Year-to-Year Variation in Stream Temperature and Implications for Water Quality Criteria

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Abstract. Temporal variation in stream temperatures occurs on four time scales – within day, day-to-day, within year, and year-to-year. All four confound water temperature measurement and the assessment of water quality. The first three are well known and in water quality regulations are commonly, but perhaps not wisely, dealt with by focusing on peak temperatures in what is usually a summer time series at a particular site. Year-to-year variation on the other hand is ignored. Does it matter? I examine one site with 9 years of individual measurements to compare the four levels of variation. I then turn to daily values from 64 USGS sites in the Pacific NW with five or more years of data to describe year-to-year variation. I focus on four common water temperature metrics – annual maxima in daily maximums (MDMT), weekly maximums (MWMT), daily average (MDAT) and weekly averages (MWAT) – are all peak values in a complete annual or partial annual time series, thus there is one value per site per year. The year-to-year variation in these metrics is several °C for most sites, sufficient to swing some streams from suitable to unsuitable for cold water fish from year to year, or from compliance to non-compliance with regulatory criteria if year-to-year variation is not accounted for.

Introduction

Water temperatures are both spatially and temporally diverse, much like air temperature, and follow many of the same trends and patterns as air temperature. Like air temperature, temporal variation in stream temperatures occurs on four time scales – within day, day-to-day, within year, and year-to-year. The first three are readily apparent to anyone who examines a water temperature record from just one year (Figure 1). The fourth becomes apparent only by examining several years of data from the same site (Figure 2). Analysis of such multi-year temperatures records from the same site is uncommon in my experience.

Within day and within year variations are cyclical, driven by daily and annual solar cycles, and are thus quite predictable and quite familiar to even the casual observer. Day-to-day and year to year variations are more chaotic, driven by changes in the weather, and less apparent to most observers. Day-to-day changes in water temperature are due to day-to-day changes in the weather. They are best revealed in daily time series (e.g. Figure 3) that filter out diurnal cycles. These day-to-day changes can be quite dramatic in small to medium streams, but are evident to a muted extent even in larger streams. Responsiveness of streams to daily weather, while intuitive, surprises many. Year-to-year differences in stream temperatures are also intuitive. Important year-to-year weather factors that influence water temperatures include differences in air temperatures, cloudiness, and precipitation leading to stream flow. In the snowmelt driven hydrology of the intermountain west, timing and duration of snowmelt is important as well.

Regulatory Connection – Temperature Metrics

Water quality criteria typically deal with within year (seasonal) variation by focusing on peak temperatures, usually summer peak temperature, although for spawning the critical time period may not include the heat of summer. The criteria deal with diurnal cycles by collapsing within day measurements to daily values, and sometimes take into account day-to-day variation by employing seven-day running averages to smooth out day-to-day variation. In the end, for regulatory purposes a year or partial year of highly variable data is reduced to a single value for one of four temperature metrics:

MDMT – Maximum Daily Maximum Temperature, the highest daily maximum temperature recorded during a time period (typically a year) at a site. N=1, for one year's record at a site.

MWMT – Maximum Weekly Maximum Temperature, the highest weekly maximum temperature, i.e. the peak in seven-day running average of daily maximum temperatures during a time period (typically a year) at a site. N=7

MDAT – Maximum Daily Average Temperature, the highest daily average temperature recorded during a time period (typically a year) at a site. N typically = 10 to 96 (measurements every 2.4 hrs to every 15 minutes).

MWAT – Maximum Weekly Average Temperature, highest weekly mean temperature, i.e. the peak in seven-day running average of daily average temperature during the time period (typically a year) at a site. N= 70 to 672.

Although reducing a temporally complex data record to a single value per site per year loses a lot of information, these metrics continue to be those used in water quality regulations.

This series of metrics provides four values to describe the same thermograph. In comparing them, day-to-day variability expresses itself as a difference between weekly and daily metrics, such that MDMT > MWMT and MDAT > MWAT. Diurnal cycles demand that daily and weekly maximums exceed their respective averages, usually MWMT > MDAT as well. The result is that the four metrics usually array themselves in a regular order of decreasing magnitude. All four metrics shift in concert from year to year.

In typical water quality monitoring, especially that conducted by environmental and land management agencies, temperature is not monitored year round. Rather the survey period is chosen to encompass the summer warm season, such that a partial year's record confidently includes the annual peak. Alternatively, the survey period or the period of interest may not be the summer peak, e.g. a fall spawning period. In this case the MDMT etc. are the peak values during that period of interest and the time period should be stated, i.e. MDMT during fall spawning period of Sept 15th through Oct 15th was 13.8°C. The USGS data is unusual in that it usually does cover the entire year, ignoring occasional missing data due to equipment malfunction.

The Long-term Data Set

In order to examine inter-annual variation in water temperature it is necessary to have a long term record at a given location, hopefully obtained in a consistent manner. For present purposes long term means at least five years of record. Such records are rare, in part due to the only recent advent of the ability to inexpensively collect continuous water temperature, and in part because in general long term monitoring of water quality at a fixed location is rare. The USGS is perhaps the only agency that has regularly monitored water temperature over a broad area for more than a decade. Some more recent long term records are becoming available from federal land management agencies such as the US Forest Service, and state environmental regulatory agencies, but these are still uncommon and harder to come by.

Two data sets are examined here. One is from the Lochsa at Lowell, Idaho, a USGS gaging station at which the Nezperce National Forest has been monitoring summer water temperatures since 1992. Individual data values on a 2.4 to 0.5 hourly frequency were obtained. The second is a much more extensive set of temperature data collected by the USGS. Daily values were obtained for 64 sites throughout the Pacific NW states of Idaho, Oregon, and Washington where five or more years of data were nominally collected (see Map 1). These sites include 30 sites where flow was unregulated by dams; and 34 sites where flow was, for some part of the record, regulated by dams. Twenty-four (24) of the latter were flow regulated for the entire period of record for water temperature.

The data date back to 1951 at a few sites, while 21 sites continued to be monitored up through 2001. The site with the longest period of record, at 45 years, is 14181500 the North Santiam River at Niagara, OR, discontinued in 1997. The Snake River near Anatone, WA stands at 43 years of record and continues to be monitored in 2002. One site (USGS station 11492200 Crater Lake) is a lake rather than a stream, which may be well suited to examining year-to-year weather influences on water temperature. Table 1 provides a list of the USGS sites analyzed and some of their attributes.

Data processing

Although the USGS collects individual measurements at 15-minute intervals those data were not readily available. What were obtained were records of daily values by water year (Oct 1st of previous calendar year through Sep 30th). Often only the daily maximum and minimum were reported, in which case the daily average was calculated as the (max+min)/2, an approximation that previous experience has shown to be quite reasonable for the regular sinusoidal cycles of daily temperature fluxes, well within the 0.5°C precision most of the daily values were reported in. Seven-day running averages (weekly values) were then calculated from the daily values for maximum and average. Figure 3 shows the four resulting time series for an example site and illustrates the derivation of the four metrics characterizing peak temperatures used to summarize the data.

Most sites had years with incomplete data. As water temperatures usually peak in July or August, water years that did not include these two months were excluded. Years with partial records for the months of July and August were evaluated on a case-by-case basis to make a judgment of whether peak temperatures were likely missing. In a few cases an entire or nearly entire year of data was missing. Thus the number of years of useful data was often less than the nominal number of years reported in Table 1.

The precision with which the USGS reported temperature varied from 1.0 to 0.1 °C. In large mainstem rivers (e.g. Kootenai River), or below dams, the diurnal range was often less than a degree. Thus at several sites there was no apparent diurnal variation in peak summer temperatures in some years (MDMT=MDAT), presumably an artifact of measurement reporting precision. In some years there was even no apparent change in water temperature within the warmest week, so that all four metric were equal.

Results

Figure 4 depicts data from the Lochsa at Lowell, ID as a four panel series of daily time series. This series shows inter-annual variability in daily values, short of reduction to single values per year. These are like those in Figure 3 except that with nine years of data overlain in each graph one can see the year-to-year variation. This is probably a more illuminating way to look at year to year variability of these data than are the four peak metrics, but it is immaterial to evaluation of existing water quality standards. It also becomes cumbersome with many years of data from dozens of sites, as in the USGS long-term data set.

For the USGS data each site's data was reduced to a single figure showing the variation in MDMT, MWMT, MDAT and MWAT from year-to-year. Two examples are provided. In figure 5 the data are from an unregulated site in a largely undeveloped watershed. Figure 6 shows another site in which the period of record spans construction of a dam on a major tributary a few miles upstream. All the sites show considerable year-to-year variations, although unregulated sites are somewhat more variable.

Table 2 summarizes the USGS data for all 64 sites by tallying the number of sites for which the range of values in the four common metrics for the period of record is less than 3°C, between 3 and 6°C, or greater than 6°C. The tally is also broken down by sites (24) where dams were regulating flow through out the period of record, and sites (30) that were without flow regulation throughout the period of record. An additional ten sites were regulated by dams for a portion of the period of temperature records.

These data show that the range in these temperature metrics is frequently more than 3°C, particularly for unregulated sites. A range of three degrees is sufficient to swing many sites from compliance with water quality standards to non-compliance from year-to-year. It is also sufficient to cause streams whose temperature typically peaks in the mid to upper teens to vary from optimal to non-optimal for salmonids from year-to-year.

Discussion

Knowing the variation in stream temperatures from year-to-year is basic to understanding thermal regimes, how those regimes affect or support aquatic communities, and particularly the long term stability or viability of fish populations. Temporal variation has important implications in developing and applying water quality criteria for temperature – how comparable are laboratory studies at constant temperatures to a constantly varying stream; how should temperature regimes be compared; are average or extreme conditions more biologically meaningful, and if the latter how extreme? While not answering these specific questions the work presented here sheds light on the magnitude of year-to-year variations in water temperature, a dimension of variability that is easily and usually overlooked. These year-to-year variations are considerable and would be expected to result in significant shifts of thermally suitable habitat up and down the watershed over time.

If history is any indication, the expected approach of the regulatory community to year to year variation will be to further focus on peak temperatures, that is to regulate the rare extremes of temperature that are seen only once in ten years or less. This could be unwise, depending on the actual values chosen as criteria, condemning even high quality streams to perpetual non-compliance. Certainly expecting rare extremes to be within species optimal preferences anywhere but in prime habitat is unreasonable.

An alternative to expecting the extreme highs of year-to-year variation to meet ideal criteria would be to expect temperatures up to the peaks in typical or median years to meet ideal criteria and allow for somewhat warmer temperatures for the brief periods they occur in other years. However, if criteria were set at levels expected to be ideal only in median years, one is presented with the problem of how to assess anything but the median year. Adjusting either the criteria or the measured temperature metric for year-to-year variation could accomplish this. One approach would be use of the ratio of day-to-day variation in water temperature in a single year's record at a given site to nearby air temperature. This ratio would be an index to the responsiveness of that site to changes in air temperature. While such a response factor could only account for variations in water temperature caused by differences in air temperature – air temperature is a prime factor in natural water temperature variations along with flow.

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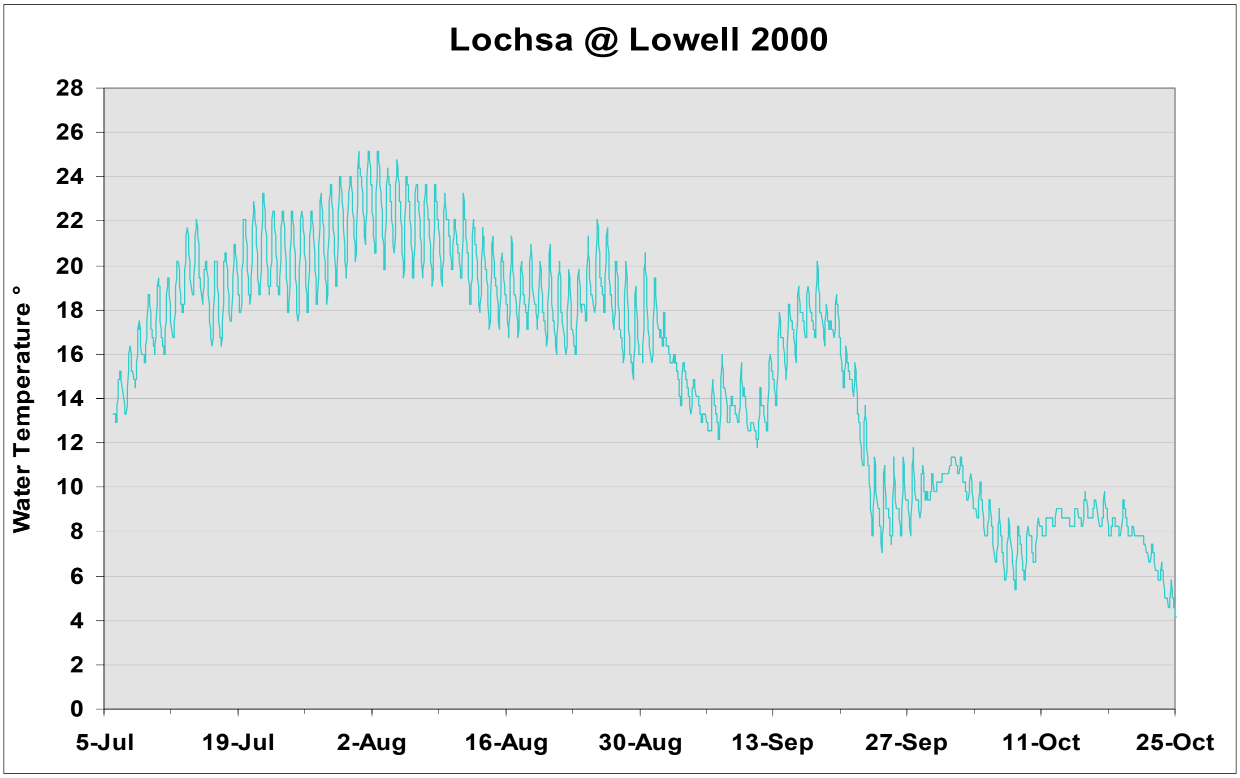


Figure 1. A typical single year temperature record showing diurnal, day-to-day, and seasonal variability in water temperatures.

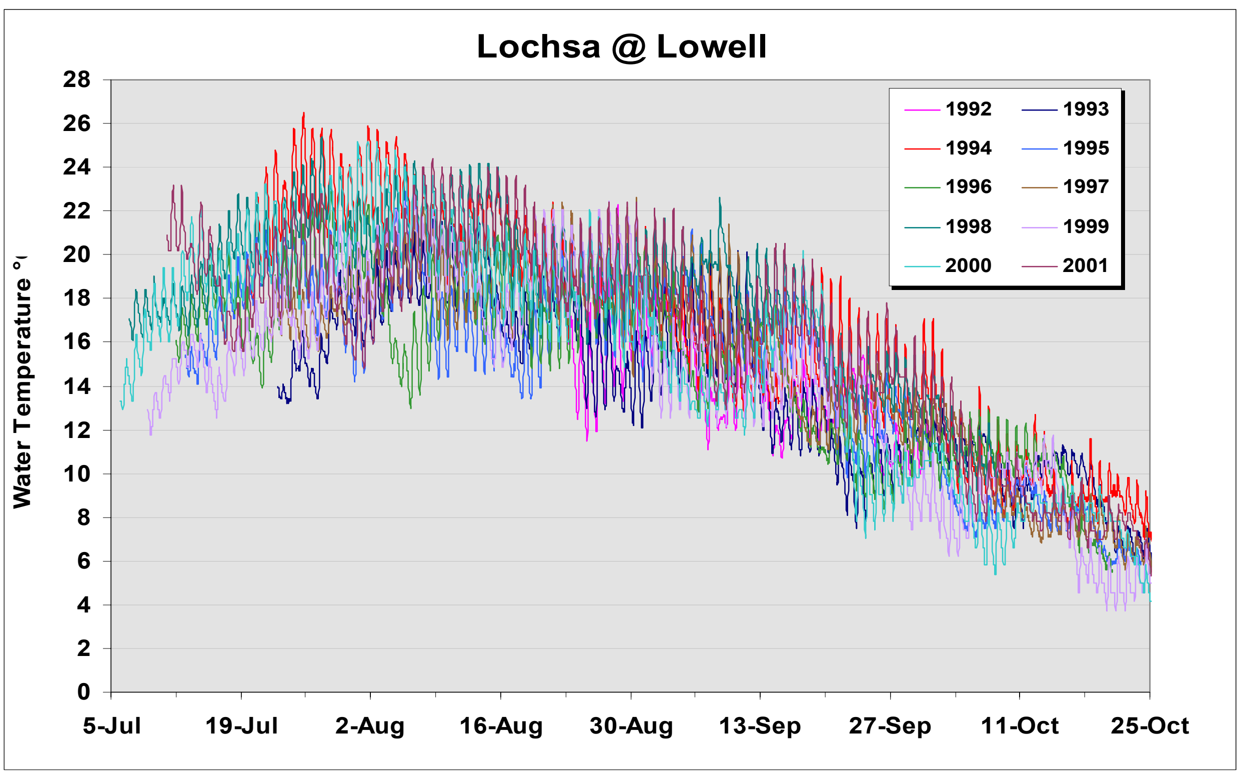


Figure 2. Ten consecutive years of temperatures records from the same site. Multiple years of data adds the fourth level of temporal variation – year to year.

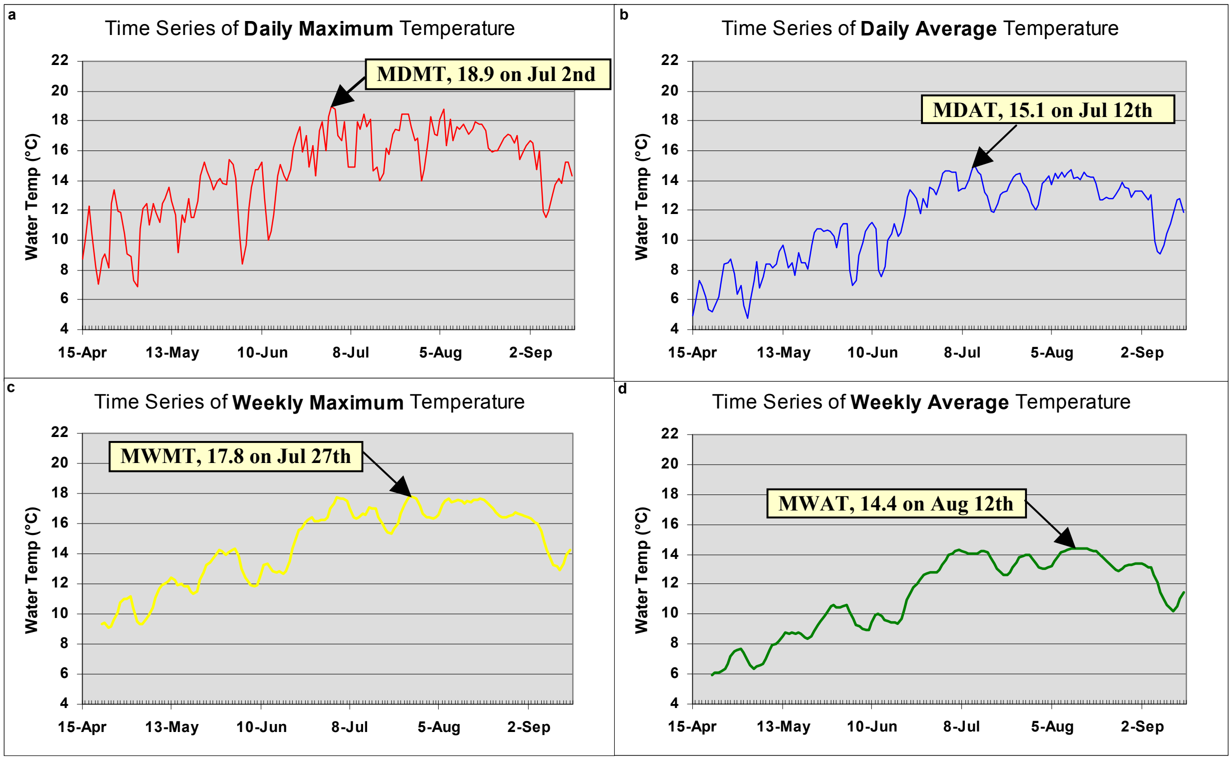


Figure 3. Comparison of four daily time series for one site (Little Loon Creek) to illustrate derivation of four common temperature metrics. Weekly values are seven day running averages so that after the sixth day there is a value for each day.

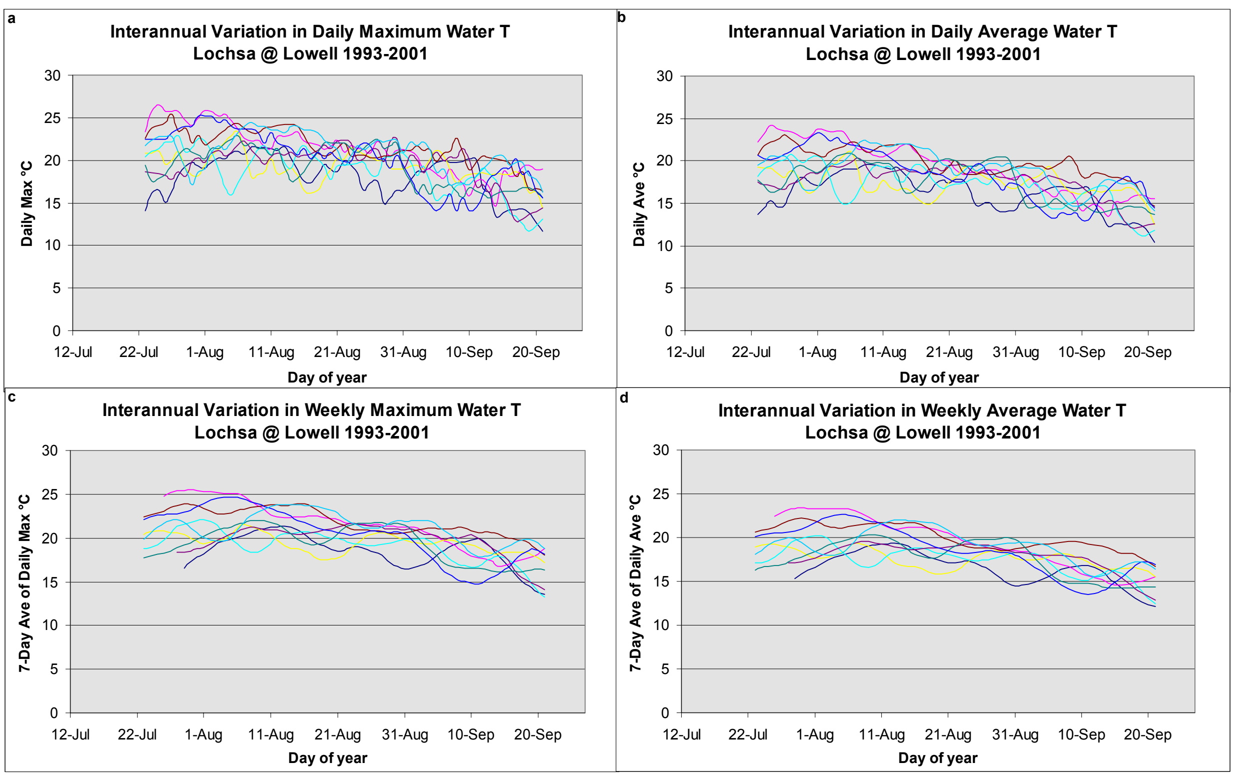
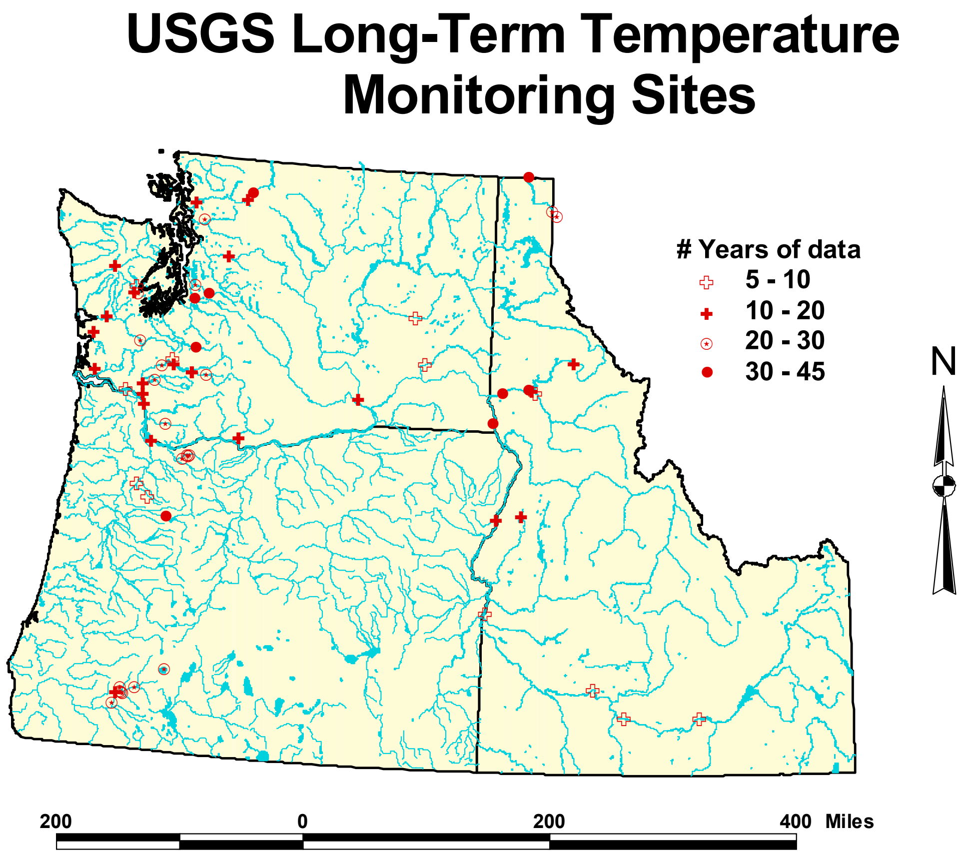


Figure 4. Year-to-year (inter-annual) variation in daily times series for nine years in the Lochsa River at Lowell. Data trimmed to a common annual time period, 1992 excluded due to insufficient data.

Table 2. Tally of number of sites by range in value of four common temperature metrics over the period of record for USGS sites with long-term (>5 years) temperature data.

	All Sites (n=64)			Sites without Dams (n=30)			Sites with Dams (n=24)		
	Range in T metric, °C			Range in T metric, °C			Range in T metric, °C		
	<3	3-6	>6	<3	3-6	>6	<3	3-6	>6
MDMT	10	42	12	2	23	5	8	15	1
MWMT	12	41	9	3	23	4	9	15	0
MDAT	19	37	8	3	25	2	16	8	0
MWAT	18	39	7	4	24	2	14	10	0


USGS Long-Term Temperature
Monitoring Sites
Years of data
5 - 10
10 - 20
20 - 30
30 - 45
N
200
0
200
400 Miles

Map 1

Table 1. USGS Station List with selected site attributes.

Station#	Description	State	Latitude	Longitude	Num of Years	Years	Regu-lated	Current T	Range in MDMT	MWMT	MDAT	MWAT
11492200	CRATER LAKE	OR	42°58'45"	122°04'45"	25	77-01	No	Y	4.0	4.20	3.95	4.19
12010000	NASELLE RIVER NEAR NASSELLE	WA	46°22'27"	123°44'32"	12	62-73	No	N	3.8	4.44	3.30	3.88
12017000	NORTH RIVER NEAR RAYMOND	WA	46°48'27"	123°50'58"	11	63-73	No	N	3.3	3.73	3.05	3.46
12027500	CHEHALIS RIVER NEAR GRAND MOUND	WA	46°46'34"	123°02'04"	23	52-74	Part	N	5.6	5.12	5.55	5.26
12037400	WYNOOCHEE RIVER ABOVE BLACK CREEK NR MONTESANO	WA	47°00'42"	123°39'15"	17	70-86	Part	N	5.6	4.28	4.45	3.45
12039300	NORTH FORK QUINAULT RIVER NEAR AMANDA PARK	WA	47°35'46"	123°37'23"	15	65-79	No	N	3.8	3.87	3.60	3.66
12058800	NORTH FORK SKOKOMISH R BL LOWER CUSHMAN DAM NR POTLATCH	WA	47°23'27"	123°12'30"	9	93-01	Yes	Y	2.3	2.13	2.15	2.16
12059500	NORTH FORK SKOKOMISH RIVER NEAR POTLATCH	WA	47°19'42"	123°14'33"	18	65-82	Yes	N	3.3	2.86	2.10	2.26
12061500	SKOKOMISH RIVER NEAR POTLATCH	WA	47°18'36"	123°10'33"	28	55-82	Yes	N	3.6	3.23	2.20	2.03
12082500	NISQUALLY RIVER NEAR NAT IONAL	WA	46°45'10"	122°04'57"	31	52-82	No	N	5.3	6.10	3.40	3.98
12113000	GREEN NEAR AUBURN	WA	47°18'45"	122°12'10"	35	52-86	Part	N	7.2	5.87	6.40	5.36
12117500	CEDAR RIVER NEAR LANDSBURG	WA	47°23'38"	121°57'12"	32	54-85	Yes	N	6.1	5.43	5.30	4.87
12119000	CEDAR RIVER AT RENTON	WA	47°28'58"	122°12'08"	24	78-01	Yes	Y	5.1	4.97	3.60	4.09
12135000	WALLACE RIVER AT GOLD BAR	WA	47°51'51"	121°40'53"	18	55-72	No	N	5.1	5.24	4.20	4.69
12168500	PILCHUCK RIVER NEAR BRYANT	WA	48°15'58"	122°09'46"	21	52-72	No	N	9.5	8.00	8.05	6.50
12179000	SKAGIT RIVER ABOVE ALMA CREEK NR MARBLEMOUNT	WA	48°36'27"	121°21'37"	31	53-83	Part	N	3.9	4.45	3.60	3.70
12181000	SKAGIT RIVER AT MARBLEMOUNT	WA	48°32'02"	121°25'43"	16	86-01	Yes	Y	2.3	2.18	1.65	1.59
12200500	SKAGIT RIVER NEAR MOUNT VERNON	WA	48°26'42"	122°20'03"	18	62-70,74-82	Yes	N	4.5	4.61	2.80	3.04
12304500	YAAK RIVER NR TROY	MT	48°33'43"	115°58'09"	23	63-73,75-85,00	No	N	6.7	6.26	3.75	4.00
12305000	KOOTENAI RIVER AT LEONIA	ID	48°37'04"	116°02'47"	20	62,65-75,77-86	Part	N	5.0	5.21	5.00	5.50
12322000	KOOTENAI RIVER AT PORTHILL	ID	49°00'00"	116°30'10"	37	64-00	Part	N	7.5	7.07	6.75	6.50
12464770	CRAB CREEK AT MARCELLUS ROAD NR RITZVILLE	WA	47°18'10"	118°22'05"	8	93-95,97-01	No	N	1.5	1.48	2.55	2.22
12473520	COLUMBIA RIVER AT RICHLAND	WA	46°18'46"	119°15'28"	19	74-92	Yes	N	2.3	2.29	2.50	2.30
13081500	SNAKE RIVER NEAR MINIDOKA	ID	42°40'23"	113°29'58"	5	93,94,96,98,00	Yes	N	3.0	3.00	3.00	3.00
13094000	SNAKE RIVER NEAR BUHL	ID	42°39'58"	114°42'41"	6	93,94,97-00	Yes	N	3.8	3.11	2.70	2.73
13154500	SNAKE RIVER AT KINGHILL	ID	43°00'08"	115°12'06"	6	73-74,93-96	Yes	N	4.0	3.93	2.55	2.73
13213100	SNAKE RIVER AT NYSSA	ID	43°52'36"	116°59'02"	7	89-92,97,98,00	Yes	N	1.9	2.08	1.85	2.03
13251300	WEST BRANCH WEISER RIVER NEAR TAMARACK	ID	45°01'14"	116°26'06"	18	59-76	No	N	3.4	3.12	3.35	2.83
13290200	SNAKE RIVER BL PINE CREK AT OXBOW	ID	44°58'40"	116°51'25"	16	58-73	Yes	N	4.5	4.72	4.25	4.47
13334300	SNAKE RIVER NEAR ANATONE	WA	46°05'50"	116°58'36"	43	59-01	Yes	Y	4.0	3.84	3.25	3.25
13340000	CLEARWATER RIVER AT OROFINO	ID	46°28'43"	116°15'23"	9	93-01	No	Y	4.0	3.79	3.00	3.46

Station#	Description	State	Latitude	Longitude	Num of Years	Years	Regu-lated	Current T	Range in			
									MDMT	MWMT	MDAT	MWAT
13340600	NORTH FORK CLEARWATER RIVER NR CANYON RANGER STATION	ID	46°50'26"	115°37'11"	19	83-01	No	Y	4.5	4.14	4.25	4.28
13341000	NORTH FORK CLEARWATER RIVER AT AHSAHKA	ID	46°30'16"	116°19'10"	12	59-70	No	N	5.9	5.86	5.75	5.38
13341050	CLEARWATER RIVER NR PECK	ID	46°30'00"	116°23'30"	38	64-01	Part	Y	8.0	8.64	8.50	8.68
13342500	CLEARWATER RIVER AT SPALDING	ID	46°26'55"	116°49'35"	40	61-70,72-01	Part	Y	8.5	8.07	8.70	8.36
13351000	PALOUSE RIVER AT HOOPER	WA	46°45'31"	118°08'52"	8	94-01	No	Y	4.6	3.54	3.70	3.05
14113000	KLICKITAT RIVER NEAR PITT	WA	45°45'24"	121°12'32"	20	51-70	No	N	5.0	4.49		
14138850	BULLRUN RIVER NEAR MULTNOMAH FALLS	OR	45°29'54"	122°00'40"	24	78-01	Yes	Y	3.3	3.49	3.45	3.61
14138870	FIRCREEKNEAR BRIGHTWOOD	OR	45°28'49"	122°01'28"	24	78-01	No	Y	3.2	3.30	3.25	3.26
14138900	NFBULLRUN RIVER NEAR MULTNOMAH FALLS	OR	45°29'40"	122°02'05"	23	79-01	Yes	Y	2.3	2.19	2.00	1.90
14139800	SF BULL RUN RIVER NEAR BULL RUN	OR	45°26'41"	122°06'30"	23	79-01	No	Y	3.5	3.44	3.30	3.18
14144700	COLUMBIA RIVER AT VANCOUVER	WA	45°37'15"	122°40'20"	12	67-79	Yes	N	3.1	3.18	2.85	3.06
14181500	NORTH SANTIAM RIVER AT NIAGARA	OR	44°45'10"	122°17'50"	45	53-97	Yes	Y	2.9	2.54	2.65	2.54
14200400	LITTLE ABIQUA CREEK NEAR SCOTTS MILLS	OR	44°57'21"	122°37'38"	9	93-01	No	Y	2.3	1.77	1.80	1.36
14201300	ZOLLNER CREEK NEAR MOUNT ANGEL	OR	45°06'02"	122°49'14"	9	93-01	No	Y	3.9	3.31	3.70	3.18
14222500	EAST FORK LEWIS RIVER NEAR HEISSON	WA	45°50'13"	122°27'54"	23	50-72	No	N	5.3	4.92	4.20	3.99
14223500	KALAMA RIVER BL ITALIAN CREEK NR KALAMA	WA	46°02'10"	122°51'20"	18	55-72	No	N	5.0	5.17	4.70	4.30
14232500	CISPUS RIVER NEAR RANDLE	WA	46°26'50"	121°51'46"	23	50-72	No	N	4.5	4.76	3.90	4.10
14233400	COWLITZ RIVER NEAR RANDLE	WA	46°28'13"	122°05'51"	13	69-82	No	N	3.4	4.00	3.60	3.85
14233500	COWLITZ RIVER NR KOSMOS	WA	46°27'59"	122°06'28"	16	53-86	No	N	4.4	4.23	3.90	4.04
14234810	COWLITZ RIVER BL MOSSYROCK DAM	WA	46°32'07"	122°25'26"	13	70-82	Yes	N	2.7	2.20	2.45	2.06
14236200	TILTON RIVER AB BEAR CANYON NR CINEBAR	WA	46°35'44"	122°27'30"	7	65-71	No	N	4.4	3.87	3.60	3.21
14238000	COWLITZ RIVER BL MAYFIELD DAM	WA	46°30'38"	122°36'54"	28	55-82	Part	N	8.7	7.63	9.05	8.68
14242500	TOUTLE RIVER NEAR SILVER LAKE	WA	46°20'11"	122°43'27"	22	51-72	No	N	6.1	5.17	4.40	4.20
14243000	COWLITZ RIVER AT CASTLE ROCK	WA	46°16'30"	122°54'48"	20	55-74	Part	N	6.7	6.89	7.50	7.40
14245000	COWEMAN RIVER NEAR KELSO	WA	46°08'57"	122°53'45"	14	51-64	No	N	5.6	4.62	5.25	4.49
14246900	COLUMBIA RIVER AT BEAVER ARMY TERMINAL	OR	46°10'54"	123°10'58"	10	92-01	Yes	Y	2.2	1.74	1.80	1.62
14330000	ROGUE RIVER BELOW PROSPECT	OR	42°43'50"	122°30'55"	25	77-01	No	Y	3.1	2.37	2.21	2.19
14337500	BIG BUTTE NEAR MCLEOD	OR	42°39'05"	122°41'25"	23	78-00	Yes	N	3.2	4.52	2.70	2.84
14337600	ROGUE RIVER NEAR MCLEOD	OR	42°39'20"	122°42'50"	23	79-01	Yes	N	5.0	4.98	4.30	4.48
14337870	WEST BRANCH ELK CREEK NEAR TRAIL	OR	42°42'40"	122°44'55"	23	78-00	No	N	6.9	7.12	5.75	6.12
14338000	ELK CREEK NEAR TRAIL	OR	42°40'30"	122°44'38"	23	79-01	No	Y	7.0	5.85	6.50	4.76
14338100	ROGUE RIVER AT TRAIL	OR	42°38'51"	122°48'18"	13	88-00	Yes	N	3.7	3.60	2.55	2.59
14339000	ROGUE RIVER AT DODGE BRIDGE	OR	42°31'30"	122°50'30"	23	79-01	Yes	Y	5.1	5.16	4.55	4.50

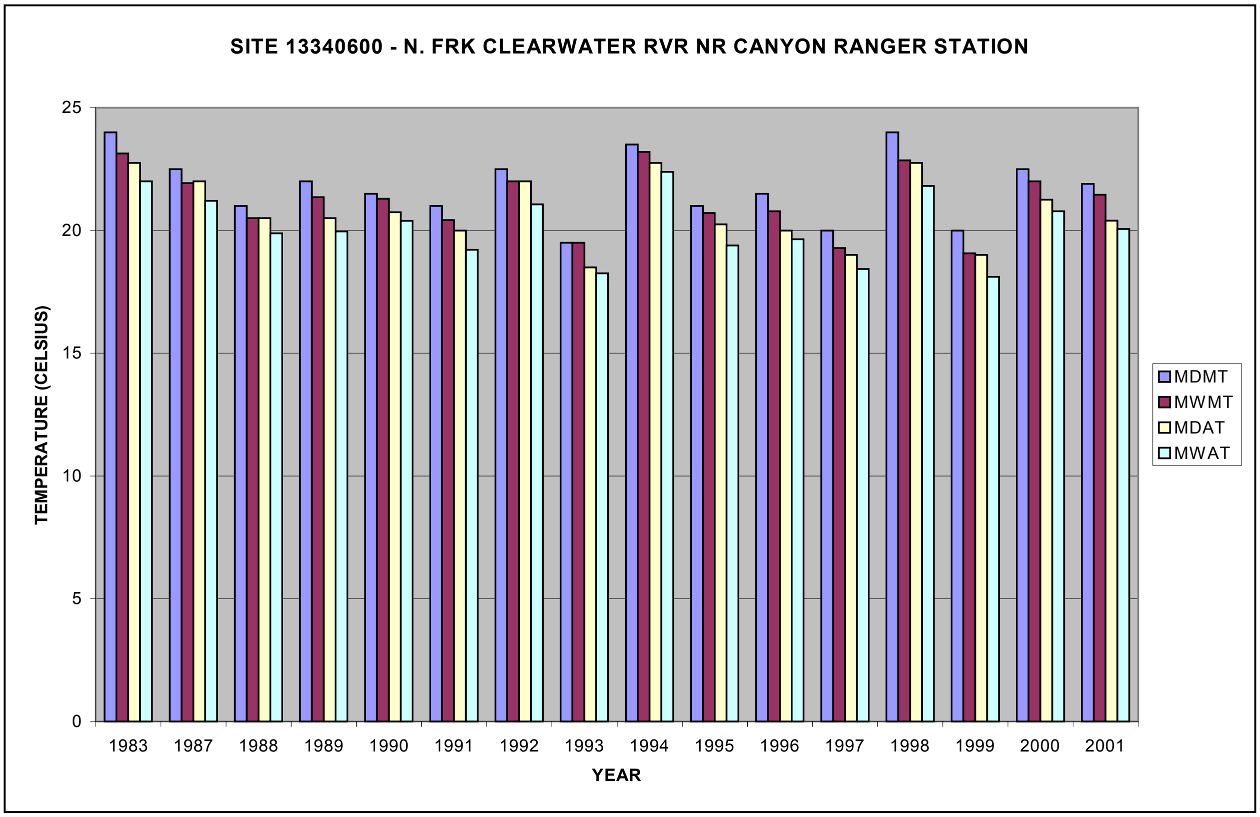


Figure 5. Example of summary chart on year-to-year variation in common temperature metrics at a USGS long term temperature monitoring site. This site is unregulated and continues to be monitored.

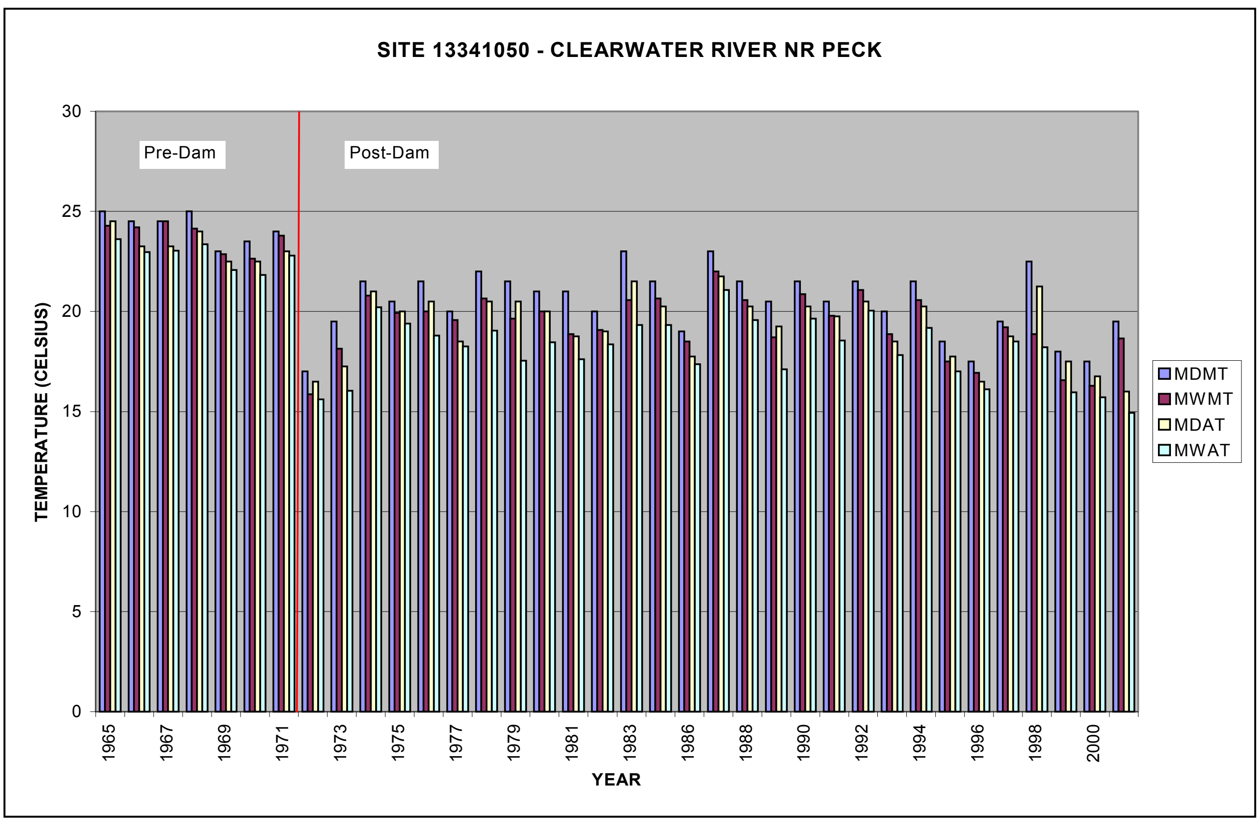


Figure 6. Summary chart of site showing effect of dam with deep reservoir and selective elevation of release on magnitude and variability of water temperature metrics.