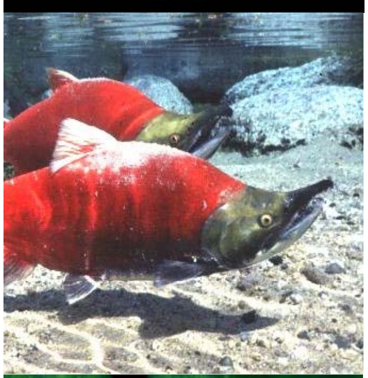
Magnitude-Duration Based Water Quality Objectives for Temperature and Turbidity in Millionaire Creek



Summary Report

Prepared for:

Environmental Quality Section
Environmental Protection Division
Lower Mainland Region
BC Ministry of Environment

Prepared by:

Aquatic Informatics Inc.

Reference to this report:

Quilty, E.J. and S.W. Fleming. 2005. *Magnitude-Duration Based Water Quality Objectives for Turbidity and Temperature in Millionaire Creek: Summary Report.* Prepared for the Environmental Quality Section, Environmental Protection Branch, British Columbia Ministry of Environment, Surrey. Prepared by Aquatic Informatics Inc., Vancouver.

Acknowledgements

The British Columbia Ministry of Environment (MOE) has provided funding for this study. Special thanks to Rod Shead for providing data, administrative support, and review comments.

Caveat

Certain portions of this report present results from forward-looking R&D work performed by Aquatic Informatics Inc. (AI) on contract to BC MOE. As such, some of the methodologies summarized in this report remain experimental. This pertains, in particular but not necessarily exclusively, to the risk-based temperature and turbidity guidelines discussed in the report

Table of Contents

Executive Summary

Millionaire Creek is a high-value fisheries stream in the Silver Valley, Maple Ridge, British Columbia. It is one of the largest tributaries to enter the Alouette River, and drains the southern sections of the UBC Research Forest and Golden Ears Park. Until recently, the watershed was relatively undeveloped with just some hobby farms in the lower reaches. A large residential development plan was proposed for the area in the late 1990s, and development proceeded during 2002 to 2004.

In 2000, the Ministry of Environment (MOE) initiated a water quality monitoring program in Millionaire Creek to assess non-point source impacts from urban land use. As part of this program, an automated water quality monitoring station was installed in late 2001. In 2004, MOE contracted Aquatic Informatics Inc. to review the data collected to date, to validate and correct the automated data, and to develop water quality objectives for water temperature and turbidity that recognize both magnitude and duration. The Ministry plans to amend the Coquitlam-Pitt River Water Quality Objectives to include objectives for Millionaire Creek.

The objective of this Summary Report is to develop magnitude-duration based temperature and turbidity *Water Quality Objectives* for Millionaire Creek. This report is based on work detailed in the accompanying Technical Report entitled:

> Fleming, S.W., Quilty, E.J., Farahmand, T., Hudson, P. 2005. *Magnitude-Duration Based Ecological Risk Assessment for Turbidity and Chronic Temperature Impacts: Method Development and Application to Millionaire Creek.* Prepared for the Environmental Quality Section, Environmental Protection Branch, British Columbia Ministry of Environment, Surrey. Prepared by Aquatic Informatics Inc., Vancouver.

Temperatures in Millionaire Creek during 2002 – 2004 were found to be well below those that could cause acute (lethal) effects to coho and steelhead salmon, but are sufficiently high to induce chronic impacts, as measured by total growth risk (*TGR*). High turbidity events in Millionaire Creek were determined to pose minor to moderate risk to fish, as determined by the cumulative turbidity risk (*CTR*). The maximum *TGR* and *CTR* values observed during the monitoring record were used to develop a Risk Quotient, *RQ*, for each parameter. Any future $RQ > 1$ indicates unacceptable risk to Millionaire Creek salmonids and cause for management concern and, potentially, further action. The implied management goal is to ensure that the Millionaire Creek water quality is not degraded beyond 2001 to 2004 conditions, which were likely non-impacted to moderately impacted by prior watershed activities. In addition, a site-specific look-up table was developed for quick assessment of whether an individual turbidity event exceeds acceptable conditions.

The following water quality objectives are proposed specifically for Millionaire Creek, and are designed to protect aquatic life (**Table 1** and **2**). These objectives reflect existing water quality in Millionaire Creek, and are based on both *magnitude and duration* of water quality events. We believe that these objectives are more appropriate as site-specific water quality objectives for Millionaire Creek than the generic provincial guidelines.

Table 1. Recommended Per-Event Turbidity Water Quality Objectives for Millionaire Creek

Duration			Magnitude (*NTU*)
hrs	days	weeks	
0.25			497
0.5			365
1			269
2			198
4			145
8			107
12			89
24	1		66
	2		48
	4		36
	5		32
	7	1	28
		2	20
		4	15
		8	11
		16	8
		32	6
Baseline			4

Table 2. Proposed Cumulative Risk-Based Water Quality Objectives for Millionaire Creek

Parameter	Risk Quotient	Note
Turbidity	1 (max.)	*RQ* based on $CTR_{ref} = 110$
Temperature	1 (max.)	*RQ* based on ${}^{steelhead}TGR_{ref} = 7\%$

Preface

Water Quality Objectives

British Columbia *Water Quality Guidelines* and *Water Quality Objectives* (collectively referred to as *Water Quality Criteria*) are both allowable levels of a particular substance for the protection of a designated water use (e.g. drinking water, aquatic life, livestock watering, recreation), but differ in their scope. *Guidelines* are set to protect a designated water use in general, whereas *Objectives* are set to protect a designated water use at a specific location. *Objectives* are a combination of *Water Quality Guidelines* plus the site characteristics that may influence the toxic action of the substance of concern. Unless *Water Quality Objectives* have been established for a specific water body, the *Water Quality Guidelines* are the default criteria.

Purpose of Water Quality Objectives

Water quality objectives are prepared for specific bodies of fresh, estuarine and coastal marine surface waters of British Columbia as part of the Ministry of Environment's mandate to manage water quality. Objectives are prepared only for those waterbodies and water quality characteristics that may be affected by human activity now or in the near future.

How Objectives Are Determined

Water quality objectives are based on the BC approved and working criteria as well as national water quality guidelines. Water quality criteria and guidelines are safe limits of the physical, chemical, or biological characteristics of water, biota (plant and animal life) or sediment, which protect water use. Objectives are established in British Columbia for waterbodies on a site-specific basis. They are derived from the criteria by considering local water quality, water uses, water movement, waste discharges, and socio-economic factors.

Water quality objectives are set to protect the most sensitive designated water use at a specific location. A designated water use is one that is protected in a given location and is one of the following:

- raw drinking water, public water supply, and food processing
- aquatic life and wildlife
- agriculture (livestock watering and irrigation)
- recreation and aesthetics
- industrial water supplies.

Each objective for a location may be based on the protection of a different water use, depending on the uses that are most sensitive to the physical, chemical or biological characteristics affecting that waterbody.

How Objectives Are Used

Water quality objectives routinely provide policy direction for resource managers for the protection of water uses in specific waterbodies. Objectives guide the evaluation of water quality, the issuing of permits, licenses and orders, and the management of fisheries and the province's land base. They also provide a reference against which the state of water quality in a particular waterbody can be checked, and help to determine whether basin-wide water quality studies should be initiated.

Water quality objectives are also a standard for assessing the Ministry's performance in protecting water quality. While water quality objectives have no legal standing and are not directly enforced, these objectives become legally enforceable when included as a requirement of a permit, license, order, or regulation, such as the *Forest Practices Code Act*, *Water Act* regulations or *Environmental Management Act* regulations.

Objectives and Monitoring

Water quality objectives are established to protect all uses that may take place in a waterbody. Monitoring (sometimes called sampling) is undertaken to determine if all the designated water uses are being protected. Traditionally, monitoring takes place at a critical time when a water quality specialist has determined that the water quality objectives may not be met. It is assumed that if all designated water uses are protected at the critical time, then they also will be protected at other times when the threat is less. The monitoring usually takes place during a five-week period, which allows the specialists to measure the presumed worst, as well as the average, conditions in the water.

In recent years, the Ministry has moved toward automated monitoring of water quality, augmented by grab sampling, rather than the traditional monitoring program composed solely of grab sampling. This change has focused largely on watersheds where the water quality is largely event-driven, such as in smaller watersheds, and can be altered over short time periods by meteorological, hydrological, or other events. As typical low frequency grab sampling data would not adequately represent the drainage's water quality, a decision was made to implement automated monitoring, whereby water quality measurements can be recorded every fifteen minutes. As these measurements are limited in terms of the range of water quality parameters that can be sampled, there remains a grab sampling aspect of the monitoring program.

New Directions in Setting Water Quality Objectives

Water quality criterion values have traditionally been (and continue to be) maximum or minimum values. However, it is recognized that it is not only the magnitude of a particular exposure, but also the duration of the exposure, that has environmental relevance. Unlike traditional grab sampling, automated water quality monitoring allows for the assessment of impacts based on both magnitude and duration, and facilitates the development of more protective and/or appropriate water quality criteria. In this document, we summarize new methods we developed for setting water quality objectives based on magnitude and duration of exposure, and recommend specific exposure-based objectives for Millionaire Creek. These methods and results remain only proposals at the current time.

Introduction

This Summary Report provides an overview of the accompanying Technical Report:

> Fleming, S.W., Quilty, E.J., Farahmand, T., Hudson, P. 2005. *Magnitude-Duration Based Ecological Risk Assessment for Turbidity and Chronic Temperature Impacts: Method Development and Application to Millionaire Creek.* Prepared for the Environmental Quality Section, Environmental Protection Branch, British Columbia Ministry of Environment, Surrey. Prepared by Aquatic Informatics Inc., Vancouver.

Study Background and Objectives

Millionaire Creek is a high value fisheries stream in the Silver Valley area of Maple Ridge, British Columbia. It is one of the largest tributaries to enter the Alouette River, and drains the southern sections of the UBC Research Forest and Golden Ears Park (**Figure 1**). The creek

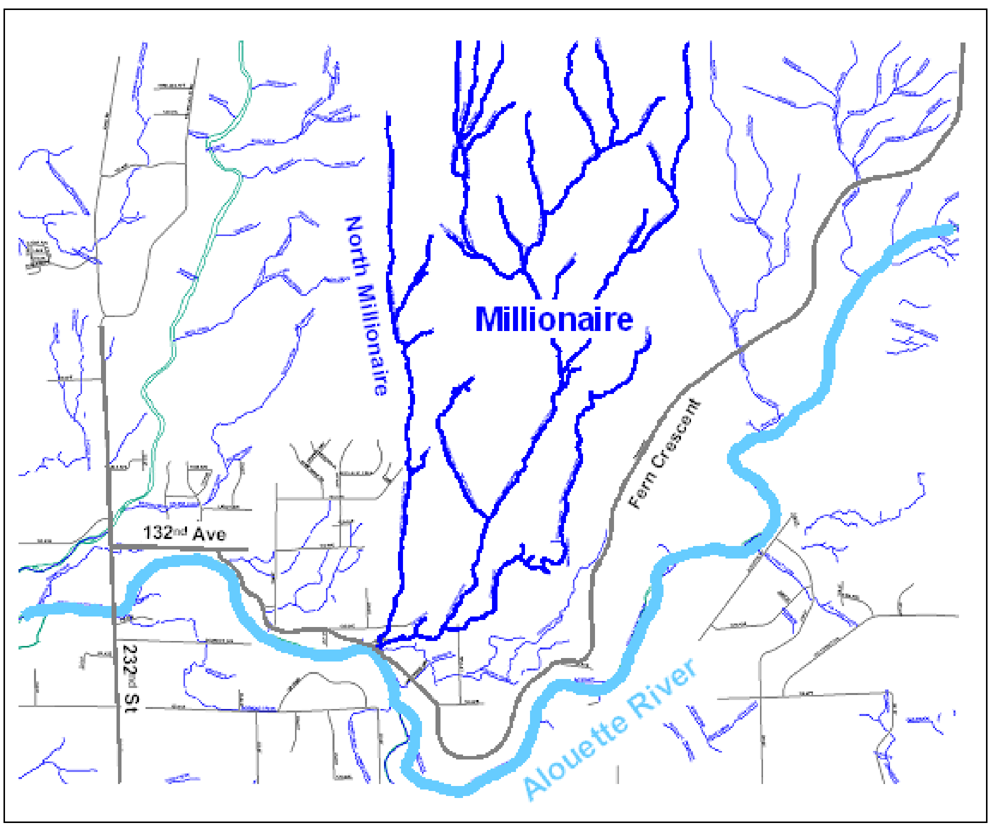


Figure 1. Location map, modified from CDMR (2005)

supports coho, pink and chum salmon as well as rainbow and cutthroat trout and mountain whitefish (Quilty, 2001). Until recently, the watershed was relatively undeveloped with only small hobby farms in the lower areas. A large residential development plan was submitted to the District of Maple Ridge in 1997. After a thorough public and government consultation process, the development plans for the Silver Valley area were approved in 2002, and some limited development has since begun. **Figure 2** (modified from CDMR, 2005) illustrates land uses.

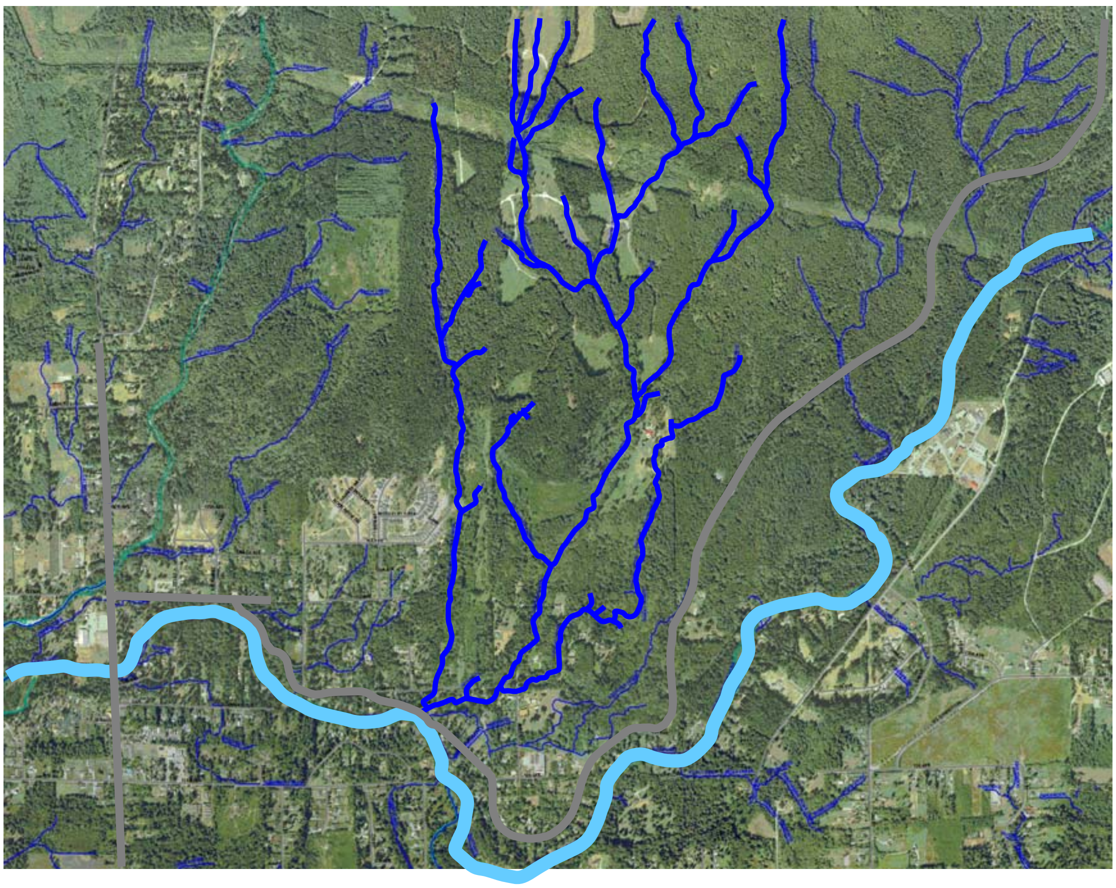


Figure 2. Aerial photograph of Millionaire Creek watershed and surrounding area

In anticipation of the development, the Environmental Quality Section of the Ministry of Environment (MOE) conducted a reconnaissance survey in Millionaire Creek during the summer of 2000. The survey included a limited collection of water quality and benthic invertebrate samples (Quilty, 2001). In October 2001, MOE installed an automated water quality monitoring station near the mouth of Millionaire Creek, and augmented the automated monitoring with an ongoing grab-sampling program. The station is located about 10 m downstream from the confluence of North Millionaire Creek and about 25 m upstream of Fern Crescent (see **Figure 1**). The automated station has since collected near-continuous data (every 15 minutes) for the following parameters: water temperature, pH, dissolved oxygen, conductivity, turbidity, and water level. A summary of automated data collected and preliminary analysis was completed in March 2004 (Quilty et al., 2004b).

The overall objective of this report is to develop magnitude-duration based *Water Quality Objectives* for temperature and turbidity in Millionaire Creek. MOE established *Water Quality Objectives* for the Alouette River in 1989. Now, with almost four years of high-resolution data for Millionaire Creek, the Ministry intends to develop water quality objectives for water temperature and turbidity that recognize both magnitude and duration, and amend the *Coquitlam-Pitt River Water Quality Objectives* to include objectives for Millionaire Creek.

Magnitude-Duration Based Water Quality Objectives

Near-continuous data allows for a much more detailed assessment of water quality conditions. Instead of weekly, monthly or intermittent grab sampling, whereby transient storms or unique events are often missed, continuous monitoring can be highly effective at characterizing all stream conditions. Natural variability, and the effects of local anthropogenic activities such as logging and urban development, can be easier to discern from each other. Extremes can be captured and their magnitude and duration of exposure calculated. Though it is recognized that the <u>duration</u> of the exposure has as much environmental relevance as magnitude, water quality criteria are usually set at a static magnitude thresholds, such as maximum or minimum values. Furthermore, thresholds that are appropriate to one river system will not necessarily work in another. For instance, a temperature threshold high enough to account for naturally warm streams may leave thermal pollution in a colder river undetected, and a threshold low enough to detect thermal pollution in a cool river may flag naturally warmer rivers as being in violation (for a detailed discussion, see Poole et al., 2001). It is therefore clearly more appropriate, and potentially more protective, to set water quality objectives based on both magnitude and duration of exposure. In this document, we summarize new methods developed in the Technical Report for setting water quality objectives based on magnitude and duration of exposure, and recommend specific exposure based temperature and turbidity objectives for Millionaire Creek.

Effects of Stream Temperature on Fish

Elevated stream water temperatures present two general kinds of risks to salmonids: acute (lethal), and chronic (sub-lethal, or cumulative). Acute effects occur when fish are exposed to sufficiently high water temperatures for a sufficient amount of time to experience mortality. Chronic effects occur when fish are exposed to sufficiently high temperatures to compromise feeding, growth, disease resistance, competitive ability, predator avoidance, and migration and spawning success, primarily via bioenergetic (metabolic) pathways (Poole et al., 2001). Temperatures at which chronic effects occur are substantially lower than those associated with acute risks, and are therefore more likely to be encountered. While chronic exposures by definition do not directly cause fish mortality over the short term, they can contribute to eventual mortality of individual fish and potentially lead to severe degradation of overall population viability (Poole et al., 2001).

Recent work has shown how acute temperature risks can be quantitatively assessed in a logistically feasible manner using a magnitude-duration curve approach (Sullivan et al., 2000; Quilty et al., 2004a). In addition, Sullivan et al. (2000) developed a growth model to assess chronic temperature risks to salmonids and considered the potential effects of both magnitude and duration. Ultimately, however, Sullivan et al. (2000) reduced the results to a risk-based temperature threshold for chronic impacts. While those thresholds are simple to implement, they do not incorporate heterogeneity in natural thermal regimes, or recognize the combined impact of magnitude and duration upon chronic thermal risk in a fully explicit manner.

In this study, we develop a generalized method for quantitatively assessing chronic risks to salmonids from high stream temperatures. The method implements techniques from toxicological risk assessment, whereby a risk index is developed (for background, see Technical Report). The resulting protocol is divided into two steps. Phase I yields a primarily visual assessment, and phase II provides a single but comprehensive risk index, the risk quotient (*RQ*), which gives a clear flag for the presence of ecologically negative changes in river thermal regime.

Effects of Turbidity on Fish

The optical effects of sediment suspended in the water column can harm fisheries resources in a variety of ways, including reductions in the volume of the photic zone and thus in primary production, initiating a negative trophic cascade throughout the ecosystem and potentially altering natural species assemblages and diversity; and harmful alteration of natural feeding efficiency, behaviour patterns, and predator-prey interactions. For recent reviews, see Caux et al. (1997), Welch et al. (1998), and Newcombe (2003).

Fluvial suspended sediment concentrations and lack of visual water clarity are increased by activities and land use changes within a watershed which potentially enhance erosion rates, including logging, road construction, mining, agriculture, and of quickly increasing concern, urban development. There is, therefore, a strong need to monitor, assess, and manage attendant water quality changes. Due to logistical considerations, suspended sediment concentrations and water clarity are most often measured as turbidity in nephelometric turbidity units or *NTU*. The use of a constant upper *NTU* threshold as a fixed criterion for water quality within a given regulatory jurisdiction is usually appropriate for setting drinking water standards, particularly if treatment facilities or multiple reservoirs are available, giving some flexibility to the water supply system if the threshold is exceeded. From a more general watershed and ecological management perspective, however, such an approach is subject to two very strong limitations (for full discussion, see Technical Report): (1) The turbidity of natural streams is extremely variable in both space and time. (2) Employing a single *NTU* value as an upper limit addresses only the magnitude, not the duration, of turbidity events.

In this study, we propose a generalized method for quantitatively assessing risks to fish from individual turbidity events, and a second method to assess cumulative risks. Both are extensions of the severity-of-ill-effect index developed by Newcombe (2003) for optical, or visual clarity, impacts. The first yields a look-up table, which provides an easily-applied protocol for making action-no action management decisions on an event-by-event basis as they occur. This is valuable for real-time applications. The second provides a formal risk assessment framework and is phrased in terms of duration-magnitude curves and, ultimately, a risk quotient, analogous to those also introduced in this report for chronic temperature effects.

Methods

Data Collection

The Ministry of Environment installed a multi-parameter automated water quality monitoring station in Millionaire Creek during October 2001 (**Figure 3**). The station includes a Hydrolab sonde that is programmed to collect water level, water temperature, pH, conductivity, turbidity, and dissolved oxygen data at 15-minute intervals. The station is visited approximately every four weeks for maintenance and for downloading data. Grab samples for water chemistry are also collected intermittently.

Figure 3. The Millionaire Creek monitoring station.

Data Validation and Correction

Automated near-continuous water quality data was validated and corrected using **AQUARIUS**™ software, developed by Aquatic Informatics Inc. This software uses relationships between the water quality parameter of interest and other variables at the site, or from different sites, to validate and correct data. For example, water temperature data collected from the Millionaire Creek station was validated using models built on water temperature data from nearby streams (Jameson Creek and Chester Creek). When the models suggest that a data point is likely erroneous (e.g. outliers from calibration visits, or drifts in pH or dissolved oxygen), the software then flags and corrects the data using the models. This technique was also used to fill gaps.

Development of Magnitude-Duration Based Water Quality Objectives

This section gives an overview of new methods developed to establish magnitude-duration based water quality objectives in Millionaire Creek. Our goal was to first characterize water quality conditions in Millionaire Creek during the pre-development (early development) stage, and to then develop water quality objectives that prevent deterioration from these conditions. Water quality conditions were characterized by their suitability for native fish. We focused on two parameters that are important to fish, are known to be sensitive to land development, and have been monitored continuously in Millionaire Creek: water temperature and turbidity. The challenge in this approach, of course, is to set objectives that are stringent enough to be protective while allowing for natural variability. A more complete discussion of our methods is provided in the accompanying Technical Report.

Assessing Chronic Risks from High Temperatures

Temperatures in Millionaire Creek are naturally quite cool, typically ranging from 0 – 19^{o}C (Quilty et al., 2004b). Although these are below temperatures that would cause acute effects, which begin at roughly 24^{o}C (Quilty et al., 2004a), they are high enough to potentially cause chronic effects. Growth is an effective metric for assessing the chronic impacts of water temperature upon fish (e.g., McCullough, 1999; Sullivan et al., 2000). The implication is not that maximization of growth should be regarded as management goal, which can have unexpectedly negative repercussions (see Poole et al., 2001). Rather, consistent with previous fisheries research (e.g., McCullough, 1999; Sullivan et al., 2000), we consider growth rate to be an effective general measure of the chronic biological impacts of elevated water temperature.

One significant difference between assessing chronic versus acute risk, however, is that acute risk occurs when a certain temperature is exceeded continuously for a certain amount of time. In contrast, chronic risk is cumulative over the year. For example, under this framework, five days in a row of sub-optimally high temperatures have the same growth effect as five days of the same sub-optimally high temperatures interspersed with a few days of optimal temperatures.

Salmonids present in Millionaire Creek are coho, pink, and chum salmon, rainbow and cutthroat trout, and mountain whitefish (see Quilty, 2001). Specific growth curves are readily available for steelhead (sea-run rainbow trout) and coho (Sullivan et al., 2000). As can be seen in **Figure 2**, growth curves are both temperature- and food-dependent. For the purposes of this report, we have assumed near-satiation rations for fish in Millionaire Creek (see Technical report).

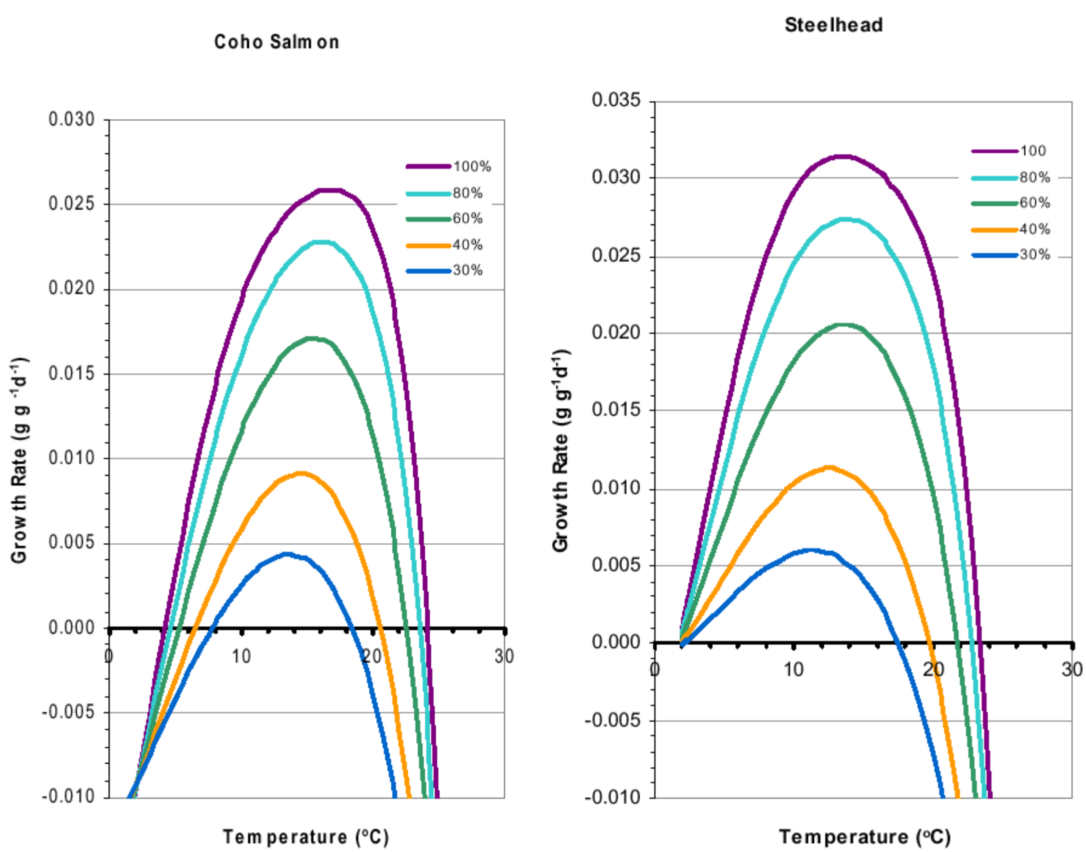


Figure 4. Specific growth rate curves for coho and steelhead salmon. Each coloured line represents percent satiation (100% = at least as much food as fish can eat).

To assess chronic temperature risks to salmonids, we developed a 2-step approach:

1. Estimate the potential for chronic risk through plotting of Cumulative Magnitude-Duration (*CMD*) Risk Curves.
2. If, based on the *CMD* curves, a chronic risk is likely then ensure the risk does not exceed the established Risk Quotient (*RQ*).

Step 1: Cumulative Magnitude-Duration Risk Curves

The method first entails constructing a graph illustrating the number of days over the course of a summer or a year during which a range of daily mean temperatures were matched or exceeded. As an example, Millionaire Creek stream temperature data from 2002 is plotted in **Figure 5**. Superimposed upon this graph of observed values are a series of vertical lines, each representing a temperature corresponding to a different daily growth risk, *DGR*. Daily growth risk measures the negative effects of high water temperatures upon fish growth on a day-to-day basis, and depends upon the particular species (see Technical Report for details). Data points lying to the right of the *DGR*=0% line indicate days for which growth risks were incurred. This step, while quantitatively based, serves primarily as a visual check of water temperature data.

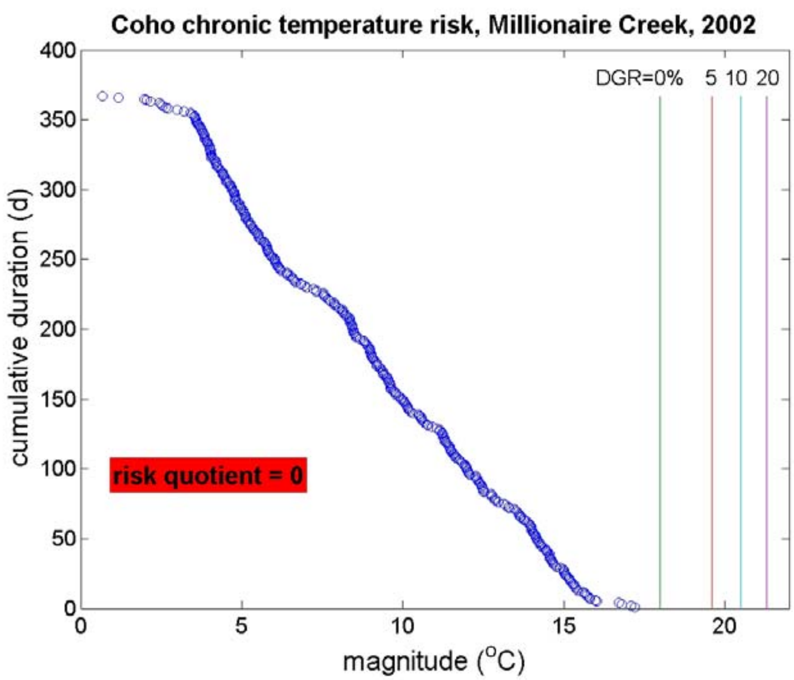


Figure 5. *CMD* curve and daily growth risk (*DGR*) for coho salmon in Millionaire Creek, 2002.

Step 2: Risk Quotient for Chronic Growth Impacts

The second step, fully complementary to the above *CMD* method, yields a single number that can be used as a powerful guideline for risk assessment: a chronic risk quotient. Unlike a single fixed upper temperature threshold, however, the chronic risk quotient incorporates both magnitude and duration considerations, explicitly reflects bioenergetic requirements and assumptions, and is tuned to the natural temperature conditions of individual watersheds.

For this method, we introduce a percentage total growth risk, *TGR*, analogous to *DGR* but cumulative over the year (for a detailed explanation of *TGR* and how it is calculated, see the Technical Report). *TGR* gives the loss in percent total yearly fish growth due specifically to high temperature, relative to the growth that would have occurred under optimal thermal conditions. We also define a risk quotient, *RQ*, analogous to the risk or hazard quotients widely used in conventional (toxicologically oriented) ecological and human health risk assessment, which quantifies the chronic effects of sub-optimally high water temperatures through a simple ratio:

$$RQ = \frac{TGR_{obs}}{TGR_{ref}}$$

where TGR_{obs} is the observed value of *TGR* in a given year, and TGR_{ref} is a reference value which describes the acceptable chronic total growth risk, preferably on the basis of observations obtained over a baseline period. Both *TGR* and *RQ* reflects the combined effects of exposure magnitude, exposure duration, and species-specific temperature requirements; they are sensitive specifically and exclusively to ecological effect of concern; and they may also be implemented on a near-real-time basis for day-by-day assessment of evolving seasonal chronic risk. However, *RQ* offers two significant advantages over the use of *TGR* alone: (1) Normalization of the observed risk in a given year by a reference *TGR* value, obtained from the same river over a baseline period, yields a more reliable metric of chronic thermal risk due to watershed modification (see Technical Report for explanation). (2) The risk quotient leads to a formal, simple, and robust decision rule for risk assessment and watershed management:

$$RQ > 1: \textit{unacceptable risk}$$
$$RQ \leq 1: \textit{acceptable risk}$$

Observed $RQ > 1$ indicates high-temperature chronic growth risks in excess of typical / acceptable levels. Note that $RQ = 0$ indicates no chronic high-temperature risk at all that year, and $0 < RQ \leq 1$ indicates that such risk was incurred but was within acceptable (e.g., natural historical) limits; only if $RQ > 1$ is there cause for management concern. The risk quotient method therefore provides a single, straightforward metric that serves as a clear flag for the presence of ecologically negative changes in stream temperature conditions (see Technical Report).

Assessing Risks from Turbidity

For turbidity, we introduce two approaches for assessing risk to fish. Both are extensions of the severity-of-ill-effect index developed by Newcombe (2003):

1. The first focuses on individual turbidity events and yields a look-up table, which provides an easily-applied algorithm for making action-no action management decisions on an event-by-event basis as they occur. This is valuable for real-time applications.
2. The second provides a formal risk assessment framework for evaluating the cumulative risk to fisheries health from lack of water clarity. It is phrased in terms of duration-magnitude curves and, ultimately, a risk quotient, analogous to those introduced in this report for chronic temperature effects.

Both approaches are referenced to historical watershed conditions and explicitly incorporate magnitude and duration considerations.

The severity-of-ill-effect index, *SEV*, was introduced by Newcombe (2003). It assesses the impacts of water clarity losses to clear-water fish species as a function of both the magnitude and duration of turbidity events. Newcombe (2003) proposed the following rating scheme, which has since been used for practical applications in watershed management (e.g., Quilty et al., 2004):

***SEV* rating criteria**

index	**effect**
$0 \leq SEV < 0.5$	nil
$0.5 \leq SEV < 3.5$	minor
$3.5 \leq SEV < 8.5$	moderate
$SEV \geq 8.5$	severe

We define any period over which *NTU* continuously > 1 as a turbidity event. For risk assessment, however, we must also decide how to pick one out of a suite of overlapping turbidity events of different magnitude and duration. We represent turbidity impacts over such an interval using the single sub-event having the largest associated *SEV* (see Technical Report).

Approach 1: Real-time Risk Assessment

The first method provides a robust measure of the risk associated with a turbidity event of a given magnitude and elapsed duration. Such a management tool would be particularly useful in conjunction with real-time data acquisition (which is not currently used in Millionaire Creek, but could be in the near future). This would permit assessment of the state of a river before an observed turbidity event is over or even before it has peaked, facilitating prompt and proactive measures (such as a site visit or contacting stakeholders) if appropriate.

The look-up table we introduce here consists simply of a list of magnitudes, corresponding to a broad array of set durations, as calculated from a reference *SEV* value. The preferred method for setting this SEV_{ref} is to use a baseline turbidity dataset from the river under evaluation. The magnitude and duration of an observed turbidity event may then be compared against those listed on the look-up table; if the observed combination of magnitude and duration exceed those listed on the table, there is cause for concern with respect to that individual event. The advantages of this procedure are that it incorporates both magnitude and duration considerations; it adjusts the assessment for the baseline characteristics of study watershed; and it does so in a precise and fully explicit manner. Full details of how the look-up table is constructed are given in the Technical Report.

Approach 2: Cumulative Risk Assessment

The second approach considers the cumulative impacts of multiple turbidity events on stream ecology. Cumulative impacts should be considered because, for example, a large number of moderate-*SEV* events may ultimately have an equal or greater net ecological impact relative to one or two high-*SEV* events. Here we introduce and summarize our method (for a detailed description of the method, see Technical Report) for assessing cumulative risk in a manner that explicitly incorporates magnitude and duration of individual events, the frequency of events, and local watershed characteristics, and collapses the resulting information into a single risk index.

We define the cumulative turbidity risk, *CTR*, as the sum of risks from each turbidity event over the entire year. We then introduce a risk quotient, closely analogous to that defined with respect to chronic temperature risks in the preceding section of this report and used extensively in toxicological risk assessment:

$$RQ = \frac{CTR_{obs}}{CTR_{ref}}$$

where CTR_{obs} is the observed *CTR* for a given assessment interval, and CTR_{ref} is a reference *CTR* value, preferably evaluated from baseline data for the study river (see Technical Report). The *CTR* values may be adjusted or unadjusted for data gaps (see Technical Report). This *RQ* definition again leads to a formal, simple, and robust decision rule for risk assessment and watershed management:

$$RQ > 1: \textit{unacceptable risk}$$
$$RQ \leq 1: \textit{acceptable risk}$$

Observed $RQ > 1$ thus indicates cumulative turbidity risk in excess of typical/acceptable levels. As for temperature risks (see above), $RQ = 0$ indicates no risk at all over that analysis interval (although this is generally unlikely for turbidity), and $0 < RQ \leq 1$ indicates that such risk was incurred but was within acceptable (e.g., natural historical) limits. Only if $RQ > 1$ is there cause for management concern. As was the case for the method we introduced for temperature, use of the turbidity *RQ* is not limited to retrospective analyses; one could recalculate *RQ* on a real-time and potentially automated basis.

Results

Water Temperature

The magnitude-duration curve and risk quotient methods introduced above, and detailed in the Technical Report, were applied to water temperature data from Millionaire Creek on a yearly basis using a Matlab™ script written for the purpose. We employed daily mean temperatures as calculated from corrected and validated 15-minute raw data. The available temperature time series spans late October 2001 to late September 2004; note that the 2004 data sufficiently bracket the local range of days over which, potentially, chronic temperature risks could conceivably occur. Analyses were therefore performed for 2002, 2003, and 2004.

Results from the daily and total growth risk analyses analysis are provided in **Figure 6** (coho) and **Figure 7** (steelhead). *TGR* values were generally 0% growth risk for coho, with the maximum annual value (0.005%) occurring during 2004. For steelhead, *TGR* values ranged from 0 – 10% growth risk, again with the highest risk (7%) in 2004. We used each of these maximum values as the Reference Total Growth Rate (TGR_{ref}) for each species, meaning that future *TGR* values should not exceed TGR_{ref}, or (equivalently) future *RQ* values must not be greater than 1. The implied management goal is to ensure that the Millionaire Creek thermal regime is not degraded beyond recent (2002 to 2004) conditions, which were likely non-impacted to moderately impacted.

Although the higher water temperatures and risk for 2004 loosely coincide with intensified development activity in the watershed, two considerations suggest that there may be little or no causal relationship in this case. First, analyses for turbidity risk (see following section) indicate that turbidity levels, which are also sensitive to development activity, are low to moderate in 2004 relative to prior years. Second, regional daily mean and maximum regional air temperatures were substantially higher during 2004 than in 2002 and 2003, which generally corresponds to higher water temperatures (see Technical Report).

a. b. c.

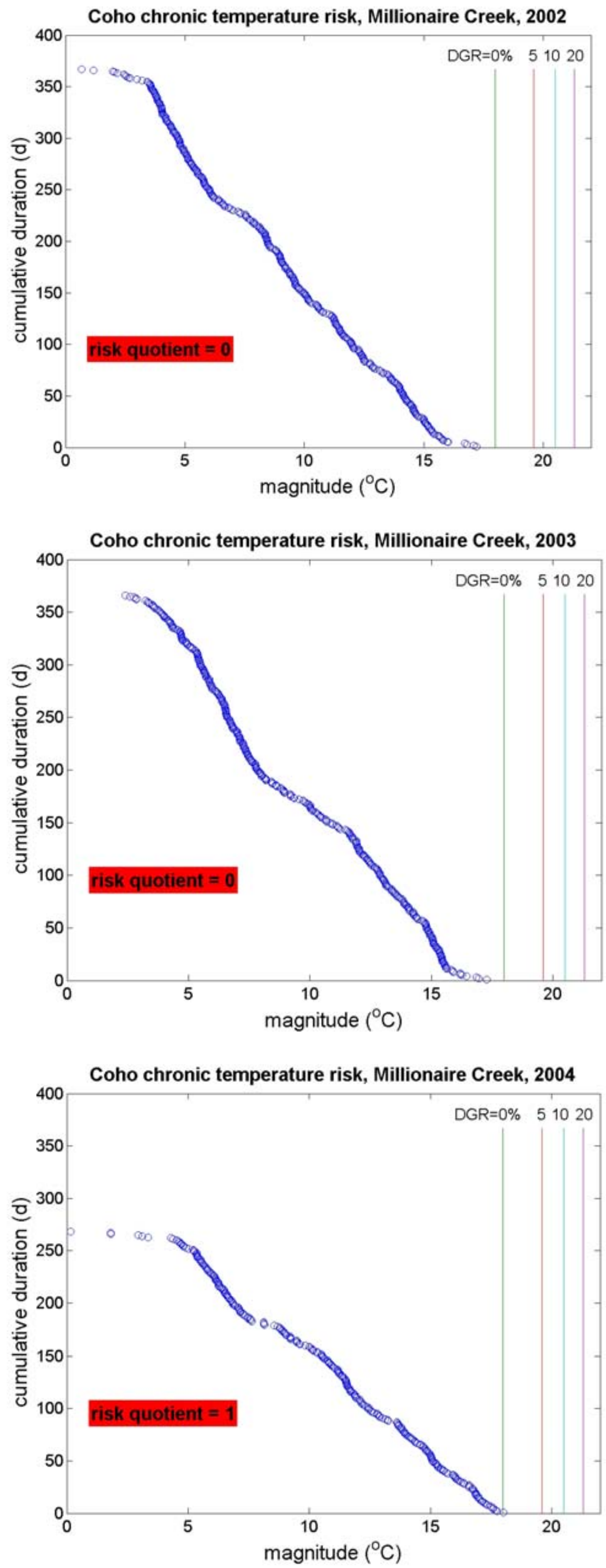


Figure 6. Cumulative Magnitude-Duration (*CMD*) and Daily Growth Risk (*DGR*) curves, and the corresponding annual Total Growth Risk (*TGR*) expressed as a risk quotient, for coho: a) 2002, b) 2003, and c) 2004. The risk quotient (*RQ*) is set relative to the *TGR* in 2004.

a. b. c.

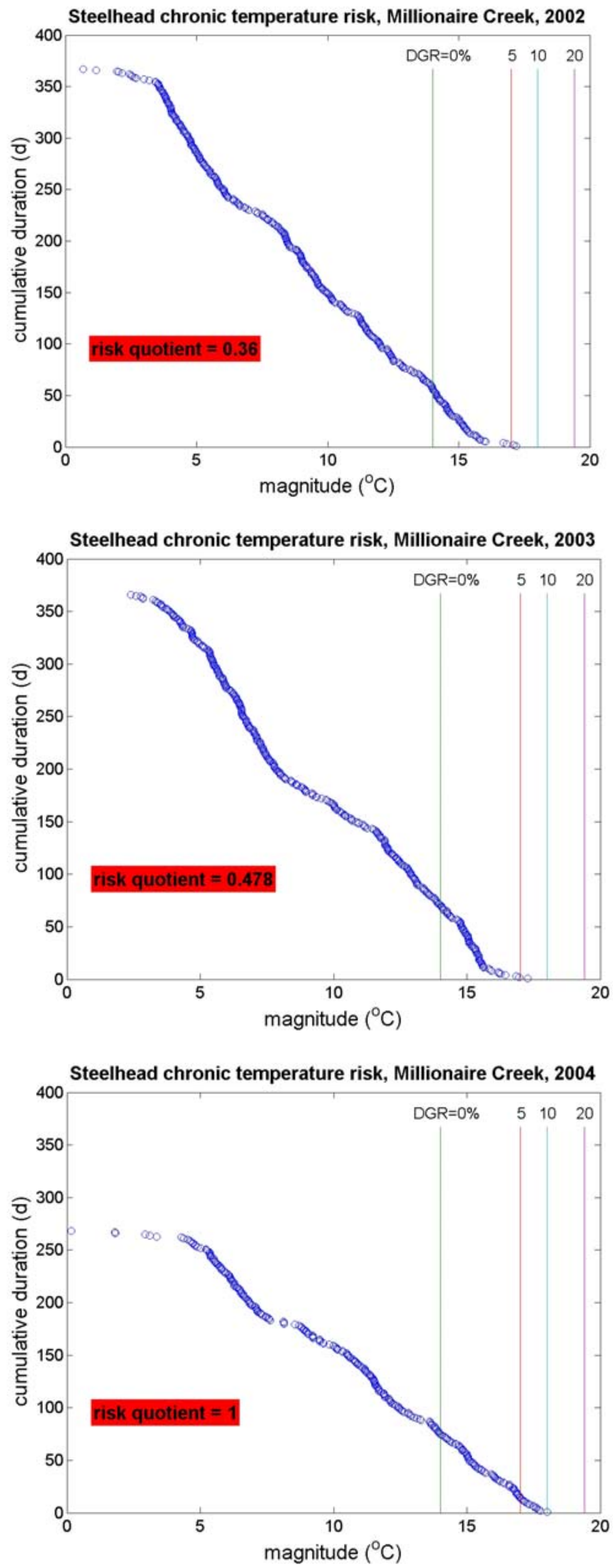


Figure 7. Cumulative Magnitude-Duration (*CMD*) and Daily Growth Risk (*DGR*) curves, and the corresponding annual Total Growth Risk (*TGR*) expressed as a risk quotient, for steelhead: a) 2002, b) 2003, and c) 2004. The risk quotient (*RQ*) is set relative to the *TGR* in 2004.

Turbidity

Millionaire Creek near-continuous (15-minute interval) turbidity data were available from 2001 to 2004. Low-pass filtering (statistical) and data validation were completed prior to analysis (Quilty et al., 2004). Missing data were not interpolated. A total of 214 turbidity events were observed over the baseline period. Seasonality in the turbidity time series was found to be surprisingly low. Although turbidity events tended to be larger, longer, and more frequent during the winter rainy season, it was found that substantial events could occur at any time of year. Of the 214 events, 74 exhibited $SEV \geq 0.5$ (minor or greater risk). The 90th percentile of the observed minor or worse *SEV* values was ~4.6 (moderate risk), and was taken to be SEV_{ref}. From this, a broad range of prescribed durations yields a risk look-up table for Millionaire Creek. Events with observed combinations of magnitude and duration less than those in the table have $SEV < SEV_{ref}$ and are considered acceptable:

Table 1. Maximum acceptable risk-per-event, Millionaire Creek

Duration			Magnitude (*NTU*)
hrs	**days**	**weeks**	
0.25			497
0.5			365
1			269
2			198
4			145
8			107
12			89
24	1		66
	2		48
	4		36
	5		32
	7	1	28
		2	20
		4	15
		8	11
		16	8
		32	6
Baseline			4

Cumulative Turbidity Risk (*CTR*) was considered for a yearly analysis interval. Results are summarized in **Figures 8** to **11**. The maximum *CTR* value observed over the baseline period was ~110 and occurred in 2003. As was done for temperature, maximum *CTR* defined the reference *CTR* (CTR_{ref}); hence *RQ* = 1 in 2003. There is a generally good correspondence between precipitation and cumulative turbidity risk (see Technical Report). Thus, precipitation appears to be the primary driver of interannual variability in turbidity risk for Millionaire Creek, which is fully consistent with general understanding of natural temporal variability in turbidity levels. Interestingly, 2004 *RQ* is the second-lowest of the four years, suggesting that renewed development activity in the watershed that year (see preceding section) did not pose a significant turbidity risk. Any future annual *RQ* > 1 would indicate a deterioration of watershed health from its 2001-2004 state and be cause for management concern.

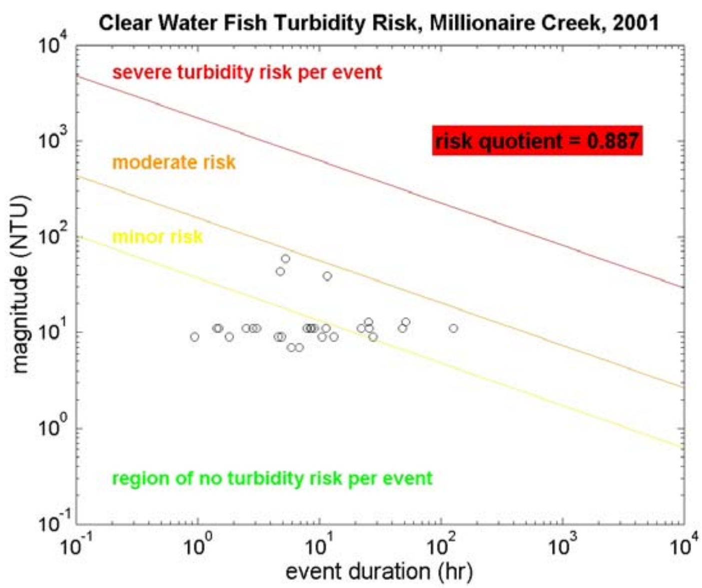


Figure 8. Turbidity risk to clear water fish, Millionaire Creek, 2001.

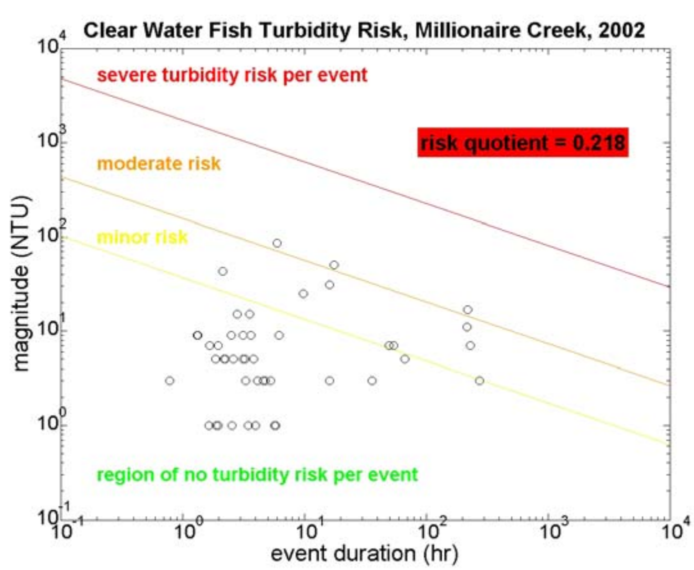


Figure 9. Turbidity risk to clear water fish, Millionaire Creek, 2002.

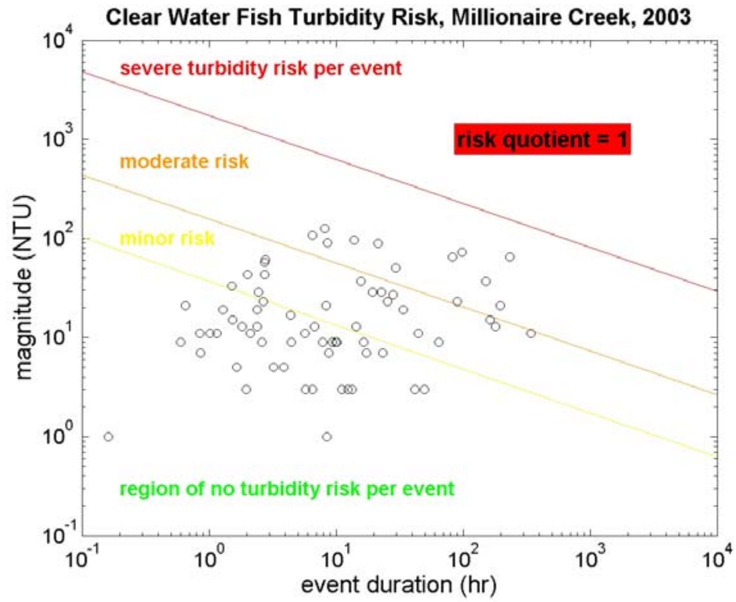


Figure 10. Turbidity risk to clear water fish, Millionaire Creek, 2003.

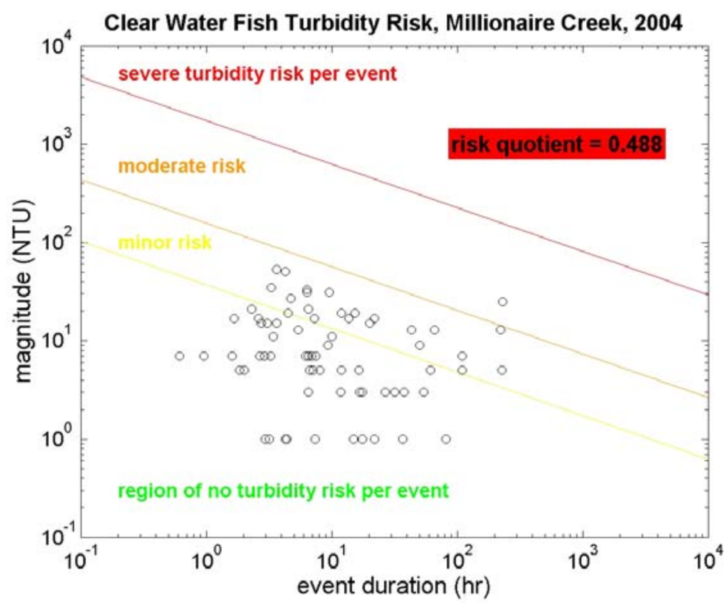


Figure 11. Turbidity risk to clear water fish, Millionaire Creek, 2004.

Summary and Conclusions

- The Millionaire Creek automated electronic monitoring station has collected near-continuous (15-minute interval) water temperature, conductivity, pH, dissolved oxygen, turbidity, and water level data from 2001 to present.
- Temperature and turbidity in Millionaire Creek were evaluated for the observation period.
- We developed new risk assessment methodologies for chronic temperature and turbidity risks to fish. The proposed methods incorporated both magnitude and duration of events. The primary product of both protocols is a risk quotient, *RQ*, which yields a straightforward decision rule for watershed managers concerned about the potential water quality impacts of ongoing or future activities in the catchment. In addition, a method for developing catchment-specific look-up tables to establish ecologically acceptable turbidity conditions, and whether an individual turbidity event exceeds those conditions, was introduced.
- Temperatures were found to be well below those which could cause acute (lethal) effects to coho salmon and steelhead. Chronic risks were evaluated through the calculation of Total Growth Risk (*TGR*). During the baseline period, there were minimal growth risks to coho, and less than 10% for steelhead.
- High turbidity events in Millionaire Creek were determined to have minor to moderate risk to fish, as measured by the cumulative turbidity risk (*CTR*). A look-up table was developed for watershed managers to assess, in real- or near real-time, whether an individual turbidity episode constitutes a water quality condition posing unacceptable impacts.
- The observed *TGR* and *CTR* values were used to develop Risk Quotients, *RQ*s. Any future temperature or turbidity $RQ > 1$ will indicate unacceptable risk to Millionaire Creek salmonids and cause for management concern and, potentially, further action. The implied management goal is to ensure that the Millionaire Creek water quality is not degraded beyond recent (2001 to 2004) conditions, which were likely non-impacted to moderately impacted.

Proposed Water Quality Objectives

The following water quality objectives are developed specifically for Millionaire Creek, and are designed to protect aquatic life (**Tables 1** and **2**). These objectives directly reflect existing water quality in Millionaire Creek, and are based on both *magnitude and duration* of water quality events. These site-specific objectives are more appropriate, and potentially more protective than generic provincial guidelines.

Table 1. Recommended Per-event Turbidity Water Quality Objectives for Millionaire Creek

Duration			**Magnitude (*NTU*)**
hrs	**days**	**weeks**	
0.25			497
0.5			365
1			269
2			198
4			145
8			107
12			89
24	1		66
	2		48
	4		36
	5		32
	7	1	28
		2	20
		4	15
		8	11
		16	8
		32	6
Baseline			4

Table 2. Recommended Cumulative Water Quality Objectives for Millionaire Creek

Parameter	**Risk Quotient**	**Note**
Turbidity	1 (max.)	RQ based on CTR_{ref} = 110
Temperature	1 (max.)	RQ based on ${}^{steelhead}TGR_{ref}$ =7 %

References

Caux, P.-Y., Moore, D.R.J., MacDonald, D. 1997. *Ambient Water Quality Guidelines (Criteria) for Turbidity, Suspended and Benthic Sediments: Technical Appendix.* Prepared for the British Columbia Ministry of Environment. Cadmus Group Inc. and MacDonald Environmental Sciences Ltd.: Victoria. Available online at: wlapwww.gov.bc.ca/ wat/ wq/ BCguidelines/ turbiditytech.pdf.

CDMR, 2005. *Maple Ridge Water Course Inventory Phases 1-4, SIS Viewer and Data Files, Version 1.2.0.* Corporation of the District of Maple Ridge: Maple Ridge.

Fleming, S.W., Quilty, E.J., Farahmand, T., Hudson, P. 2005. *Magnitude-Duration Based Ecological Risk Assessment for Turbidity and Chronic Temperature Impacts: Method Development and Application to Millionaire Creek.* Prepared for the Environmental Quality Section, Environmental Protection Branch, British Columbia Ministry of Environment, Surrey. Prepared by Aquatic Informatics Inc., Vancouver.

McCullough, D.A. 1999. *A Review and Synthesis of Effects of Alterations to the Water Temperature Regime on Freshwater Life Stages of Salmonids, with Special Reference to Chinook Salmon, EPA 910-R-99- 010.* Prepared for U.S. EPA by the Columbia River Inter-Tribal Fish Commission. U.S. Environmental Protection Agency: Washington, DC.

Newcombe, C.P. 2003. Impact assessment model for clear water fishes exposed to excessively cloudy water, *J. Am. Water Resour. Assoc.*, 39(3), 529-544.

Poole, G., Dunham, J., Hicks, M., Keenan, D., Lockwood, J., Materna, E., McCullough, D., Mebane, C., Risley, J., Sauter, S., Spalding, S., Sturdevant, D. 2001. *Technical Synthesis: Scientific Issues Relating to Temperature Criteria for Salmon, Trout, and Char Native to the Pacific Northwest, EPA 910-R-01-007.* U.S. Environmental Protection Agency: Washington, DC.

Quilty, E.J. 2001. *Water Quality Reconnaissance Survey: Millionaire Creek, North Millionaire Creek, Hennipen Creek, and Anderson Creek.* Prepared for the British Columbia Ministry of Environment, Surrey. QA Environmental: Vancouver.

Quilty, E.J., Hudson, P., Farahmand, T. 2004a. *Living on the Edge: Climate Change and Salmon in Lang Creek, British Columbia.* Prepared for the British Columbia Ministry of Environment, Surrey. Aquatic Informatics Inc.: Vancouver.

Quilty, E.J., Hudson, P., Farahmand, T. 2004b. *Preliminary Assessment of Millionaire Creek Automated Water Quality Monitoring Data.* Prepared for the British Columbia Ministry of Environment, Surrey. Aquatic Informatics Inc.: Vancouver.

Singleton, H. 2001. *Ambient Water Quality Guidelines (Criteria) for Turbidity, Suspended and Benthic Sediments: Overview Report.* Ministry of Environment: Victoria. Available online at: wlapwww.gov.bc.ca/ wat/ wq/ BCguidelines/ turbidity.html.

Sullivan, K., Martin, D.J., Cardwell, R.D., Toll, J.E., Duke, S. 2000. *An Analysis of the Effects of Temperature on Salmonids of the Pacific Northwest with Implications for Selecting Temperature Criteria.* Sustainable Ecosystems Institute: Portland, OR.

Welch, E.B., Jacoby, J.M., May, C.W. 1998. Stream Quality. In *River Ecology and Management*, Naiman, R.J., Bilby, R.E. (eds). Springer: New York, 69-94.