Jones, R.E., R.J. Petrell and D. Pauly. 1999. Using modified length-weight relationships to assess the condition of fishes. *Aquacultural Engineering* 20: 261-176.

Using modified length–weight relationships to assess the condition of fish

R.E. Jones [a], R.J. Petrell [b,*], D. Pauly [c]

[a] *ECL Envirowest Consultants, Suite 204, 800 McBride Blvd., New Westminster, BC V3L 2B8, Canada*
[b] *Department of Chemical and Bio-Resource Engineering, University of British Columbia, 2357 Main Mall, 76A Macmillan Bld, Vancouver, BC V6T 1Z4, Canada*
[c] *Fisheries Centre, 2204 Main Mall, University of British Columbia, Vancouver, BC, Canada*

Received 18 February 1999; accepted 23 June 1999

Abstract

This paper develops a model to replace classical fish models used to assess weight and condition. Results from two classical models ($M = KL^3$ and $M = aL^b$) were compared to results from the proposed model ($M = BL^2H$) to find which one could be most accurately applied over the widest range of genetic, morphological and physiological states. A large database of physical measurements was analyzed. The newly proposed model decreased the variability in calculating weight by between 38 and 44% as compared to the conventional fisheries model $M = KL^3$ and was consistently more accurate than $M = aL^b$. Condition factor K of the two salmon species studied increased with fish weight, while the B factor was generally invariant. With regards to the salmonids, the B factor indicates a type of bodily streamlining, important for swimming functions. A low B factor indicates a fish has less cross sectional area per unit length than a high B value fish has. As well, the B factor can be used to calculate girth. The new model can, therefore, be used to more accurately predict weight and physical state than other conventional models can.

Keywords: Condition; Growth; Modeling; Girth; Height; Length; Salmon; Mass; Drag

* Corresponding author. Tel.: + 1-604-8222565; fax: + 1-604-8225407.
E-mail address: pretrell@unixg.ubc.ca (R.J. Petrell)

PII: S0144-8609(99)00020-5

1. Introduction

In general, the change in weight of fish can be described by the relationship $M = aL^b$, where W is observed fish weight, L is observed fish length, and a and b are estimated by $\log W = \log a + \log L$ (i.e. a is the regression intercept and b is the regression slope). Therefore, the case where $b < 3$ represents fish that become less rotund as length increases, whereas when $b > 3$ fish become more rotund as length increases. These are both examples of allometric growth. When $b = 3$, growth may be isometric (growth with unchanged body proportions and specific gravity), although it is possible for shape to change when $b = 3$, due to changes in a (Anderson and Gutreuter, 1983; Cone, 1989).

The study of condition assumes that heavier fish of a given length are in better condition. Condition indices have been used by fish culturists as indicators of the general 'well-being or fitness' of the population under consideration. In a review paper, Bolger and Connolly (1989) identified eight forms of index that have been used to analyze and measure the condition of fish. These indices fall into two categories: those which measure the condition of individual fish, i.e. 'condition factors', and those which measure the condition of subpopulations as a whole. However, several publications have pointed out the problems inherent with the condition factors currently in use (Bolger and Connolly, 1989; Cone, 1989; Hayes et al., 1995). In particular, Cone (1989) raises the question that the 'conversion of the two-dimensional weight–length relationship into a single statistic results in a loss of information and, in many cases, an inaccurate representation of that relationship.' Hayes et al. (1995) performed simulations of length–weight regressions and found that for sample sizes commonly used in fisheries research, estimates of the mean-weight-at-length were biased low, whereas estimates of the intercept were biased high.

The earliest condition factor developed was Fulton's condition factor (K), which assumes isometric growth and is of the form $K = xWL^{-3}$ where x is an arbitrary scaling constant that varies with units of measure (Fulton, 1911). It is still one of the most commonly used indices today (Kristinsson et al., 1985; Kjartansson et al., 1988; Fries, 1994). However, there are many instances when the assumption of isometric growth will not be met, i.e. the slope of the weight-length relationship will not be 3.0. If, for example, $b > 3$, there is a significant positive relationship between K and fish length, indicating that K will increase with increasing length (Anderson and Gutreuter, 1983; Cone, 1989). Conversely, there is a negative relationship between K and fish length when $b < 3$, which leads to a decrease in K with increasing length (Cone, 1989).

Ricker (1975) developed an extension of Fulton's condition factor that assumes allometric growth, known as the relative condition factor: $K' = WL^{-b}$. The relative condition factor must, however, be confined in its uses to comparisons between fish which are homogeneous for b, as b is based on the assumption that the slopes of all samples to be compared are equal to some value specific for that sample or set of samples (Bolger and Connolly, 1989; Cone, 1989).

The third commonly used condition index is relative weight, which is described by the following equation: $W_r = 100WW_s^{-1}$ where W is the weight of an individual and W_s is a length-specific standard weight. W_s is derived from $W_{S=a'L^{b'}\text{ where }a'\text{ and}}$ b' ideally account for genetically determined shape characteristics of a species and yield W_r values of 100 for fish that have been well fed. Therefore, this statistic assumes the same slope and intercept as the ideal population, rendering determination of the ideal relationship extremely critical.

Some debate exists as to the method of estimating a and b. Due to the fact that length cannot be considered to be truly independent of weight, Ricker (1975) proposed using the geometric mean of the regression of weight on length and the inverse of the regression of length on weight as the appropriate linear regression for weight-length comparisons. Anderson and Gutreuter (1983) also recommend geometric mean regression techniques, however Cone (1989) favors the use of ordinary least-squares regression due to the difficulty of interpretation of geometric mean regression.

Length–weight models are used to predict growth (in terms of weight as some function of length) and to assess nutritional status as defined by condition. The importance of an accurate model for determining both growth and condition is immense. Daily feed ration is based on the estimated weight or length of fish. Condition is also crucial for determining the health of a population. A model that is sensitive to and reflects small changes in condition can alert a fish culturist to the onset of disease, stress due to overcrowding, or other physiological effects before high mortality rates are suffered.

Girth–length relationships have been previously examined in relation to determining mesh size in capture fisheries. Beverton and Holt (1957) found, for instance, a linear association between girth and length. This implies that girth could be used in much the same way as length to estimate weight. The objectives of this research were to: (1) examine the potential of using another body dimension along with length in a model to estimate mass. (2) Compare different estimators of mass to determine which model is the most accurate over a wide range of morphologies and (3) determine if a new index of condition can be found which is more sensitive than those commonly used to assess the status of fish.

2. Materials and methods

2.1. Model development

The general idea was to respect the concept of density (ρ = mass over volume) as an independent physical property of material as in the following general model:

$$\text{Mass} = \rho' L_1^a L_2^b L_3^c,$$

where $L_1 \ldots L_3$ represent three body lengths and ρ', the proportionality constant. All attempts were made to find an accurate relationship in which the superscripts (denoted as a, b, and c) would be invariant with fish size. In this way, the proportionality constant would be the only regression parameter to be determined, and unlike other models, it could be used to compare different populations. The proposed model, which was tested against two conventional fisheries models, is $M = BL^2H$, where M is fish mass, B is a parameter determined by regression, L is fork length and H is height. As length to height ratio is an important parameter defining swimming drag (Blake, 1983), it was hypothesized that adding height to the traditional models would provide a means to make more concise comparisons of state between different subgroups and more accurate mass estimates.

Relationships of weight with girth and thickness were also sought in a preliminary analysis of data. Although correlation coefficients showed improvement over traditional fisheries models, these relationships were not investigated further, for the reasons provided below. Firstly, the relationships tended to produce more variation in regression parameters than the proposed model did. Secondly, a model where only one side of a fish needed to be measured required less measuring time and reduced handling. Both length and height were quickly measured after a fish was placed on a ruled measuring board. Measurements on a fish's profile can also be easily done underwater with a video camera (Petrell et al., 1997). Girth measurements, on the other hand, require wrapping a fish with a string (small fish) or measuring tape, and two people are needed for large fish. Finally, certain measurements are difficult to obtain without the probability of a high degree of error. Thickness, for example, is the smallest whole body measurement, and as a result would need to be measured very accurately. However, it is sometimes difficult to judge without using excessive handling where the thickness part of the body lies.

2.2. Physical sampling

A large database of physical measurements was available to be analyzed. Over the course of several previous investigations, physical measurements of both chinook salmon (*Oncorhynchus tshawytscha)* and Atlantic salmon (*Salmo salar)* had been obtained by direct sampling. They all had been grown under rearing conditions typical of the fish farming industry and were not part of a particular experimental treatment. Fish of several strains were measured. Measurements were gathered from cages at the Fisheries and Oceans Pacific Biological Station, Nanaimo, B.C.; rearing tanks at the Fisheries and Oceans West Vancouver Laboratory, West Vancouver; and cages on various salmon farms in British Columbia.

For every cage or tank sampled, between 50 and 100 fish were measured. The measurements (to three significant digits) included length (the length from the nose to the fork of the tail), height (measured just before the dorsal fin at the tallest part of the fish) and weight. A total of 1539 Atlantic salmon were measured from 18 enclosures, ranging in size from 0.42 to 8.50 kg. There were 840 chinook salmon measured from 17 enclosures, ranging in size from 0.009 to 4.91 kg. Girth was measured on fewer fish (695 and 447 Atlantic and chinook salmons, respectively), as many site managers restricted fish handling and time out of water.

2.3. Units of measurement

Standard SI units [mass in kilograms (kg) and length in meters (m)] were used wherever possible. However, in many cases mass was expressed in grams (g) and length was expressed in centimeters (cm), due to the conventional usage in the fisheries and aquaculture fields. Note also that the terms fish weight (denoted as W and used in the introduction) and fish mass (M) are used interchangeably. The designation "weight" is used in deference to convention, even though it is actually a force (SI unit of Newton).

The units for K are g cm^{-3}. It is multiplied by 100 to get values near unity. The units for B are the same, but the value is multiplied by 1000, as this gives a value corresponding to that achieved with SI units (i.e. kg m^{-3}).

2.4. Statistical analysis and data presentation

Regression techniques were used to find the parameters of the three length–weight models that were compared. For the model $M = KL^3$, Fulton's condition factor (K) was estimated using a linear regression of M versus L^3. In the next model, $M = BL^2H$, B was estimated with a linear regression of M versus L^2H. The intercept was forced through the origin for B and K determinations. For $M = aL^b$, a and b were estimated using a linear regression of log (M) versus log (L) (power law relation).

For every fish, K and B were also calculated using appropriate equations to determine which one is the least variable. The test for equality of variances was used (Sachs, 1984). Independent random samples from normally distributed populations (a requirement for the test of equality of variance) was assumed.

To test the level of association between length on height, coefficients of determination (r^2) were computed using data obtained from the various populations and a combined data set. Power and linear models were tested. The power law equation was tested as it gave consistently higher r^2s over other models in initial trials.

To illustrate the range of K, a and B which is likely to occur among a diverse range of species, published morphometric data from various parts of the world, and representing widely different body shapes, were extracted from FishBase, a large database on the biology of fish (Froese and Pauly, 1998). The parameters K and a were estimated by solving the appropriate equations, given the weight and length of mid-sized specimens, and B was estimated by using the corresponding value of H, as obtained from either taxonomically correct figures or field data.

3. Results and discussion

In every case, there was a tighter relationship (expressed as the coefficient of determination, r^2, from the regression equation) using $M = BL^2H$ than either of the other two equations ($M = aL^b$ and $M = KL^3$), and the coefficients of determination between $M = aL^b$ and $M = KL^3$ were very similar (Tables 1 and 2). The increase in accuracy using $M = BL^2H$ is presented using scatter diagrams of mass generated with B and K against the true measured mass (shown for the sake of brevity for $M = KL^3$ and $M = BL^2H$ only). For both species, there is a tighter relationship with B than with K (Figs. 1 and 2). From inspection of Figs. 1 and 2, the $M = KL^3$ model works well for fish of small size, but becomes less accurate at larger size.

When standardized K and B values are plotted against mass for both species (Figs. 3 and 4), three observations can be made. Firstly, as already mentioned, there is considerably less scatter for the B values than for the K values. Secondly, the B values had little dependency on or relationship with size, whereas the K values increased with increasing size in the two salmons. Thirdly, the average value of B appears to depend on the species. It ranged from 52.0 to 61.8 for Atlantic salmon and from 56.5 to 69.0 for chinook salmon, and averaged 62.4 for chinook salmon and 56.8 for Atlantic salmon.

In the case of chinook salmon, both K and B increased linearly with fish weight. The increase in K was 45% higher than the increase in B over the same weight increment. The shape (especially the profile) of the chinook salmon tends to change with age, it becomes deep and full bodied from its early torpedo shape, while the profile of the Atlantic salmon remains more or less the same. The B factor for Chinook salmon changes less as fish age, as H in the model is able to capture much of the shape change. The relative invariability of B with age of fish permits a way to compare condition as a fish ages, something not possible with K.

The coefficients of variation for the B and K values of Atlantic salmon were 8.08 and 14.35, respectively, and were found to be significantly different from each other

Table 1
Coefficients of determination (r^2) for the different types of regressions performed on Atlantic salmon data

Sample #	$M = BL^2H$	$M = KL^3$	$M = aL^b$	L/H
1	0.91	0.78	0.81	0.65
2	0.93	0.80	0.82	0.68
3	0.88	0.71	0.75	0.54
4	0.89	0.84	0.86	0.61
5	0.94	0.88	0.87	0.66
6	0.94	0.84	0.85	0.66
7	0.92	0.83	0.81	0.57
8	0.95	0.79	0.81	0.57
9	0.94	0.83	0.83	0.63
10	0.94	0.86	0.86	0.68
11	0.94	0.87	0.86	0.72
12	0.85	0.61	0.65	0.24
13	0.94	0.80	0.81	0.71
14	0.91	0.80	0.80	0.65
15	0.96	0.89	0.89	0.75
16	0.95	0.86	0.85	0.63
17	0.90	0.77	0.77	0.55
18	0.91	0.72	0.71	0.59

Table 2
Coefficients of determination (r^2) for the different types of regressions performed on chinook salmon data

Sample #	$M = BL^2H$	$M = KL^3$	$M = aL^b$	L/H
1	0.96	0.90	0.91	0.79
2	0.93	0.88	0.88	0.82
3	0.96	0.93	0.93	0.81
4	0.90	0.70	0.71	0.51
5	0.93	0.83	0.84	0.70
6	0.96	0.87	0.87	0.62
7	0.96	0.89	0.92	0.77
8	0.94	0.84	0.85	0.70
9	0.90	0.83	0.86	0.62
10	0.92	0.85	0.86	0.65
11	0.92	0.80	0.88	0.65
12	0.91	0.78	0.80	0.63
13	0.96	0.91	0.94	0.77
14	0.94	0.78	0.77	0.52
15	0.99	0.91	0.96	0.86
16	0.96	0.94	0.94	0.70
17	0.99	0.95	0.95	0.82

(F statistic). For chinook salmon, the coefficients of variation for the B and K values were 7.65 and 12.34, respectively, and were also found to be significantly different from each other. The percentage decrease in variability by using B instead of K was 43.7% for Atlantic salmon and 38.0% for chinook salmon.

Although it might be argued that length and height are not truly independent of each other, it can be seen by inspection of Fig. 5 that over a wide range of fish size a non-linear relationship exists between the two dimensions. In both salmonid species, the relationship between length and height was best represented in the form of a power law relation. Further, as can be seen in Tables 1 and 2, low r^2 values for the regression of length/height on mass exist. Weatherley (1959) found that even when depth and breadth of Tench (*Tinca tinca*) was linearly related to length, K tended to increase with length.

Table 3 shows that the B values of fishes with widely different shapes vary from 38 to 58% less than their value of K and a, as the parameter H captured much of the variance associated with shape differences between eely, fusiform, and aberrantly deep-bodied fishes.

4. Applications

The model $M = BL^2H$ is more sensitive to changes in the physical state of fish because it is nearly invariant with size; the same value of B can be found for any size of Atlantic salmon and gradually increases with size for chinook salmon (Figs. 3 and 4). The parameter B is a better indicator of physical state, as the proposed

Table 3
Parameters from length–weight relationships and ancillary statistics in 13 species of fishes with widely differing shapes, ranked in order of ascending relative body height (H/L)[a]

Species[b]	H/L ratio	Height (cm)	TL (cm)	Weight (g)	*b*	*a*	*K*	*B*
Syngnathus typhle	0.04	0.60	15	1	2.9	0.035	0.03	7.5
Strongylura leiura	0.05	1.9	37	79	3.1	0.097	0.16	30
Anguilla anguilla	0.06	4.5	75	445	3.3	0.027	0.11	17.5
Trichiurus lepturus	0.07	4.2	60	153	3.3	0.022	0.07	10
Engraulis ringens	0.15	1.8	12	12	3.0	0.67	0.69	46
Salmo salar	0.20	11.0	56	1367	3.0	0.64	1.1	56
Oncorhynchus tshawytscha	0.24	11.0	46	1892	3.3	0.58	1.56	62
Lutjanus analis	0.30	12.0	40	756	3.0	1.0	1.18	40
Oreochromis niloticus	0.37	12.0	32	849	3.3	1.1	2.59	69
Lactophrys triqueter	0.42	10.0	24	427	3.0	3.1	3.1	74
Cantherinus macroceros	0.46	11.0	23	207	3.0	1.7	1.7	35
Chaetodon ocellatus	0.63	6.3	10	32	3.0	3.3	3.2	50
Antigonia capros	0.91	14.0	15	116	3.0	3.9	3.4	37
Mean	0.30	7.7	34	487	3.1	1.2	1.5	41
S.D.	0.26	4.0	21	603	0.2	1.4	1.2	20
Coefficient of variation, %	86	52	62	124	6.5	116	80	49

[a] Note decline of coefficient of variation from *a* to *K* and *B*.

[b] Representative lengths, weights, and heights, except for the two salmonids, were taken from data in FishBase (Froese and Pauly, 1998). The salmonid figures are grand means of the field data.

model accounts for two dimensions, leaving the thickness to be captured by B. It is also subject to less variability within a given population than K. There are several different ways in which the higher degree of accuracy and sensitivity of this model can be illustrated. For example, say an experiment had been carried out to test the effect of a diet on growth and condition of Atlantic salmon. At the beginning of the experiment, length and height were measured, and parameters K, a and B were calculated. Results from our research show that the variability in K or a would have been higher than the variability in B ($>30\%$). At the end of the experimental

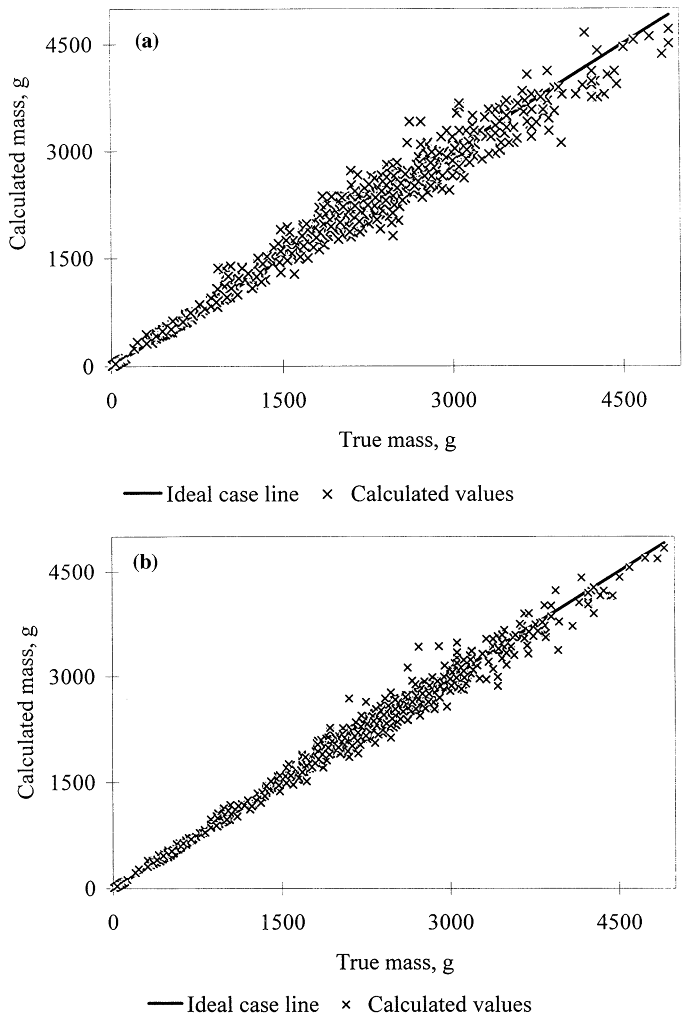

Fig. 1. Scatter diagrams showing the accuracy of the calculated mass for individual chinook salmon ($n = 840$). The straight line represents theoretically perfect correlation between measured and calculated values. (a) Mass calculated using K obtained through regression. (b) Mass calculated using B obtained through regression.

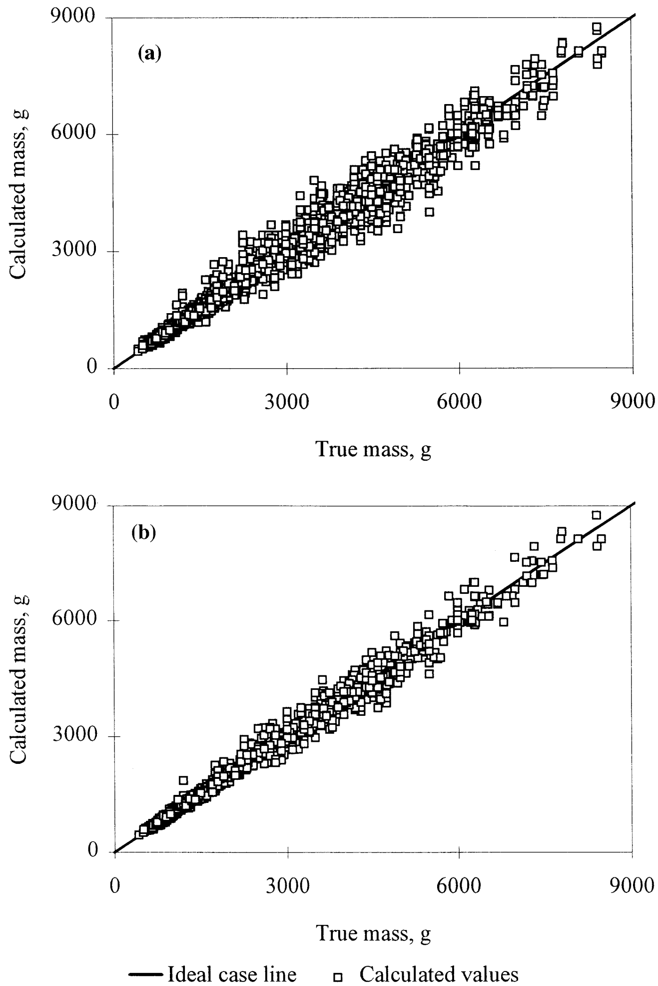

Fig. 2. Scatter diagrams showing the accuracy of the calculated mass for individual Atlantic salmon ($n = 1539$). The straight line represents theoretically perfect correlation between measured and calculated values. (a) Mass calculated using K obtained through regression. (b) Mass calculated using B obtained through regression.

period, K, a and B were calculated again using new measurements. As before K would have been 30% more variable than B. In fact, the increased variability may have precluded a statistical significant difference in the two sets of K's. Also, as K increases naturally with fish age, the second set of K values would not have reflected the actual change in K due to the treatment. The B value would not have suffered these problems of high variability and age-related effects. A significantly higher B value at the end of the experiment could have indicated a wider fish.

The proposed method is more useful for estimating mass even in a population where K is directly measured. The high variability in K would skew the results (as showed in Figs. 1 and 2) and impart a high degree of uncertainty to the measurements. The B factor has been used to estimate fish using an underwater imaging system, as it gives population mean mass within $\pm 5\%$ of the true value (Petrell et al., 1997).

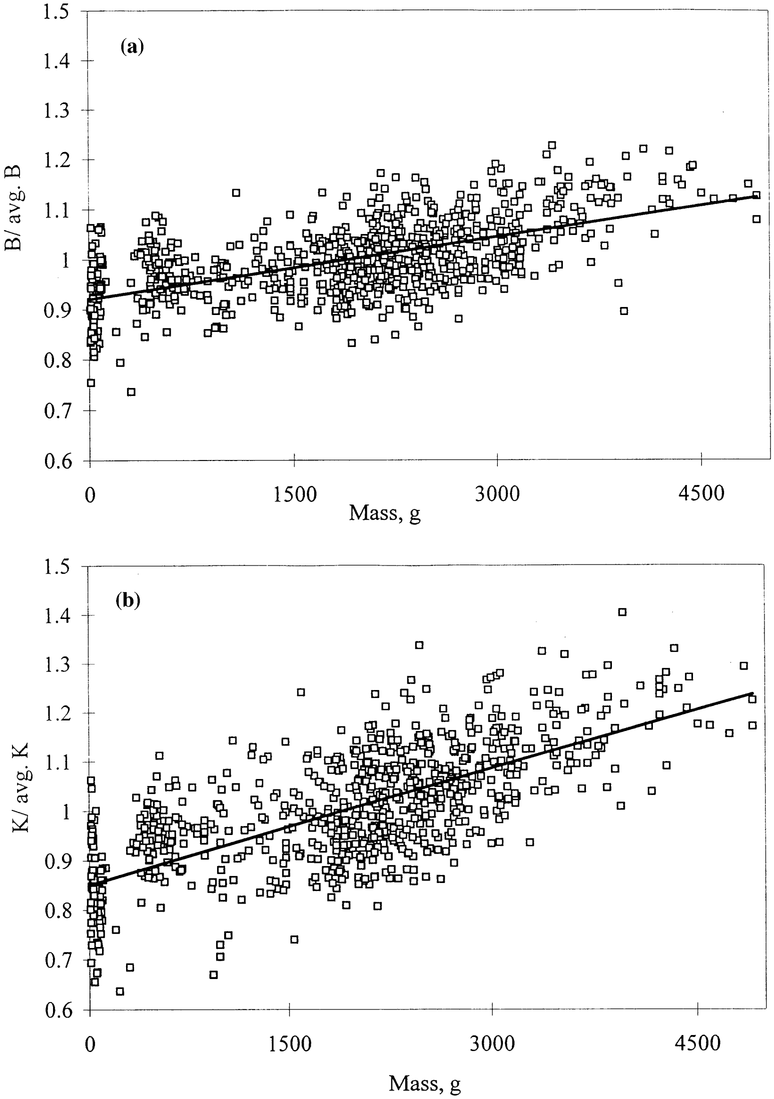

Fig. 3. Scatter plot with a linear trend line of (a) standardized B values and (b) standardized K values against mass for chinook salmon ($n = 840$). In this case, B and K were calculated for every fish by M/L^2H and M/L^3, respectively. Note the higher level of variability in the K values as compared to the B values.

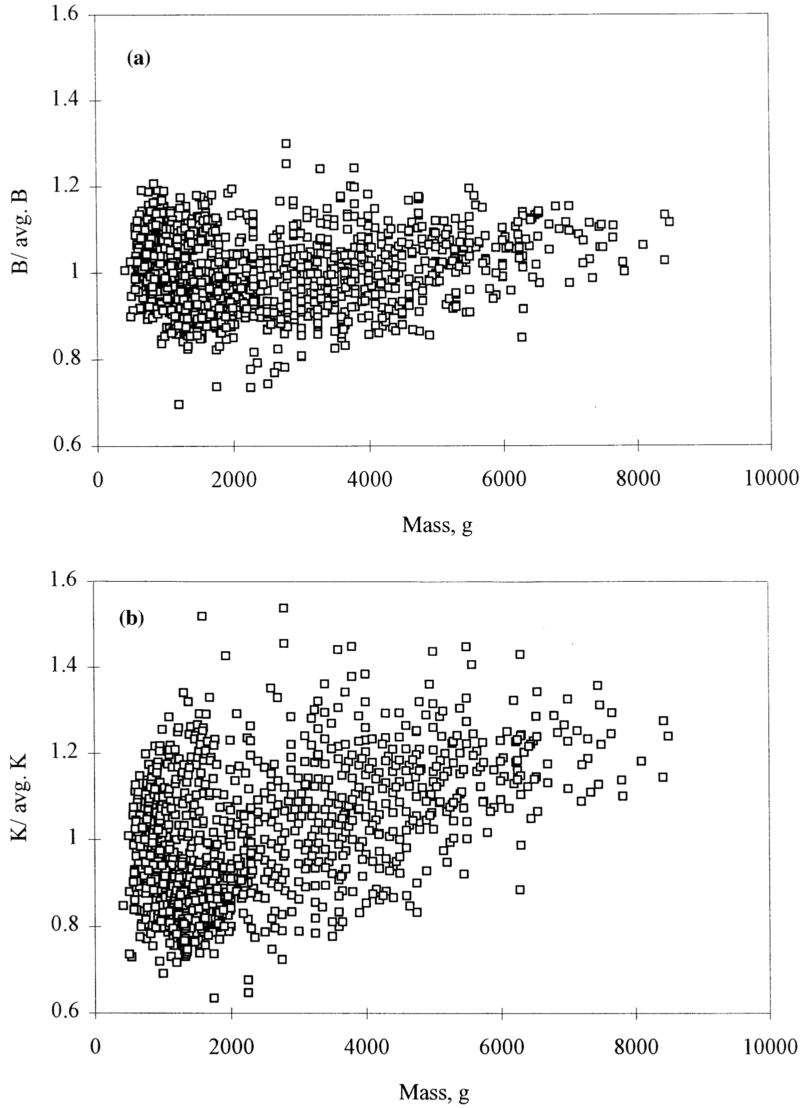

Fig. 4. Scatter plot of (a) standardized B values and (b) standardized K values against mass for Atlantic salmon ($n = 1539$).). In this case, B and K were calculated for every fish by M/L^2H and M/L^3, respectively. As in the previous figure, note the higher level of variability in the K values as compared to the B values.

Even if the exact B-value were not known for a population, the model incorporating height to predict mass would be more accurate than the other fisheries models. For instance, Atlantic salmon have been observed to continue to grow in length at a greater rate than that for either height or girth when fed a maintenance diet, leading to a population of 'eely' fish, i.e. fish that are very long and thin (Ang and Petrell, 1996). In this situation, using a growth model based only on sampled length would over estimate the fish mass. The model including sampled height would automatically decrease the mass of the fish, even if an incorrect *B* value were used.

This high degree of sensitivity in *B* value can be seen in Fig. 6, wherein length/girth ratios were plotted against the parameter *B* (termed *B* factor) of chinook and Atlantic salmons. As the length/girth ratio decreases, *B* factor tends to increase. In other words, a low *B* factor indicates a slender (more streamlined) morphology, while a high *B* factor indicates a shorter, thicker and deep-bodied

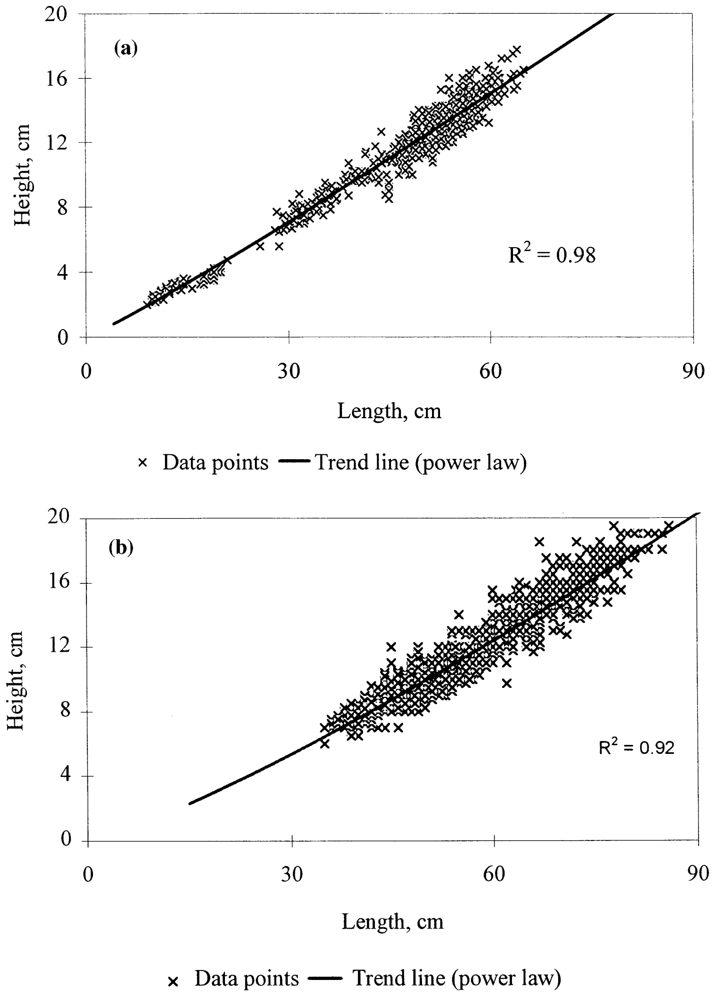

Fig. 5. The variability of height with length for (a) chinook salmon ($n = 840$) and (b) Atlantic salmon ($n = 1149$).

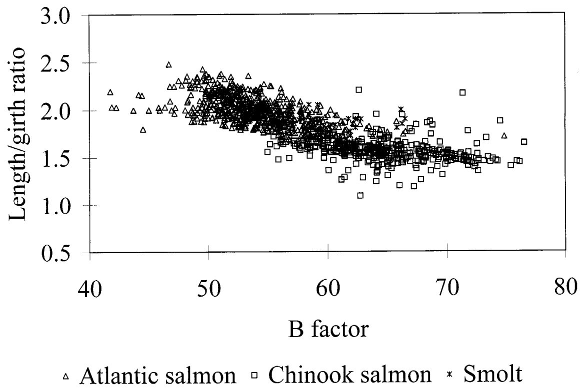

Fig. 6. The change in B with length/girth ratio in salmon ($n = 1149$). Smolts of chinook salmon are identified separately from older fish.

morphology. The relationship between length/girth and B factor permits the determination of girth from B factor and length.

The relationship between length/girth and B factor also associates the B factor to the ability of a particular fish to overcome drag while swimming. The drag on a fish decreases as the area on its body subjected to the flow per given length decreases (length/girth ratio increases) and the level of bodily streamlining (which decreases drag coefficient) decreases (Blake, 1983; Petrell and Jones, 1999). A low B factor salmon is, therefore, subjected to less drag than a higher B factor fish of similar length and swimming speed. A low B factor fish is, however, not necessarily the better-conditioned fish, as it is not carrying its full potential in weight per unit length. Apparently under less than ideal conditions a salmon will trade-off weight for the ability to use less energy while swimming (overcoming drag). Future work will focus on the association of body reserves with the B factor to determine the optimal B factor.

The final application that will be described will involve the fitness of fish in terms of its potential for harvest. If the B factor is lower than expected in a fish, it may not have the energy reserves for migration or spawning. Again, knowing just the length and mass does not provide information on condition as the length based models are unreliable. To help conserve a species, the B factor for fry, juvenile and adults can be compared to find where the fish of any species loses condition or form. Then, depending on the results, fishing quotas can be allocated. If the B factor is low (not the optimal for the species), then fewer fish should be permitted to be harvested. Length and mass measurements alone do not provide information on condition, as the length-based models are unreliable. It can be seen from the above applications of this model that making the extra measurement is, indeed, worth the effort.

5. Summary of findings and conclusions

When two length–weight relationships commonly used in fisheries research ($M = KL^3$ and $M = aL^b$) were compared with a new model ($M = BL^2H$) developed during the course of this study, it was found that the new model consistently gave more accurate results over much wider ranges of size and shape than either of the other models. This is of course largely due to the fact that instead of attempting to describe the growth and condition of fish using only one body parameter, that of length, the model incorporates a second body parameter, fish height.

One feature of this model that makes it useful for fish culturists is its increased sensitivity to changes in the physical state of a fish, reflected in changes in the parameter B. Another advantage is its invariance over a wide range of sizes and ages. Finally, for salmon the B factor is an indicator of bodily streamlining and the ability to reduce drag.

Acknowledgements

We would like to thank A. Shieh, K. Ang, Pacific National Group, Heritage Aquaculture, Pacific Salmon Farming Partners, Paradise Bay Seafarms, Fisheries and Oceans Canada, and the British Columbia Ministry of Environment for their help supplying and measuring fish. Financial support was provided by National Science and Engineering Research Council Canada.

References

Anderson, R.O., Gutreuter, S.J., 1983. Length weight and associated structural indices. In: Nielsen, L.A., Johnson, D.L. (Eds.), Fisheries Techniques. American Fisheries Society, Bethesda, Maryland, pp. 283–300.

Ang, K.P., Petrell, R.J., 1996. Control of feed dispensation in seacages using underwater video monitoring: effects on growth and food conversion. Aquacult. Eng. 16, 45–62.

Beverton, R.J., Holt, S.J., 1957. On the Dynamics of Exploited Fish Populations. Chapman and Hall, London, p. 230.

Blake, R.W., 1983. Fish Locomotion. Cambridge University Press, New York, 208 pp.

Bolger, T., Connolly, P.L., 1989. The selection of suitable indices for the measurement and analysis of fish condition. J. Fish Biol. 34, 171–182.

Cone, R.S., 1989. The need to reconsider the use of condition indices in fishery science. Trans. Am. Fish. Soc. 118 (5), 510–514.

Fries, J.N., 1994. SAMCALC: A computer program for fish culturists. Progr. Fish-Culturist 56, 62–64.

Froese, R., Pauly, D., 1998. FishBase 98: Concepts, Design and Data Sources (http://www.fishbase.org/manual/contents.htm). ICLARM, Manila, 293 p.

Fulton, T.W., 1911. The Sovereignty of the Sea. London, Edinburgh.

Hayes, D.B., Brodziak, J.K.T., O'Gorman, J.B., 1995. Efficiency and bias of estimators and sampling designs for determining length–weight relationships of fish. Can. J. Fish. Aquat. Sci. 52, 84–92.

Kjartansson, H., Fivelstad, S., Thomassen, J.M., Smith, M.J., 1988. Effects of different stocking densities on physiological parameters and growth of adult Atlantic salmon (*Salmo salar* L.). Aquaculture 73, 261–274.

Kristinsson, J.B., Saunders, R.L., Wiggs, A.J., 1985. Growth dynamics during the development of bimodal length–frequency distribution in juvenile Atlantic salmon (*Salmo salar* L.). Aquaculture 45 (1), 1–20.

Petrell, R.J., Jones, R.E., 1999. Power requirement of swimming in fish, and its implications for food conversion and growth performance. Aquacult. Eng. Accepted.

Petrell, R.J., Shi, X., Ward, R.K., Naiberg, A., Savage, C.R., 1997. Determining fish size and swimming speed in cages and tanks using simple video techniques. Aquacult. Eng. 16, 63–84.

Ricker, W.E., 1975. Computation and interpretation of the biological statistics of fish populations. Bull. Fish. Res. Board Can. 191, 1–382.

Sachs, L., 1984. Applied Statistics. Springer-Verlag, New York, p. 495.

Weatherley, A.H., 1959. Some features of the biology of the tench *Tinca tinca* (Linnaeus) in Tasmania. J. Anim. Ecol. 28, 73–87.