

Estimating Stream Temperature from Air Temperature: Implications for Future Water Quality

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Abstract: This study examines the air temperature / stream temperature relationship at a geographically diverse set of streams. We evaluate the general temperature relationships (both linear and nonlinear) that apply to these streams, and then examine how changes in stream temperature associated with climate variability or climate warming might affect dissolved oxygen levels. The majority of streams showed an increase in water

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temperature of about 0.6-0.8°C for every 1°C increase in air temperature, with very few streams displaying a linear 1:1 air/water temperature trend. For most of the streams, a nonlinear model produced a better fit than did a simple linear model. Understanding the relationship between air temperature and water temperature is important if people want to estimate how stream temperatures are likely to respond to anticipated future increases in surface air temperature. Surface water temperature in many streams will likely increase 2-3°C as air temperature increases 3-5°C. At sites with currently low dissolved oxygen content, an increase in summer stream temperatures could cause the dissolved oxygen levels to fall into a critically low range, threatening the health of many aquatic species.

INTRODUCTION

Water temperature in streams and rivers is an important attribute of water quality and controls the health of freshwater ecosystems. Over the past century and a half, the global average air temperature has increased by nearly 1°C, and it is expected to continue to increase by 1-3°C by the middle to end of this century in response to a buildup of greenhouse gases (IPCC 1999). If water temperatures increase, especially at critical times of the year, water quality would be adversely affected. Shifts in aquatic biota could result, due in part to a reduction in dissolved oxygen. Distribution, growth, metabolism, food availability, migration and reproduction are all influenced by water temperature.

The effect that increasing air temperature will have on stream temperature and streamflow depends on the timing of the increase. Some climate studies suggest that the greatest warming in the northern hemisphere will occur in the upper latitudes, with nighttime lows increasing more than daytime highs (IPCC 2001). Warmer winters or

springs could indirectly affect stream temperature by shifting snow to rain, changing the timing of the snowmelt, or both. Less or earlier snowmelt could lead to warmer spring and summer water temperatures in some locations. Less snowmelt could also result in lower stream flows, and hence shallower streams that would warm faster.

Previous studies examine recent trends in water temperature in a variety of locations (Austria – Webb and Nobilis (1994; 1995, 1997; United Kingdom – Webb and Walling (1992, 1883), Langan et al. (2001)). Webb (1996) provides a through overview of earlier studies and the many factors influencing stream temperature. Other studies have look at the possible effects of global warming on stream temperatures in the United States (Cooter and Cooter (1990); Mohseni et al. (1999)). Stefan et al (2001) project that under a doubled-CO₂ environment, summertime killing of fish in lakes may increase and the habitat for coldwater fish is likely to decrease by up to 30%. Cooter and Cooter (1990) consider the effect that altered stream shading due to shifting vegetation regimes would have on net radiation and found increases in stream temperature of up to 7°C in some locations in the southeastern United States; when combined with point source discharge, this was enough to cause critically low dissolved oxygen levels in some areas.

This study examines the empirical relationship between stream and air temperature using linear and nonlinear relationships for 43 U.S. and international sites. These relationships are used to estimate the effect that increases in air temperatures, based on an increased-emissions scenario, would have on water temperatures, and to estimate resulting changes in stream dissolved oxygen.

Many factors may influence stream temperature, including distance from the source of the stream, shading, human industrial use, temperature of incoming water

(precipitation, surface runoff, groundwater), and heating and cooling by heat exchange at the water / air interface. By developing a predictive relationship between only air temperature and stream temperature, we are implicitly assuming that this last factor is the most important influence on the stream temperature.

DATA AND METHODS

Data from 43 river and stream sites in 13 countries came from the Global Learning and Observations to Benefit the Environment (GLOBE) program database (web server www.globe.gov). GLOBE is an international K-12 science and education program. Active schools make instantaneous surface water measurements at weekly to monthly intervals at the same time of day. Most GLOBE sites also have complete daily air temperature records consisting of an instantaneous temperature measurement within 1 hour of solar noon (noon temperature), and the maximum and minimum daily air temperature within the previous day; the latter were averaged to give a single mean daily value. Although over 1400 GLOBE participants have reported water temperature data, only streams for which more than 80 measurements have been made were used in the current analysis. Most of the sites are in the U.S. and western Europe (Table 1). All GLOBE data used in this study were collected between Jan 1, 1996 and August 31, 2001.

Stream temperatures were measured with alcohol thermometers with a minimum accuracy of $\pm 0.5^{\circ}\text{C}$. Air temperatures were measured with mercury maximum/minimum thermometers, with a minimum accuracy of $\pm 1^{\circ}\text{C}$. Dissolved oxygen data were measured using the modified Winkler titration method. Sampling protocols, analytical method and calibration procedures are documented in GLOBE (1997) and at www.globe.gov.

Although GLOBE data show slightly more scatter than those collected by professional organizations, when used for averages or trends they are judged to be quite useful for water quality assessments (Clemons 2000).

Air temperature data for future temperature scenarios came from the United Kingdom Meteorology Office (UKMO) Hadley Centre's climate model (HadCM3) simulations for the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES). (IPCC 2000) We used the results from the SRES B3 scenario. In this scenario, the world population will be double its 1990 level by 2100; average CO₂ levels will be at 601 ppmv by 2100, with annual emissions increasing from 6.0 to 13.8 gigatons carbon. Improvements in technology are assumed to lead to lower emissions of SO_x (70.9 megatons sulfur reduced to 47.9) but NO_x emissions will increase from 31 to 61 megatons nitrogen.

Previous research showed that weekly and monthly averages of stream temperature and air temperatures are better correlated with each other than are daily values (Stefan and Preud'homme, 1993; Pilgrim et al. 1998; Erickson and Stefan, 2000). Three air-temperature averaging schemes were evaluated for use with the periodic water temperature measurements: same-day values, a three-day average (the same day plus the two previous days) and a weekly average (the same day plus the previous six days). As there were some missing data, an average was calculated if at least two days existed for the three-day average or four days of data existed for the weekly average. Water temperature measurements, which generally were taken only once a week, were not averaged. For the linear regression, time periods for which the air temperature was at or below freezing were eliminated, as the linear relationship is only valid for temperatures

above 0°C. (However, separate linear regression for air temperature above and below freezing could also be used).

For 22 sites with the most comprehensive year-round coverage, stream temperatures were also evaluated relative to the averaged air temperature using a nonlinear regression equation (Mohseni et al. 1998):

$$T_s = \mu + \frac{\alpha - \mu}{1 + e^{\gamma(\beta - T_a)}} \quad (1)$$

where T_s is estimated stream temperature and T_a is measured air temperature for the period of interest. There are four parameters: μ is minimum stream temperature, α is maximum stream temperature, γ is a function of the steepest slope (inflection point) of the T_s function (when plotted against T_a) and β is the air temperature at this inflection point. The main advantage of this method over the linear regression is that it can better represent the tendency of some water bodies to have a threshold waters at higher air temperatures (Mohseni and Stefan, 1999).

The parameter α was calculated from

$$\alpha = \bar{T}_{s \max} + K_E S_{\max} \quad (2)$$

where $\bar{T}_{s \max}$ and S_{\max} are the average and standard deviations of a maximum weekly stream temperature time series (Mohseni et al. 1999). The maximum temperature time series for a site consists of the top 4% of the stream temperatures, which is equivalent to two maximum temperatures per year at sites with complete weekly coverage (i.e. 52 values per year). The parameter K_E , an enveloping standard deviate derived from a large number of maximum stream temperature series, was determined by Mohseni et al. (2002) to be 4.88 in an analysis of 141 streams from five geographically diverse U.S. states.

After α was determined, it was used in equation (1) to calculate the remaining parameters for each series. The parameters μ , γ and β were calculated iteratively to minimize root mean square error (RMSE).

Efficiency of fit for both the linear and nonlinear methods was determined with the Nash-Sutcliffe coefficient of efficiency (NSC):

$$NSC = 1 - \frac{\sum_{i=1}^n (T_{sim,i} - T_{obs,i})^2}{\sum_{i=1}^n (T_{obs,i} - \bar{T}_{obs})^2} \quad (3)$$

where T_{sim} and T_{obs} are the simulated and observed values of stream temperature, respectively and \bar{T}_{obs} is the mean observed water temperature. NSC has a maximum perfect score of 1.0 and no minimum, with values greater than 0 indicating satisfactory results. Physically NSC is 1 minus the ratio of the mean-square error to the variance of the observed data.

It is similar the coefficient of determination, R^2

$$R^2 = \left(\frac{\sum_{i=1}^n (T_{obs,i} - \bar{T}_{obs})(T_{sim,i} - \bar{T}_{sim})}{\left[\sum_{i=1}^n (T_{obs,i} - \bar{T}_{obs})^2 \right]^{0.5} \left[\sum_{i=1}^n (T_{sim,i} - \bar{T}_{sim})^2 \right]^{0.5}} \right)^2 \quad (4)$$

NSC values will always be equal or less than R^2 values. For the linear regressions in the study, there was no difference between the calculated NSC and R^2 at any of the points.

In this study, RMSE was calculated after Mohseni et al. (1998) from

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (T_{sim,i} - T_{obs,i})^2}{n-4}} \quad (5)$$

where n is the number of data points. In other studies, especially of the linear relationships, the denominator in calculating RMSE (or standard error of prediction), was $n-1$ or n , which would result it slightly lower, but similar errors.

Once the equations relating stream temperature to air temperature were developed for each site, they were used to estimate future stream temperature using the simulated increases in summer air temperature predicted by the Hadley HadCM3 model for each location (IPCC, 2000). For the eight streams with NSC > 0.8 that had reported dissolved oxygen data, future stream temperatures were calculated based on the mean air temperature predicted for 2095-2099 by the HadCM3 using the IPCC SRES B2 Scenario (IPCC, 2000). Estimated air temperatures came from the model grid cell in which each particular site is located. The mean monthly air temperatures for June-August 1995-1999 (T_{a2}) were compared to those estimated for 2095-2099. The mean monthly difference was added to each of the observed air temperature values for that month to produce a comparable future time series (T_{a4}). Future stream temperatures were estimated from T_{a4} using the nonlinear method with the lowest NSC. These predicted stream temperatures were used to calculate saturated dissolved oxygen, and to estimate low future dissolved oxygen levels by assuming that the maximum and mean monthly dissolved oxygen deficits (amount below saturation) remain at their current levels for each stream.

RESULTS

As the daily air temperatures were averaged over longer times, the correlation between air temperature and instantaneous stream temperature improved. The average RMSE for all 43 sites decreased (2.65, 2.46 and 2.38°C for 1, 3 and 7 days, respectively) and NSC increased (0.69, 0.72 and 0.74). For 33 of the 43 streams the best linear correlation with stream temperature occurred for the weekly (7-day) air temperatures; for the other 10 the best correlation was for a shorter averaging period for air temperature. Only 7 of the 43 streams had slope coefficients of the linear best-fit regression lines (A from $T_a=AT_s+B$; see Table 2) greater than 0.9, with 16 streams having slope coefficients between 0.7 and 0.9. Most of the sites in this range had high NSC's, ranging from 0.72 to 0.93. The average elevation within the set of points increased from 48 to 463 m as the slope coefficient decreased from approximately 1 to 0.7. The remaining 11 streams had slope coefficients below 0.6, with NSC's tending to be lower at these sites as well. The three sites with slope coefficients less than 0.4 were at high elevations. Three of the four California sites (Elk Creek, Kings River and the South Fork of the American River) are situated downstream of reservoirs, and had NSC's of 0.44, 0.49 and 0.50 and slope coefficients of 0.6, 0.4 and 0.4, respectively. However, 20 sites had NSC of 0.8 or greater and 35 sites had NSC's of 0.7 or greater. There was no correlation between drainage basin size and the air-temperature / stream temperature relationship.

Efficiency coefficients for the nonlinear regression were higher than those for the linear regression at 20 of the 22 sites. The two sites with the highest linear NSC (Sippican River, NSC=0.93 and Daggett Brook, NSC=0.92) had lower nonlinear NSC by only 0.01, which is not significant, and higher RMSE's. Neither stream showed the

definite leveling at higher air temperatures that is characteristic of the shape of the non-linear function. The nonlinear regression RMSE's were generally lower than those of the linear regression, with the average decrease in RMSE being 0.14°C ; the maximum improvement (0.52°C) occurred for the El Dorado stream in California. Some of the improvement in nonlinear versus linear RMSE may result from the inclusion of the low temperature points associated with the below-freezing air temperatures.

The non-simultaneous 95% confidence intervals (CI) associated with the observed stream temperature estimates were calculated. For most sites, these tended to be about 4°C , with lower values at colder air temperatures and higher CI at warmer air temperatures. The narrowest average CI's (2.7°C , 2.9°C) occurred at Lober River and Opatawicki River, sites with moderate NSC's (0.87, 0.83, respectively). The largest average CI of 6°C occurred at Lackawanna River. Average confidence intervals for all 22 sites were within $\pm 0.1^{\circ}\text{C}$ for the linear and nonlinear methods.

DISCUSSION

1.1 Linear and Nonlinear Relationships

The majority of our linear results comparing daily water temperature to weekly average air temperature are consistent with previous studies that examined the linear relationship between weekly average surface air temperature and weekly average stream temperature. Webb (1987, 1992) found an almost 1:1 relationship between weekly and monthly averages of stream and air temperature for 36 streams in the United Kingdom. Slopes were lower for daily temperatures. Stefan and Preud'homme (1993) looked at 11 Mississippi Basin streams and reported an average linear slope coefficient ~ 0.89 using weekly average temperatures, with error from 1.4 - 2.1°C . Pilgrim et al (1998) used 39

Minnesota streams and found a slope near 1 for weekly and monthly data ($R^2 = 0.85$ for weekly averages, error 2.3°C), but lower slopes and higher errors for daily data. Webb and Nobilis (1997) found a slope of 0.69 ($R^2 = 0.97$, $\text{RMSE} < 0.8^\circ\text{C}$) for the Krems River in Austria using 90 years of monthly data. Erickson and Stefan (2000) concluded that during open water-periods, streams in Minnesota had a linear air/water temperature correlation ($R^2 = 0.85$, $\text{RMSE} = 2.30^\circ\text{C}$), but in warmer Oklahoma ($R^2 = 0.83$, $\text{RMSE} = 2.42^\circ\text{C}$), the relationship became non-linear when air temperature exceeded 25°C , most likely due to evaporative cooling. Future modeled mean monthly and weekly air temperatures at most of these sites in this study exceed 25°C , even if the current temperatures do not.

The improvement in RMSE and NSC using the nonlinear model supports the idea that the air-stream temperature relationship is best fitted with a S-shaped function. The nonlinear RMSE's in this study were slightly higher than those found in previous studies. Mohseni et al. (1998) found that their method worked ($\text{NSC} > 0.7$) for 573 USGS gauging stations (98% of 584 sites evaluated), with RMSE of $1.64 \pm 0.46^\circ\text{C}$. For these 22 sites, average RMSE was $2.20 \pm 0.47^\circ\text{C}$. The relationship between air temperature and stream temperature estimated in the current analysis may have RMSE's slightly higher than those noted above because there are fewer data, temporal coverage is more sporadic, and a single daily stream temperature is being compared with a weekly-average air temperature. Comparisons of daily stream temperatures to daily air temperature had higher RMSEs than using the weekly air temperature values.

By using the linear regression model, we can see that for over 83% of the sites we evaluated, stream temperature did not increase at a 1:1 relationship with air temperature.

With a linear model, we would predict that more than 74% of the 43 streams should experience a rise of at least 0.6°C for every 1°C increase in air temperature. With the nonlinear model, the rate at which the water temperature increase will decrease as air temperature past the inflection point β and approach and pass the value of α . The 22 streams in the nonlinear analysis have an average rate of increase in predicted stream temperature of 0.6°C when the air temperature is 3°C below α . The rate of change of water temperature is 0.4°C when the air temperature is at $\alpha+1$, and only 0.2°C at $\alpha+7$.

Neither of these models consistently captured the highest observed values of stream temperatures, and may underpredict stream temperature at air temperatures greater than 20°C at some of the sites. The nonlinear model does an excellent job of capturing the tendency of the water temperature of the Lober River in Germany to plateau around 22.5°C (Figure 1), whereas the linear model would be likely to overpredict the water temperatures in the stream at air temperatures greater than 25°C. In contrast, in streams where the linear NSC is high, indicating a good linear relationship, the nonlinear method may offer only scant, if any, improvement. For the Sippican River in Massachusetts (Figure 2), the stream temperature data did not all show an obvious tapering off at high air temperatures. As a result, use of the nonlinear model, may result in underpredicted stream temperatures at the highest air temperatures (> 27°C) of most interest in global climate change scenarios.

Another factor considered was the effect of seasonal hysteresis, i.e. stream temperature being different for the same air temperature at different times of the year. One common cause of seasonal hysteresis is the influx of cold rain or meltwater in the spring, which results in spring water temperatures being lower than autumn water

temperatures at the same air temperature (Webb and Nobilis, 1997). Mohseni et al (1998, 1999) discuss this in further detail, separating the annual cycle into periods of rising and falling temperature, and calculating the T_w/T_a relationship separately. 43% of stream in the continental U.S. exhibit some degree of seasonal hysteresis. When this method was used for these twenty-two streams, clear improvements (higher NSC, lower RMSE) occurred at three of the sites, with minor improvements at another fourteen. The results were not statistically different from those using the non-linear model without hysteresis at most of the streams (data not shown).

1.2 Implications for Dissolved Oxygen

The timing of water temperature increases will depend on the timing of air temperature increases, both seasonally and diurnally. If the largest air temperature increases occur during fall and spring, or if the minimum air temperatures increase but the maximum air temperatures remain about the same, then the water temperature may not increase as much as under other possible scenarios. Saturated dissolved oxygen is lowest at higher stream temperatures, which generally occur during the summer. The observed dissolved oxygen (DO) levels will depend on the amount of oxygen being used by chemical and biological processes. Some of the GLOBE streams currently have observed dissolved oxygen levels near critically low levels for many species.

Future DO levels were estimated for the summer months for eight streams. Three of these 8 sites (Krapina River in Croatia, and Dagget Brook and Sippican River in Massachusetts) currently have minimum DO levels below 5 ppm. One other site, Elk Creek in California, also has low observed summer DO levels of 5.5 ppm, but because of the poor correlation (NSC=0.52) between air temperature and stream temperature, we

could not estimate future stream temperature based on predicted air temperature. One important assumption is that future summer water flow and future DO use will both be the same as they are currently. This is a fairly significant assumption. If the water flow in the streams should change, the dissolved oxygen deficit could be also affected through a different amount of mixing or temperature increases due to shallower water.

Evaporation could also increase due to higher air temperatures, leading to shallower water. Earlier snowmelt due to higher spring temperature could lead to shallower depths in the summer. Changes in the annual and summer precipitation regimes could also influence summer water depths.

Figure 3 shows the current observed and future predicted monthly average air and stream temperatures, the saturated dissolved oxygen content as a function of stream temperature and elevation, and the dissolved oxygen content. Future DO levels were calculated by subtracting the monthly mean DO deficit from mean saturated value. The high and low streams temperatures were used to calculate the upper and lower saturated DO levels, which in turn were used for calculating the stream DO levels.

As air temperatures increase, stream temperatures increase and dissolved oxygen levels decrease. At Krapina River, the only site where the average value of DO is currently below 5 ppm for both July and August, the future DO levels will drop even farther. Dagget Brook and the Sippican River currently have individual values that fall below 5 ppm but the average observed monthly values for the period of record is still above 5 ppm. In July for Dagget Brook and July and August for the Sippican River, the future average DO levels will be near or below 5 ppm. The Oulu River shows current and future predicted monthly mean DO levels above 6 ppm. The other 4 sites all have

much higher current mean observed DO levels (between 7 and 9 ppm), and the predicted future mean DO levels, even accounting for the range in uncertainties in the temperature estimation, are still above 6 ppm.

CONCLUSIONS

Comparing daily stream temperature values to mean weekly air temperature using linear and nonlinear regression showed similar results to other studies comparing weekly stream and air temperatures, although with fewer sites and shorter time series, the mean RMSE tended to be higher. The improvement in RMSE and coefficient of efficiency using the nonlinear model supports the idea that the air-stream temperature relationship is best fitted with a S-shaped function.

Changes in stream temperatures will reflect the change in air temperature, although often at a reduced amplitude. Temperatures at most of the streams in this study are likely to increase under a global warming scenario. If summertime stream water temperatures only increase slightly, summertime dissolved oxygen levels will decrease. In several streams monitored by GLOBE, where the DO is already bordering the critical range (4-5 ppm), any future decrease could cause the DO to reach critically low levels.

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Table 1. Characteristics of sites used in current analysis

	Water body, Country	Lat.*	Lon.*	No. Measurements		Approx
				Elevation, m	Measurements	Drainage Area, km ²
1	Serpentine River, Australia	-32.33	115.95	20	186	1,200
2	Grote Gete, Belgium	50.80	4.93	50	139	326
3	Stream, China	36.15	120.42	14	752	<25
4	Krapina River, Croatia	46.05	16.19	150	81	1,224
5	Potok Burnjak, Croatia	45.98	16.02	199	180	<25
6	Odjenica River, Croatia	45.83	17.38	118	120	
7	Sava River, Croatia	45.16	18.02	88	114	34,000
8	Cidlina River, Czech Rep.	50.44	15.35	868	269	1,177
9	Becva River, Czech Rep.	49.45	17.97	320	265	1,260
10	Becva River, Czech Rep.	49.46	17.97	292	144	1,260
11	Bystrice River, Czech Rep.	49.52	16.26	570	254	379
12	Ohře River, Czech Rep.	50.35	13.70	182	166	5,614
13	Dlouhá strouha, Czech. Rep.	50.20	16.24	438	79	
14	Lober River, Germany	51.63	12.27	55	642	360
15	Schwillach River, Germany	48.19	11.90	483	219	<25
16	Parnu River, Estonia	58.88	25.56	200	138	6,690
17	Sillamae River, Estonia	59.38	27.79	30	185	
18	Juaanjoki, Finland	63.24	29.23	110	794	<25
19	Oulu River, Finland	64.76	26.43	78	108	22,841
20	Hazawa River, Japan	38.65	141.29	35	310	
21	Crni Drim River, Macedonia	41.18	20.68	750	123	3,350
22	Stream, Norway	61.08	9.13	545	227	<25
23	Hagelva River, Norway	68.08	13.55	3	95	
24	Opatowicki River, Poland	51.10	17.12	116	127	
25	Wisloka River, Poland	50.04	22.01	199	93	> 50,000

26	Elk Creek, CA, U.S.	41.75	-124.18	202	264	115
27	S Fork of American R, CA, U.S.	38.80	-120.91	258	128	1,630
28	Kings River, CA, U.S.	36.52	-119.51	84	117	4,300
29	El Dorado Stream, CA, U.S.	33.81	-118.09	17	283	<25
30	Harvey's Folly, MA, U.S.	41.71	-70.77	3	203	<25
31	Dagget Brook, MA, U.S.	41.73	-70.79	5	205	<50
32	Sippican River, MA, U.S.	41.73	-70.78	4	208	75
33	W Branch Sebasticook, ME, U.S.	44.88	-69.45	105	223	<50
34	Heron Creek, MI, U.S.	42.68	-84.46	209	120	<25
35	Mill Creek, MO, U.S.	45.46	-112.19	1430	126	50
36	Scott Creek, NC, U.S.	35.39	-83.20	830	138	100
37	Lackawanna, PA, U.S.	41.47	-75.61	257	171	360
38	Shenango River, PA, U.S.	41.35	-80.40	319	267	870
39	Wallace Run, PA, U.S.	39.75	-77.57	123	204	<25
40	Buffalo Bayou, TX, U.S.	29.74	-95.51	7	90	820
41	W Branch Little River, VT U.S.	44.46	-72.68	212	105	<25
42	Portage Creek, WA, U.S.	48.18	-122.12	157	199	<25
43	Sybill Creek, WY, U.S.	42.06	-104.96	1445	254	1,300

*Latitude and longitude rounded from four to two significant digits

Table 2. Linear regression results for 43 points, using the 7-day mean T_a .

Slope Range	Count <i>n</i>	Average of parameter value for <i>n</i> sites ^a								
		NSC	RMSE	Elevation m	Slope A	Y-Intercept B		T_a	T_s	Stream numbers ^b
>1	2	0.77	2.56	48	1.09	0.46		14.0	16.6	19 29
0.9 - 1.0	5	0.81	2.99	80	0.95	0.72		12.1	12.4	3 14 18 24 33
0.8 - .9	10	0.82	2.48	152	0.84	1.19		11.9	10.4	6 7 9 23 25 31 32 38 38 41
0.7 - .8	6	0.83	2.21	463	0.75	2.15		12.4	11.2	4 8 11 13 21 30
0.6 - .7	9	0.73	2.13	146	0.66	2.42		13.8	11.5	1 2 5 10 12 26 34 42 42
0.5 to .6	2	0.69	2.41	33	0.59	4.94		11.6	12.21	17 20
0.4 to .5	6	0.60	2.36	330	0.43	5.80		13.7	11.1	15 16 27 28 36 39
< .4	3	0.42	2.02	1140	0.35	4.13		9.0	7.0	22 35 43
All	43	0.73	2.37	253	0.71	2.56		12.4	11.2	

^a The parameters A and B come from the equation for the linear best fit line: T_a and T_s are observed air and stream temperatures.

^b Numbers refer to Table 1

Table 3. Linear and nonlinear NSC and RMSE values and the differences between the nonlinear and the linear methods for 22 sites.

No.	Water body, Country	Linear	Nonlinear	Change in	Linear	Nonlinear	Change in
		NSC	NSC	NSC	RMSE	RMSE	RMSE
4	Krapina River, Croatia	0.86	0.89	0.03	2.04	1.87	-0.17
5	Potok Burnjak, Croatia	0.88	0.90	0.02	1.80	1.72	-0.09
8	Cidlina River, Czech Rep.	0.88	0.91	0.03	1.86	1.80	-0.05
9	Becva River, Czech Rep.	0.83	0.86	0.04	2.51	2.33	-0.18
11	Bystrice River, Czech Rep.	0.72	0.78	0.06	2.85	2.69	-0.16
12	Ohře River, Czech Rep.	0.79	0.82	0.03	2.43	2.34	-0.09
14	Lober River, Germany	0.86	0.88	0.02	2.27	2.15	-0.12
16	Parnu River, Estonia	0.66	0.77	0.11	1.54	1.57	0.02
17	Sillamae River, Estonia	0.54	0.78	0.24	2.21	2.27	0.06
18	Juaanjoki, Finland	0.85	0.86	0.02	2.13	2.09	-0.04
19	Oulu River, Finland	0.76	0.78	0.02	3.05	2.98	-0.06
20	Hazawa River, Japan	0.79	0.80	0.01	2.47	2.48	0.01
21	Crni Drim River, Macedonia	0.87	0.88	0.01	2.10	2.05	-0.05
23	Hagelva River, Norway	0.81	0.84	0.03	1.60	1.47	-0.13
24	Opatowicki River, Poland	0.79	0.81	0.03	3.04	2.86	-0.18
29	El Dorado Creek, CA, U.S.	0.78	0.79	0.01	2.21	2.13	-0.08
31	Dagget Brook, MA, U.S.	0.92	0.91	-0.01	1.90	2.09	0.20
32	Sippican River, MA, U.S.	0.93	0.92	-0.02	1.89	2.16	0.27
33	W Br. Sebasticook, ME, U.S.	0.92	0.95	0.03	2.33	2.06	-0.27
37	Lackawanna River, PA, U.S.	0.79	0.83	0.05	3.25	3.02	-0.23
38	Shenango River, PA, U.S.	0.84	0.88	0.04	2.72	2.60	-0.12
42	Portage Creek, WA, U.S.	0.75	0.77	0.02	1.83	1.77	-0.06
	Average	0.81	0.85	0.04	2.27	2.20	-0.07
	Maximum	0.93	0.95	0.24	3.25	3.02	0.27
	Minimum	0.54	0.77	-0.02	1.54	1.47	-0.27

Figure Captions

Figure 1. Linear and non-linear correlation plots of weekly mean air temperature and instantaneous stream temperatures for Lober River, Germany.

Figure 2. Linear and non-linear correlation plots of weekly mean air temperature and instantaneous stream temperatures for Sippican River, Massachusetts, United States.

Figure 3. Current observed (x) and predicted future (filled circles) air temperature, stream temperature, saturated dissolved oxygen and actual dissolved oxygen at 8 sites.





