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A NUMERICAL MODEL FOR ESTIMATING FISH PRODUCTIVITY OF LARGE LAKES: TECHNICAL SUMMARY

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ABSTRACT

Factors influencing lake productivity could be grouped into three categories; climatic, edaphic, and morphometric factors. These factors are represented by latitude, circulation type, and mean depth in this study. The productivity index(PI) was formulated in the following equation: PI=LC/M where C=circulation type, L=latitude code, M=log(mean depth+1). Fourty-one large lakes(surface area >500 km^2)throughout the world were tested with this model. The regression equation describing the linear relation between fish productivity(P) and fish productivity index(PI) is P=1.65PI-13.41 where N=41, r^2=0.84, p<0.0001. The non-linear relationship was also obtained from utilizing general linear regression between selected variables and fish productivity in the following equation: $Log(P) = 0.38L + 0.009C^2 + 0.52M^{-1} - 1.02$ where N=41, r^2 =0.85, p<0.0001. Both index and model should have application to nearly 200 large freshwater lake worldwide.

INTRODUCTION

Approximately 250 large lakes of the world (surface area in excess of 500 km^2) account for 88% of the total volume of freshwater(Figure 1). For most of the large lakes, utilization as food sources is a minor exploitation compared with other uses, e.g., municipal water supply, transportation, and recreation. These large lakes normally serve as prime food sources for only small communities

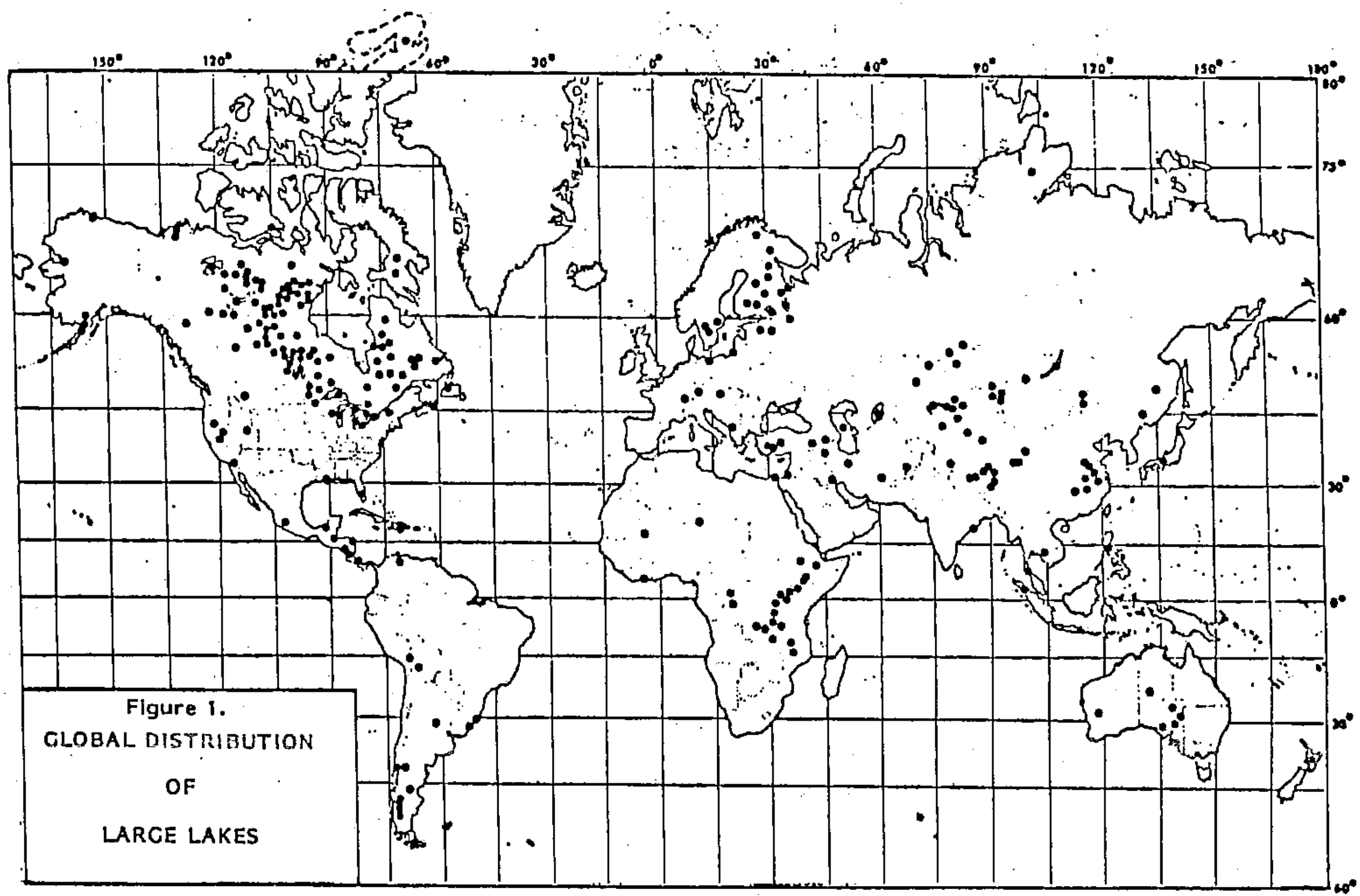

Figure 1.
GLOBAL DISTRIBUTION
OF
LARGE LAKES

adjacent to them. The development and management of these natural resources is essential to obtain the maximum sustainable fish productivity and to expand the range of lake utilization. The expected annual fish production is necessary at this point as a reference for a suitable selection in developing sites for the management programs. Reliable fish productivity data is available for less than 20 percent of 253 large lakes.

The purpose of this study is to develop a model for annual fish yield estimation of large lakes throughout the world by utilizing easily gathered morphological and physical variables as specific characters for each lakes.

METHOD

In this study 41 lakes(Table 1) were included as the database because of their large areal coverage (surface area> 500 km^2), different geographical locations, and their available information about physical(latitude, longitude, elevation, annual precipitation, annual evaporation, and circulation type), morphological(area, drainage basin, maximum depth, mean depth, volume, length, breadth, shoreline length, and shoreline development), and biological variables(fish productivity).

Lake Distribution

The source of information on geographic coordinates of these lakes , with exception of the Canadian lakes, was obtained from the

TABLE 1 LAKE CHARACTERISTICS UTILIZED FOR MODEL DEVELOPMENT

lake	area (km**2)	latitude (degree)	mean depth (m)	circulation type	fish yield (kg/hectare.y)
Albert	5590	1.67 n	25	polymictic	50.40(17)
Athabasca	7935	59.18 n	26	dimictic	0.88(14)
Baikal	31500	54.00 n	680	meromictic	2.30(12)
Balaton	590	46.83 n	4	monomictic	23.50(4)
Big trout	661	53.77 n	15.8	dimictic	0.73(16)
Churchill	559	56.00 n	8.96	dimictic	4.28(1)
Constance	540	47.58 n	90	dimictic	12.00(8)
Cree	1434	57.48 n	14.9	dimictic	1.46(1)
Cross	755	54.72 n	5.1	dimictic	3.79(1)
Edward	2150	0.35 s	34	polymictic	69.7(17)
Erie	25657	42.15 n	19	monomictic	9.72(7)
Frobisher	516	56.37 n	5.49	dimictic	2.20(17)
Geneva	580	46.42 n	150	dimictic	25.2(10,21)
G.bear	31326	66.00 n	143	dimictic	0.3(16)
G.slave	28568	61.78 n	234	dimictic	1.31(11)
Huron	59500	45.00 n	59	monomictic	2.90(20)
Kyoga	4430	1.50 n	6	polymictic	181.00(17)
L.slave	1169	55.43 n	11.7	dimictic	7.5(13)
Malaren	1140	59.50 n	21.5	monomictic	3.4(17)
Manitoba	4625	50.92 n	8.96	dimictic	5.32(13)
Michigan	57750	44.00 n	85	monomictic	2.24(2)
Nipigon	4848	49.83 n	53.8	dimictic	1.56(18)
Ontario	19000	42.65 n	86	monomictic	1.25(16)
Peter pond	778	55.95 n	13.70	dimictic	8.80(14)
Rainy	940	48.70 n	11.9	dimictic	5.26(5)
Red	1170	48.02 n	3.9	dimictic	4.14(19)
Reindeer	6650	57.30 n	17	dimictic	1.12(14)
Ronge	1413	55.13 n	14.6	dimictic	2.71(14)
St.clair	1113	42.47 n	4.11	dimictic	7.12(9)
Scutari	600	42.17 n	5	dimictic	50.00(3)
Seul	1658	50.38 n	10.7	dimictic	1.59(16)
Superior	82100	47.55 n	149	monomictic	1.19(2)
Tangan-yika	32000	6.00 s	574	meromictic	22.00(22)
Upemba	530	8.60 s	1	polymictic	226.00(17)
Vanern	5580	58.92 n	31.3	monomictic	3.5(17)
Vattern	1910	58.40 n	41.90	dimictic	1.57(6)
Victoria	62940	1.00 s	40	polymictic	49.05(15)
Winnipeg	24387	52.52 n	12.9	dimictic	2.98(13)
Winnipe-gosis	5375	52.58 n	4	dimictic	4.35(13)
Wollaston	2681	58.23 n	17.4	dimictic	5.58(11)
Woods	4350	49.25 n	7.70	dimictic	6.28(11)

1. Atton (?) 2. Baldwin and Saalfeld (1962) 3. Beeton (1983) 4. Biro(1970) 5. Chevalier (1977) 6. Grimas (1972) 7. Hartman (1972) 8. Hartmann And Numann (1972) 9. Johnston (1977) 10. Laurent (1972) 11.Matuszek (1978) 12. Moskalenko (1972) 13. Rawson (1952) 14.Rawson (1960) 15. Regier (1971) 16. Ryder (1965) 17.Schlesinger and Regier (1982) 18. Schupp and Macins (1977) 19. Smith (1977) 20. Spangler (1973) 21. Vivier (1975) 22. Welcomme (1972)

table prepared by Showers(1977). For Canadian Lakes, the inventory published by Environmental Canada Inland Water Directorate (Gilliland et al. 1973) was utilized as the information source.

The lake latitudes were classified as classes in the following manner to be more compatible with other variables in model usage: class 1 from 80-89 degrees, class 2 from 70-79 degrees, class 3 from 60- 69 degrees, and so on until class 9 from 0-9 degrees.

Morphometric Data

For only about 20 percent of mean depth data is available for large lakes. Without such information, calculation of productivity index is impossible. A simple plot of maximum depth versus mean depth for large lakes with complete bathymetric surveys shows the following relationships (Herdendorf,1982)

Maximum depth range(m)	ratio of max to mean depth
0-250	1 : 0.32
250-500	1 : 0.35
500-1500	1 : 0.38
1500-2000	1 : 0.40

From these relationship, the correlation coefficient of 0.901 ($p<0.0001$) was obtained between actual and predicted mean depth ($N=25$). The mean depth can be estimated from the available maximum depth by using this equation :

Mean Depth = 0.39Maximum Depth - 4.98

Drainage basin area, the area of the catchment basin of the surface area of the lake, is missing for more than half of the large lakes. Shoreline lengths were obtained by using a Hewlett-Packard electronic digitizer and maps(1:500,000 scale aeronautical charts). Shoreline development, a measure of irregularity of the shore based on the rati of length to the circumference of a circle that has the same area as the lake, was calculated for each lake(Lind, 1979). Length and breadth measurements were gathered from a variety of sources and it is difficult to determine the criterion each author used for his measurements.

Edaphic Data

Annual precipitation and annual evaporation are categorized to this group because of their relation with nutrient input and nutrient dilution. Circulation patterns, related to nutrient distribution in lake systems, were recorded, based on the classification offered by Hutchinson and Loffler(1975), on a scale:

class 1 - amictic(no circulation, continuously stratified)

class 2 - meromictic(partly circulation)

class 3 - monomictic(one circulation per year)

class 4 - dimictic(two circulations per year)

class 5 - polymictic(more than 2 circulations per year)

Biological Data

Average fish productivity was obtained from catch records for several years, or from ppublished estimates based on intensive fishery surveys and is expressed as the average annual yield (kg/hectare-year)(Table 1).

Index Development

The relationship among each variable and fish production for 41 lakes were determined by simple correlation and general linear regression analysis in Statistical Analysis System Packages (SAS) (Helwig, 1985). The correlation coefficients were used as criteria for screening the representative variables utilized in fish productivity index and models.

RESULTS

Upon examining the literature and the statistical outcome, three variables have been carefully selected to represent the productivity controlling factors (Table 2). The selected variables are latitude code, circulation type, and 1/log(mean depth+1) from climatic, edaphic, and morphometric category respectively.

Correlation between annual fish production and selected variables.

The highest correlation was found between latitude code and annual fish yield ($r=0.76$, $p<0.0001$, Table 3). However, the correlation was enhanced by substituting logarithmic value of the fish yield ($r=0.87$, $p<0.0001$), indicating the non-linear relationship between these two specific variables. Thus, when the latitude code is increased, moving closer to equator from north or south, the expected annual fish production is increased in a non-linear manner.

TABLE 2 CODED LAKE DATA UTILIZED FOR PRODUCTIVITY MODEL

lake	latitude code	circulation type code	log(z+1)	productivity index	fish yield kg/hectare/y
Albert	9	5	1.41	31.05	50.4
Athabasca	3	4	1.43	8.40	0.88
Baikal	4	2	2.83	2.80	2.3
Balaton	5	3	0.70	31.35	23.5
Big trout	4	4	1.22	13.12	0.73
Champlain	5	4	1.61	12.40	4.0
Churchill	4	4	0.99	16.80	4.28
Constance	5	4	1.96	10.00	12.0
Cree	4	4	1.20	13.28	1.46
Cross	4	4	0.71	22.40	3.76
Edward	9	5	1.54	29.25	69.7
Erie	5	3	1.30	11.70	9.72
Frobisher	4	4	0.81	19.68	2.20
Geneva	5	4	2.22	21.22	25.2
G.bear	3	4	2.17	5.52	0.3
G.slave	3	4	1.79	6.72	1.31
Huron	5	3	1.82	8.25	1.55
Kyoga	9	5	0.85	53.10	130.0
L. slave	4	4	1.10	14.56	7.5
Malaren	3	3	1.33	7.83	3.4
Manitoba	4	4	1.00	16.00	5.32
Michigan	5	3	1.93	7.80	2.24
Nipigon	4	4	1.73	9.12	1.56
Ontario	5	3	1.94	7.80	1.25
Peter pond	4	4	1.17	13.76	8.8
Rainy	5	4	1.07	19.20	5.26
Red	5	4	0.59	24.60	4.14
Reindeer	4	4	1.85	12.64	1.12
Ronge	4	4	1.11	14.08	2.71
St.clair	5	4	0.71	34.00	7.21
Scutari	5	4	0.78	25.80	50.0
Seul	4	4	1.06	15.04	1.59
Superior	5	3	2.17	6.90	1.19
Tanganyika	9	2	2.78	6.48	22.0
Tumba	9	5	0.40	112.50	115.0
Upemba	9	5	0.30	149.40	226.0
Vanern	4	3	1.51	7.92	3.5
Vattern	4	4	1.62	9.92	1.57
Victoria	9	5	1.59	28.35	49.05
Winnipeg	4	4	1.15	13.92	2.98
Winnipeg-osis	4	4	0.70	22.88	4.35
Wollaston	4	4	1.33	12.00	1.90
Woods	5	4	0.95	21.00	6.28

TABLE 3

Correlation coefficients among variables utilized in the fish productivity models and annual fish yield (normal and logarithmic values). (N = 41)

	fish productivity		log (fish productivity)	
	r	p	r	p
annual evaporation	0.218	0.1214	0.331	0.0167
annual precipitation	0.320	0.0207	0.490	0.0002
area	-0.197	0.1667	-0.273	0.0523
breadth	-0.161	0.2579	-0.313	0.0252
circulation type	0.459	0.0001 *	0.352	0.0067
drainage basin	-0.019	0.0001	0.404	0.0721
elevation	0.375	0.0062	0.462	0.0006
latitude	-0.705	0.0001	-0.787	0.0001
latitude code	0.764	0.0001 *	0.873	0.0001
length	-0.226	0.1079	-0.219	0.1180
log(Z+1)	0.632	0.0001 *	0.478	0.0001
longitude	-0.462	0.0006	-0.484	0.0003
max.depth	-0.094	0.5155	0.004	0.9764
shoreline development	-0.170	0.2524	-0.161	0.2805
shoreline length	-0.201	0.1708	-0.332	0.0213
square circulation	0.579	0.0061	0.449	0.0004
square log(Z+1)	0.670	0.0001	0.479	0.0001
volume	-0.184	0.2757	-0.194	0.2494

p - probability
r - correlation coefficient

The best correlation between morphometric factors and annual fish yield was obtained from 1/log(mean depth+1) ($r=0.63$, $p<0.0001$). The strength of the correlation increased when substituting 1/log(mean depth+1) with the square of the same data($r=0.67$,$p<0.0001$). This relationship indicated that in the deep lake, the expected fish production declined in non-linear fashion. The same trend was presented by Rawson(1955) in the relationship between the plankton standing crop and mean depth in large temperate lakes.

Circulation type was also non-linearly realted to fish productivity. This was suggested by improve of correlation from 45.9 to 57.9 % when square circulation was utilized ($p<0.0001$) (Table 3).

Correlations between fish productivity model and index with fish productivity.

The highest coefficient of determination was found ($r^2=0.85$, $p<0.0001$) for a general linear model using log(fish productivity) and three variables: latitude code, circulation type, and 1/log(mean depth+1) (Table 4). In this equation (eq. 8) circulation code square was utilized and resulted in the improvement of r^2(Figure 2).

In the next case, the productivity index(PI) which was formulated by :

$PI = CL/\log(Z+1)$

C - circulation type (1-5)

TABLE 4

General linear regression equations and coefficients of determination (r^2) showing interrelationship among the weighted variables and annual fish production. (N = 41)

Model	coefficient of determination
1. $P = 25.54L - 75.73$	0.58
2. $P = 58.49C - 75.63$	0.25
3. $P = 90.77M - 19.95$	0.40
4. $P = 3.36L + 2.16L^2 - 26.25$	0.53
5. $P = -428.91C + 136.43C^2 + 325.22$	0.67
6. $P = -13.21M + 55.70M^2 + 15.58$	0.45
7. $P = 1.65P.I. - 13.41$	0.84
8. $LP = 0.38L + 0.009C^2 + 0.52M - 1.02$	0.85

C -circulation type code

L -latitude code

LP -log (fish productivity)

M -1/log (mean depth+1)

P -fish productivity

P.I-fish productivity index

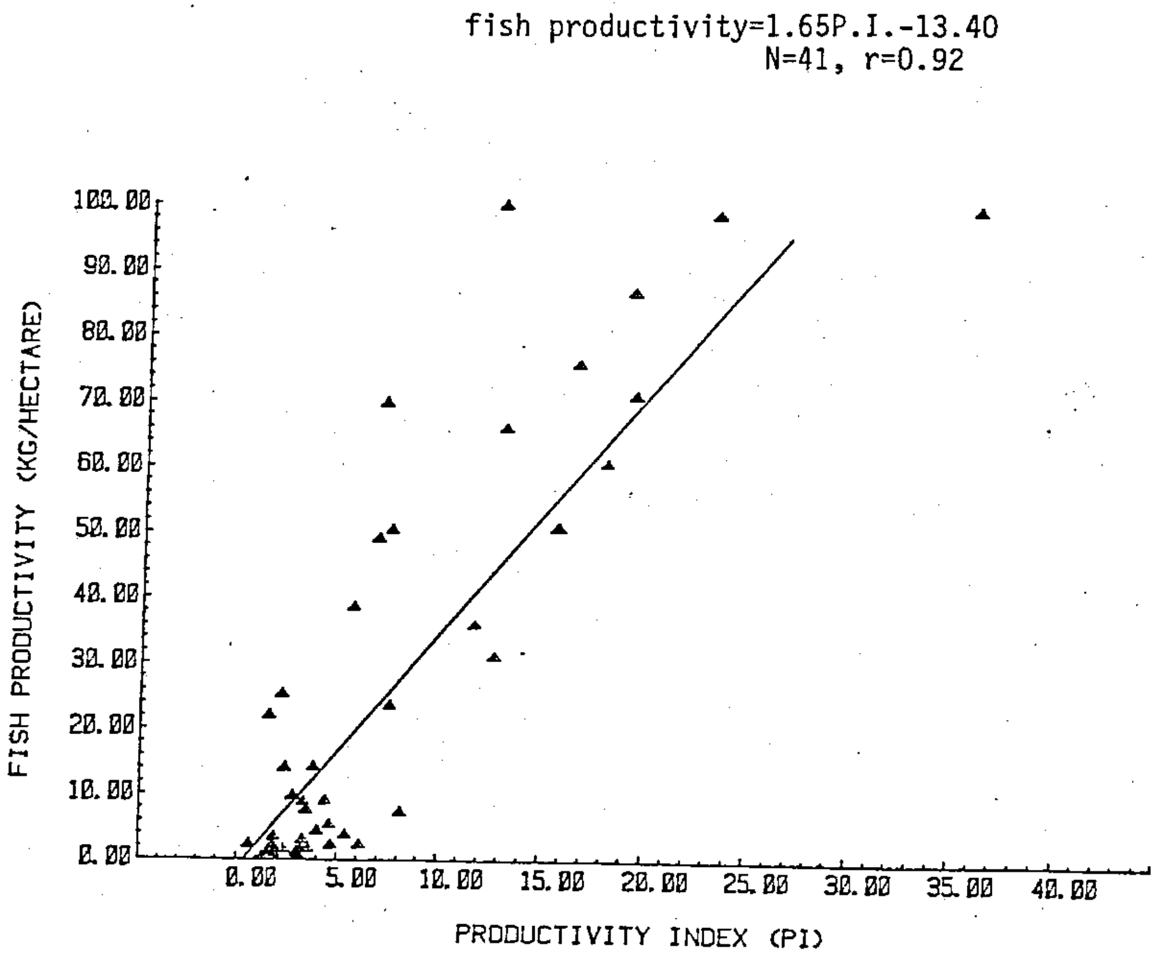

FIGURE 2 The relationship between productivity index (PI) and actual fish productivity.

$$\text{Actual fish productivity} = 0.85\ \text{Predicted fish productivity} - 0.005(\text{Predicted fish productivity})^2 + 0.045$$

$N = 41$, $r^2 = 0.89$

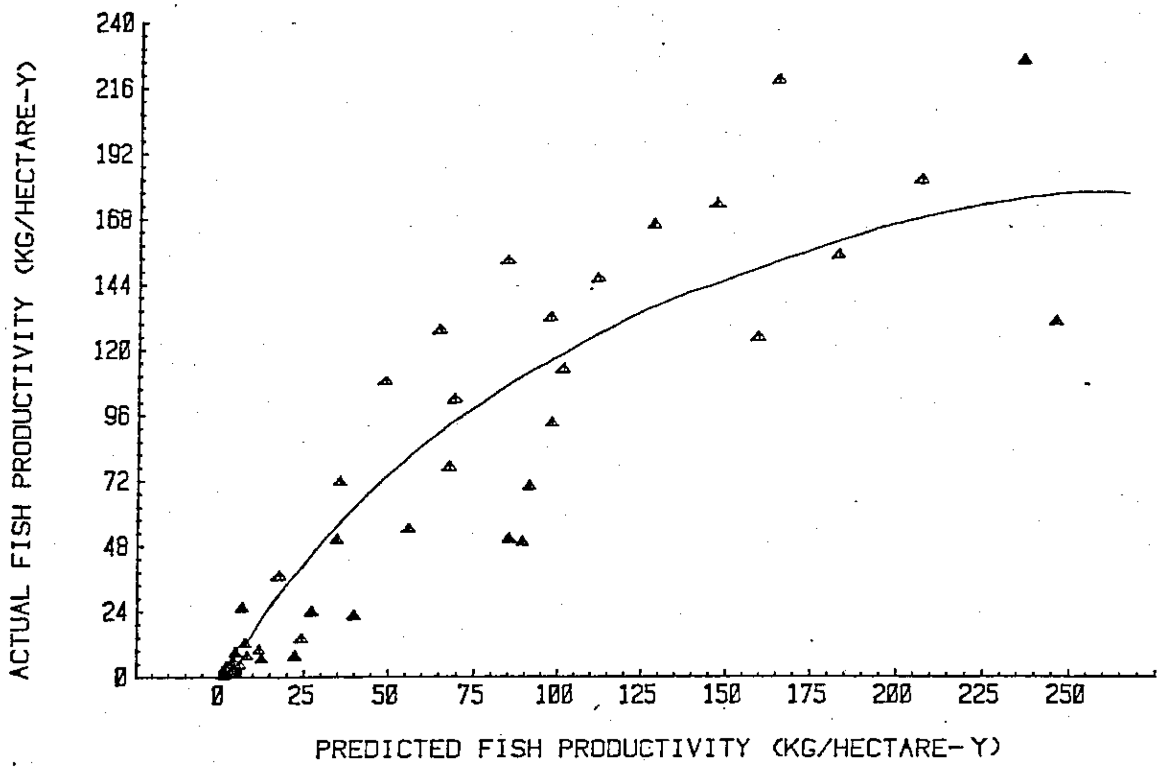

FIGURE 3 The relationship between predicted values from fish productivity model and actual fish productivity.

L - latitude code (1-9)

PI - productivity index

Z - mean depth (m)

showed a high correlation with the fish productivity ($r=0.92, p<0.0001$) (Table 4, equation 7). This index accounts for 84% of the variability in the annual fish yield (Figure 3).

DISCUSSION

Assessment of existing models

After the model development study, it can be summarized that morpedaphic index (Ryder, 1965) is an empirically derived formula that was first described as a method to rapidly calculate potential fish yield of unexploited temperate lakes. This index was formulated by the ratio between total dissolved solids and mean depth. There is no climatic variable in this index, therefore; application is limited to regional analyses.

Brylinsky and Mann(1973) provided a large reference of relationships between both abiotic and biotic variables and lake productivity. In regression models, detail variables, eg, thremocline depth, epilimnion temperature, and phytoplankton chlorophyll a, which are relatively difficult to obtain than principle variables, eg, mean depth, air temperature, latitude, were included in the models. This occurance explained the inconvenience and limitation in the application of these models compared to MEI.

A non-linear relationship was suggeated between mean depth and fish production the plankton production and mean depth for North American large lakes(Rawson,1955) which supported the usage of log (mean depth+1) rather than normal mean depth in this study.

The final outcomes of this study are in the form of productivity index (PI)(eq.7,Table 4)and productivity model (eq.8,Table 4). The PI is the better fish productivity estimator when fish yield is relatively high (>10 kg/ha-y). This is due to the linear relationship between PI and annual fish yield which makes the slope constant. However, the most available data in this study are from temperate large lakes which yield lower fish productivity compared to tropical lakes. This clump of data impaired the PI predictive ability at low fish productivity level. On the other hand, the curvilinear relationship between fish productivity and selected variables acts as a better predictor when fish yield is relatively low (<10 kg/ha-y). This result can be explained by the continuously change of slope throughout the curve and level off when approaching the high fish productivity (Figure 3). The combination of productivity index and model usage will compensate the single application disadvantage of either PI or productivity model and enhance the accuracy in annual fish yield prediction over the whole range of productivity.