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Abstract

Extremes of water temperatures limit the presence of various fishes in streams and lakes. Upper extreme water temperatures and their uncertainties are determined by several statistical methods from a large field database. There are over 140 000 weekly mean fish/stream temperature matched pairs in the database. Three different techniques are employed to estimate upper extremes of habitat temperatures for 12 fish species. To quantify the uncertainty of the estimated extremes the bootstrap method, the method of moments and the residual method are applied. The data above the maximum growth temperature are matched well by a type III extremal or a three-parameter lognormal distribution. Standard error of the estimated extreme habitat temperatures depends on species and varies from 0.1°C to 0.6°C at the 95% cumulative probability of occurrence.

Keywords: Water temperatures; Temperature statistics; Fish growth; Temperature tolerance; Fish

1. Introduction

Among the many parameters which influence fish growth, survival and reproduction, water temperature may be the most fundamental. An upper extreme habitat temperature (UEHT) is a key design parameter for many engineered ecosystems. Values of this parameter have been difficult to establish with reliabil-

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ity, especially for fishes. To quantify the relationships between water temperatures and fish responses, laboratory experiments are often conducted but exposure conditions in the laboratory environment are far less complex than those that occur in nature. To avoid the uncertainties associated with not knowing the ecological significance of laboratory-derived values, the United States Environmental Protection Agency Environmental Research Laboratory-Duluth (USEPA/ERLD) has assembled an extensive field data base (Fish and Temperature Database Matching System, FTDMS) in which field observations of 29 fish species are paired with mean weekly water temperature measurements made in the same stream-reaches. There are now 141 208 "Fish/Temperature (F/T) matched pairs" in that database. The development of that database and its present status is the topic of a recent paper by Eaton et al. (1995). Upper extreme habitat temperatures for the various fishes can be estimated from the FTDMS. For example, following an approach by Biesinger et al. (1979) the highest 95 percentile value of the warmest week was selected as the maximum temperature value at which a fish species or guild would be present in a water body. This approach was also followed by Eaton et al. (1995) except that the highest 5% of all field data are used instead of the warmest week. Using the 95th percentile seemed appropriate (instead of the 100 percentile) in light of the wide geographic data distribution and the range of time-scales over which measurements had been made. Possible sources of error such as measurement errors, fish presence due to refugia, and lack of temporal correspondence of fish and temperature records affect the database. Upper extreme habitat temperatures obtained in this way compare favorably with laboratory test results involving exposures of several days (e.g. FTDMS 95 percentile values are mostly 1° to 3°C lower than acute laboratory derived mortality temperatures), but comparable to upper zero net growth temperatures (Stefan et al., 1992). The presence or absence of a fish species or guild does not imply a direct relationship to mortality because the upper lethal temperature is strongly related to changes in physiology at high temperatures which can only be studied in laboratory experiments.

This paper examines alternative methods for estimating UEHT from fish field distribution data. The primary goal is to illustrate the applicability and usefulness of some extreme value theories to the statistical analysis of extreme temperatures for fish presence or absence. In so doing a special effort is made to quantify the degree of uncertainty of the estimated extreme temperatures. To do this three different techniques are employed, i.e. the method of moments, the bootstrap method, and the residual method.

2. Methods

2.1. FTDMS database

The data analyzed herein are mean weekly water temperatures obtained from stream sites at widely dispersed locations within the conterminous U.S. Stream temperatures are used because streams tend to be well mixed water masses where temperatures are more likely to be homogenous insuring that water temperature values match those of actual exposure temperatures of observed fish. All fish observations used in these fish presence/ambient temperature matches were made within a stream reach adjacent to the temperature gauging station. The fish observations were made at any time of the year. Fish presence observations within a year are matched temporally with stream weekly mean water temperatures for that same year to create "F/T matched pairs". To be accepted for creating an F/T dataset, each selected fish collection station to be matched with a water temperature data entry must be (Eaton et al., 1995): (1) on the same branch of a river as the temperature station, (2) within 15 km of the temperature station, and (3) with no tributaries joining the river branch between the two stations, as determined by the Geographic Information System coverage of major rivers and streams in the area. Separate data are kept for each species.

For most species the database contains water temperatures beginning at 0°C and extends to the maximum recorded for that species. Fig. 1a displays as an example the F/T sets for the walleye. To determine the upper extreme habitat temperature for a species, the lower temperatures were excluded. Exclusion of lower temperatures was done differently by each of the methods to be discussed. The following describes how, why and the consequences of the three methods used.

2.2. Extreme temperature computation procedure

2.2.1. Maximum 95th percentile weekly water temperature

An UEHT for each fish species was estimated following the approach suggested by Biesinger et al. (1979). The estimated values are given for example by Stefan et al. (1992). The 95th percentiles of the FTDMS temperatures for each week are estimated for the entire year. The week with the largest measured 95th percentile (shaded box in Fig. 1a) is retained, and the 95th percentile of this week is then identified as the UEHT for the particular fish species. The foregoing procedure is simple, but requires a large database. It is, however, not the only method by which an extreme habitat temperature can be estimated from the database. We shall examine some alternatives, and explain their respective advantages and disadvantages.

2.2.2. Parametric method

A visual examination of the FTDMS database example in Fig. 1a shows that by analyzing the data week by week and selecting only the week with the highest 95th percentile FTDMS temperature, many high temperature values fail to make a contribution to the calculated UEHT. This is especially disturbing when the variability or confidence interval of the 95th percentile FTDMS temperature is determined.

This real or perceived loss of information by weekly analysis is remedied in the "threshold series" method. In this method, all temperatures above a certain

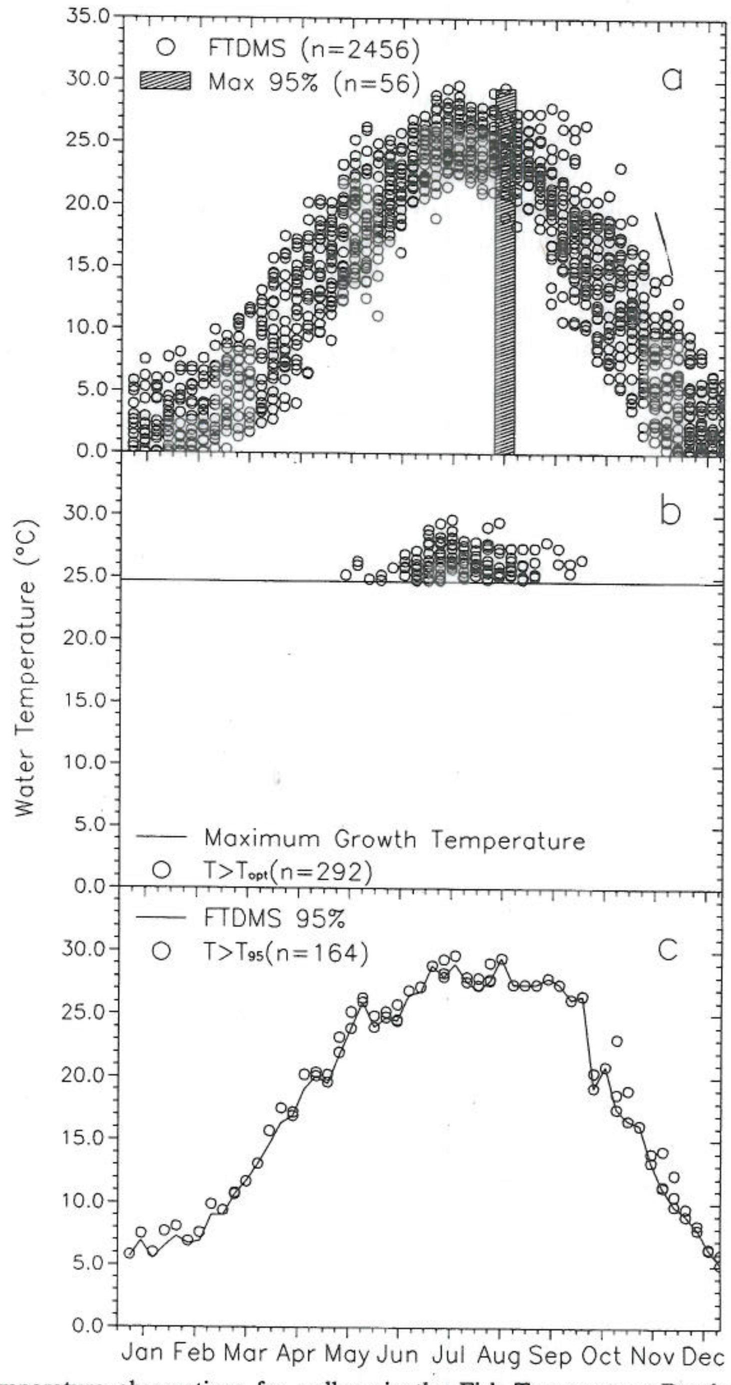

Fig. 1. Fish/temperature observations for walleye in the Fish Temperature Database Management System (FTDMS). (a) All data and week with maximum weekly 95% FTDMS temperature. (b) Data above maximum growth (T_{opt}) temperature. (c) Residual data above weekly 95% FTDMS temperature.

(threshold) magnitude are retained for the extreme temperature analysis of the particular fish species. The threshold magnitude is herein taken as the maximum growth (optimum) temperature, i.e. all temperatures above the maximum growth

Table 1
Fish species/Temperature statistics

Species		UTTL (°C)	Max 95% weekly temperature (°C)	Maximum growth temperature (°C)	Sample size above max growth	PD func.	Goodness of fit	Max 95% weekly temperature: Equivalent probability (%)	SE (°C)	CI (°C)
Cold	Brown trout	25.3 Frost and Brown, 1967	23.8	18.0 Brown, 1946	512	T3E	0.99	99	0.4	0.8
	Chum salmon	23.8 Brett, 1952	19.2	13.5 Rowan, 1975	151	T3E	0.94	97	0.5	1.0
	Coho salmon	25.0 Brett, 1952	23.3	15.0 USDI, 1970	591	T3E	0.98	98	0.2	0.4
	Rainbow trout	26.6 Charlon et al., 1970	34.0	18.1 Hokanson et al., 1977	917	T3E	0.99	96	0.2	0.4
Cool	Black crappie	32.5 Hokanson and Kleiner, 1981	30.9	28.3 Neill and Magnuson, 1974	344	T3E	0.98	99	0.3	0.6
	Sauger	30.4 Smith and Koenst, 1975	30.4	22.0 Smith and Koenst, 1975	548	T3E	0.98	98	0.3	0.6
	White crappie	32.8 Peterson et al., 1974	31.8	28.5 Gammon, 1973	717	T3E	0.99	97	0.2	0.4
	Yellow Perch	33.0 McCormick, 1976	29.5	26.8 McCormick, 1976	54	LN3	0.90	96	0.4	0.8
Warm	Carp	36.0 Meuwis and Heuts, 1957	31.0	30.0 Tatarko, 1970	112	T3E	0.93	66	0.1	0.2
	Freshwater drum	32.8 Cvancara et al., 1977	31.7	31.3 Reutter and Herendorf, 1976	23	LN3	0.80	71	0.1	0.2
	Golden shiner	34.7 Hart, 1952	30.7	23.8 Cincotta and Stauffer, 1984	395	T3E	0.98	97	0.3	0.6
	Smallmouth bass	35.0 Cherry et al., 1977	29.3	28.2 Horning and Pearson, 1973	88	T3E	0.95	56	0.1	0.2

UTTL = upper thermal tolerance limit, PD = probability distribution, T3E = type III extremal distribution, LN3 = three-parameter lognormal distribution, SE = standard error, and CI = confidence interval.

temperature are included in the analysis (Fig. 1b). The maximum growth temperature is considered a meaningful threshold, because water temperatures above the maximum growth temperature affect fish growth adversely. Examples of maximum growth temperatures of 12 different fish species reported in the literature are given in Table 1. The actual value of the maximum growth temperature has only small relevance, because only the extreme upper end of the data is crucial to the analysis. Therefore, if the optimum growth temperature is unknown for a given species of fish it's guild mean may be used, with little or no change in the final analysis.

Continuous probability distributions are used to define the magnitude of the extreme temperature corresponding to a given cumulative probability for the particular fish species. To fit probability or frequency distributions to the data (above the optimum temperature) two steps were necessary: (1) to find a probability distribution, if any, which follows the data, and (2) to estimate the parameters of the chosen probability distribution in order to minimize the differences between observed and fitted temperatures. The data in the FTDMS are only a sample in time and space, and subject to measurement errors, thus the fitting procedure must minimize these errors in an efficient way.

Four probability distributions, i.e. type III extremal distribution (T3E), three-parameter lognormal (LN3), Pearson type III, and log-Pearson type III distributions were considered potential candidates for the analysis. The type III extremal distribution or the three parameter log-normal distributions were found to give the best fits for 24 fish species (Stefan et al., 1994). Examples of cumulative probability distributions of 12 fish species are given in Fig. 2. The type III extremal cumulative probability distribution function is

$$P(x) = 1 - \exp^{-(x-\gamma/\beta-\gamma)^{\alpha}} \tag{1}$$

and the probability density function is

$$p(x) = \frac{\alpha}{\beta-\gamma}\left(\frac{x-\gamma}{\beta-\gamma}\right)^{\alpha-1} \exp^{-(x-\gamma/\beta-\gamma)^{\alpha}} \tag{2}$$

where α is the scale parameter equal to the order of the lowest derivative of the probability function that is not zero at $x = \gamma$ (Kite, 1986), β is the characteristic temperature (location parameter), and γ is the lower limit to the water temperature (variable x). The probability density function for the three-parameter lognormal distribution is

$$p(x) = \frac{1}{(x-a)\sigma_y\sqrt{2\pi}} \exp^{-\{[ln(x-a)-\mu_y]^2/2\sigma_y^2\}} \tag{3}$$

where σ_y^2 is the scale parameter (variance of the logarithms of $(x-a)$), μ_y is the form parameter (mean of the logarithms of $(x-a)$), and "a" is the lower boundary of x. The cumulative probability distribution was obtained numerically because Eq. (3) is not analytically integrable.

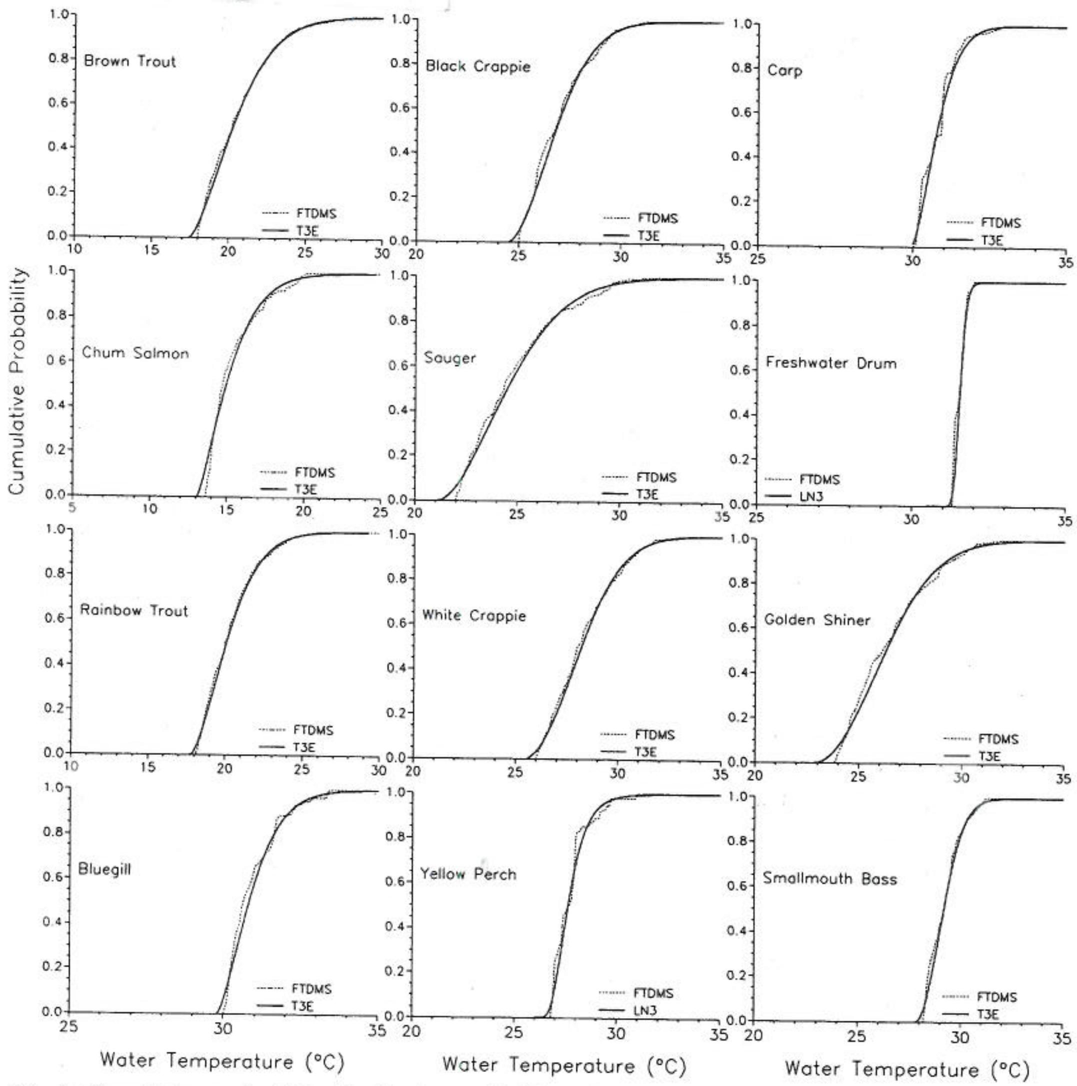

Fig. 2. Cumulative probability distributions of higher than threshold temperatures. Fitted values are denoted by solid lines. Values derived from the FTDMS are denoted by dashed lines.

The method of moments and the method of maximum likelihood (Haan, 1977; Kite, 1988) were used as techniques for the parameter estimation for the particular distributions. Two criteria were used for the probability distribution acceptance. The first is goodness of fit between the observed and predicted (fitted) temperatures

$$r^2 = 1 - \frac{\sum_{i=1}^{N} (T_{\text{fit}} - T)^2}{\sum_{i=1}^{N} (T - \overline{T})^2} \tag{4}$$

where T_{fit} is fitted temperature, T is observed temperature, $\overline{T}$ is an average of the observed temperature, and N is the total number of data above the optimum temperature. The second criterion was introduced in order to examine qualitatively the upper end of the probability distribution, i.e. the region where the upper thermal tolerance limit is most likely to occur. For this purpose the quantile-quantile (QQ) plots (Graedel and Kleiner, 1985) were used. The corresponding point on the QQ plots is given by the coordinate pair

$$\mathrm{QQ}(i) = \left[F^{-1}\left(\frac{n}{N}\right);\ x(i)\right] \tag{5}$$

where i is the coordinate number, F^{-1} is the inverse of the theoretical probability distribution, n is the number of observed temperatures for a particular class, N is the total number of temperatures above the optimum temperature for a particular species, and $x(i)$ is the observed temperature. The first term in the square bracket is the fitted (predicted) and the second term is observed temperature. A perfect fit would be indicated by all points being on the line with a slope of 1:1.

2.2.3. Bootstrap method

The bootstrap method extends the basic idea of an estimate for the accuracy of the mean, i.e. standard deviation, to any estimator (Efron and Gong, 1983). An estimator is customarily defined as a procedure for deriving an estimate from a sample. We are concerned with extreme (95th percentile) temperatures; therefore, the method was applied to the 95th percentile estimator. For each fish species a bootstrap sample was drawn 1000 times and the 95th percentile estimator was computed as

$$\hat{T}_{95}^{B} = \frac{\sum_{b=1}^{B} \hat{T}_{95}^{b}}{B} \tag{6}$$

where $b = 1$ is the first draw from the fish bootstrap sample, and B is the total number of the bootstrap draws. Note that one bootstrap sample ($b = 1$) means randomly sampling N times the temperature data set of size N for the particular fish species.

2.3. Extreme temperature uncertainty estimation

2.3.1. Method of moments

A measure of the variability of the estimated extreme temperature is the standard error of estimate. The standard error of estimate is defined (Kite, 1988) as

$$\mathrm{SE}_M = \delta\sqrt{\frac{\mu_2}{N}} \tag{7}$$

where μ_2 is the second statistical moment, and δ is tabulated for the different percentile levels and different probability distributions (Kite, 1988).

2.3.2. Bootstrap method

The bootstrap method is a nonparametric computational method for the standard error of a data-based prediction (Efron and Gong, 1983). The method was applied to the standard error of the 95th percentile estimator. For each fish species a bootstrap sample was drawn 1000 times and the standard error was computed as

$$\mathrm{SE}_B = \left[\sum_{b=1}^{B} \frac{\left(\hat{T}_{95}^{b} - \hat{T}_{95}^{B}\right)^2}{B-1} \right]^{1/2} \tag{8}$$

2.3.3. Residual method

A third method to estimate standard error of the of the 95th percentile FTDMS value uses the temperature residuals above the 95th percentile value in all 52 weeks in a year. The graphical illustration of the residuals is given for walleye in Fig. 1c. The method considers residual temperature values above the 95th percentile for all 52 weeks of the entire year, but could be applied to a smaller number of weeks also. The standard error of estimate for the 95th percentiles is defined as

$$\mathrm{SE}_r = \left[\sum_{i=1}^{n} \frac{\left(T_i - \hat{T}_{95i}\right)^2}{N-1} \right]^{1/2} \quad \text{for } T_i > \hat{T}_{95i} \tag{9}$$

where the $\hat{T}_{95i}$ is the estimated 95th percentile for the particular week, T_i is the temperature above the 95th percentile, and SE_r is the yearly standard error of estimate for the 95th percentiles.

2.3.4. Confidence interval

Once the standard error of the estimate is computed it is often desirable to estimate the confidence interval for the temperature percentile in question. In order to proceed, the assumption is made that the distribution of the T-percentile is normal so that the confidence interval is given by

$$\mathrm{CI} = T_{\%} \pm t\ \mathrm{SE} \tag{10}$$

where t is the standard normal deviate for the desired confidence level ($t = 1.96$ for the 95% cumulative probability), and $T_{\%}$ is the temperature estimate for the required cumulative probability.

3. Results

3.1. Extreme temperature computation

3.1.1. Maximum 95th percentile weekly temperatures

Maximum 95th percentile temperature estimates for the week when the highest 95th percentile temperature occurred are given in Table 1 (under the column "Maximum 95% Weekly Temperature"). Estimated UEHT values were lower than the upper temperature tolerance limit (UTTL) from the laboratory experiments. Average differences between weekly UEHT and UTTL temperatures were 2.1, 2.0, and 4.5°C for fish in the cold-, cool-, and warmwater fish guilds, respectively. The greater difference for the warmwater fishes is believed due to the fact that the data for some species in this guild do not include higher temperatures from sites at the extreme southern limits of their distribution, south of the U.S. border (Mexico), where such fishes can still exist. Data collection does not extend south of the U.S. border.

3.1.2. Probability distributions fitted to temperatures above maximum growth temperature (Parametric method)

The parametric procedure was applied as an alternative second method for the extreme temperature estimation. The "samples" contained all temperatures above the maximum growth temperature for the particular fish species. Fitted and "observed" cumulative probability distributions of the water temperatures for 12 fish species are given in Fig. 2. Good agreement between the observed and fitted temperatures is evident. Quantile plots for the observed and fitted temperatures are given in Fig. 3. Qualitative measures of agreement between the observed and fitted temperature (Eq. 4), are given in Table 1 under the column "Goodness of fit". In most cases the "Goodness of fit" had an r^2 value above 0.95. This implies that 95% of the observed temperature variability was explained by the fitted probability distribution. For brown bulhead, channel catfish, freshwater drum, and gizzard shad, the goodness of fit was not as close (Stefan et al., 1994). These less well fitted data are mainly due to temperature "extremes" above the probability distributions (Fig. 3). It is noteworthy that these extremes were always above the estimated maximum 95th percentile weekly temperatures. This is one more justification for selecting the 95th percentile rather than the very highest temperature observed as a lethal temperature (maximum 95th percentile weekly temperatures are also shown in Fig. 3 to illustrate how far below the very highest observed temperatures they may be).

Cumulative probabilities above maximum growth temperature equivalent to the maximum 95th percentile temperature estimates were also determined and are given in Table 1 under the heading "Equivalent probability". Cold- and coolwater fishes had equivalent cumulative probabilities from 92 to 99%. Warmwater fishes had equivalent cumulative probabilities from 56% (smallmouth bass) to 97% (white bass). A low cumulative percentile indicates that many high temperature

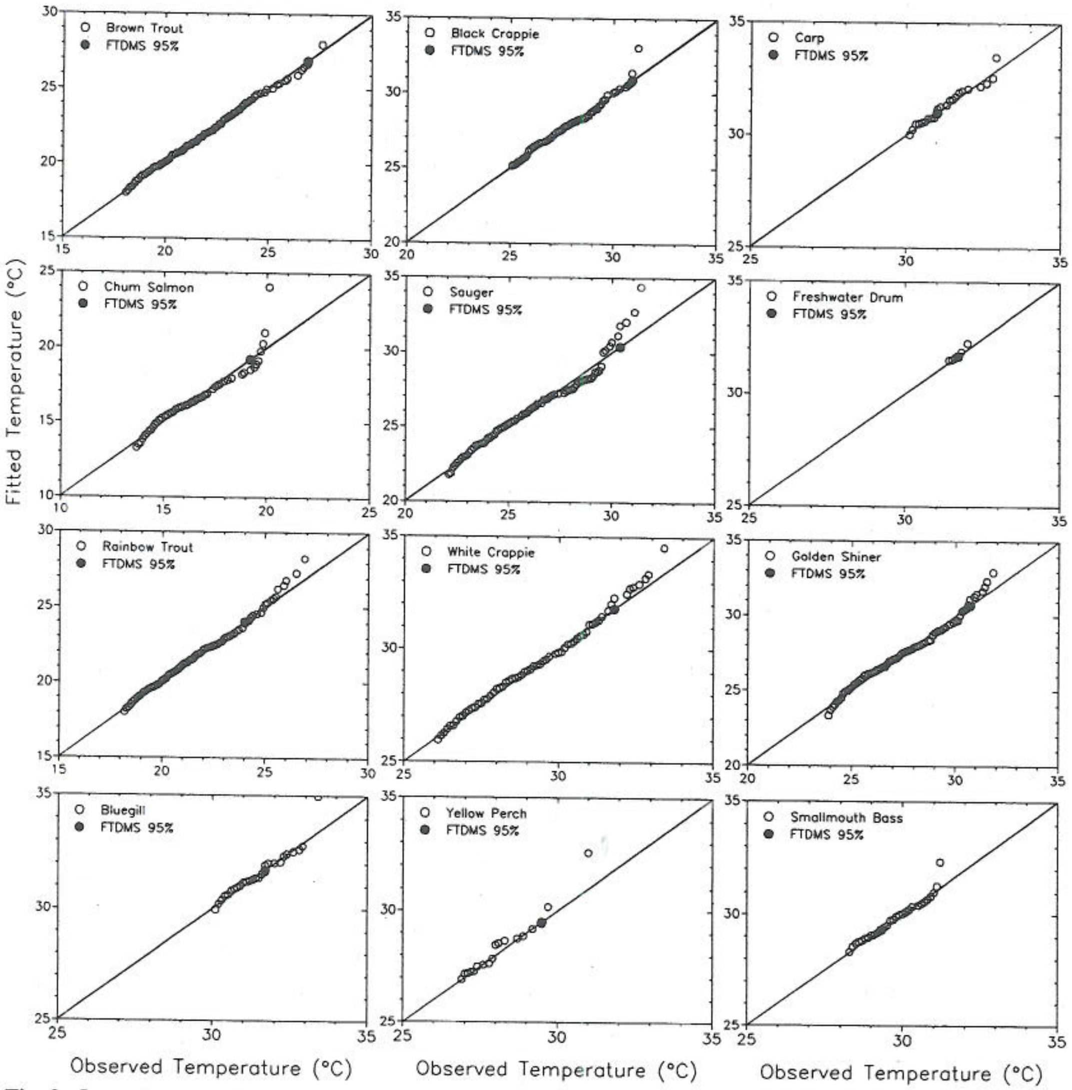

Fig. 3. Quantile-quantile plots for distributions fitted by method of moments to fish/temperature pairs in the FTDMS. Horizontal axes are observed and the vertical axes are fitted temperatures. The solid line would be a perfect fit.

estimates were ignored in the maximum 95th percentile weekly temperature estimate which then is not a relative value.

3.1.3. 95th and 99th percentile temperatures above maximum growth temperature

The parametric method and the bootstrap method were used to estimate the 95th and 99th percentiles of temperatures above the maximum growth temperatures. Estimated temperatures are given in Table 2 under the heading "95%" or "99%". The temperatures estimated by the bootstrap and the parametric method are very close. That is an indication that the fitted theoretical distributions adequately describe the temperature samples.

Table 2
95% and 99% temperatures and their standard errors as determined by the bootstrap method and by the fitted cumulative probability function (parametric) method using temperature data above maximum growth temperature

Species	Bootstrap				Parametric			
	95% (°C)	SE (°C)	99% (°C)	SE (°C)	95% (°C)	SE (°C)	99% (°C)	SE (°C)
Brown trout	24.6	0.4	27.0	0.5	24.7	0.2	27.0	0.4
Chum salmon	19.1	0.5	19.8	0.2	18.6	0.4	20.7	0.8
Coho salmon	21.9	0.2	23.5	0.2	22.1	0.2	23.9	0.3
Rainbow trout	23.9	0.1	25.1	0.2	23.6	0.1	25.4	0.3
Black crappie	29.6	0.2	30.8	0.2	29.7	0.2	31.0	0.3
Sauger	29.4	0.1	30.2	0.2	28.9	0.2	31.0	0.4
White crappie	31.2	0.1	32.1	0.3	31.2	0.1	32.6	0.2
Yellow perch	29.4	0.4	30.0	0.6	29.4	0.4	30.6	0.9
Carp	31.8	0.2	32.5	0.3	31.9	0.1	32.6	0.2
Freshwater drum	31.8	0.1	31.9	0.1	31.9	0.1	32.0	0.1
Golden shiner	30.2	0.1	31.0	0.3	30.0	0.2	31.7	0.3
Smallmouth bass	31.0	0.1	30.6	0.2	30.7	0.2	31.3	0.3

SE = standard error.

3.2. *Uncertainty of extreme temperature computation*

3.2.1. *Method of moments*

Standard errors of estimated maximum 95th percentiles weekly temperatures are given in Table 1. These values were obtained by the method of moments. An average standard error was 0.3, 0.3, and 0.1°C for the cold-, cool-, and warmwater fishes, respectively. With these standard errors the confidence intervals (95%) for the estimated maximum 95th percentile weekly temperatures were obtained and are given in Table 1 under the heading "Confidence interval (CI)".

The uncertainty of estimated extreme values (see Fig. 3) would be expected to increase towards the higher temperatures. To test this increase, standard errors of extreme water temperatures at cumulative probabilities of occurrence increasing from 50 percentile to 99 percentile were also estimated by the method of moments. The results for different fish species and different cumulative probability levels are summarized in Fig. 4. Indeed the standard error increases less than 0.3°C at 50% to up to 1°C at 99%, with considerable variation among species. The excedance level, which is also shown in Fig. 4 is defined as 100-α, where α is the cumulative probability.

3.2.2. *Bootstrap method*

Uncertainty was also computed by applying the bootstrap method. For the 95th and 99th percentile cumulative probabilities the standard errors are given in Table

Fig. 4. Standard errors of temperature estimates for different cumulative probabilities or excedance levels above maximum growth temperature.

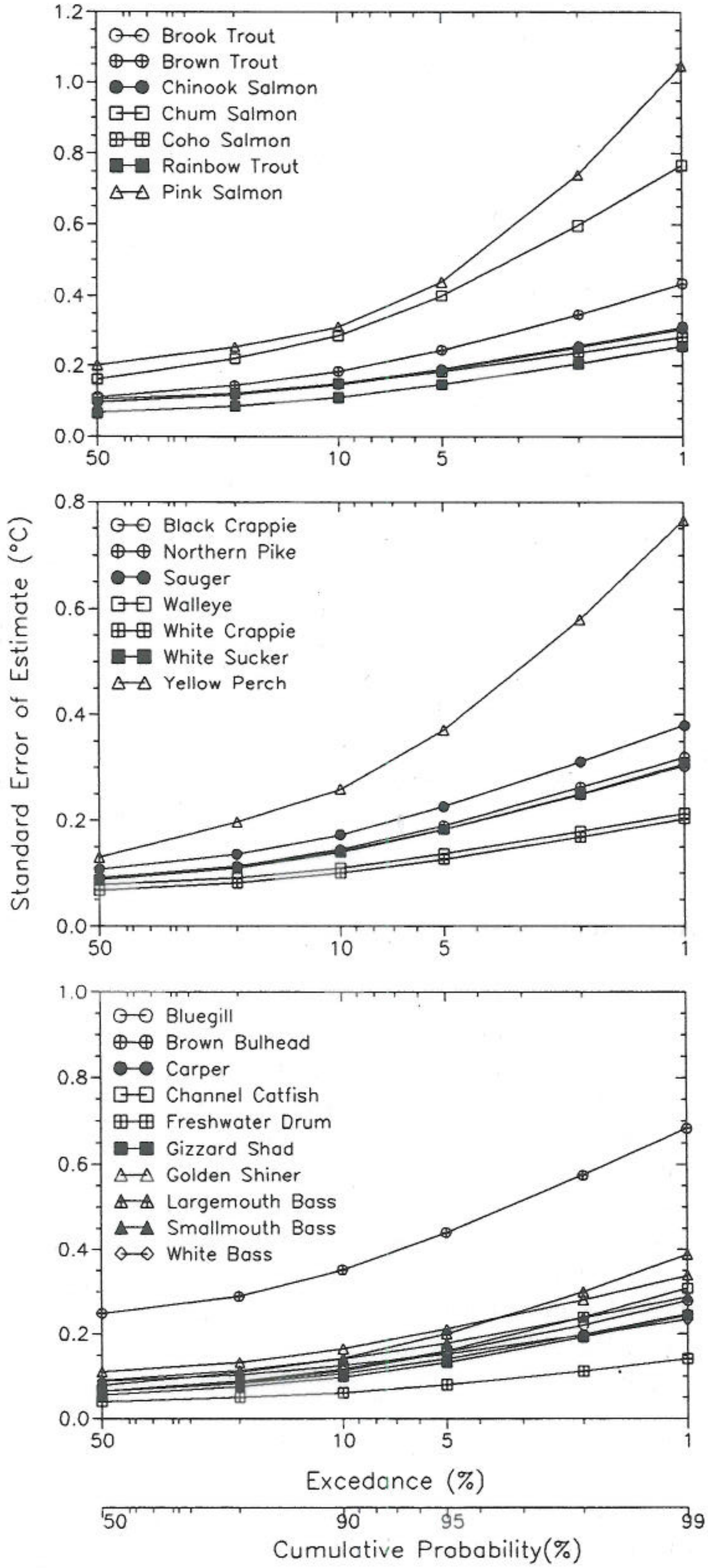
Brook Trout
Brown Trout
Chinook Salmon
Chum Salmon
Coho Salmon
Rainbow Trout
Pink Salmon
Black Crappie
Northern Pike
Sauger
Walleye
White Crappie
White Sucker
Yellow Perch
Bluegill
Brown Bulhead
Carper
Channel Catfish
Freshwater Drum
Gizzard Shad
Golden Shiner
Largemouth Bass
Smallmouth Bass
White Bass
Standard Error of Estimate (°C)
Excedance (%)
Cumulative Probability(%)
50
10
5
1
90
95
99

Table 3
Standard errors of maximum 95% weekly water temperatures as determined by analysis of residuals above maximum 95% weekly values

Coldwater species	SE (°C)	Coolwater species	SE (°C)	Warmwater species	SE (°C)
Brook trout	1.3	Black crappie	1.5	Bluegill	1.1
Brown trout	1.0	Northern pike	0.5	Brown bullhead	1.5
Chinook salmon	0.9	Sauger	1.2	Carp	2.0
Chum salmon	0.8	Walleye	0.7	Channel catfish	1.4
Coho salmon	1.3	White crappie	0.8	Freshwater drum	1.6
Pink salmon	1.3	White sucker	2.0	Gizzard shad	0.7
Rainbow trout	1.5	Yellow perch	1.7	Golden shiner	1.0
				Largemouth bass	1.6
				Smallmouth bass	1.6
				White bass	1.7

SE = standard error.

2 under the heading "Bootstrap". The method of moments was applied to the same sample for comparison. The estimated standard errors are given in Table 2 under the heading "Parametric". The bootstrap estimates are in some cases (walleye, white sucker, chum salmon, bluegill, brown bullhead, channel catfish, largemouth bass, white bass) higher for the 95th percentile than for the 99th percentile (Stefan et al., 1994). This unexplainable trend is considered to be a deficiency of the bootstrap method in comparison to the parametric estimates. Overall the two methods give very similar results for the same cumulative probability levels.

3.2.3. Residual method

Prior to the uncertainty analysis by the method of moments and the bootstrap method, a residual method had been applied. It used as a basic data set the residual temperatures above the maximum weekly 95th percentile weekly temperatures (see Fig. 1c, and Section 4.3) for all weeks of the year. The method makes use of data from all seasons of the year. Standard errors of estimated maximum 95th percentile weekly temperatures obtained by residual method are given in Table 3. The estimated standard error therefore reflects an annual average of uncertainty for all 52 weekly 95 percentile temperature values, rather than the maximum value of the year. To obtain an uncertainty estimate for the warmest season, standard error a 5 week average around the week with the maximum 95th percentile weekly temperature was also computed. These latter values are on the average lower than the annual average error, but still higher than the standard errors in Tables 1 and 2.

4. Discussion

Upper extreme habitat temperatures have to be known in aquaculture/fish pond management, for setting of water temperature standards, for specification of cooling water effluent mixing zones, and in climate effect studies. Herein, upper extreme habitat water temperature values and their uncertainties are determined by several statistical methods from a large field database (Fish and Temperature Database Matching System, FTDMS, Eaton et al., 1995). The results place previous estimates of UEHT in a broader statistical context, and provide confidence intervals for these estimates. The reader should be aware that the FTDMS database is continually growing and therefore that this paper presents options for summarizing the data and not the final values for maximum habitat temperatures.

One expression of the UEHT was chosen to be the 95th percentile of weekly mean temperatures occurring in the week with the highest weekly mean temperature for each fish species. Herein the data are reduced to only those temperature values which lie above the maximum (optimum) growth temperature (threshold) of a fish species. Above this threshold water temperature adversely affects fish growth. The data above the maximum growth temperature are analyzed by two different methods: (1) a parametric method, which fits a theoretical probability distribution to the data, and (2) a non-parametric (bootstrap) method. The type III extremal distribution or the three-parameter lognormal distribution provide a good fit to the data (Figs. 2 and 3).

Extreme high temperature values and their uncertainties are determined by both the parametric and the bootstrap method and give similar results. Examples of the 95 and 99% cumulative probability levels are given in Table 2 for 12 fish species. The increase of uncertainty with cumulative probability is illustrated in Fig. 4. Standard error ranges from less than 0.3°C at 50% to more than 1°C at 99%, with a strong dependence on the species of fish. The higher uncertainties in lethal temperature estimates as measured by the high standard error of estimate in Fig. 4 for yellow perch, rainbow trout, pink salmon, and brown bullhead, are caused by either the small sample size (54 temperature data points above maximum growth for yellow perch, and 26 for brown bullhead) and/or unusually poor fit of the frequency distributions in the high temperature range as illustrated in Figs. 2 and 3.

The uncertainty of the maximum 95th percentile weekly temperature value has a standard error which has been estimated, by the method of moments from the parametric (fitted) distributions, to be between 0.2 to 0.5°C for coldwater species, 0.2 to 0.4°C for coolwater fishes, and from 0.1 to 0.4°C for warmwater fishes. The database for the warmwater fishes does not, however, extend far enough south to include the high temperature extremes for some members of that guild.

In conclusion the significance of this study lies in the following main points:

(a) Known methods of extreme value analysis used in other fields (e.g. flood frequency analysis) have been applied to broaden the usefulness of a large fish/temperature field database.
(b) Extreme values for 12 fish species were found to follow two extreme value frequency distributions. They are the type III extremal and the three-parameter lognormal distributions. Therefore, smaller datasets can be used to estimate more reliably UEHT values.

(c) By providing a theoretically well-founded methodology, the uncertainty of the UEHT values which are essential in the design and operation of aquaculture/fish pond management systems has been established more exactly.

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