North American Journal of Fisheries Management 27:405–424, 2007

DOI: 10.1577/M05-146.1

[Article]

A Science-Based Approach for Identifying Temperature-Sensitive Streams for Rainbow Trout

MARC A. NELITZ[1]
School of Resource and Environmental Management, Simon Fraser University,
8888 University Boulevard, Burnaby, British Columbia V5A 1S6, Canada

ERLAND A. MACISAAC
Fisheries and Oceans Canada, Cooperative Resource Management Institute, Simon Fraser University,
Burnaby, British Columbia V5A 1S6, Canada

RANDALL M. PETERMAN*
School of Resource and Environmental Management, Simon Fraser University,
8888 University Boulevard, Burnaby, British Columbia V5A 1S6, Canada

Abstract.—To regulate human-induced changes to fish habitat, resource managers commonly set standards based on maximum allowable changes. For example, new legislation in British Columbia (BC), Canada, calls for restrictions on harvesting of trees and related activities near temperature-sensitive streams. However, methods for designating such streams are still evolving. Our objective was to help develop such methods by (1) improving understanding of the temperature-dependent responses of fish and (2) devising improved methods for estimating the effects of forestry-related activities on stream temperature as well as the chance of exceeding upper temperature limits. Using previously published models, we found that for rainbow trout *Oncorhynchus mykiss* particular increases in stream temperature led to different effects on juvenile growth rate, egg survival rate, and resistance to mortality from diseases. In a separate analysis, to evaluate the chance that cumulative forestry activities will increase stream temperature by various amounts, we compiled summer temperature data for 104 streams in central BC that reflected different watershed features, contrasting summer climates, and various levels of land use. A classification and regression tree analysis of a summer maximum weekly average temperature (MWAT) index grouped streams into six categories as a function of watershed size, watershed elevation, and air temperature. We then analyzed the remaining unexplained variation among stream temperature indices using Bayesian regression. We found high probabilities that increases in road density and the density of road crossings of streams within watersheds are associated with increases in residual temperature. For instance, a Bayesian regression indicated a 6-in-10 chance that the MWAT in our study area will increase by 1.25°C for a road density of 2 km/km^2 of watershed area and by 3.25°C for a road density of 4 km/km^2. These analyses illustrate some possible ways to help designate temperature-sensitive streams.

Understanding the linkages among human land use activities, fish habitat, and fish productivity is important. Long-term reductions in abundance of Pacific salmon *Oncorhynchus* spp. in the Pacific Northwest of North America have been related to changes in land use (Bradford and Irvine 2000) and degradation of fish habitat (Slaney et al. 1996). Because of such linkages, government management agencies often attempt to protect freshwater fish populations by minimizing human impacts on habitat (e.g., DFO 1986). To do so, scientists and resource managers usually set regulations based on data from monitoring fish habitat variables rather than more direct indices of fish abundance, productivity, or survival rates, in part because habitat indicators are more readily available. Furthermore, large year-to-year fluctuations in fish abundance and survival rate can hinder detection of habitat quality effects on fish abundance (Rose 2000). Scientists' attempts to clearly identify and quantify the relative importance of different types of habitat disturbances for fish are further impeded by numerous possible indicators of habitat quality and complicated cause-and-effect pathways (Jones et al. 1996). Given this situation, there is a need to improve upon existing methods of evaluating and regulating the effects of proposed human activities on fish habitat.

British Columbia (BC), Canada, provides an ideal setting for research on this topic. In BC, the Forest and Range Practices Act calls for the designation of

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* Corresponding author: peterman@sfu.ca

[1] Present address: ESSA Technologies, Ltd., Suite 300, 1765 West Eighth Avenue, Vancouver, British Columbia V6J 5C6, Canada.

Received August 16, 2005; accepted February 21, 2006

"temperature-sensitive streams" to help set acceptable limits on disturbance of fish habitat (Province of British Columbia 2002). Water temperature is an important habitat variable to investigate because there are often strong connections among forest harvesting, stream temperature, and fish productivity. In particular, when riparian vegetation is removed through harvesting, summer water temperature can increase owing to increasing direct solar radiation and convective heating of streams (Poole and Berman 2001). Such changes can affect fish by altering the structure and productivity of their food (macroinvertebrate communities) and by changing temperature-dependent processes that influence early development, growth, and survival (reviewed by Beschta et al. 1987; Richter and Kolmes 2005). Identification of temperature-sensitive streams has been proposed as a way to help regulate forestry activities, such as logging and road building, and to minimize impacts on fish by excluding sensitive watershed areas from harvest or by stipulating substantial riparian buffers to maintain stream temperatures. For our purposes, we defined a temperature-sensitive stream as one in which there was a high probability that proposed forestry activities would increase summer stream temperature beyond some desired conditions for stream biota. Identification of a temperature-sensitive stream thus requires the designation of a temperature threshold and a predicted stream temperature effect of a forestry activity that would trigger a change in the proposed activity. The aim would be to reduce impacts on fish.

In this paper, we seek to (1) improve understanding of temperature-dependent responses and the temperature indices used to set acceptable upper limits to summer temperature for fish in streams and (2) devise better methods to estimate the effects of human activities on stream temperature, which could assist in determining the chance of exceeding those upper limits. To deal with the first objective, we analyzed two of the main methods that are currently used for setting such limits (direct and indirect, as defined below). For the second objective, we explored a case example of the effect of forest harvesting and road building on summer stream temperature.

Setting Upper Limits to Stream Temperature

In the Pacific Northwest, there are two contrasting approaches to setting upper limits for water temperature to maintain salmon populations in the long term (e.g., BCMWLAP 1998; State of Washington 2003; Oregon Department of Environmental Quality 2004). The most common approach bases temperature standards on known direct links to biological responses. This approach requires that scientists and managers have good knowledge of habitat use (e.g., distribution of fish species and life stages within and among watersheds) and the biological effects of changes in temperature (e.g., effect on survival rates in the early life stage). Acceptable temperatures are then based on the most biologically suitable temperature range. For instance, to ensure high hatching rates, thresholds could be set so that daily temperature does not deviate from a 9–13°C range during the egg incubation period of rainbow trout *O. mykiss*.

A second approach to setting acceptable temperature limits aims to indirectly account for fish responses to changing temperatures based on the natural temperature range that has normally been encountered by the fish population of interest. The concept is that the resident fish in an area have already adapted to dealing successfully with the magnitude of temperature change that results from natural disturbances. The assumption is that this naturally occurring range of temperatures can then be used to define acceptable limits to human-induced changes. This concept is consistent with one application of the continually evolving paradigm of ecosystem-based management, in which human disturbances are intended to mimic natural ones by operating within the range of natural variation (Fowler and Hobbs 2002). In this case, thresholds could be set so that average daily water temperature remains within average natural conditions, which could be defined as the maximum range that fish in streams within a geographically defined area typically experience as a result of natural annual variations in climate and stream processes.

To apply this indirect approach, the expected baseline conditions in a watershed must be identified so that natural fluctuations among streams and years can be distinguished from changes due to human activities. However, the geographic extent and period of sampling needed to capture this range of natural variability can vary widely among situations (Landres et al. 1999), and there are few examples to guide analyses of stream temperature. Furthermore, it is not practical to monitor temperature for lengthy periods in all streams that may be affected by future forestry activities.

We therefore sought to improve understanding of the relative contribution of natural versus human-induced processes to among-stream variation in temperature characteristics. The analysis was complicated by the fact that in BC, human activities such as road building and forestry are already widespread, leaving few locations for which the true range of natural variation can be described. In such cases, the only reasonable alternative is to attempt to separate the total observed variation in temperature among streams into variation that is due to natural phenomena and variation that is due to human activities. To the extent that statistical or other analyses successfully accomplish this separation, the natural segment could then represent the range of natural variation or reference conditions that would form a basis for deciding on acceptable limits to stream temperature changes due to land use activities. We partially addressed this problem by applying a statistical method that is not normally used in research on fish habitat, namely classification and regression trees (C&RTs; Brieman et al. 1984), as described later. Although we were not able to completely separate the natural and human-induced variation in stream temperature, we were able to illustrate how this method could help in situations where more appropriate data are available.

Estimating the Effects of Human Activities on Stream Temperature

After setting acceptable upper limits on summer temperature in streams, scientists and managers typically attempt to estimate the effects of proposed human activities on the resulting temperatures to determine the chance of exceeding those limits. It is well known that in many cases, forest harvesting and associated road building tend to increase summer temperatures in streams (e.g., Johnson and Jones 2000; Herunter et al. 2003). However, the typical question is, "How great an effect do such human activities have?" Because it is not usually possible to use a before–after sampling design to answer that question, researchers are often forced to rely on a contrasting-treatments design, which compares locations that have had different magnitudes of tree harvesting or road construction, for example. However, use of such spatial comparisons to interpret the effects of those activities can still be confounded due to the noise added to observations by sampling error, natural sources of variation in temperature, and observation error in estimating the extent of human activities.

To reduce the effect of this confounding, we determined the effect of forestry activities by conducting analyses based on the residual stream temperature variation that remained after a C&RT analysis was completed. That is, some of the among-stream variation in summer temperature was removed by classifying streams into groups based on the C&RT analysis. This "cleaned-up" set of residual temperature variations was thus more likely to provide reliable estimates of the effects of forestry activities on temperature than analyses with the original temperature data. To reflect uncertainty in these estimated effects, we used another method that is rarely applied to fish habitat studies, Bayesian regression (Press 1989), as described below. Although we applied the C&RT and Bayesian regression methods to streams in central BC, the techniques are generally applicable to a wide range of regions and situations.

Methods

Study Area

We obtained temperature data from 104 study streams located within a geographically diverse area of central BC spanning approximately 106,000 km^2 of the upper Fraser and upper Skeena rivers (Figure 1). This area lies at the northern extent of the Interior Plateau physiographic region. The subboreal spruce biogeoclimatic zone dominates forest ecosystems there (Meidinger and Pojar 1991). Within the study area, air temperature data collected between 1942 and 1999 for the cities of Prince George and Smithers indicate annual average temperatures of 0.8–5.8°C and summer highs commonly exceeding 30°C (Environment Canada 2001). Precipitation in those cities was also similar; annual averages ranged from 312 to 845 mm during 1942–1999 (Environment Canada 2001). Seasonal patterns of streamflow in the region are characteristic of inland watersheds dominated by snowmelt runoff. Peak flows occur in spring as snow packs melt with increasing air temperature; flows decline through summer to low flows over the fall and winter months. Streams from the region support several economically and regionally significant salmonid species, notably rainbow trout and bull trout *Salvelinus confluentus*, as well as Chinook salmon *O. tshawytscha*, coho salmon *O. kisutch*, and sockeye salmon *O. nerka* (Scott and Crossman 1998).

Summer Stream Temperature

Stream temperature data.—We gathered temperature data from several government agencies and forest industry contractors who were monitoring stream temperature and studying the effects of forest practices on stream temperature (data sources are listed in Table 1). Data were provided as hourly or daily measurements and were summarized by daily maximum, minimum, and mean temperatures. In most cases, information regarding the accuracy of the instruments used to collect these data was not available. We therefore had to assume that these data sets were sufficiently accurate for our purposes. We restricted our evaluation of temperature to the period from June 9 to September 15 because the warmest conditions occur during this time and because high temperatures can affect survival and growth rates of salmonids, as noted above. Our data set reflects thermal conditions in streams with different watershed features, contrasting summer climates, and various levels of land use.

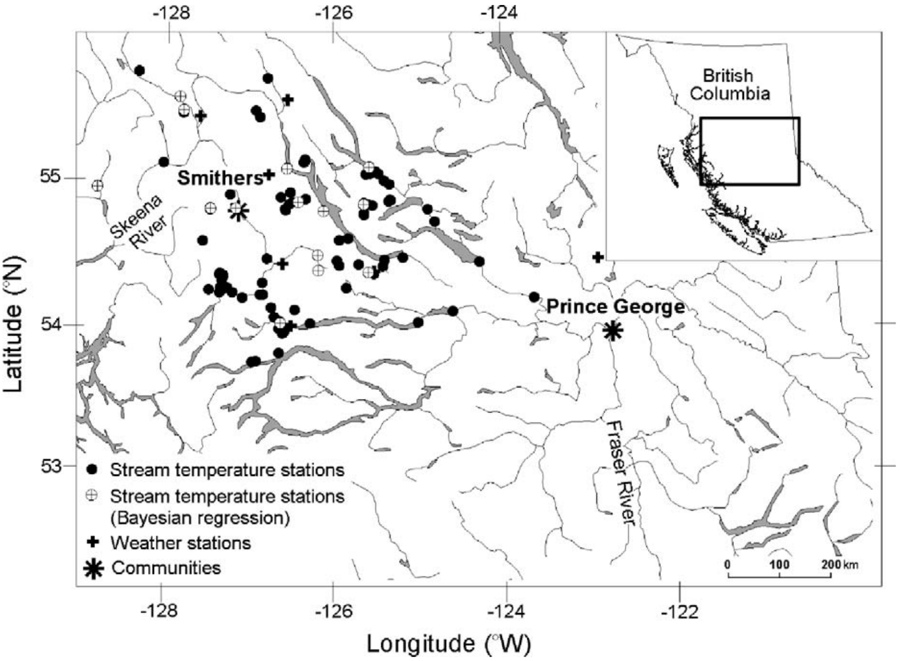

FIGURE 1.—Study area and locations of 104 stream temperature stations and 7 air temperature stations monitored in central British Columbia. Also shown is the subset of sites with stream temperature data used in the Bayesian regressions.

To generate the final sample of streams listed in Table 1, we compiled all available data from 250 streams in central BC and narrowed our sample by means of four criteria. First, we only included streams with natural flows (i.e., not regulated by hydroelectric operations). Second, a stream had to be mapped at the scale for which we possessed spatially referenced land use data. This constraint restricted us to watersheds larger than 1 km^2. Third, we used data from only one location per stream to avoid problems with spatial pseudoreplication (Hurlbert 1984). Fourth, we only included streams from a single geographic area, defined as the northwestern portion of the Interior Plateau, to ensure that our analyses applied to streams with similar physiographic characteristics. Using these criteria, we ended up with the 104 streams that are identified in Table 1.

In addition to these spatial considerations, we selected only one summer's data from each stream, in part because of the effect of pseudoreplication in time on our analyses. Another reason was that we could not do a full within- and among-stream comparison of the effect of year-to-year changes in climate because almost 80% of the 104 sites had fewer than 3 years of stream temperature data and because those years did not consistently overlap among streams. We therefore used three criteria to select a single year of data from the 104 identified streams. First, we only analyzed recent years between 1990 and 2002. Second, we used different years of data for monitoring stations that were located in adjacent or nearby watersheds to reduce potential concerns with spatial autocorrelation. Third, we selected years that spanned a range of climatic conditions to ensure that our sample included streams with contrasting summer air temperatures. Using these additional criteria, we selected the years of data for the 104 study streams.

Temperature indices.—There are many possible indicators of a stream's thermal regime because of daily, seasonal, and interannual fluctuations. We selected as our temperature index the maximum of a 7-d average of the daily mean temperature (also known as the maximum weekly average temperature [MWAT], or MX[4] in Table 2) because this index is commonly used to set standards for stream temperature (e.g., BCMWLAP 1998; State of Washington 2003; Oregon Department of Environmental Quality 2004).

We also calculated 16 different stream temperature indices (Table 2) to examine correlations among them. For 73 streams, data were available for fewer than the 99 d from June 9 to September 15. Therefore, we were only able to calculate all 16 indices for 31 streams and only 5 indices for all 104 streams (Table 2). We found that MWAT was highly correlated with several other temperature indices listed in Table 2 (Appendix 1).

Identification of Ranges in Stream Temperature Variation

Watershed features.—We mapped the locations at which stream temperature was monitored and conducted various spatial analyses in ArcView 3.2 (Environmental Systems Research Institute, Redlands, California), a geographical information systems software. We measured seven spatial variables that reflected each watershed's physical features and that could potentially affect temperature at each stream location: latitude, distance to the Pacific coast, average elevation of the upstream basin, drainage area, compass orientation of the stream channel, biogeoclimatic zone, and surficial geology (measurements are summarized and explained in Table 1). We calculated latitude and distance from each stream to the coast by use of coordinates and maps provided with the temperature data. Higher-latitude streams that were nearest to the coast were expected to have lower summer temperatures than lower-latitude streams that were further from the coast. We therefore determined the average elevation of the basin upstream from each stream temperature station using a gridded digital elevation model (DEM; provided by the BC Ministry of Sustainable Resource Management, Base Mapping and Geomatic Services Branch) with a 25-m resolution. We also used the DEM to delineate and calculate the drainage area upstream of each stream site. Next, we approximated the compass direction of water flow from a point 600 m upstream from each monitoring location, and we allocated each stream to one of four orientation classes (northwest–northeast, northeast–southeast, southeast–southwest, and southwest–northwest). Stream channels that had similar orientations were grouped together because it was assumed that their sunlight exposure and heating influences would be similar. We also cross-referenced streams with biogeoclimatic polygons (Meidinger and Pojar 1991) to identify which of four types of riparian forest were adjacent to each monitoring station and to investigate potential differences in stream shading. Finally, we overlaid streams with a map of surficial geology (Fulton 1995) to identify which of four types of surficial material were located subsurface to each stream location and to investigate potential influences of groundwater zones on stream temperature. We suspected that streams flowing through the most porous surficial materials would have the greatest groundwater influences and as a result would have the lowest temperatures.

Climatic setting.—We used air temperatures (provided by the BC Ministry of Forests, Forest Service Protection Program) from seven weather stations (Figure 1) to examine the influence of among-year weather differences on stream temperature. We assumed that these seven stations would estimate streamside weather influences because air temperature has in some cases been used to reliably predict daily stream temperature (Stefan and Preud'homme 1993). To standardize for differences in the magnitude of summer air temperature among sites, we used temperature anomalies—that is, the difference between an average summer air temperature for a given year and a 13-year average (May 1–August 31, 1990–2002) at each weather station. Therefore, the value for an air temperature anomaly at each of the 104 study streams (Table 1) was calculated as the annual deviation at the nearest weather station for the year in which stream temperature was measured. Streams and years with similar anomaly values thus represented year types with above-average, average, or below-average air temperatures.

Regression trees.—Classifications of streams based on indices of similarity or difference provide useful tools for managing freshwater environments (Naiman et al. 1992). Therefore, to provide information for the indirect approach to setting temperature limits noted previously, we used the eight explanatory variables described in Table 1 (seven watershed features plus air temperature) in a C&RT analysis (Brieman et al. 1984) to group the 104 streams into categories with similar temperature profiles as represented by MWATs. We specifically applied this type of nonparametric analysis because it is an objective way to develop a classification scheme that can capture the potentially nonadditive interactions and nonlinear relations among stream temperature and the eight explanatory variables. The results can also be easily interpreted by watershed managers.

We used the regression tree algorithm in S-Plus 2000 software (Insightful Corp., Seattle, Washington), which recursively searched for values or categories within all explanatory variables to split the temperature data for all streams into two groups, termed nodes, so as to minimize the within-node variance. This splitting procedure was repeated until a minimum node size ($n = 10$) or minimum reduction in node variance (complexity parameter = 0.001) was reached. Once either criterion was surpassed in all branches, a tree was generated. These criteria ensured that final groupings contained reasonable sample sizes and that each new variable added some explanatory power to the model. By definition, each group of streams had a range of variation in MWAT that was less than the

TABLE 1.—Stream temperature data, watershed features, and climatic setting for the 104 British Columbia streams used in this study.

Region	Station number[a]	Year[b]	MWAT index (°C)[c]	Easting[d]	Northing[d]	Drainage area (km^2)	Basin elevation (m)
Babine Lake	1	2000	10.8	668261	6112791	1.1	943
	2	2000	10.0	667466	6111384	3.9	1,157
	3	2001	12.2	667176	6111437	3.8	1,162
	4	2000	11.1	668146	6112874	1.9	955
	5	2001	11.7	668370	6113620	2.8	968
	6	2001	12.0	628394	6149896	131.0	1,096
	7	2002	9.2	316836	6053031	125.7	1,148
	8	2002	10.9	309607	6051741	30.3	1,257
	9	2000	10.0	358656	6036620	6.0	1,159
	10	2000	10.5	344194	6035482	5.2	1,013
	11*	2000	13.5	684461	6074707	93.9	1,135
	12*	2000	12.3	654708	6106557	34.7	894
	13	2001	13.1	636821	6175415	3.9	1,051
	14	2001	11.1	632016	6145058	1.7	1,246
Baptiste Creek	15	1997	11.1	350299	6081540	2.9	1,190
	16	1996	9.3	350935	6081338	1.4	1,202
	17	1998	11.1	350930	6081330	1.1	1,228
	18	1999	11.2	349902	6080966	3.2	1,076
	19	1997	10.5	349357	6080249	1.4	1,086
Bivouac Creek	20	1997	11.5	335559	6105552	39.6	1,178
Bulkley River	21*	2000	14.3	681023	6040358	69.5	1,116
	22*	2001	12.7	682238	6028479	71.4	1,088
	23	2001	8.3	591178	6047696	54.5	1,488
	24	2001	9.3	641796	6035559	64.9	1,228
	25*	2001	15.6	616081	6073989	38.0	935
	26	1997	11.9	611175	6084288	75.9	1,028
Endako River	27	2002	10.3	307211	6036055	4.2	1,066
	28	2002	11.2	308695	6032440	9.4	1,005
	29	2000	14.2	313439	6014821	2.8	1,068
Fleming Creek	30	2002	9.7	329791	6070923	4.5	1,045
	31	2002	10.2	329829	6071978	2.4	1,031
	32	2002	9.8	336536	6077842	4.9	1,159
	33	2002	17.1	330127	6079879	171.4	1,249
	34*	2002	11.3	329793	6079114	24.3	1,092
	35	2002	9.8	329695	6078981	3.2	987
	36	2002	9.1	332840	6078937	2.9	971
Forfar Creek	37	1991	13.1	342311	6102160	37.8	1,308
Fulton River	38	2000	11.1	669990	6083160	2.6	968
	39	2000	15.2	659413	6079986	326.1	1,127
	40	2000	14.6	658007	6087710	95.7	1,002
	41	2001	9.7	654184	6074711	6.4	1,218
	42	2001	7.2	654577	6073894	19.0	1,385
	43	2001	16.2	650841	6083501	16.0	1,116
	44*	2000	13.1	664521	6080705	50.3	1,056
	45	2000	10.1	657223	6078556	23.9	1,171
Gates Creek	46	1995	13.4	653752	5983733	21.5	1,069
	47	1994	11.7	653752	5983733	38.5	1,208
	48	1994	12.8	656237	5978929	2.0	1,246
	49	1994	11.4	656862	5981496	7.5	1,165
	50	1994	11.8	657250	5980130	3.2	1,070
	51*	1995	13.7	654080	5987312	83.1	1,074
	52	1995	11.5	656652	5980315	6.0	1,202
	53	1995	11.4	653782	5982801	33.3	1,243
	54	2000	10.6	653129	5982159	3.1	1,070
Gluskie Creek	55	1997	13.1	339420	6103611	48.9	1,285
	56	1997	9.2	332285	6102236	25.0	1,424
	57	1998	10.9	335603	6102488	34.0	1,342
	58	1999	9.9	333255	6102426	29.7	1,379
Kispiox River	59*	1998	12.8	572473	6148644	24.4	1,014
	60	1999	11.4	572139	6145945	18.3	1,149
	61*	2001	15.6	568989	6158730	122.4	672
	62	1998	11.0	536360	6176742	70.8	1,055
Kitsumkalum	63*	1997	12.5	507649	6087067	41.9	717
Kitwanga River	64	1996	19.6	558508	6107015	832.6	924
Kynock Creek	65	1992	12.9	346401	6096660	71.2	1,251
Leo Creek	66*	1998	16.3	335377	6107809	92.5	1,081

TABLE 1.—Extended.

Region	Station number[a]	Air temp. anomaly (°C)[e]	Air temp. station[f]	Distance to coast (km)	Orientation[g]	Surficial geology[h]	BEC zone[i]	Source[j]
Babine Lake	1	−0.86	Upper Fulton	266	SW–NW	Tb	SBS	4
	2	−0.86	Upper Fulton	265	SW–NW	Tb	SBS	4
	3	−1.55	Upper Fulton	265	SE–SW	Tb	SBS	4
	4	−0.86	Upper Fulton	266	SW–NW	Tb	SBS	4
	5	−1.55	Upper Fulton	267	SW–NW	Tb	SBS	4
	6	−1.37	Nilkitkwa	243	SW–NW	Tb	SBS	3
	7	−1.20	Augier	292	SE–SW	Tb	SBS	5
	8	−1.20	Augier	285	SW–NW	Tb	SBS	5
	9	−1.31	Augier	320	SW–NW	Tb	SBS	8
	10	−1.31	Augier	308	NE–SE	Tb	SBS	8
	11*	−0.86	Upper Fulton	274	SW–NW	Tb	SBS	8
	12*	−0.86	Upper Fulton	252	SW–NW	Tb	SBS	8
	13	−1.37	Nilkitkwa	263	NW–NE	Tb	SBS	9
	14	−1.37	Nilkitkwa	244	SE–SW	Tb	ESSF	9
Baptiste Creek	15	1.22	Augier	326	NE–SE	Ra	SBS	1
	16	−1.59	Augier	326	NE–SE	Tb	SBS	1
	17	1.84	Augier	326	SE–SW	Tb	SBS	1
	18	−0.31	Augier	325	SW–NW	Ra	SBS	1
	19	1.22	Augier	325	SE–SW	Ra	SBS	1
Bivouac Creek	20	0.57	Upper Fulton	314	SE–SW	Tv	SBS	1
Bulkley River	21*	−0.60	Houston	268	NW–NE	Tb	SBS	8
	22*	−1.52	Houston	263	SW–NW	Tb	SBS	3
	23	−1.52	Houston	179	SE–SW	Tv	SBS	3
	24	−1.52	Houston	229	SE–SW	Tb	SBS	3
	25*	−1.55	Upper Fulton	206	NW–NE	Tb	SBS	3
	26	0.57	Upper Fulton	204	SE–SW	Tb	SBS	3
Endako River	27	−1.20	Augier	278	NW–NE	Tb	SBS	5
	28	−1.20	Augier	277	NE–SE	Tb	SBS	5
	29	−1.31	Augier	271	SE–SW	Tb	SBS	8
Fleming Creek	30	−1.20	Augier	305	SW–NW	Tb	SBS	5
	31	−1.20	Augier	305	SW–NW	Tb	SBS	5
	32	−1.20	Augier	312	NW–NE	Tb	SBS	5
	33	−1.20	Augier	305	SW–NW	Tb	SBS	5
	34*	−1.20	Augier	305	SW–NW	Tb	SBS	5
	35	−1.20	Augier	305	SE–SW	Tb	SBS	5
	36	−1.20	Augier	308	NW–NE	Tb	SBS	5
Forfar Creek	37	0.29	Augier	320	SE–SW	Tb	SBS	1
Fulton River	38	−0.86	Upper Fulton	261	NW–NE	Tb	SBS	4
	39	−0.86	Upper Fulton	250	SE–SW	Tb	SBS	8
	40	−0.86	Upper Fulton	250	NW–NE	Tb	SBS	8
	41	−1.55	Upper Fulton	244	SW–NW	Tb	ESSF	9
	42	−1.55	Upper Fulton	244	SW–NW	Tb	ESSF	9
	43	−1.55	Upper Fulton	242	SW–NW	Tb	SBS	9
	44*	−0.86	Upper. Fulton	255	NW–NE	Tb	SBS	8
	45	−0.86	Upper Fulton	248	SW–NW	Tb	SBS	8
Gates Creek	46	0.04	Peden	212	NE–SE	Tb	SBS	1
	47	0.48	Peden	212	SE–SW	Tb	SBS	1
	48	0.48	Peden	210	SE–SW	Tb	ESSF	1
	49	0.48	Peden	213	SE–SW	Tb	SBS	1
	50	0.48	Peden	212	SE–SW	Tb	SBS	1
	51*	0.04	Peden	214	SW–NW	Tb	SBS	1
	52	0.04	Peden	212	SE–SW	Tb	SBS	1
	53	0.04	Peden	211	SE–SW	Tb	SBS	1
	54	−0.35	Peden	210	SW–NW	Tb	SBS	4
Gluskie Creek	55	1.22	Augier	317	SE–SW	Tv	SBS	2
	56	0.57	Upper Fulton	310	SE–SW	Tv	SBS	1
	57	1.84	Augier	313	SW–NW	Tv	SBS	1
	58	−0.31	Augier	311	SW–NW	Tv	SBS	1
Kispiox River	59*	2.00	Kispiox	194	SE–SW	Tb	ICH	6
	60	−0.88	Kispiox	193	SW–NW	Tb	ICH	6
	61*	−1.41	Kispiox	196	NW–NE	Tb	ICH	3
	62	2.00	Kispiox	177	SW–NW	Tb	ICH	3
Kitsumkalum	63*	0.68	Kispiox	107	NW–NE	Tb	CWH	3
Kitwanga River	64	−1.24	Kispiox	162	NW–NE	Tv	ICH	3
Kynock Creek	65	1.17	Augier	323	SE–SW	Tv	SBS	1
Leo Creek	66*	1.91	Upper Fulton	314	NW–NE	Tv	SBS	1

TABLE 1.—Continued.

Region	Station number[a]	Year[b]	MWAT index (°C)[c]	Easting[d]	Northing[d]	Drainage area (km^2)	Basin elevation (m)
Middle River	67	1998	20.5	339964	6103933	5,682.1	1,058
	68	1991	18.9	350622	6093655	6,006.8	1,055
Morice River	69	1997	14.4	597331	6010294	191.4	1,103
	70	1999	11.7	606965	6017914	41.9	1,288
	71	1999	9.7	607995	6022093	9.5	1,155
	72	1999	10.7	606272	6012149	12.8	1,144
	73	1999	10.5	607158	6010252	9.6	987
	74	1999	10.8	605469	6023120	2.6	1,059
	75	1999	5.4	605163	6022440	6.4	1,190
	76	1997	13.3	605494	6008380	530.6	1,156
	77	1999	18.1	646293	5998398	81.2	971
	78	1999	16.0	639824	6007737	213.1	966
	79	1999	12.5	637535	6007790	37.3	1,022
	80	1999	11.8	638820	6016753	247.6	1,192
	81	1999	12.5	615541	6008673	19.5	1,094
	82	1999	13.2	623890	6005250	3,141.4	1,197
	83	2000	9.9	607614	6019925	1.0	985
	84	2001	9.2	608160	6020875	1.5	1,072
	85	2001	9.0	611290	6011990	2.7	1,211
Nadina River	86	1994	18.8	653200	5988327	902.1	1,091
Nautley River	87	1992	21.3	395379	5994195	6,553.5	948
Parrott Creek	88	1999	21.2	664898	5997254	158.8	1,024
	89	1999	18.1	677364	5987574	395.3	980
Peter Alec Creek	90	1994	15.6	649186	5991428	69.3	1,124
Pinkut Creek	91	2002	10.9	324097	6032451	18.8	1,112
	92*	2002	15.6	331169	6026417	36.4	1,095
	93	2000	18.0	342628	6030444	803.1	1,093
	94	2000	16.4	335747	6024864	28.1	1,125
Stellako River	95	1993	18.4	368631	5986427	4,016.9	968
Stuart River	96	1997	18.8	417650	6031000	14,211.9	958
	97	1998	22.6	458993	6002045	14,863.7	951
Tachie River	98	1995	18.5	379074	6073312	8,627.9	1,022
	99	1994	19.7	384226	6063202	10,216.8	1,001
Tahtsa Lake	100	1999	13.3	636141	5956550	3.8	1,096
	101	1999	14.4	633225	5955940	21.9	1,000
	102	1999	16.0	653963	5963657	209.1	1,035
Zymoetz River	103	2001	15.1	596128	6072317	133.9	1,260
	104*	1998	12.4	596053	6073377	51.1	1,095
Average			12.9			777.4	1,102
Maximum			22.6			14,863.7	1,488
Minimum			5.4			1.0	672
SD			3.4			2,568.1	129

[a] The station number uniquely identifies the monitoring location for each stream used in this analysis. Stations with an asterisk were used in the Bayesian regression to analyze the effects of forestry activities on stream temperature.

[b] Year in which summer stream temperature data were summarized for a particular monitoring station.

[c] The MWAT index represents the maximum weekly average temperature (MX[4] in Table 2) calculated from the summer temperatures for the year listed.

[d] Easting and northing reflect latitude and longitude, respectively. Streams with easting values from 300,000 to 400,000 are from Universal Transverse Mercator zone 10, those with values from 500,000 to 600,000 are from zone 9.

[e] Air temperature anomaly values above 0 represent year-types in which a regional measure of summer air temperatures was warmer than a 13-year average; values below 0 represent year-types in which this measure was cooler than a 13-year average.

[f] Climate stations used to derive the air temperature anomaly. Station names and coordinates in decimal degrees are as follows: Augier Lake (54.36°N, 125.52°W); Bear Lake (54.51°N, 122.69°W); Houston (54.41°N, 126.63°W); Kispiox (55.44°N, 127.65°W); Nilkitkwa (55.55°N, 126.58°W); Peden (53.99°N, 126.52°W); and Upper Fulton (55.03°N, 126.80°W).

[g] Orientation and compass directions associated with each stream are as follows: NW–NE (0–45°, 315–360°); NE–SE (45–135°); SE–SW (135–225°); SW–NW (225–315°).

[h] Surficial geology classes: Tb = till blanket; Ra = alpine complexes; Tv = till veneer; and fL = fine-grained (glacio) lacustrine.

[i] BEC (biogeoclimatic ecosystem classification) zones: CWH = coastal western hemlock *Tsuga heterophylla*; ESSF = Engelmann spruce *Picea engelmannii* –subalpine fir *Abies lasiocarpa*; ICH = interior cedar–hemlock; and SBS = sub-boreal spruce.

[j] Data sources are as follows: 1. Herb Herunter, Fisheries and Oceans Canada, Burnaby, BC (personal communication); 2. Terry Sowden, Fisheries and Oceans Canada, Sidney, BC (water temperature [WATEMP] database); 3. Barry Finnegan, Fisheries and Oceans Canada, Nanaimo, BC (personal communication); 4. Patrick Hudson, Freshwater Resources, Smithers, BC (personal communication); 5. Lisa Torunski and Jessica Chaplin, McElhanney Consulting Ltd. collected for Baptiste Forest Products, Smithers, BC (personal communication); 6. Ian Sharpe, BC Ministry of Water, Land, and Air Protection, Smithers (personal communication); 7. AGRA (2000); 8. McElhanney Consulting, Ltd. (2001); 9. McElhanney Consulting, Ltd. (2002).

TABLE 1.—Extended Continued.

Region	Station number[a]	Air temp. anomaly (°C)[e]	Air temp. station[f]	Distance to coast (km)	Orientation[g]	Surficial geology[h]	BEC zone[i]	Source[j]
Middle River	67	1.84	Augier	318	NW–NE	Tb	SBS	1
	68	0.29	Augier	327	SW–NW	Tv	SBS	2
Morice River	69	0.35	Houston	186	NW–NE	Tv	SBS	7
	70	−1.16	Houston	195	NE–SE	Tv	SBS	7
	71	−1.16	Houston	195	NE–SE	Tv	SBS	7
	72	−1.16	Houston	195	NE–SE	Tb	SBS	7
	73	−1.16	Houston	194	NE–SE	Tb	SBS	7
	74	−1.16	Houston	193	NW–NE	Tv	SBS	7
	75	−1.16	Houston	193	SW–NW	Tv	SBS	7
	76	0.35	Houston	192	SW–NW	Tb	SBS	3
	77	−1.60	Peden	216	SE–SW	Tb	SBS	7
	78	−1.16	Houston	217	SE–SW	Tb	SBS	7
	79	−1.16	Houston	215	SE–SW	Tb	SBS	7
	80	−1.16	Houston	222	SW–NW	Tb	SBS	7
	81	−1.16	Houston	200	SW–NW	Tv	SBS	7
	82	−1.16	Houston	204	SW–NW	Tb	SBS	3
	83	−0.60	Houston	195	NE–SE	Tv	SBS	4
	84	−1.52	Houston	196	NE–SE	Tv	SBS	4
	85	−1.52	Houston	199	NE–SE	Tv	SBS	4
Nadina River	86	0.48	Peden	214	SW–NW	Tb	SBS	1
Nautley River	87	1.17	Augier	325	SW–NW	Tb	SBS	2
Parrott Creek	88	−1.60	Peden	229	SW–NW	Tb	SBS	7
	89	−1.60	Peden	232	SW–NW	Tb	SBS	7
Peter Alec Creek	90	0.48	Peden	213	SW–NW	Tb	SBS	1
Pinkut Creek	91	−1.20	Augier	290	SE–SW	Tb	SBS	5
	92*	−1.20	Augier	292	NE–SE	Tb	SBS	5
	93	−1.31	Augier	304	SE–SW	Tb	SBS	8
	94	−1.31	Augier	295	SW–NW	Tb	SBS	8
Stellako River	95	0.26	Augier	299	SW–NW	Tb	SBS	2
Stuart River	96	1.22	Augier	365	NW–NE	fL	SBS	2
	97	2.31	Bear	382	SW–NW	fL	SBS	2
Tachie River	98	0.47	Augier	354	SW–NW	Tb	SBS	2
	99	0.49	Augier	356	NW–NE	Tb	SBS	2
Tahtsa Lake	100	−1.60	Peden	181	NE–SE	Tb	SBS	7
	101	−1.60	Peden	178	NW–NE	Tb	SBS	7
	102	−1.60	Peden	199	SW–NW	Tb	SBS	7
Zymoetz River	103	−1.55	Upper Fulton	187	NE–SE	Tb	SBS	3
	104*	1.91	Upper Fulton	187	NW–NE	Tv	SBS	3
Average		−0.50		253				
Maximum		2.31		382				
Minimum		−1.60		107				
SD		1.10		55				

range that would have existed if all 104 streams had been pooled. The resulting explanatory variables for producing groups were thus useful at reducing the initial unexplained variation in MWAT.

A 10-fold cross-validation method (Brieman et al. 1984) explored the relation between the complexity of the regression tree (i.e., number of terminal nodes or stream temperature classes) and a measure of tree prediction error (i.e., misclassification rates of streams). This approach first split all 104 streams into 10 equally sized groups. A tree was then generated from 9 of the groups, and the accuracy of this tree was tested by using it to classify streams in the 10th group. This testing was repeated 10 times, each time with a different group removed. In each trial, a measure of the tree's prediction error was calculated as the number of terminal nodes increased. Values of prediction error were then averaged across all 10 trials and plotted against the size of the tree (i.e., number of terminal nodes). We selected a tree size that minimized the error calculated from this cross-validation procedure (Brieman et al. 1984).

Identification of Biologically Suitable Ranges in Stream Temperature

Biological processes.—The above methods were used to describe and account for some of the variation in temperature conditions among streams. We then identified the most biologically suitable thermal regimes to help set regulations directly. We applied several models to examine how daily water temperature affects rainbow trout population processes, such as egg survival rate, juvenile growth, and resistance to mortality from disease. The rainbow trout was the

TABLE 2.—Descriptions of 16 indices used to characterize a stream temperature profile as derived from temperature data recorded from June 9 to September 15 in British Columbia streams ($n = 104$). Given the available data, we calculated indices marked by asterisks for all streams, whereas indices without asterisks were calculated for only 31 streams. Indices are grouped by description type: annual peak of a temperature profile (MX), number of days that temperature exceeds a threshold value (TH), daily fluctuation in temperature (DF), seasonal rate of temperature change (RT), or timing of annual maximum temperature (TM).

Index	Description
MX(1)*	Annual maximum of the daily maximum temperature
MX(2)*	Annual maximum of a 7-d average of the daily maximum temperature
MX(3)*	Annual maximum of a 7-d average of the daily minimum temperature
MX(4)*[a]	Annual maximum of a 7-d average of the daily mean temperature
MX(5)	Value representing the 95th percentile of the daily mean temperature
MX(6)	Median value of the daily mean temperature
MX(7)	Average of the daily mean temperature
TH(1)	Number of days the daily maximum temperature exceeds 19°C
TH(2)	Number of days the daily maximum temperature exceeds 15°C
TH(3)	Number of days that a 7-d average of the daily maximum temperature (MX[2]) exceeds 18°C
DF(1)	Maximum difference between the daily maximum and the daily minimum temperature
DF(2)	Minimum difference between the daily maximum and the daily minimum temperature
DF(3)	Summer average of the difference between the daily maximum and the daily minimum temperature
RT(1)	Average rate of increase (°C/d) from the daily minimum temperature on Jun 9 to the maximum of the daily maximum temperature (MX[1])
RT(2)	Average rate of decrease (°C/d) from the maximum of the daily maximum temperature (MX[1]) to the daily minimum temperature on Sep 15
TM(10	Date of the maximum of the daily maximum temperature (MX[1])

[a] Throughout this paper, MX(4) is referred to as the maximum weekly average temperature (MWAT) index.

species of interest because (1) it is the most common salmonid in our study area, (2) relations between water temperature and physiology of rainbow trout have been well studied, and (3) this species spawns at a time that allowed us to use the available temperature data to assess effects.

Models.—Three models estimated the responses of rainbow trout to day-to-day fluctuations in stream temperature over the summer. First, to determine the effect of stream temperature on the survival rate of rainbow trout eggs, we used models and parameter values from McLean et al. (1991) and Jensen et al. (2002) to predict the number of days from fertilization (June 9) to the date when 50% of eggs are expected to hatch and then to predict the proportion of fertilized eggs surviving to that median hatch date.

Next, due to the lack of an appropriate model for rainbow trout, we used a two-part growth model (Sullivan et al. 2000) for steelhead, an anadromous life history form of rainbow trout, to estimate the effects of temperature on the end-of-summer weight of juvenile rainbow trout. The first part, based on a bioenergetics model, expressed daily food consumption as a function of water temperature, fish weight, and food ration. The second part of the model related daily growth rate to a stream's observed daily temperature and an individual's daily consumption. We also modeled growth at four food rations (40, 60, 80, and 100% satiation) because water temperature can influence macroinvertebrates (Vannote and Sweeney 1980), an important food source for rainbow trout.

Finally, we used information on two common bacterial pathogens of Pacific Northwest rainbow trout, *Flavobacterium columnare* (formerly *Flexibacter columnaris*) and *Aeromonas salmonicida* (Fryer and Pilcher 1974), to examine the relation between thermal regime and resistance of juvenile rainbow trout to mortality from the diseases caused by these pathogens (see Appendix 2 for details). We first calculated the water temperature that resulted in 50% mortality of an exposed sample of fish (i.e., median lethal temperature [LT50]) based on data from two previous studies (Fryer and Pilcher 1974; Fryer et al. 1976) and then summed the number of days over the summer in which a stream's daily maximum temperature was below the LT50. We considered disease resistance because higher water temperature can affect a fish's immune response and increase growth rates of some bacterial diseases (Fryer and Pilcher 1974).

For those streams and years that had complete daily temperature records from June 9 to September 15 (31 of 104 streams), we used these three models to estimate a fish's response to thermal regime by translating summer daily stream temperatures into more biologically meaningful measures of survival rate, growth rate, and resistance to disease. For each stream, we then plotted end-of-season predictions for these three population processes against MWAT, which is simpler than daily values as an aggregate index of summer temperature. Using least-squares regression, we fit equations to these data to predict indicators of population processes (Y) as a function of a stream's measured MWAT (X). For indices of egg survival rate and juvenile growth rate, the equations were both of the form $Y = a + bX + cX^2$, whereas for the index of resistance to disease mortality, we used a simple linear model, $Y = a + bX$. To fit the relation between MWAT and proportional egg survival rate, we used an arcsine transformation of the survival rate (Sokal and Rohlf 1995) to standardize variances and improve normality of residuals. We then calculated the MWAT ranges that predicted the highest survival rate of eggs, the largest end-of-summer body weight, and the greatest resistance to mortality from disease. We defined these ranges as the upper and lower MWATs that resulted in a 5% reduction from the modeled maximum (following Sullivan et al. 2000) for each of the three indicators.

These analyses required an important assumption, namely that each model would only estimate the relative effects of one temperature-dependent process on rainbow trout. Population processes can obviously interact or be influenced by other habitat variables that vary widely among streams. These models could therefore not evaluate the overall net effect of temperature on rainbow trout populations because interactions among temperature-dependent processes are not well understood and because the additional habitat information was not available for all study streams.

Effects of Forestry Practices

Watershed-scale activities.—The effects of streamside forestry activities (e.g., riparian harvesting and road crossings) and their lingering effects on stream temperature in the immediate vicinity have been well documented (Beschta et al. 1987). Unfortunately, the effects of these nearby influences could not be assessed in this study because harvest-related activities adjacent to the monitoring locations were not measured for our 104 streams. However, on a larger scale, measures of the total amount of forestry activity in each watershed were available for our study streams. The cumulative effects of such activities summed across a watershed are worthy of further investigation because the results to date at this scale are conflicting (Beschta and Taylor 1988; Bettinger et al. 1998; Zwieniecki and Newton 1999). We therefore estimated the relation between each stream's MWAT and the index of logging-related activities in the larger upstream area.

We used the BC Watershed Statistics Database (provided by the BC Ministry of Sustainable Resource Management, Business Solutions Branch) to summarize into four variables the amount of forest harvesting and road building in the watersheds for which we had stream temperature data:

1. the proportion of a watershed that had been logged (>15 ha) or selectively logged (>30 ha) within the previous 20 years (km^2 of logged area per km^2 of watershed area),
2. the proportion of streams (mapped at a 1:20,000 scale) in a watershed that had been logged or selectively logged to the bank (km of logged riparian area per km of stream within a watershed),
3. the density of roads within a watershed (km of road per km^2 of watershed area), and
4. the density of stream crossings by roads within a watershed (number of road crossings per km^2 of watershed area).

However, these watershed-level activities could only be summed for predefined watershed polygons. In many instances, these polygons did not coincide with the drainage areas associated with our stream temperature locations. Therefore, only a subset of stream temperature data sets could be analyzed for cumulative effects from upstream land use.

Thermal impacts of forestry activities.—As an alternative to standard linear regression for estimating the relations between a stream temperature index (Y) and each of these four indicators of land use (X), we used Bayesian regression (Press 1989). This method quantifies statistical uncertainty in the slope and intercept parameters of a regression and thus in the magnitude and chance of various thermal impacts. Bayesian regression estimates the range of underlying slopes that are possible and assigns a degree of belief (posterior probability) to each slope (Ellison 1996). This method also allows for results from other independent studies (prior information) to be incorporated into the analysis. However, we did not use such additional information here. Instead, we used a noninformative prior probability distribution and relied solely on the observed field data.

Analysis of the effects of forest practices on stream temperature employed the final six stream classes (or categories) that were generated by the C&RT analysis. The resulting stratification attributed some of the variation in MWAT to a stream's watershed features and climatic setting. Next, we calculated regression tree residuals as the difference between a stream's MWAT and the average MWAT for that stream's temperature class (I–VI). These residuals thus reflected the deviations in MWAT for a stream from the mean MWAT of all streams in that category (i.e., deviations that were unexplained by watershed features or climate). By removing some of the among-stream variation in MWAT with these explanatory variables, we thereby improved the chance of detecting effects of watershed-scale influences of forestry activities on stream temperature. Finally, we used Bayesian regression to examine the relations between these regression tree residuals of temperature and each of the four measures of forestry development. As noted above, due to limited data on watershed-level activities, we could only estimate these relations for a single category of 14 streams (Class II) (see asterisks in second column of Table 1); the other classes contained less than seven streams.

Results

Ranges of Variation in Stream Temperature

The regression tree analysis evaluated the influence of the eight explanatory variables on MWAT for each stream. We identified two watershed variables (drainage area and basin elevation) and one climatic variable (a summer air temperature anomaly) that stratified streams and reduced the range of unexplained variation in MWAT from 17°C across all 104 streams to a range of approximately 5°C within each stream class (Figure 2). The 10-fold cross validation procedure indicated that a tree with five splits and six terminal nodes provided the best fit to the MWAT data. This tree explained 78% of the variance in MWAT. The first split partitioned the temperature data into groups with the most similar thermal regimes based on watershed drainage area. Smaller streams with drainage areas less than 132 km^2 tended to have lower MWATs than larger streams with drainage areas of 132 km^2 or more (Figure 2). Subsequent splits showed that streams with lower basin elevations tended to have higher MWATs than streams with higher elevations (e.g., compare classes V and VI, Figure 2), while streams exposed to low summer air temperatures tended to have lower MWATs than streams exposed to higher air temperatures (compare classes III and IV, Figure 2). As expected, the lower MWATs of smaller ($<$12 km^2) headwater streams (Class I) contrasted with the much higher MWATs of larger ($>$132 km^2) main channels (Class V) at similar elevations. Classes I, II, V, and VI described groups of streams that were characterized by different average basin elevations and drainage areas, whereas those features were the same for Class III and Class IV streams. These latter categories of small, high-elevation streams were the only ones that were distinguishable by variations in air temperature. Latitude, distance to the Pacific coast, compass orientation of the stream channel, surficial geology, and the biogeoclimatic zone of the stream did not contribute consistently to splits in the regression tree.

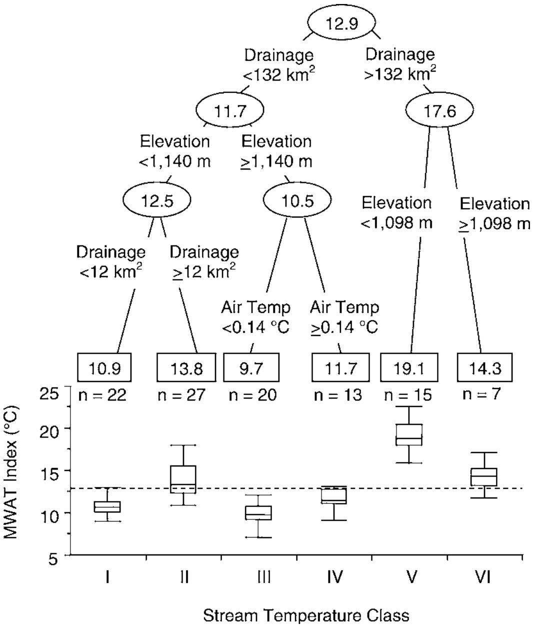

FIGURE 2.—Dendrogram from a classification and regression tree analysis showing the variables and values used to partition maximum weekly average temperatures (MWATs) for 104 British Columbia streams from the root and intermediate nodes (ovals) to the terminal nodes (rectangles). The value within each node represents the average MWAT for the group of streams as described by the variables in the branch lines above that node. Sample sizes of streams (*n*) are also indicated for terminal nodes. Variables are drainage (the drainage area [km^2] upstream of a temperature station), elevation (the average elevation [m] above sea level of the upstream basin), and air temperature (air temp, i.e., the difference between the average summer air temperature for a particular year and the 13-year average at the closest weather station). Box plots represent median, interquartile range, and 10th and 90th percentiles of stream temperature data for each group (stream temperature class) of streams. The dashed horizontal line represents the average MWAT for all 104 streams.

Biologically Suitable Ranges in Stream Temperature

In spite of differences in thermal regime among streams and years, there was a tight nonlinear relation between MWAT and each index of rainbow trout processes (all $r^2 > 0.84$; Figure 3). The MWAT was thus a useful, but simple, index of the aggregate effects of daily summer temperature profile on the predicted rate of egg survival to median hatch date, juvenile growth rate, and resistance to diseases. The MWAT ranges that estimated maximum growth at four food rations (Figure 3b; 11.8–17.2°C at 40%, 13.0–18.3°C at 60%, 13.3–18.9°C at 80%, and 13.5–19.2°C at 100%) were consistently higher than the MWAT ranges that

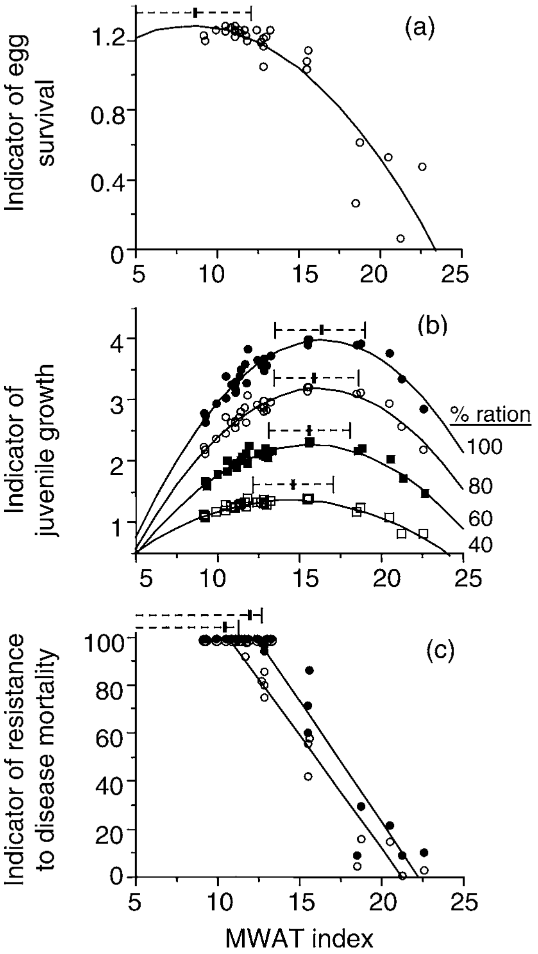

FIGURE 3.—Relations between a maximum weekly average temperature (MWAT) index in British Columbia streams and each of three indicators of temperature-dependent processes in rainbow trout: **(a)** the arcsine-transformed (radians) proportion of eggs surviving to the median hatch date ($Y = 1.83 - 0.05X - 0.006[X - 12.9]^2$, $r^2 = 0.85$), **(b)** end-of-summer weight (g) at four food rations (40% satiation [open squares]: $Y = 0.98 + 0.03X - 0.01[X - 12.9]^2$, $r^2 = 0.91$; 60% satiation [filled squares]: $Y = 1.06 + 0.09X - 0.02[X - 12.9]^2$, $r^2 = 0.90$; 80% satiation [open circles]: $Y = 1.21 + 0.14X - 0.02[X - 12.9]^2$, $r^2 = 0.89$; and 100% satiation [filled circles]: $Y = 1.47 + 0.17X - 0.02[X - 12.9]^2$, $r^2 = 0.89$), and **(c)** the number of days for which temperature remains below the median lethal temperature for exposure to two pathogens (*Aeromonas salmonicida* [open circles]: $Y = 200 - 9.33X$, for $X > 10.8$°C, $r^2 = 0.94$; *Flavobacterium columnare* [filled circles]: $Y = 225 - 10.1X$, for $X > 12.5$°C, $r^2 = 0.91$). Each data point represents a stream's thermal regime (represented by an observed MWAT) and the biological response in a stream (represented by the end-of-season model predictions described in the text). Only 31 of 104 study streams had appropriate data for this analysis. Solid lines represent the best-fit relations between MWAT and each indicator of population processes. Ranges of MWATs that predict up to a 5% reduction from the maximum of each relation are represented by horizontal error bars with vertical whiskers.

predicted maximum egg survival rate (Figure 3a; 5.0–11.8°C) and maximum resistance to mortality from diseases (Figure 3c; *A. salmonicida*: <11.3°C; *F. columnare*: <13.0°C).

The direction of a rainbow trout population's response to a stream temperature increase that might result from land use activities will thus depend on the biological indicator of interest and a stream's measured MWAT. For instance, the best-fit relation at 100% food ration (solid circles in Figure 3b) estimated that a stream with an initial MWAT of 12°C would show increasing growth in rainbow trout body weight as MWAT increased to about 17°C, above which growth rates would be predicted to decline to that of the initial 12°C levels near an MWAT of 22°C. In contrast, Figure 3a suggests that increases in temperature above an initial MWAT of 12°C would lead to reduced egg survival rates.

Effects of Forestry Practices

Marginal posterior probability distributions of slope parameters estimated by the Bayesian regressions indicated an important cumulative effect of road density, as well as road crossing density, on regression tree MWAT residuals (Figure 4). Specifically, the slopes estimated the amount (°C) of increase in a stream's MWAT for each unit increase in road density (km/km^2; Figure 4a) or road crossing density (crossings/km^2; Figure 4b). Each distribution in Figure 4 indicates the degree of belief in specific values for the regression's slope parameter. These probability distributions indicate a 93% chance that there is a positive slope for the relation between stream temperature residuals and road density (Figure 4a) and a 74% chance that the slope is positive for the relation with road crossing density (Figure 4b). Although neither of the best-fit estimates of the slopes (i.e., slopes with the maximum probability) was statistically significant at the 0.05 level based on classical statistical hypothesis testing methods, the Bayesian posterior probability distributions showed degrees of belief in what could be biologically or economically important slopes in terms of their effects on fish (yet to be determined).

For instance, the posterior probability distributions for slopes in Figure 4 can be combined with road density to give examples of predicted changes in stream temperature. Typical road density in watersheds within the study area ranged from 0.0 to 6.6 km/km^2 (mean = 0.29 km/km^2), whereas road crossing density ranged from 0.0 to 5.2 crossings/km^2 (mean = 0.21 crossings/km^2). For road density, there is a 59% chance (or probability) that the slope will be 1.0 or greater (area to the right of the slope of 1.0 in Figure 4a); these slope values would be associated with a y-intercept of

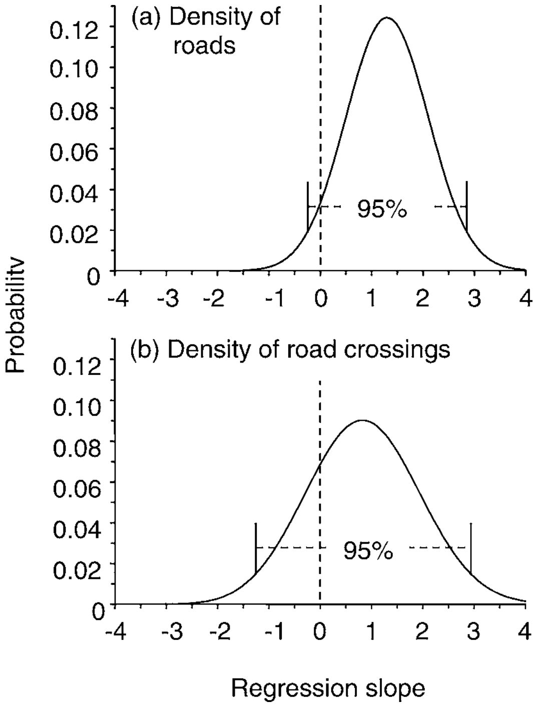

FIGURE 4.—Marginal posterior probability distributions of the slope parameters from a Bayesian regression of regression tree residual temperature (i.e., maximum weekly average temperature [MWAT]) on each of two measures of watershed-scale forestry activities in British Columbia streams: **(a)** the density of roads within the upstream basin (km of road/km^2 of watershed area) and **(b)** the density of roads that crossed streams within the upstream basin (number of road crossings/km^2 of watershed area). Slopes are in units of the change in MWAT (°C) per unit of road density or road crossing density. Distributions were derived from data from streams in Class II—specifically, 14 streams with drainage areas of at least 12 km^2 but less than 132 km^2 and average basin elevations less than 1,140 m. The dashed vertical line emphasizes the point at which the regression slope equals zero; dashed horizontal error bars represent 95% probability intervals.

–0.75 or less. At an example road density of 2 km/km^2, this means that the stream temperature (MWAT residual) in that watershed is predicted to increase by at least 1.25°C (i.e., –0.75 + [1·2]) relative to a roadless watershed, whereas in those watersheds with higher road densities of 4 km/km^2, MWAT would be expected to increase by at least 3.25°C (i.e., –0.75 + [1·4]). Even worse, the right side of Figure 4a shows that there is a 15% chance that the slope will be 2 or greater (i.e., the *y*-intercept would be −1.25 or less). These parameter values predicted an increase in MWAT residuals of 2.75°C for a road density of 2 km/km^2 and 6.75°C for a road density of 4 km/km^2.

For the other two measures of cumulative forestry activities (proportion of watershed logged and proportion of streams in a watershed that had been logged to the streambank), we found only a slight tendency to have negatively sloped relations with MWAT residuals. These latter two posterior probability distributions were centered just below zero and were symmetric.

Discussion

This research may assist in the more effective management of land use activities that influence the temperature of fish-bearing streams. First, our work complements previous studies that demonstrate how managers can directly set temperature thresholds based on anticipated biological responses (Brungs and Jones 1977; Armour 1991; Sullivan et al. 2000). Our results are also consistent with other studies of temperature-dependent responses (Welsh et al. 2001; Dunham et al. 2003; Wehrly et al. 2003). These findings have implications for the way in which temperature thresholds are set. We found that several commonly used indices of stream temperature are highly correlated, whereas certain classes of temperature indicators reflect different thermal properties of streams (Appendix 1). Thus, temperature indices such as MWAT may not reflect other attributes of a thermal profile (e.g., level of diurnal or seasonal variation) that could potentially affect various biological responses. In our example, we used summer MWAT to reflect thermal conditions in a stream and found that a given MWAT cannot be simultaneously optimal for rainbow trout egg survival, growth, and resistance to diseases (Figure 3). Sullivan et al. (2000) used an indicator similar to MWAT and also identified different optimal ranges for growth of different species in addition to rainbow trout. Hence, managers should not expect that a single biologically based upper temperature limit will protect all life stages and fish species in a stream (Boulton 1999; Richter and Kolmes 2005). Instead, models of interacting processes of population dynamics are needed that reflect the full life cycle of the fish to examine the net effect of temperature on different life stages, components of the aquatic ecosystem (including prey, predators, and competitors), and density-dependent processes.

Such comprehensive population dynamics models should produce output indicators that are directly relevant to management objectives, which need to be clearly specified (Jones et al. 1996). For instance, when identifying temperature-sensitive streams with some upper limit on acceptable temperature, is the objective to (1) maintain (or maximize) biological diversity as measured in some specified way, (2) maintain abundance of some indicator population of a particular species (e.g., bull trout) above some lower conservation threshold, or (3) achieve some other purpose? Obviously, our research does not address this issue of management objectives, but effective future scientific research on the topic of temperature-sensitive streams needs to be focused by the use of clear management objectives.

If such clear objectives are not yet articulated, then in the interim a manager could identify the highest-priority limiting factor on fish population abundance in a new stream of interest and manage the habitat to optimize conditions based on that factor alone. For instance, if research shows that adult fish abundance is limited by juvenile abundance and that the compensatory mortality rate in a later life stage is low, then managers may aim for thermal conditions that maximize egg survival rate and resistance to disease rather than those that maximize juvenile growth. Also, in unproductive waters where food rations are limiting because of natural or anthropogenic influences, allowing tree harvesting activities to heat a stream that has an MWAT below the optimum would provide minimal benefits to growth.

Where feasible, managers should set regulations related to stream temperature based not only on the above direct measures of temperature suitability but also on the more indirect method of managing land use activities by keeping stream temperatures within the range of natural variability (USEPA 2003; Poole et al. 2004). As noted in the Introduction, definition of such a range requires one to find completely pristine habitat that is unaffected by humans and then to extrapolate it to other regions with similar watershed features. Although we lacked data on such pristine habitats because of human influences on our sample of streams, our C&RT analysis found that three watershed indices (drainage area, basin elevation, and regional influence of summer air temperature) reliably partitioned the broad sample of 104 streams into six stream temperature classes. Other researchers have also associated these same three variables with stream temperature (Stefan and Preud'homme 1993; Lewis et al. 2000; Isaak and Hubert 2001). Our resulting unexplained variation in the MWAT was reduced from 17°C across all 104 streams to about 5°C for each class of streams. If appropriate data were available, this temperature range within each stream class could be reduced further by taking into account additional catchment-scale influences, such as the presence of lakes in a watershed (Mellina et al. 2002), or site-specific factors, such as the interaction of groundwater (Story et al. 2003) and amount of riparian shading (Macdonald et al. 2003). Regardless, our results from the C&RT analysis only help to suggest the *maximum* temperature, or upper limit to the range of variability, within each class of streams (rather than the natural range in the absence of human activity) because (1) land use activities usually increase (or do not affect)—rather than decrease—summer maximum temperature and (2) some of the observed temperatures at the high end of the range in our samples were probably attributable to the human land use activities that have already occurred.

There are at least two ways in which a manager could use such estimates from the C&RT analysis of the maximum range of variability in stream temperature. First, the observed ranges in each stream class could be used "as is" to set management thresholds (e.g., 10th and 90th percentiles) and evaluate potential water temperature changes due to human activities. For example, streams with MWATs near the 90th-percentile temperature in their class (e.g., 13°C in Class I; Figure 2) and streams with fish species whose critical processes will be hindered at higher temperatures could be considered for designation as "sensitive," because even small human-induced temperature increases may increase MWATs beyond the observed range. Such a relatively excessive temperature would be more likely to occur in such streams than in streams that have an identical MWAT of 13°C but that belong to other stream classes for which 13°C is near the 50th percentile of observed values (e.g., Class II; Figure 2). The second way to use the distributions of MWATs within each stream class is to somehow reduce the temperatures at the upper end of the ranges to reflect the human actions that affected the observations (assuming that the lower end of the temperature distributions is likely to be valid). Although that scaling-down process could be done arbitrarily if no information is available, it should ideally be done by modeling land use effects on surface water and groundwater processes, as well as other processes affecting stream temperature (e.g., Sullivan et al. 1990; LeBlanc et al. 1997; Chen et al. 1998). Finally, a spin-off of the C&RT analysis is a simple scheme—based on three simple physical features of the watersheds—that can be used to classify streams for which temperature data are lacking.

Another contribution of our work relates to illustrating the Bayesian method for estimating the magnitude of increase in summer stream temperature from the cumulative effects of activities related to logging. To improve the reliability of such estimates in our example, we used the residuals in observed MWAT for 14 Class II streams as the dependent variable. Those residuals reduced the potentially confounding effects of drainage area, basin elevation, and regional influence of summer air temperature on estimates of human land use effects. Our Bayesian regression analysis indicated that MWAT residuals tended to increase as road density and road crossing density increased (Figure 4). This analysis also produced a measure of the uncertainty in estimated regression slopes and intercepts, which permitted a calculation of the chance or probability of stream temperature increasing by various amounts for a given change in the independent variable (road density or road crossing density). As illustrated in our worked examples, there is at least a 59% chance that the summer MWAT would increase by about 1–3°C and at least a 15% chance that it would increase by about 2–6°C if road densities were between 2 and 4 km/km^2 in our study region. The first results can also be stated differently to clarify this meaning of chance. In roughly 6 out of every 10 streams in our study region with similar characteristics to the Class II streams analyzed here, we would expect to see the increases in stream temperature indicated for the given road densities.

Such increases are very likely to be biologically important given our modeled responses of hatching rate, growth rate, and resistance to diseases. Managers who must make decisions about acceptable upper limits for changes to stream temperature will thus have to take into account the probability of each of these (and other) outcomes occurring and the severity of their respective effects on fish. Those probabilities and severities could in turn feed into broader risk assessments or benefit–cost analyses of cumulative effects of forestry-related activities. Such calculations will not be possible if scientists continue to focus on the use of classical statistical hypothesis testing methods (Johnson 1999). The feasibility of conducting these more comprehensive types of applied analyses is one of the advantages of Bayesian statistical methods, which we therefore highly recommend (Ellison 1996; Wade 2000).

Limitations of Our Analyses

There are four important limitations of our analyses. First, stream temperatures from a single location may not accurately represent thermal patterns throughout a stream, and climatic data from a distant meteorological station may not adequately reflect streamside conditions. Second, the application of biological models from other studies, regions, and species to predict the effect of water temperature on rainbow trout in central BC may be inappropriate. The populations upon which these models were developed may have adapted to different local conditions, and specific parameter values may therefore be different than those in central BC. Furthermore, responses of juvenile steelhead to changing temperatures were assumed to estimate responses for juvenile rainbow trout, and results from laboratory experiments with constant temperatures were assumed to represent responses in streams that have diurnally and seasonally variable temperatures. Third, the streams used in our analyses were not sampled randomly from the total population of streams in the region; hence, they may or may not be representative of a larger group of streams. This lack of probabilistic samples precludes reliable extrapolation of our quantitative results to a wider group of streams (Schwarz 1998). Nevertheless, we have demonstrated that the C&RT and Bayesian regression methods may be useful in other analyses of this type. Fourth, although we observed an important effect of roads on water temperature, we did not find an effect of more direct measures of logging. There are at least three reasons for the latter: (1) data on logging in BC's Watershed Statistics Database were summarized over 20 years (no shorter period was available), which may have been inappropriate for our purposes because at least some streams may have recovered to prelogging thermal conditions during that time; (2) because of the crude temporal scale of logging data, there were undoubtedly temporal mismatches between the year in which temperature data were measured and the year(s) in which logging took place; and (3) logging activities were summed over an entire watershed, and local and more distant upstream influences were weighted equally even though local activities can have stronger effects on stream temperature.

Future Research

To improve the methods for designating temperature-sensitive streams, scientists need more accurate measurements of watershed-scale and streamside forestry activities. These variables can then be included in both the C&RT analysis for categorizing streams and the Bayesian analysis of effects of those activities on stream temperature. Scientists and managers should be aware that choosing streams or watersheds opportunistically, rather than randomly, for research of this type will restrict the ability to reliably extrapolate to a new group of streams or new situations (Schwarz 1998). Ideally, the streams that are used to generate the classification tree should be sampled randomly and stratified spatially and should include watersheds with contrasting levels of human activity and natural disturbances. A regression tree analysis could then identify stream categories and the relative influence of different levels of forest harvesting and natural disturbance on stream temperature. Next, measures of human disturbance could be used to estimate the effect of similar and proposed activities on stream temperature. Allowable levels of forestry activity could then be selected based on (1) the range of temperatures observed in watersheds that were affected mainly by natural disturbances and (2) the probability distribution of potential effects of that activity. This approach could lead to a relatively consistent process for making decisions about temperature-sensitive streams.

Acknowledgments

Many thanks go to Barry Finnegan, Herb Herunter, Patrick Hudson, Ian Sharpe, Terry Sowden, and Lisa Torunski for providing stream temperature data and to the additional field staff who collected them. The Forest Investment Initiative provided funding for collection of some of these data. Eric Meyer with the BC Forest Service Protection Program supplied air temperature data, and Malcolm Gray with the BC Ministry of Sustainable Resource Management contributed the Watershed Statistics Database. The BC Ministry of Sustainable Resource Management provided additional spatial information in the form of a DEM. Gottfried Pestal provided helpful advice on the use of C&RTs. We are also grateful to Mike Bradford, Dan Moore, and Eric Parkinson for their extremely useful comments on an earlier draft. This research was funded by the Natural Science and Engineering Research Council of Canada and Fisheries and Oceans Canada.

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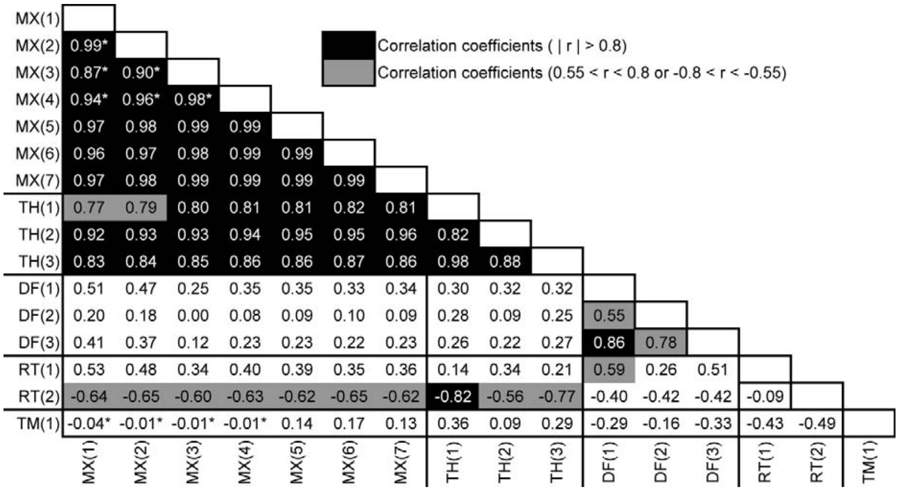
Appendix 1: Indices of Stream Temperature

To explore similarities among the 16 indicators of stream temperature (Table 2), we calculated Pearson's product-moment correlation coefficients for all pairwise comparisons (Figure A.1.1). Several stream temperature indices that described similar aspects of thermal regimes were significantly ($P < 0.05$) and positively correlated ($r > 0.55$; Figure A.1.1). For example, the two groups of indices that summarized a stream's warmest period over the summer were highly correlated (e.g., pairwise correlations of MX and TH indices; Figure A.1.1). As indicated in the Methods section, we used the MWAT index (MX[4]) for each stream (Table 1) in our other analyses.

We also conducted an exploratory analysis to examine the responsiveness of each temperature indicator to variation in the landscape features and climatic variables measured at each study stream. We did not observe any linear or nonlinear relationships between our watershed and climatic variables and most of the DF, RT, and TM groups.



■ Correlation coefficients (| r | > 0.8)

▨ Correlation coefficients (0.55 < r < 0.8 or -0.8 < r < -0.55)

	MX(1)	MX(2)	MX(3)	MX(4)	MX(5)	MX(6)	MX(7)	TH(1)	TH(2)	TH(3)	DF(1)	DF(2)	DF(3)	RT(1)	RT(2)	TM(1)
MX(1)																
MX(2)	0.99*															
MX(3)	0.87*	0.90*														
MX(4)	0.94*	0.96*	0.98*													
MX(5)	0.97	0.98	0.99	0.99												
MX(6)	0.96	0.97	0.98	0.99	0.99											
MX(7)	0.97	0.98	0.99	0.99	0.99	0.99										
TH(1)	0.77	0.79	0.80	0.81	0.81	0.82	0.81									
TH(2)	0.92	0.93	0.93	0.94	0.95	0.95	0.96	0.82								
TH(3)	0.83	0.84	0.85	0.86	0.86	0.87	0.86	0.98	0.88							
DF(1)	0.51	0.47	0.25	0.35	0.35	0.33	0.34	0.30	0.32	0.32						
DF(2)	0.20	0.18	0.00	0.08	0.09	0.10	0.09	0.28	0.09	0.25	0.55					
DF(3)	0.41	0.37	0.12	0.23	0.23	0.22	0.23	0.26	0.22	0.27	0.86	0.78				
RT(1)	0.53	0.48	0.34	0.40	0.39	0.35	0.36	0.14	0.34	0.21	0.59	0.26	0.51			
RT(2)	-0.64	-0.65	-0.60	-0.63	-0.62	-0.65	-0.62	-0.82	-0.56	-0.77	-0.40	-0.42	-0.42	-0.09		
TM(1)	-0.04*	-0.01*	-0.01*	-0.01*	0.14	0.17	0.13	0.36	0.09	0.29	-0.29	-0.16	-0.33	-0.43	-0.49	

FIGURE A.1.1.—Pairwise correlations among 16 stream temperature indices (defined in Table 2) calculated for British Columbia streams. The maximum weekly average temperature (MWAT) index is represented here by MX(4). All correlation coefficients (r) in either type of shaded box (light or dark) are less than −0.55 or greater than 0.55 and statistically significant ($P < 0.05$). Correlation coefficients denoted by asterisks were calculated from data from all 104 streams; those without asterisks were calculated from data from 31 streams.

We only found relations between these variables and some indicators in the MX and TH groups. These latter indices were also the only ones to result in clear relations with the modeled biological responses (e.g., growth, egg survival, and resistance to disease-related mortality).

Appendix 2: Resistance of Juvenile Rainbow Trout to Mortality from Two Bacterial Diseases

To examine the resistance of rainbow trout to disease mortality, we selected two bacterial pathogens that commonly target this species, *Flavobacterium columnare* and *Aeromonas salmonicida*. We then compiled data from previous studies that related the proportion of juvenile rainbow trout or steelhead that survived exposure to the pathogens at various water temperatures (Fryer and Pilcher 1974; Fryer et al. 1976). These data described a typical sigmoid dose–response relationship between constant water temperatures from 3.9°C to 23.3°C and mortality rate of exposed fish. Next, we used probit analysis (Finney 1971) to estimate the water temperature that resulted in 50% mortality of the exposed sample of fish (i.e., LT50). We used data from trials at 12.2, 15.0, and 17.8°C because these water temperatures were well below the lethal values for rainbow trout, which meant that mortalities were probably the result of disease exposures and not related to excessive heating. Using this procedure, we estimated that 50% of a sample of juvenile rainbow trout would die from exposure to *A. salmonicida* in an environment with a constant temperature of 13.5°C. A slightly warmer temperature of 15.0°C was needed to observe the same mortality of rainbow trout exposed to *F. columnare*. We then created an index of resistance to disease mortality by summing the number of days that a stream's daily maximum temperature was below these two LT50s. Therefore, streams with a high index value and a greater number of days below the LT50 had thermal conditions that were more favorable for the survival of exposed fish and less favorable for the persistence of these pathogens.