately greater gain in water yield than would have resulted from harvesting vegetation in non-riparian areas in the study areas. While the forest types of South Africa are significantly different from British Columbia's, Scott's study further illustrates the potential influence that riparian vegetation has on streamflow. In British Columbia, evapotranspiration "gains" from riparian vegetation removal should be minimal, however, as current forest practices generally designate riparian reserves for zero to limited development within low flow source areas.

Snowmelt and Accumulation

Alteration of forest canopy can also influence snow accumulation and melt (Golding and Swanson 1986; Troendle *et al.* 1988; Hardy and Hansen-Bristow 1990; Winkler 1999). The effects of forest harvesting on snow processes are complex and varied. In general, forest harvesting can produce greater accumulations of

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Peter Tschaplinski

Example of low flow and high flow conditions at Carnation Creek, B.C. (Note: example is a coastal watershed).

snow in clearings versus an adjacent forest (Golding and Swanson 1986; Toews and Gluns 1986). As a result, increased snow accumulation increases water available for soil moisture storage and groundwater that contribute to streamflow (MacDonald and Stednick 2003).

Snow in openings created by forest harvesting has greater exposure to wind and solar radiation that causes earlier initiation of snowmelt (Winkler 1999). One may expect that this would reduce flows in the low flow period. However, this expectation is not supported by numerous North American studies completed in snowmelt-dominated watersheds. For example, Troendle and Stednick (1999) and Troendle *et al.* (2001) have shown that the primary effect of harvesting is an earlier start to the freshet period, with higher flows on the rising limb and peak of the snowmelt hydrograph, and little or no effect on the recession limb. The earlier onset of snowmelt is offset by an increased volume of water associated with increased snow accumulation and reduced evapotranspiration in the low flow period; therefore, no reductions in low flows are observed (MacDonald and Stednick 2003). As forests grow, however, and canopy densities return to pre-harvest levels, these effects should diminish to pre-harvest conditions.

Infiltration, Soil Moisture, and Runoff Generation

Forests influence the routing and storage characteristics of water in a watershed. Water readily infiltrates most forest soils; as a result, surface runoff (overland flow) rarely occurs outside of stream channels and saturated riparian areas in forested watersheds (Hetherington 1987). Lower losses of water generally lead to higher moisture levels in the soil matrix due to a higher proportion of precipitation reaching the ground. The result is typically higher water tables in cleared areas, although the upper layers of the soil may appear drier due to increased exposure to evaporation.

Road building and other activities that disturb the soil surface could locally reduce infiltration and alter surface and subsurface flow paths. If connected to the natural drainage network of a watershed, roads may lead to quicker delivery of runoff (Wemple 1996). Conceptually, if ditch lines and road surfaces interrupt natural flow paths that result in accelerated water delivery to streams, this could lead to lower low flows (and higher peak flows) due to some water bypassing the normal routing pathways. Whether roads appreciably affect low flows is debatable, as hydrologic response will differ depending on a watershed's hydrologic regime (i.e., snowmelt- or rain-dominated) and storm history. "The hydrologic effects of roads depend on several factors, including the location of roads on hillslopes, characteristics of the soil profile, subsurface water flow and groundwater interception, design of drainage structures (ditches and culverts) that affect the routing of flow through the watershed, and proportion of the watershed occupied by roads" (Gucinski *et al.* [editors] 2001, p. 19).

What Is the Overall Effect of Forest Management on Low Flows?

For the most part, forestry either leads to increases in amounts of water available for streamflow by reducing "losses" or to changes in flow paths, which depending upon the spatial area affected could conceptually reduce low flows through quickened routing (i.e., roads). A few authors have summarized the results of case studies examining the overall effect of forestry on streamflow at a watershed scale. Pike and Scherer (2003) reviewed eight studies relevant to snowmelt-dominated watersheds. Four studies identified increased low flow volumes after timber harvesting, while the remaining four found non-significant or no change in low flows. None of the studies relevant to snowmelt-dominated hydrologic regimes documented a reduction in low flows (lower water volumes).

In summarizing 28 studies describing peak flow and low flow changes following timber harvesting in the United States, Austin (1999) stated that low flows increased in 16 studies, did not significantly change in 10, and decreased in 2 coastal studies (those being Harr 1982; Hicks *et al.* 1991). Only three out of the 28 studies reviewed by Austin overlap with Pike and Scherer's 2003 review. Combined, these literature summaries indicate that, in most forest types, the overriding suggestion is for streamflow to increase during the low flow period after forest harvesting.

How Long Does the Effect Last?

The longevity of increased water quantity after forest harvesting is not generally addressed in the literature because long-term studies on low flows are rare (Reiter and Beschta 1995). It is therefore difficult to draw conclusions about longevity of effects in snowmelt-dominated regimes. Conceptually, higher dry season flows should persist until pre-harvest hydrologic conditions are restored. Specifically, persistence should depend on forest type and the rate of regrowth (re-establishment of forest canopy). However, other authors have commented on the subject of longevity based on broader analyses of literature not specific to snowmelt-dominated regimes. Austin (1999) concluded that low flows generally return to pre-treatment levels approximately 3–4 years after logging due to regrowth of forest vegetation. Similarly, Johnson (1998) concluded that low flows return to pretreatment levels approximately 6 years after logging.

Does Logging Cause Low Flows?

Scientific literature relevant to the southern B.C. Interior does not support the common perception that timber harvesting results in less water available for streamflow. The volumes of low flows generally increase or do not change measurably due to forest management.

In community watersheds, often many factors other than timber harvesting affect low flow generation. Frequently, human demands exceed supply and exacerbate the situation. In managing any watershed, it is critical to acknowledge the complexity of low flow generation processes and confounding human influences affecting them. In times of limited quantity, water conservation and education may be our best management investment in balancing instream and human demands for water.

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UPDATE

Upcoming Events

February 23–25, 2005

57th Forestry Conference and Annual Meeting of the Association of BC Forest Professionals.
“Perspectives: What’s Your Passion?”

Prince George, BC.

http://www.abcfp.ca/agm57.html

February 23–25, 2005

Water - Our Limiting Resource, CWRA, BC Branch Conference.

Kelowna, BC.

http://www.cwra.org/CWRA_News_and_Events/BC_Feb_2005/bc_feb_2005.html

April 16–20, 2005

33rd Annual BCWWA Conference and Trade Show.

Penticton, BC.

Bill Harvey, Technical Program Co-Chair
E-mail: harveyb@ae.ca

April 26–27, 2005

Implications of Climate Change In BC’s Interior Forests.

Revelstoke, BC.

Optional Fieldtrip April 28.

http://www.cmiae.org/

June 20–23, 2005

HeadWater 2005: Hydrology, Ecology and Water Resources in Headwaters.

Bergen, Norway.

http://www.nve.no/headwater05/

August 16–19, 2005

The Second North American Lake Trout Symposium.

Yellowknife, NWT.

http://www.laketroutsymposium2005.ca/

Recent Publications

Conference Proceedings: Forest Land - Fish Conference II. April 26–28, 2004, Edmonton, AB

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Streamline Reader Survey

This fall we are conducting a reader survey to ensure effective management of Streamline Watershed Management Bulletin. Specifically, we would like to assess how we are doing and what improvements you would like to see.

The survey will take 5–10 minutes to complete and is available on-line at:

http://www.zoomerang.com/survey.zgi?p=WEB2S6C7LRP3

All responses will be handled confidentially, and need to be received by December 15, 2004. If you do not have computer access, please call Robin Pike at ***(250) 387-5887*** for a paper version of this survey.