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A Model for the Movement and Distribution of Fish in a Body of Water

D. L. DeAngelis

ENVIRONMENTAL SCIENCES DIVISION
Publication No. 1173

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OAK RIDGE NATIONAL LABORATORY
OPERATED BY UNION CARBIDE CORPORATION FOR THE DEPARTMENT OF ENERGY

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ABSTRACT

DEANGELIS, D. L. 1978. A model for the movement and distribution of fish in a body of water. ORNL/TM-6310. Oak Ridge National Laboratory, Oak Ridge, Tennessee. 78 pp.

A Monte Carlo mathematical model tracks the movement of fish in a body of water (e.g., a pond or reservoir) which is represented by a two-dimensional grid. For the case of a long, narrow reservoir, depth and length along the reservoir are the logical choices for coordinate axes. In the model, it is assumed that the movement of fish is influenced by gradients of temperature and dissolved oxygen, as well as food availability and habitat preference. The fish takes one spatial "step" at a time, the direction being randomly selected, but also biased by the above factors.

In trial simulations, a large number of simulated fish were allowed to distribute themselves in a hypothetical body of water. Assuming only temperature was influencing the movements of the fish, the resultant distributions are compared with experimental data on temperature preferences.

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INTRODUCTION

The distribution of fish populations in bodies of water is interesting to sportsmen, commercial fishermen, and ecologists alike. Several factors that may influence fish movements and spatial population distribution have been proposed, including temperature, dissolved oxygen in the water, pH values, the availability of food, the presence of cover for protection from predators, and the occurrence of competitors. These are not all independent. Dissolved oxygen is to some extent related to water temperature, as is the availability of certain types of prey. If the locomotor responses of fish to each of the factors were known in detail, then one could feasibly predict the average motions of a fish in a given body of water. The task of identifying and quantifying all the influences on fish locomotor behavior will not be easy, but significant progress has been made, thanks to ingenious laboratory experiments and telemetry methods useful for the field.

As the factors involved in the spatial behavior of fish begin to be understood, it can be applied to a host of practical matters. For example, one would like to know where in a body of water fish population densities will be highest at a given time of year. Also, how will the population distribution in space respond to slow or rapid changes in the condition of the water, either through natural processes such as seasonal variations, or artificial changes such as those induced by power plant operations?

Both basic research and practical applications in the area of fish movements will rely on techniques of mathematical modeling. Models incorporating specific hypotheses will form a framework for experimental research, from which the data can be used to test the hypotheses. When the fundamental parameters of the models have been quantified, the model can be used predictively. This report describes a mathematical model capable of being used in conujunction with laboratory experiments and field studies, and later, for predictive purposes.

Much experimental research has gone into the study of the effects of temperature on locomotor behavior in fishes. Temperature has been called the most important influence on the behavior of many freshwater fish (e.g., Coutant 1975). It has long been noticed that fish move to different areas of a body of water as water temperature changes. For example, largemouth bass overwinter in deep water, where the temperature is warmest. Using underwater telemetry, Warden and Lorio (1973) found that largemouth bass tend to move great distances to new home ranges in spring and fall, when water temperature is changing most rapidly. In winter, the population of largemouth bass congregate around the thermal discharges of power plants (Gibbons, Hook and Forney 1972). In a Texas cooling reservoir, it was noticed that largemouth bass sought out the cooler shoreline zones in summer mornings when the remainder of the reservoir had temperatures exceeding 37.8°C (Smith 1972).

Laboratory studies have been performed to refine the data on temperature selection of several centrarchid species (Reynolds and Casterlin 1976, Stuntz and Magnuson 1976). Researchers have also sought to relate temperature preferenda with thermoregulation and the optimization of physiological processes (e.g., McCauley and Huggins 1976, Reynolds and Casterline 1976). Growth rates of largemouth bass usually seem to be optimal near their temperature preferenda (Coutant and Cox 1976), although this does not seem to be the case for bluegills in thermal discharge areas during the summer months (Kitchell _et al_. 1974). Bluegills were shown to actively avoid lethal temperatures (Peterson and Schutsky 1976), and to vary their temperature preferenda according to their daily rations (Stuntz and Magnuson 1976).

A question that has bearing on attempts to model fish movements is what is the precise mechanism by which fish tend to center around their preferred temperatures? Neill (1976) discusses different mechanisms in detail and describes one-dimensional computer models based on some of these mechanisms. Thermoregulatory movements can be broadly categorized as predictive or reactive. In the former case, the fish is assumed to have some knowledge, by prior experience or instinct, of the temperature distribution in the body of water, and will use this knowledge to move toward the desired temperature range. For example, since lower water strata are normally cooler than upper layers, the fish should automatically move downwards when it feels too warm. Reactive behavior presupposes no prior knowledge of the temperature distribution, but only that the fish responds to different temperature regimes by altering its locomotory behavior. Several models of reactive movements have been developed. One type of model has been termed orthokinetic by Fraenkel and Gunn (1961). According to this model, fish slow their movements when in the preferred temperature range, increasing their chances of staying there. Both Fraenkel and Gunn (1961) and Neill (1976) have pointed out the inefficiency of this model for producing aggregation about the preferred temperature. Fish whose direction of motion was originally oriented away from the preferred temperature would continue to move away from it. Neill was able to obtain realistic aggregation only when his model specified a high probability of changing directions when the fish was moving away from the preferred temperature range. This form of behavior is called klinokinesis.

Dissolved oxygen and pH in the water are important to the health of the fish and, therefore, presumably influence its movements. While fish have not been shown to exhibit dissolved oxygen and pH preferenda, they might be expected to avoid unfavorable conditions. For example, at 25°C the minimum oxygen requirement of small largemouth bass is almost 0.92 ppm (Moss and Scott 1961); it would be advantageous for such fish to preferentially move away from areas with dissolved oxygen levels below this minimum.

The movement of fish in response to food availability and habitat preference probably involve learning where favorable conditions exist in a body of water. It is harder to develop models for response to these factors than it is for motion in temperature gradients, since it is difficult to know the extent of learning in the fish.

The model described in this report assumes that the fish acts as if it can sense temperature gradients and will move along a temperature gradient in the direction of its preferred temperature. We do not specify whether the fish acts this way because it actually can perceive temperature gradients or because its klinokinetic activity increases as it moves into less preferrable temperature ranges. On the scale length we are dealing with (meters vertically and kilometers horizontally), the precise mechanisms of motion on the small scale may be unimportant. We also assume that the fish will move away from dissolved oxygen levels below that which is the minimum tolerable, and that they will have a general tendency to move toward areas of greater available food and more favorable habitat. These several influences can either reinforce each other or, to some extent, cancel each other under particular circumstances. Aside from these basic assumptions, the model is very general and can be parameterized to suit a variety of situations.

The present model is offered not as a description of the way fish behave, but as a device by which a variety of hypothetical descriptions of locomotor behavior can be tested. A few examples are given to illustrate the way in which the model is used. More thorough exploration of the model will be undertaken later, in combination with field studies.

GENERAL DESCRIPTION OF THE MODEL

The intent of this model is to predict the average spatial distribution of a fish population in a closed body of water. To do this we simulate the movements of individual fish, allowing a large number of fish to start from random positions in the body of water, and to move for a certain period of time. We assume that a small number of factors influence the movements of the fish; temperature, dissolved oxygen, food availability and habitat preference.

The model is designed to apply to a two-dimensional representation of a hypothetical reservoir (Fig. 1). The two dimensions are depth and either length along the reservoir or width across a cross section. A three-dimensional representation would be preferable, but would pose

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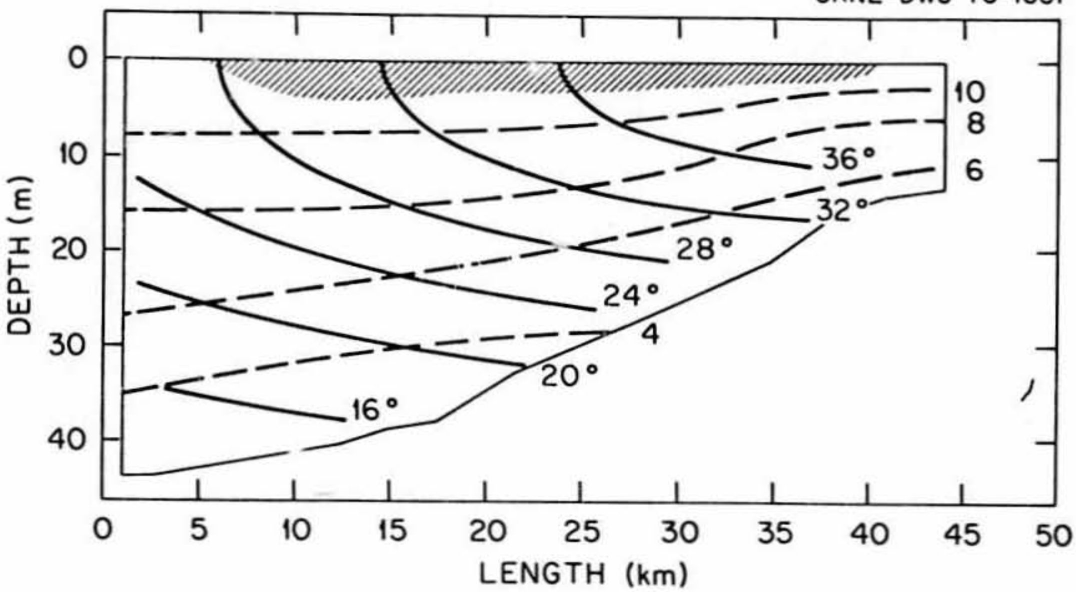

Fig. 1. A hypothetical reservoir. The vertical dimension is depth in meters (disproportionately scaled), and the horizontal dimension is length along the reservoir in kilometers, with the downstream dam at the left. Isotherms in degrees Centrigrade (solid lines) and dissolved oxygen isobars in parts per thousand (dotted lines) are sketched in. The shaded region denotes high food availability. A power plant is assumed located at the upstream end of the reservoir.

problems both computationally and graphically. It is hoped that this model will eventually be extended to three dimensions, but the present two-dimensional model is useful. Note that the scaling in the vertical (depth) dimension is greatly exaggerated relative to the horizontal coordinate. Typical temperature and dissolved oxygen isoclines are sketched in, and the area in which food availability is greatest (usually the shallow water along shore lines) is shaded. We assume that the position of those factors are stable over the time scale in which a fish can move considerable distances. A typical fish will have a preferred range of temperatures, will tend to avoid very low levels of dissolved oxygen, will be attracted by high food availability, and will prefer habitats that give it sufficient cover from predators. On this basis, the average distribution of a model fish population may be reliably predicted, though the path of a given fish is unique.

For modeling purposes, it is necessary to represent the two-dimensional space by a grid of points. Consider a fish located at some point (i,j) in the grid points (Fig. 2). The fish can move to one of eight adjacent points $(i+\delta, j+\varepsilon)$, where δ and ε take on the values -1, 0 and +1 (but both cannot be 0 simultaneously). It is assumed that the following factors influence the next location of the fish:

1. The tendency of the fish to continue moving in the general direction in which it is already moving. This can be termed the "forward inertia" of motion.
2. The preferred temperature of the fish and the temperature at the present location of the fish, (i,j), and the eight surrounding points.
3. The location of food supplies and cover.
4. The boundary of the water body, which sets limits on the motion of the fish.

These factors can be elucidated to some extent by examination of Fig. 3. Assume the fish is located at point (i,j) and has just moved from the point (i,j-1). The black points in this figure are those in the body of water while the white dots are above its surface. The isotherm of the preferred temperature is represented by black dots

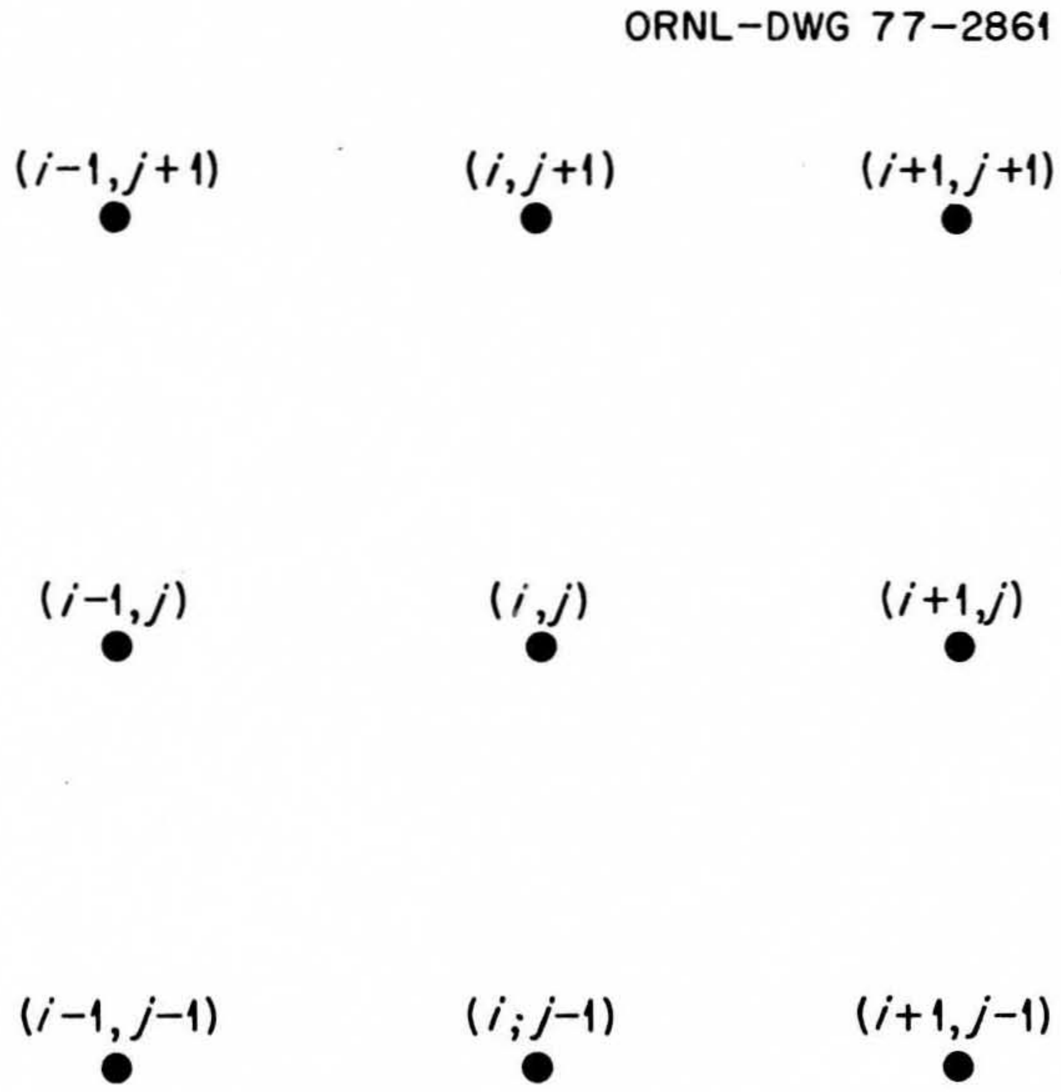

Fig. 2. The point (i,j) in a grid of points, with the adjacent points to which the fish can move in one step.

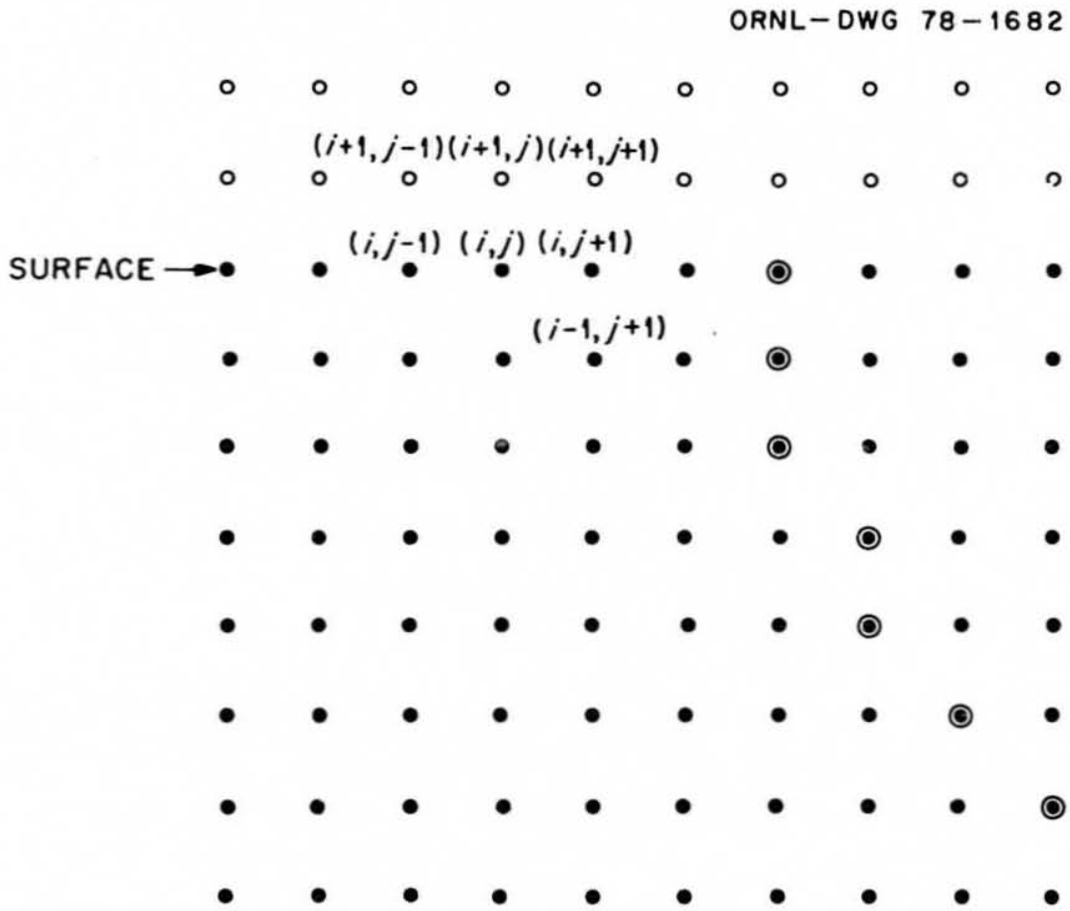

Fig. 3. A grid of points representing a portion of the reservoir. The shaded circles are water, while the open circles are above the water surface. The shaded circles surrounded by larger circles represent points along the preferred temperature isotherms.

surrounded by a circle. The most likely next "step" of the fish is to the point (i,j+1), since this is in its direction of preferred temperature as well as its direction of inertia. The fish also has a high probability of moving to point (i-1,j+1). Of course, the fish cannot move to points (i+1,j-1), (i+1,j), or (i+1,j+1) because these lie above the surface of the water.

It is conceptually and mathematically advantageous to discuss fish movements in terms of the four factors listed above, but these factors have not been quantified in detail (except for factor 4; the fish we are dealing with cannot normally leave the water). Data are available on the response of some fish species to temperature and dissolved oxygen variations, but other factors, such as food availability and habitat preferences, complicate the situation in natural bodies of water, making predictions based on mathematical models less reliable.

MATHEMATICAL DESCRIPTION OF THE MODEL

It is convenient to represent the probability of a fish moving one step from a point (i,j) to another (k,m) in a two-dimensional grid as an element of a transition matrix, $P_{ij,km}$. Since the fish can move from one grid point only to an adjacent one in a single step, k and m are constrained as follows:

$$k = i + \delta \quad (\delta = -1,0,+1) \tag{1a}$$

$$m = j + \varepsilon \quad (\varepsilon = -1,0,+1), \tag{1b}$$

(see Fig. 1). In all future discussion, k and m will be implicitly subject to the limitations (1a,1b).

The sum over all probabilities for direction of motion must equal unity:

$$\sum_{k=i-1}^{i+1} \sum_{m=j-1}^{j+1} P_{ij,km} = 1.0 \tag{2}$$

The model is event-oriented, where an event is a step in space. This means that, given a fish initially at point (i,j), the next moment of interest occurs only when the fish has moved to an adjacent grid point. Therefore, the probability of the fish being in its same position at the next locomotory event in the model is identically zero, or

$$P_{ij,ij} = 0.0. \tag{3}$$

All of the transition elements together define a transition matrix, $\underline{P}$. Let $\underline{X}(1)$ be the probability vector for the position of the fish at a given moment. The elements of $\underline{X}(1)$, which are $x_{ij}(1)$, represent the probabilities of the fish being located at any given point (i,j). The condition

$$\sum_{i=-\infty}^{+\infty} \sum_{j=-\infty}^{+\infty} x_{ij}(1) = 1.0 \tag{4}$$

must hold since the fish must be somewhere in the water body. Then

$$\underline{X}(2) = \sum_{j=m-1}^{m+1} \sum_{i=k-1}^{k+1} x_{ij} P_{ij,km} = \underline{P} \cdot \underline{X}(1) \tag{5}$$

is the probability matrix for the position of the fish after its next movement to a new grid point.

If the movement of the fish from one grid point to the next is purely random (i.e., "random walk"), then

$$P_{ij,km} = 1.0/8.0 = 0.125 \; ; \tag{6}$$

that is, there is an equal probability of 0.125 of the fish going to any of the eight adjacent points. However, the motion of the fish is biased by its forward inertia, temperature and dissolved oxygen gradients, the location of food and favored habitat, and boundaries of the body of water.

Consider first only the influence of forward inertia. It introduces a directional bias on top of random motion. The transition probability can be written

$$P_{ij,km} = \{1.0 + I(k,m)\} \,/\xi \; , \tag{7}$$

where ξ is the normalization factor,

$$\xi = \sum_{k=i-1}^{i+1} \sum_{m=j-1}^{j+1} P'_{ij,km} \; , \tag{8}$$

and

$$P'_{ij,ij} = 0.0 \tag{9a}$$

$$P_{ij,km} = 1.0 + I(k,m) \qquad (m \neq j, \text{ if } k = i) \; . \tag{9b}$$

The term $I(k,m)$ is a measure of the strength of forward inertia relative to random effects in determining the next grid point in the fish's course of movement. If $I(k,m) \ll 1.0$, then the random effects dominate the movement. On the other hand, if, say, $I(i+1,j+1) \gg 1.0$ and $I(i+1,j+1) \gg I(k,m)$ for all seven other pertinent values of k and m, then the fish is likely to move upward and to the right on its next step. The magnitude of $I(k,m)$ for particular values of k and m depends on the past motion of the fish. For this reason, $\underline{P}$ is not a Markov process matrix.

In a similar manner, the effects of temperature and dissolved oxygen can be incorporated into this mathematical scheme. If $T(k,m)$, $DO(k,m)$, $F(k,m)$ and $H(k,m)$ represent the strengths with which temperature gradients, dissolved oxygen gradients and gradients in distribution of food availability and habitat desirability, respectively, then one can write

$$p_{ij,km} = \{1.0 + I(k,m) + T(k,m) + DO(k,m) + F(k,m) + H(k,m)\} / \xi \qquad (10)$$

where ξ is defined by Eq. (8) and now

$$p'_{ij,km} = 1.0 + I(k,m) + T(k,m) + DO(k,m) + F(k,m) + H(k,m) \; . \qquad (11)$$

The effects of the boundary of the body of water on fish movement is incorporated as follows. Define $B(k,m)$ as the boundary factor, and now write $p_{ij,km}$ as

$$p_{ij,km} = \{1.0 + I(k,m) + T(k,m) + DO(k,m) + F(k,m) + H(k,m)\} B(k,m)/ \xi, \qquad (12)$$

where ξ is defined by Eq. (8) and now

$$p'_{ij,km} = \{1.0 + I(k,m) + T(k,m) + DO(k,m) + F(k,m) + H(k,m)\} B(k,m), \qquad (13)$$

where

$$B(k,m) = \begin{cases} 1, & (k,m) \text{ in the body of water} \\ 0, & (k,m) \text{ outside the body of water} \end{cases} \tag{14}$$

It is now appropriate to discuss the detailed formulations of I(k,m), T(k,m), D)(k,m), F(k,m) and H(k,m). These are developed in as simple and practical a manner as possible in the absence of definitive field measurements. Subsequent studies may require alterations of these formulations.

<u>Inertia of forward movement, I(k,m)</u>

Assume the fish is at point (i,j) and its preceding location was (i',j'), where

$$i = i' + \delta' \tag{15a}$$

$$j = j' + \varepsilon' , \tag{15b}$$

and where δ' and ε' have the same ranges of values as δ and ε [see Eqs. (1a,1b)]. Then I(k,m), where k and m are given by Eqs. (1a,1b), is a conditional probability,

$$I(k,m) = \text{Probability } (\delta, \varepsilon \text{ given } \delta', \varepsilon'), \tag{16}$$

where this probability is higher the more positive the correlation between (δ,ε) and (δ',ε'). In the model, a quantity, C, is defined, where,

$$C = |\delta-\delta'| + |\varepsilon-\varepsilon'|. \tag{17}$$

The bars represent absolute values of the enclosed differences. The quantity C can take on one of five different integer values, for each of which I(k,m) is assigned a different value, e_i, as represented in Eq.(18),

$$I(k,m) = \begin{cases} e_1 & (C = 0) \\ e_2 & (C = 1) \\ e_3 & (C = 2) \\ e_4 & (C = 3) \\ e_5 & (C = 4), \end{cases} \tag{18}$$

where the constants e_i are chosen so that $e_1 > e_2 > e_3 > e_4 > e_5$. The model fish is likely to continue in the same general direction because I(k,m) is greatest when $\delta = \delta'$ and $\varepsilon = \varepsilon'$.

Temperature term, T(k,m)

Assume the fish has a preferred temperature, $TEMP_p$. The temperature at point (i,j) is defined as TEMP(i,j). Define the absolute difference between the temperature at (i,j) and the optimal temperature by $d_T(i,j) = |TEMP(i,j) - TEMP_p|$. Then, if (k,m) is a neighboring point of (i,j), we define the temperature effect, T(k,m), by

$$T(k,m) = \begin{cases} s_T > 0.0 & d_T(k,m) < d_T(i,j) \\ 0.0 & d_T(k,m) > d_T(i,j). \end{cases} \tag{19}$$

The quantitative value of the constant s_T is assigned to reflect the strength of the effect of the temperature gradient on the fish. Estimates of values might be obtained from experiments in which only temperature effects are present.

Dissolved oxygen term, DO(k,m)

We have no information on the existence of a "preferred" DO level, but there is evidence on minimum tolerable levels. Define by $DISOX_{min}$ the minimum tolerable level and by DISOX(i,j) the dissolved oxygen at point (i,j). Then if the fish is in a spatial region in which the dissolved oxygen is below the minimum tolerable limit, (i.e., $DISOX(i,j) < DISOX_{min}$), then define the dissolved oxygen effect, DO(k,m), by

$$DO(k,m) = \begin{cases} s_{DO} > 0.0 & DISOX(k,m) > DISOX(i,j) \\ 0.0 & DISOX(k,m) < DISOX(i,j). \end{cases} \tag{20}$$

If the fish is in a region in which the amount of dissolved oxygen in the water is above the minimum tolerable limit, then DO(k,m) = 0 for all values of k and m. The constant S_{DO} is a measure of the strength of avoidance by fish of low dissolved oxygen levels.

Food availability terms, $F_q(k,m)$

Assume that there are q regions in the body of water that are attractive to fish because of high food availability. We assume that the closest of these to the current position of the fish will exert some attraction on the fish. Define by $d_{F,q}(i,j)$ the level of food availability at point (i,j). Then if (k,m) is a point neighboring (i,j), the force of attraction of the food is

$$F_q(k,m) = \begin{cases} s_{F,q} > 0.0 & d_{F,q}(k,m) < d_{F,q}(i,j) \\ 0.0 & d_{F,q}(k,m) > d_{F,q}(i,j). \end{cases} \tag{21}$$

Habitat preference terms, $H_q(k,m)$

Assume that there are $\bar{P}$ regions in the body of water that are attractive to fish because of their favorability as habitat. We assume that the closest of these to the current position of the fish will exert some attraction on the fish. Define by $d_{H,p}(i,j)$ the level of habitat favorability at point (i,j). Then if (k,m) is a point neighboring (i,j), the force of attraction of habitat is

$$H_p(k,m) = \begin{cases} s_{H,p} > 0.0 & d_{H,p}(k,m) < d_{H,p}(i,j) \\ \\ 0.0 & d_{H,p}(k,m) > d_{H,p}(i,j). \end{cases} \tag{22}$$

COMPUTER PROGRAM

The computer program consists of a MAIN PROGRAM and three subroutines, SUBROUTINE RANSET, FUNCTION URAND, SUBROUTINE PLOTT and SUBROUTINE HIST.

The MAIN PROGRAM first reads in the input data, which is described in Part A below, and then prints it out (see Part B, below). There are two ways in which data on temperature and dissolved oxygen can be entered; either by specifying each grid point values, or by using mathematical functions to express their spatial variation. As an example of the latter, temperature might be given by the function

$$\text{TEMP} = 40000./\{10000. + (i-85.)^2 + 5.0(j-55.)^2\} , \tag{23}$$

which leads to the isotherms shown in Fig. 1. Similar functions are used for dissolved oxygen. Food distribution might be modeled by functions of the form

$$\text{FOOD}_q = F_D /(1.0 + 1.0 \exp\{-\alpha_{Fq}(i-I_{Fq})^2 - \beta_{Fq}(j-J_{Fq})^2\}) , \tag{24}$$

which are plotted in Fig. 4. The peaks and plateaus in this figure represent regions of high food availability. Similar functions are used to describe habitat preferences.

In the input data, the user specifies how many fish are released at random locations in the body of water and how many spatial steps they are allowed to take. The user also chooses whether or not the paths of the fish are to be plotted. If they are not, only the final positions of the fish will be shown by a dot. The user can also have the computer print out the isotherms, if desired.

The program first randomly selects, using a pseudo-random number generator, the position and direction of motion of the fish. Thereafter, the movement of the fish from point to point on the grid is determined by the pseudo-random number generator, in combination with the transition probabilities, $p_{ij,km}$, which are computed at each step.

Information on the paths and final positions of the fish is stored for later printing.

The only purpose of SUBROUTINE RANSET and FUNCTION URAND is to generate pseudo-random numbers on the interval (0,1). These subroutines have been described elsewhere (McGarth and Irving, 1975) and so will not be discussed here. The type of simulation that uses a pseudo-random number generator is commonly referred to as a Monte Carlo simulation. SUBROUTINE PLOTT handles the plotting of the outline of the body of water, while SUBROUTINE HIST plots a histogram of the final temperature distribution of the fish.

The computer program is meant to be very general. If changes in the program are necessary, however, the documentation of the program below should be complete enough to enable the user to make these changes.

The remainder of this section consists of a description of the data input cards (Part A), the printed output of the program (Part B), and a listing of the computer program (Part C). In the next section, the use of the program is demonstrated by means of some trial simulations.

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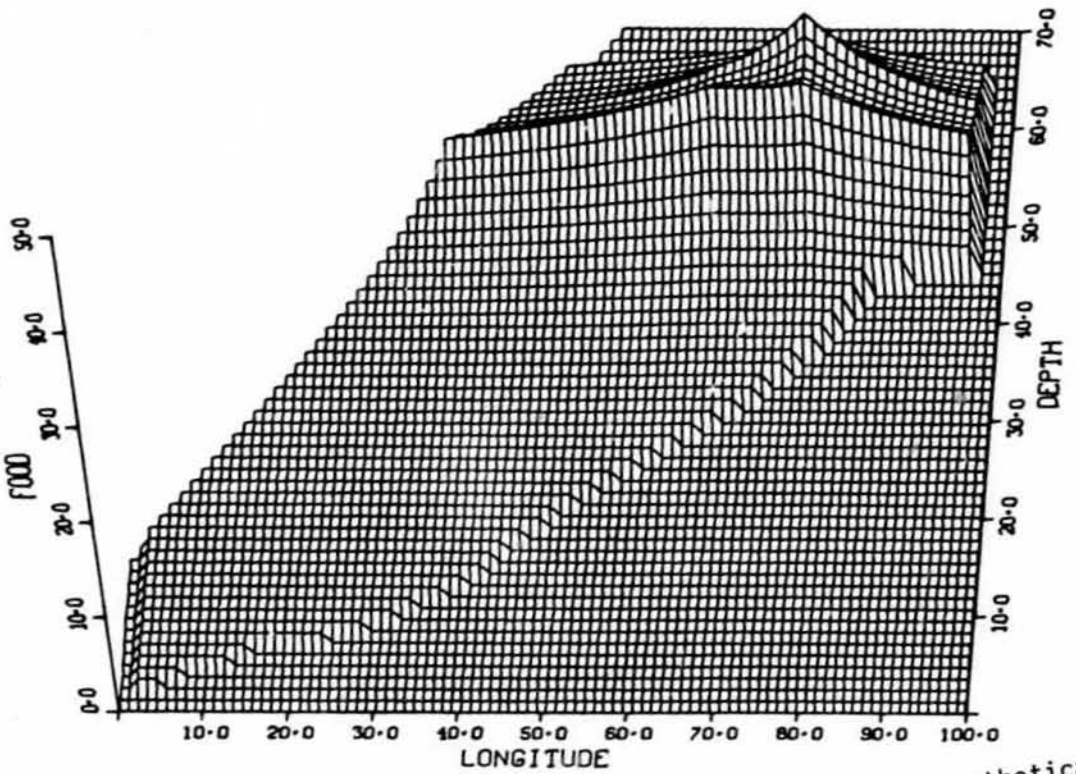

Fig. 4. A plot of food availability to fish in a hypothetical reservoir. The peaks and plateaus represent the regions of high food availability.

Part A. Input Cards

Figure 5 is a listing of the input cards relevant to an example given in the next section. These input cards are described below:

Card A

Input parameters: NHOR, NVER, NREG

Format: 4I5

NHOR = number of horizontal grid points

NVER = number of vertical grid points

NREG = number of environmental regions (usually there will be only two; (1) the body of water, and (2) the surrounding air and land

Card B

Input parameters: NREGP

Format: I5

NREGP = the number of points on the line to be drawn to define the boundary of the body of water

Card Set C

Input parameters: (ARRAYX(I), I=1,NREGP)

Format: 7E10.0

ARRAYX(I) = the horizontal coordinates of points on the line defining the boundary of the body of water

Card Set D

Input parameters: (ARRAYY(I), I=1,NREGP)

Format: 7E10.0

ARRAYY(I) = the vertical coordinates of points on the line defining the boundary of the body of water

Card Set E

Input parameters: NVER cards containing the information IREG, (IBEG(I), IEND(I), TYPE(I), I=1,IREG)

Format: I2, 8X, 6(2I2,F5.1,1X)

```
   90    60     2                                                              A
   17                                                                          B
   2.0.       5.0       10.0       15.0       20.0       25.0       30.0       C
   35.0       43.0      55.0       70.0       77.0       82.0       88.0       C
   88.0       2.0       2.0                                                    C
   3.0        3.0       4.0        5.0        6.0        7.0        9.0        D
   10.0       16.0      22.0       30.0       36.0       38.0       39.0       D
   55.0       55.0      3.0                                                    D
 1        0190  1.0                                                            E
 1        0190  1.0                                                            E
 3        0102  1.0 0305  3.0 0690  1.0                                        E
 3        0102  1.0 0307  3.0 0890  1.0                                        E
 3        0102  1.0 0312  3.0 1390  1.0                                        E
 3        0102  1.0 0314  3.0 1590  1.0                                        E
 3        0102  1.0 0322  3.0 2390  1.0                                        E
 3        0102  1.0 0326  3.0 2790  1.0                                        E
 3        0102  1.0 0329  3.0 3090  1.0                                        E
 3        0102  1.0 0331  3.0 3290  1.0                                        E
 3        0102  1.0 0334  3.0 3590  1.0                                        E
 3        0102  1.0 0336  3.0 3790  1.0                                        E
 3        0102  1.0 0338  3.0 3990  1.0                                        E
 3        0102  1.0 0339  3.0 4090  1.0                                        E
 3        0102  1.0 0340  3.0 4190  1.0                                        E
 3        0102  1.0 0342  3.0 4390  1.0                                        E
 3        0102  1.0 0344  3.0 4590  1.0                                        E
 3        0102  1.0 0345  3.0 4690  1.0                                        E
 3        0102  1.0 0347  3.0 4890  1.0                                        E
 3        0102  1.0 0349  3.0 5090  1.0                                        E
 3        0102  1.0 0351  3.0 5290  1.0                                        E
 3        0102  1.0 0353  3.0 5490  1.0                                        E
 3        0102  1.0 0355  3.0 5690  1.0                                        E
 3        0102  1.0 0357  3.0 5890  1.0                                        E
 3        0102  1.0 0359  3.0 6090  1.0                                        E
 3        0102  1.0 0361  3.0 6290  1.0                                        E
 3        0102  1.0 0363  3.0 6490  1.0                                        E
 3        0102  1.0 0365  3.0 6690  1.0                                        E
 3        0102  1.0 0366  3.0 6790  1.0                                        E
 3        0102  1.0 0368  3.0 6990  1.0                                        E
 3        0102  1.0 0369  3.0 7090  1.0                                        E
 3        0102  1.0 0371  3.0 7290  1.0                                        E
 3        0102  1.0 0372  3.0 7390  1.0                                        E
 3        0102  1.0 0373  3.0 7490  1.0                                        E
 3        0102  1.0 0374  3.0 7590  1.0                                        E
 3        0102  1.0 0375  3.0 7690  1.0                                        E
 3        0102  1.0 0376  3.0 7790  1.0                                        E
 3        0102  1.0 0380  3.0 8190  1.0                                        E
 3        0102  1.0 0387  3.0 8890  1.0                                        E
 3        0102  1.0 0387  3.0 8890  1.0                                        E
 3        0102  1.0 0387  3.0 8890  1.0                                        E
 3        0102  1.0 0387  3.0 8890  1.0                                        E
 3        0102  1.0 0387  3.0 8890  1.0                                        E
 3        0102  1.0 0387  3.0 8890  1.0                                        E
 3        0102  1.0 0387  3.0 8890  1.0                                        E
 3        0102  1.0 0387  3.0 8890  1.0                                        E
 3        0102  1.0 0387  3.0 8890  1.0                                        E
 3        0102  1.0 0387  3.0 8890  1.0                                        E
 3        0102  1.0 0387  3.0 8890  1.0                                        E
 3        0102  1.0 0387  3.0 8890  1.0                                        E
 3        0102  1.0 0387  3.0 8890  1.0                                        E
 3        0102  1.0 0387  3.0 8890  1.0                                        E
 3        0102  1.0 0387  3.0 8890  1.0                                        E
 3        0102  1.0 0387  3.0 8890  1.0                                        E
 3        0102  1.0 0387  3.0 8890  1.0                                        E
 1        0190  1.0                                                            E
 1        0190  1.0                                                            E
 1        0190  1.0                                                            E
 1        0190  1.0                                                            E
 1        0190  1.0                                                            E
    0    0                                                                     F
   29.0      1.0                                                               I
   2.0       0.0                                                               J
    0                                                                          K
   0.0                                                                         L
    0                                                                          N
   0.0                                                                         O
   0.001     0.001      10.                                                    Q
   0.1       0.1        0.1                                                    R
98765                                                                          S
  500  200                                                                     T
    0    1                                                                     U
   16.       44.        4.0                                                    V
    2  200                                                                     T
    1    1                                                                     T
```

Fig. 5. Input data for a sample trial simulation as it appears on the data cards.

IREG = number of different environmental types along a given line of grid points

IBEG(I) = the horizontal coordinate of the first grid point of a particular environmental type along a given horizontal line

IEND(I) = The horizontal coordinate of the last grid point of a particular environmental type along a given horizontal line

TYPE(I) = a numerical label attached to each environmental type to distinguish if from others

Card F

Input parameters: ITEM, IDISOX

Format: 2I5

ITEM = 0 if spatial temperature data is given by an equation in the program

= 1 of spatial temperature data is read in point by point

IDISOX = 0 if spatial dissolved oxygen is given by an equation in the program

= 1 if spatial dissolved oxygen data is read in point by point

Card Set G (included only if ITEM = 1)

Input parameters: (TEMPA(I,J), I=1,NHOR), J=1,NVER

Format: 7E10.0

TEMPA(I,J) = temperature at grid point (I,J)

Card Set H (included only if IDISOX = 1)

Input parameters: (DISOX(I,J), I=1,NHOR), J=1,NVER

Format: 7E10.0

DISOX(I,J) = dissolved oxygen level at grid point (I,J)

Card I

Input parameters: TEMPRF, TEMFOR

Format: 2E10.0

TEMPFR = preferred temperature of fish

TEMFOR = force of attraction of preferred temperature of fish

Card J

Input parameters: DOXMIN, DOXFOR

Format: 2E10.0

DOXMIN = minimum tolerable dissolved oxygen level for fish

DOXFOR = attractive force of higher dissolved oxygen levels on fish

Card K

Input parameter: NFOOD

Format: I5

NFOOD = number of centers of high food availability

Card L

Input parameter: FDATCT

Format: E10.0

FDATCT = force of attraction of food availability on fish movements

Card Set M

Input parameters: FDNUM(I), FDALP(I), FDBET(I), FDIQ(I), FDJQ(I)

Format: 5E10.0

FDNUM(I)
FDALP(I) parameters describing spatial distributions of
FDBET(I) = food about each of the centers of food
FDIQ(I) availability (see Eq. 24 and Table 1)
FDJQ(I)

Card N

Input parameter: NHAB

Format: I5

NHAB = number of centers of high habitat favorability

Card O

Input parameter: HBATCT

Format: E10.0

HBATCT = force of attraction of habitat favorability on fish movements

Card Set P

Input parameters: HBNUM(I), HBALP(I), HBBET(I), HBIQ(I), HBJQ(I)

Format: 5E10.0

HBNUM(I)	
HBALP(I)	parameters describing the spatial distribution
HBBET(I) =	of habitat favorability about the high habitat
HBIQ(I)	favorability centers (analogous to Eq. (24); also
HBJQ(I)	see Table 1 for definitions)

Card Set Q

Input parameters: RES(I), I=1,NREG

Format: 7E10.0

RES(I) = boundary crossing factors (causing fish to remain in the body of water)

Card R

Input parameters: ERTIA(I), I=1,5

Format: 5E10.0

ERTIA(I) = Inertia of forward motion, e_i (see Eq. 18)

Card S

Input parameter: IX

Format: I5

IX = pseudo-random number generator initilization or "seed". It must be an odd integer. A different value of IX should be used each time the program is run .

Card T

Input parameters: NFISH, NSTEP

Format: 2I5

NFISH = number of fish considered in the body of water

NSTEP = number of steps in space each fish is allowed to take

Card U

Input parameters: IPLOT, ISOTH

Format: 2I5

IPLOT = 1 if the fish paths are to be plotted, 0 otherwise

ISOTH = 1 if the isotherms are to be plotted, 0 otherwise

Card V

Input parameters: TEML, TEMH, TEMINT

Format: 3E10.0

TEML = minimum isotherm to be plotted

TEMH = maximum isotherm to be plotted

TEMINT = width of intervals between isotherms

Part B. Output

The printed output consists of two parts. First, the input data is printed out (Fig. 6). Second, a schemata of the body of water is plotted, into which fish paths or spatial population distribution are plotted (Figs. 7 and 8). The plotting is done using the DISSPLA graphics package (Integrated Software Systems Corporation 1970) which is available at many computer installations. Programming changes would be necessary to adapt the program to other graphics packages.

Part C. Computer program details

The complete computer program listing is printed in the Appendix. The comment cards interspersed through the program should enable the user to understand its general design. However, some additional comments may be useful.

1. The arrays are dimensioned to permit a maximum of 90x60 grid points at present. This can be changed if desired.
2. A typical run dispersing 500 fish takes about 3 minutes of CPU time in the IBM 360/91 computer, although this changes to some extent as some of the model parameters are varied. The GO step uses less than 230K of computer core.

```
FISH MOVEMENT IN A BODY CF WATEP

NUMBER OF HORIZONTAL GRID POINTS, NHOR =     90
NUMBER OF VERTICAL GRID POINTS, NVER =    60
NUMBER OF ENVIRONMENTAL REGIONS, NREG =     2

TEMPERATURE IS DESCRIBED BY A MATHEMATICAL FUNCTION

DISSOLVED OXYGEN AMOUNTS DESCRIBED BY A MATHEMATICAL FUNCTION

PREFERRED TEMPERATURE, TEMPRF =    29.0000
FORCE OF ATTRACTION OF PREFERRED TEMPERATURE, TEMFOR =     1.0000

MINIMUM TOLERABLE DISSOLVED OXYGEN LEVEL, DOXMIN =     2.0000
FORCE OF ATTRACTION OF HIGHER DISSOLVED OXYGEN LEVELS =     0.0

FORCE OF ATTRACTION OF GREATER FOOD AVAILABILITY, FDATCT =     0.0
NFOOD =     0


FORCE OF ATTRACTION OF HABITAT PREFERENCES, HBATCT =     0.0
NHAB =     0


BOUNDARY CROSSING FACTORS, RES(I) =     0.001      0.001

VALUES OF FORWARD INERTIA, ERTIA =  0.10   0.10   0.10   0.0    0.0

RANDOM NUMBER INITIATOR, IX = 98765

NUMBER OF FISH IN BODY OF WATER, NFISH =    500
NUMBER OF STEPS EACH FISH IS ALLOWED TO TAKE, NSTEPS =   200

ISOTHERMS ARE PLOTTED

MINIMUM ISOTHERM PLOTTED, TEML =    16.0000
MAXIMUM ISOTHERM PLOTTED, TEMH =    44.0000
DISTANCE BETWEEN ISOTHERMS, TEMINT =    4.0000
```

Fig. 6. Input data for a sample trial simulation as it is printed out by the computer program.

ORNL-DWG 78-2643

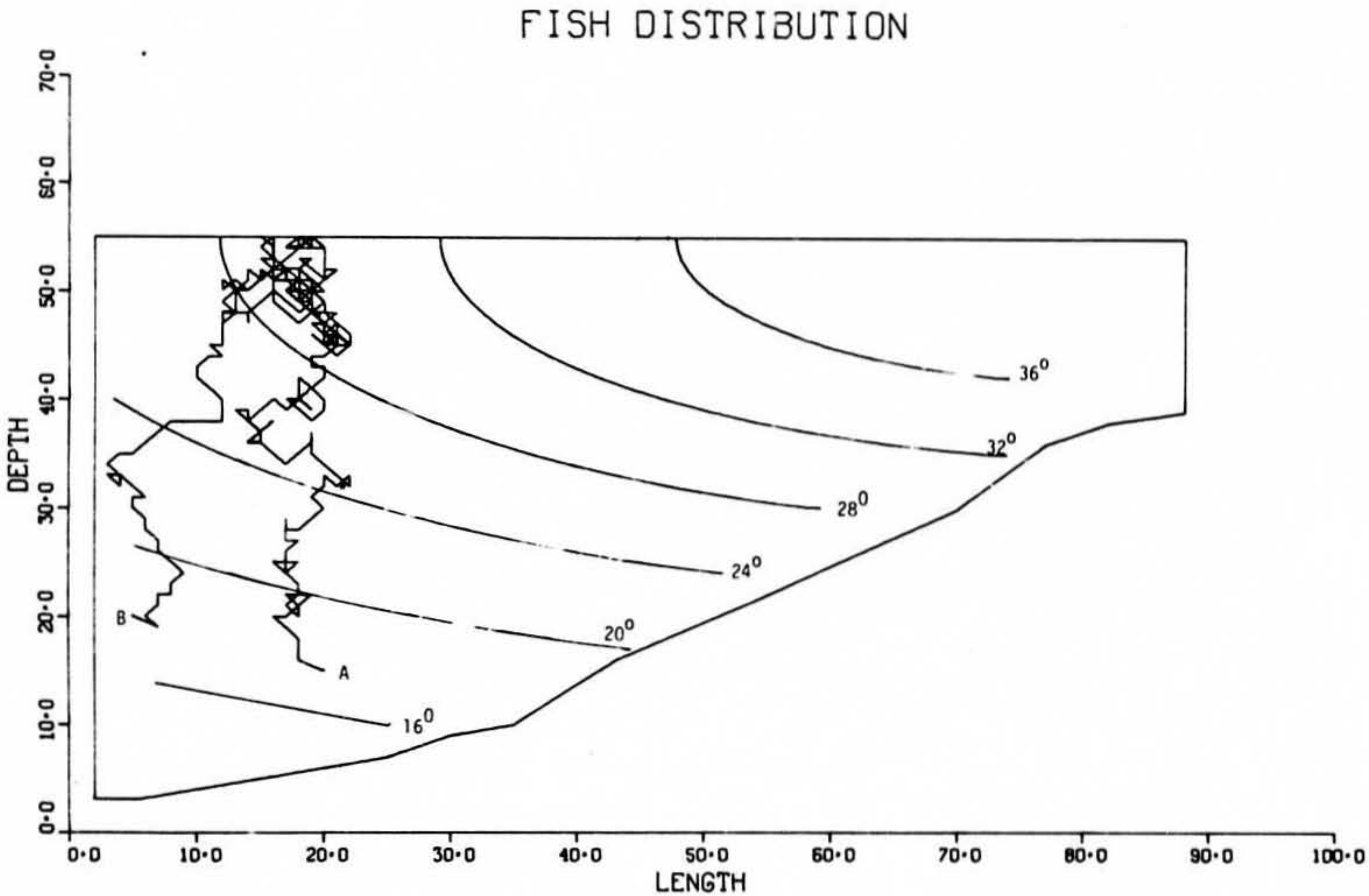

Fig. 7. Plot of simulated motions of two fish initially placed at points A and B. The assumed preferred temperature is $TEMP_p$ = 29.0°C and the force of temperature attraction, p_T, is 1.0 for case A and 50.0 for case B.

ORNL-DWG 78-2646

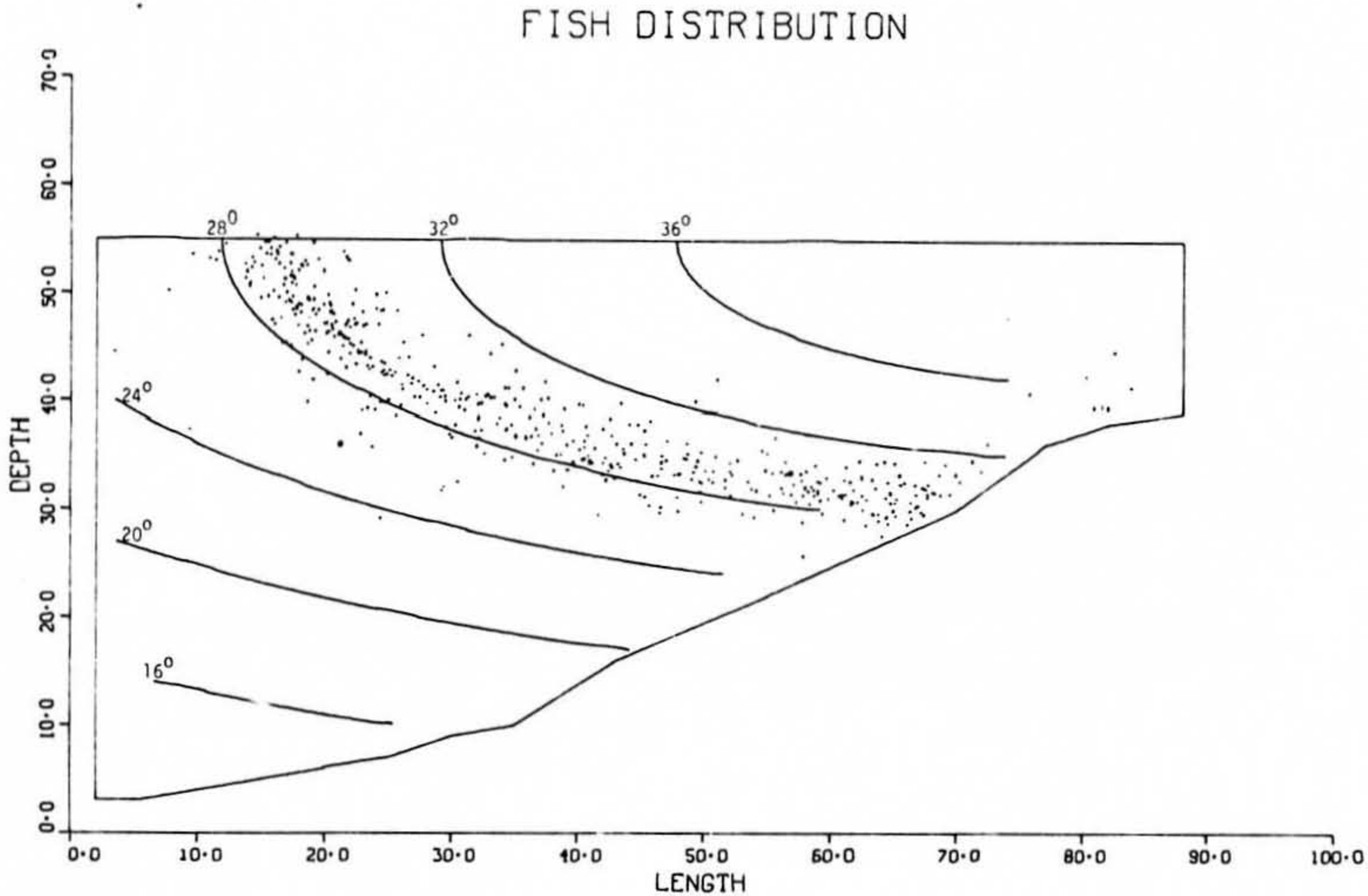

Fig. 8. The distribution of 500 fish influenced only by temperature in the reservoir after 200 steps. The assumed preferred temperature is 29.0°C. Other parameters of the model are given in Table 2.

Table 1 is a compilation of the principal FORTRAN variables in the computer program. The equivalent mathematical symbols, of any, and definitions are given as well.

TRIAL SIMULATIONS

The fundamental question that must be asked of this model is how accurately it can simulate the movements of individual fish and the spatial distribution patterns of populations of fish. There is not enough data on either of these phenomena in natural environments to allow parameters for a model to be thoroughly tested. However, laboratory experiments provide some data on fish distributions in environments in which only thermal effects are important. We shall focus on the thermal influences on the fish in our model and only briefly note how the other factors influence fish distributions in space.

Fish Movements

Consider the reservoir pictured in Fig. 7, with only the temperature gradient assumed to have an effect on the fish. The temperature isoclines are given by Eq. (23) and the remaining parameters of the model are given in Table 2. A simulated fish is placed in the reservoir at the position A; it moves, with a fair amount of meandering, toward the preferred temperature, $TEMP_p = 29.0°C$. The amount of meandering can be decreased by increasing the force of the temperature gradient on the fish movement; that is, by increasing p_T. When p_T is increased from $p_T = 1.0$ to $p_T = 50.$, and a fish is released at point B, it moves more directly toward the preferred temperature.

Fish Distribution Patterns

Allow 500 fish to be released at randomly selected initial positions in the body of water, and to move in response to temperature gradients only. After 200 steps, they have all had a chance to respond

Table 1. Principal program variables

Fortran variable name	Dimension (if array)	Mathematical symbol	Definition
ARAX	(50)		Storage array for horizontal coordinates of isotherm curves for later plotting
ARAY	(50)		Storage array for vertical coordinates of isotherm curves for later plotting
ARRAYX	(50)		Storage array for horizontal coordinates of outline of body of water
ARRAYY	(50)		Storage array for vertical coordinates of outline of body of water
D			Random number chosen from uniform distribution on the interval (0,1)
DDIFF			Difference between the dissolved oxygen level at the current position of the fish and its minimum tolerable dissolved oxygen level
DDIFFA			Difference between dissolved oxygen level of any of the next eight possible positions of the fish and its minimum tolerable dissolved oxygen level
DDR	(3,3)	I(k,m)	Measure of the strength of the inertia of forward movement of the fish
DIR	(3,3)	DO(k,m)	Attraction of point (k,m) on fish because of the difference in the dissolved oxygen level from that of the current location of the fish
DISOX	(100)	DISOX(k,m)	Storage array for dissolved oxygen levels along some given horizontal line, k
DOX		DISOX(i,j)	Level of dissolved osygen at the current position of the fish

Table 1. (continued)

Fortran variable name	Dimension (if array)	Mathematical symbol	Definition
DOXFOR		s_{DO}	Attractive force of higher dissolved oxygen level on fish movements
DOXMIN		$DISOX_{min}$	Minimum tolerable dissolved oxygen level for fish
ERTIA	(5)	e_i	Strength of forward inertia of fish
FDALP	(20)	α_{Fq}	Parameter describing the spatial distribution of food about each of the centers of food availability (see Eq. 24)
FDATCT		$s_{F,q}$	Force of attraction of food availability on fish movements
FDBET	(20)	β_{Fq}	Parameter describing the spatial distribution of food about each of the centers of food availability (see Eq. 24)
FDIQ	(20)	I_{Fq}	Parameter (horizontal coordinate) describing the spatial distribution of food about each of the centers of food availability (see Eq. 24)
FDJQ	(20)	J_{Fq}	Same as above definition (vertical coordinate)
FDNUM	(20)	F_D	Parameter describing the spatial distribution of favorable habitat about each of the centers of food availability (see Eq. 24)
FDR	(3,3)	$F_Q(k,m)$	Attraction of point (k,m) on fish because of the difference in food availability from the current location (i,j)
FOOD			Measure of the amount of food available to the fish at its current location
FOODA			Measure of the amount of food available to fish in its possible next location

Table 1. (continued)

Fortran variable name	Dimension (if array)	Mathematical symbol	Definition
GRID	(90,60)		Array that stores information on the type of region each grid point is in, as well as its temperature and dissolved oxygen level
HAB			Measure of the favorability of habitat at the current location of the fish
HABA			Measure of the favorability of habitat at the possible next location of the fish
HABALP	(20)	α_{Hq}	Parameter describing the spatial distribution of favorable habitat about each of the centers of favorable habitat (in equation analogous to Eq. 24)
HBATCT		$s_{H,q}$	Force of attraction of habit favorability on fish movements
HBBET	(20)	$\beta_{H,q}$	Parameters describing the spatial distribution of favorable habitat about each of the centers of favorable habitat (in equation analogous to Eq. 24)
HBIQ	(20)	$I_{H,q}$	Center of a region of favorable habitat (horizontal coordinate)
HBJQ	(20)	$J_{H,q}$	Center of a region of favorable habitat (vertical coordinate)
HBNUM	(20)	H_D	Parameters describing the spatial distribution of favorable habitat about each of the centers of favorable habitat (in equation analogous to Eq. 24)
IDISOX			Logical variable specifying whether dissolved oxygen levels are described by a mathematical function (IDISOX=0) or point by point (IDISOX=1)

Table 1. (continued)

Fortran variable name	Dimension (if array)	Mathematical symbol	Definition
IPLOT			Logical variable specifying whether or not fish paths are to be plotted
IPRES			Current position of the fish (horizontal coordinate)
ISOTH			Logical variable specifying whether or not the isotherms are to be plotted
ISTRT			Horizontal coordinate of the starting position of a given fish
ITEM			Logical variable specifying whether temperature is described by a mathematical function (ITEM=0) or by point-by-point data (ITEM=1)
IX			Pseudo-random number generator initiator
JPRES			Current position of the fish (vertical coordinate)
JSTRT			Starting position of the fish (vertical coordinate)
NDIST			Integer variable that increases by 1 for each step a particular fish takes. When NDIST=NSTEPS, no further steps are taken
NFISH			Number of fish simulated in the body of water
NFOOD			Number of centers of food availability
NHAB			Number of centers of high habitat favorability
NHOR			Number of horizontal grid lines
NREG			Number of environmental regions [usually there will be only two; (1) the body of water, and (2) the surrounding air and land]
NSV			Integer variable that increases by 1 for each fish that is "inserted" into the body of water. When NSV = NFISH, no further fish are inserted.

Table 1. (continued)

Fortran variable name	Dimension (if array)	Mathematical symbol	Definition
NSTEPS			Number of steps in space that each fish is allowed to take
NVER			Number of vertical grid lines
RES	(50)	$B(k,m)$	Boundary crossing factors (causing fish to remain in the body of water)
SAVI	(500)		Array that stores horizontal coordinates of fish movement for later plotting
SAVJ	(500)		Array that stores vertical coordinates of fish movement for later plotting
TDIFF		$d_T(i,j)$	Difference between temperature of current position of fish and its preferred temperature
TDIFFA		$d_T(k,m)$	Difference between temperature of possible next position of the fish and its preferred temperature
TDR	(3,3)	$T_q(k,m)$	Attraction of point (k,m) on the fish because of the difference on temperature from its current position
TEMH			Temperature of maximum isotherm to be plotted
TEMINT			Width of intervals between isotherms
TEML			Temperature of minimum isotherm to be plotted
TEMFOR		s_T	Force of attraction of preferred temperature of fish
TEMP			Temperature at current location of fish
TEMPA	(100)	$TEMP(i,j)$	Storage array for temperature data along a given horizontal line, i
TEMPRF		$TEMP_p$	Preferred temperature of the fish
V	(3,3)	$p_{ij,km}$	Transition probability from grid point (i,j) to grid point (k,m)

Table 2. Parameter values for the example in Fig. 5

NHOR = 90 NVER = 60 NREG = 2

NREGP = 17

ARRAYX(I) (I=1,17) = 2.0, 5.0, 10.0, 15.0, 20.0, 25.0, 30.0, 35.0, 43.0, 55.0, 70.0, 77.0, 82.0, 88.0, 2.0, 2.0

ARRAYY(I) (I=1,17) = 3.0, 3.0, 4.0, 5.0, 6.0, 7.0, 9.0, 10.0, 16.0, 22.0, 30.0, 36.0, 38.0, 39.0, 55.0, 55.0, 3.0

IREG	IBEG(1)	IEND(1)	TYPE(1)	IBEG(2)	IEND(2)	TYPE(2)	IBEG(3)	IEND(3)	TYPE(3)
1	01	90	1.0						
1	01	90	1.0						
3	01	02	1.0	03	05	3.0	06	90	1.0
3	01	02	1.0	03	07	3.0	08	90	1.0
3	01	02	1.0	03	12	3.0	13	90	1.0
3	01	02	1.0	03	14	3.0	15	90	1.0
3	01	02	1.0	03	22	3.0	23	90	1.0
3	01	02	1.0	03	26	3.0	27	90	1.0
3	01	02	1.0	03	29	3.0	30	90	1.0
3	01	02	1.0	03	31	3.0	32	90	1.0
3	01	02	1.0	03	34	3.0	35	90	1.0
3	01	02	1.0	03	36	3.0	37	90	1.0
3	01	02	1.0	03	38	3.0	39	90	1.0
3	01	02	1.0	03	39	3.0	40	90	1.0
3	01	02	1.0	03	40	3.0	41	90	1.0
3	01	02	1.0	03	42	3.0	43	90	1.0
3	01	02	1.0	03	44	3.0	45	90	1.0
3	01	02	1.0	03	45	3.0	46	90	1.0
3	01	02	1.0	03	47	3.0	48	90	1.0
3	01	02	1.0	03	49	3.0	50	90	1.0
3	01	02	1.0	03	51	3.0	52	90	1.0
3	01	02	1.0	03	53	3.0	54	90	1.0
3	01	02	1.0	03	55	3.0	56	90	1.0
3	01	02	1.0	03	57	3.0	58	90	1.0

Table 2. (continued)

IREG	IBEG(1)	IEND(1)	TYPE(1)	IBEG(2)	IEND(2)	TYPE(2)	IBEG(3)	IEND(3)	TYPE(3)
3	01	02	1.0	03	59	3.0	60	90	1.0
3	01	02	1.0	03	61	3.0	62	90	1.0
3	01	02	1.0	03	63	3.0	64	90	1.0
3	01	02	1.0	03	65	3.0	66	90	1.0
3	01	02	1.0	03	66	3.0	67	90	1.0
3	01	02	1.0	03	68	3.0	69	90	1.0
3	01	02	1.0	03	69	3.0	70	90	1.0
3	01	02	1.0	03	71	3.0	72	90	1.0
3	01	02	1.0	03	72	3.0	73	90	1.0
3	01	02	1.0	03	73	3.0	74	90	1.0
3	01	02	1.0	03	74	3.0	75	90	1.0
3	01	02	1.0	03	75	3.0	76	90	1.0
3	01	02	1.0	03	76	3.0	77	90	1.0
3	01	02	1.0	03	80	3.0	81	90	1.0
3	01	02	1.0	03	87	3.0	88	90	1.0
3	01	02	1.0	03	87	3.0	88	90	1.0
3	01	02	1.0	03	87	3.0	88	90	1.0
3	01	02	1.0	03	87	3.0	88	90	1.0
3	01	02	1.0	03	87	3.0	88	90	1.0
3	01	02	1.0	03	87	3.0	88	90	1.0
3	01	02	1.0	03	87	3.0	88	90	1.0
3	01	02	1.0	03	87	3.0	88	90	1.0
3	01	02	1.0	03	87	3.0	88	90	1.0
3	01	02	1.0	02	87	3.0	88	90	1.0
3	01	02	1.0	03	87	3.0	88	90	1.0
3	01	02	1.0	03	87	3.0	88	90	1.0
3	01	02	1.0	03	87	3.0	88	90	1.0
3	01	02	1.0	03	87	3.0	88	90	1.0
3	01	02	1.0	03	87	3.0	88	90	1.0
3	01	02	1.0	03	87	3.0	88	90	1.0
3	01	02	1.0	03	87	3.0	88	90	1.0
1	01	90	1.0						
1	01	90	1.0						
1	01	90	1.0						
1	01	90	1.0						
1	01	90	1.0						

Table 2. (continued)

```
ITEM = 0        IDISOX = 0
TEMPA(I,J)  not entered
DISOX(I,J)  not entered
TEMPRF = 29.0          TEMFOR = 1.0
DOXMIN = 2.0           DOXFOR = 0.0
NFOOD = 0              FDATCT = 0.0
FDNUM(I), FDALP(I), FDBET(I), FDIQ(I), FDJQ(I)   not entered
NHAB = 0               HBATCT = 0.0
HBNUM(I), HBALP(I), HBBET(I), HBIQ(I), HBJQ(I)   not entered
RES(I) (I=1,3) = 0.001, 0.001, 10.0
ERTIA(I) (I=1,5) = 0.1, 0.1, 0.1, 0.0, 0.0
IX = 98765
NFISH = 2              NSTEP = 200
IPLOT = 1              ISOTH = 1
TEML = 16.0            TEMH = 44.0          TEMINT = 4.0
```

to the preferred temperature. The distribution of fish after 200 steps is shown in Fig. 8, for parameter values given in Table 2, except that now NFISH = 500 and IPLOT = 0. It is interesting to look at the histogram describing the percent distribution of fish about the preferred temperature of 29.0°C (Fig. 9), since this can be compared with laboratory data, such as that shown in Fig. 10 for largemouth bass (Reynolds and Casterlin 1975). The agreement is not bad (although the model results are more peaked and lack the skewing seen in the experiment), which is some indication that we have chosen a reasonable set of parameters for our model; however, other choices of parameter values may give better results.

Next we add in the effects of dissolved oxygen (Fig. 1), food availability (Fig. 4), and habitat preferenda, with the appropriate changes in parameter values from Table 2 shown in Table 3. The ultimate average distribution of fish is now greatly altered (Fig. 11).

DISCUSSION AND SUMMARY

The model described in this report is designed to simulate the movements of individual fish in a body of water and to predict the spatial patterns of a population of fish under the influence of temperature, dissolved oxygen levels, food availability and habitat preferences. The body of water is represented by a two-dimensional grid of points, with water depth and longitudinal axis being the coordinates. The simulated fish takes one spatial step at a time, the direction of travel being chosen by a pseudo-random number generator, but biased by the initial direction of motion of the fish, as well as its response to temperature gradients and the other factors mentioned above. Model output is plotted in graphs.

This model is designed for use in planning and evaluating the results of experimental laboratory and field studies of fish movement and spatial distribution. The application of the model to experimental data is still in a preliminary stage, and the development of the model into an effective predictive tool will take continued work. The model

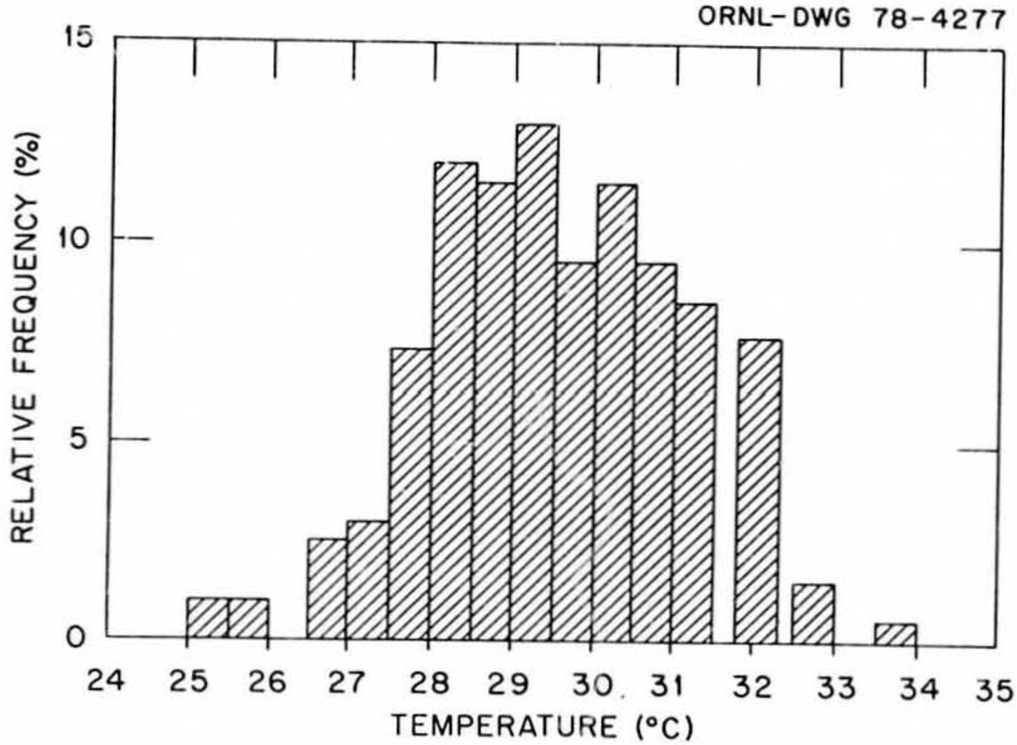

Fig. 9. Histogram of percent distribution of fish in Fig. 8 about the preferred temperature of 29.0°C.

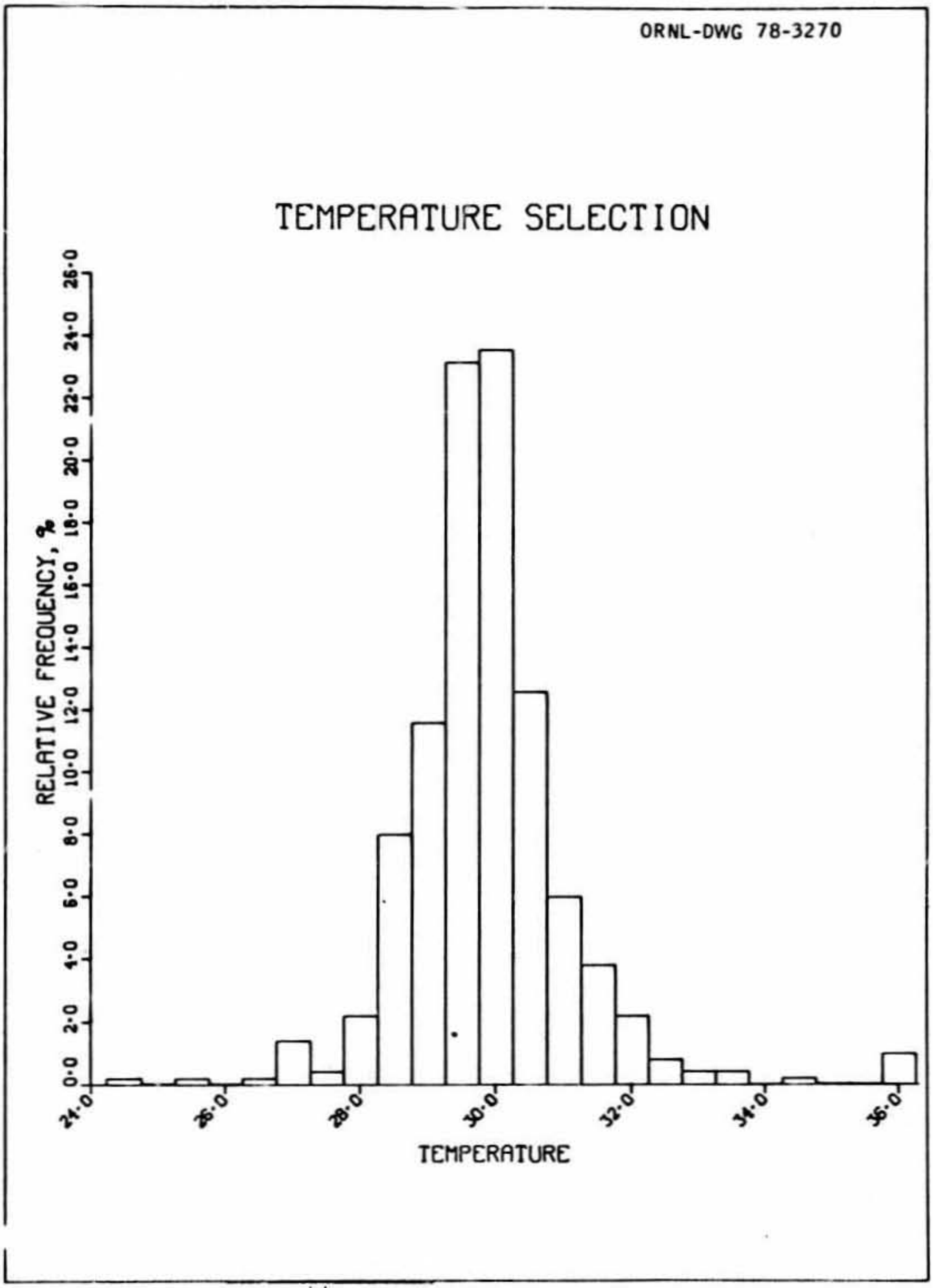

Fig. 10. Histogram of relative frequency of largemouth bass in ambient water temperatures during daytime (from Reynolds and Casterlin 1977).

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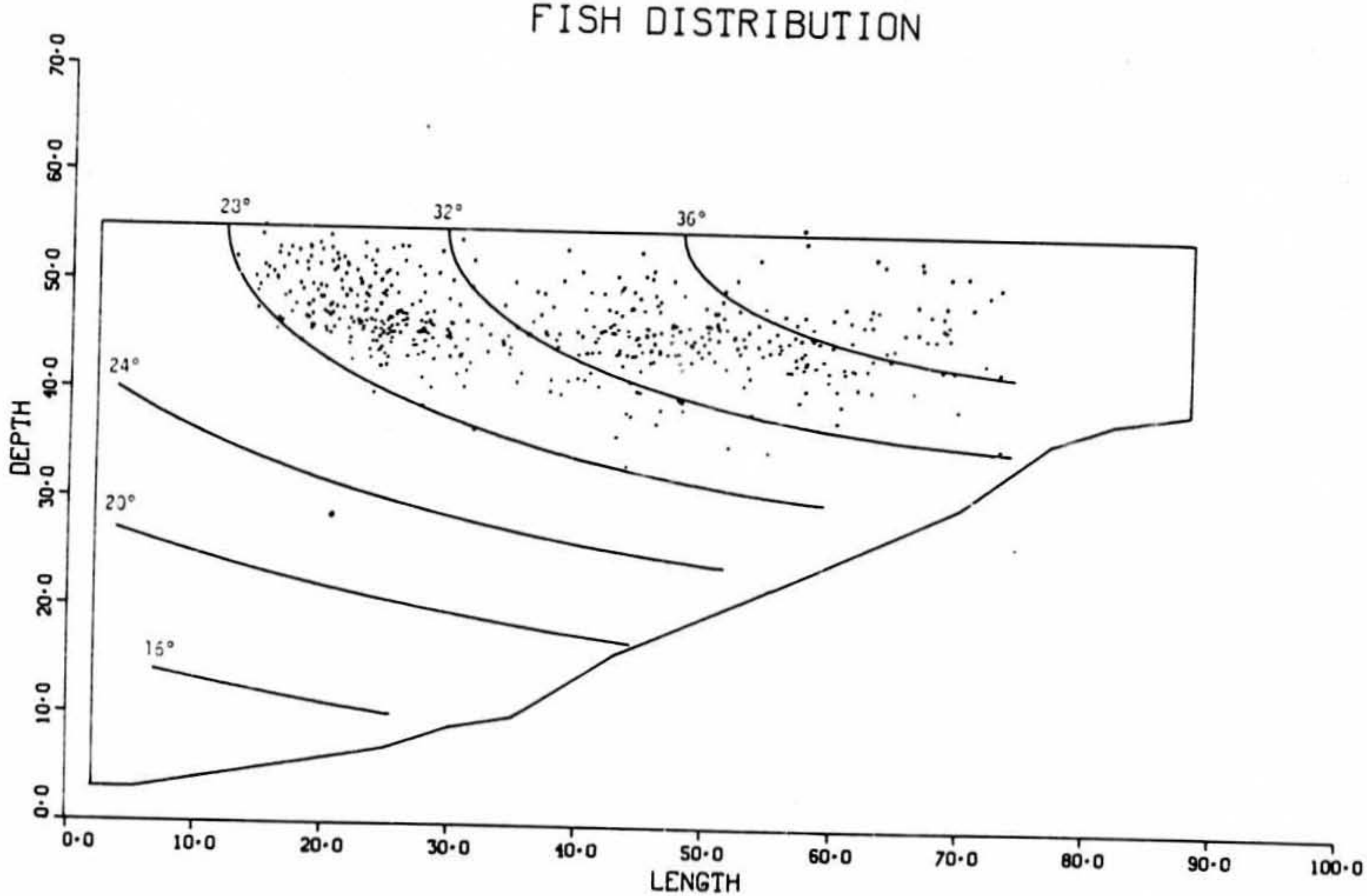

Fig. 11. The distribution of 500 fish influenced by temperature, dissolved oxygen, food availability and habitat favorability in the reservoir after 200 steps. Parameter values are given in Table 3.

Table 3. Changes in paremeter values from Table 2. relevant to the case shown in Fig. 11

NFOOD = 1		
FDNUM(1) = 10.0	FDALP(1) = 0.02	FDBET(1) = 0.2
FDIQ(1) = 60.0	FDJQ(1) = 45.0	
FDNUM(2) = 10.0	FDALP(2) = 0.10	FDBET(2) = 0.20
FDIQ(2) = 70.0	FDJQ(2) = 50.0	
NHAB = 1		
HBNUM(1) = 10.0	HBALP(1) = 0.05	HBET(1) = 0.20
HBIQ(1) = 45.0	HBJQ(1) = 53.0	
HBNUM(2) = 10.0	HBALP(2) = 0.05	HBBET(2) = 0.2
HBIQ(2) = 45.0	HBJQ(2) = 53.0	
NFISH = 500		
IPLOT = 0		

is flexible enough to take into account most of the important factors influencing fish movement, but considerable effort needs to be expended in quantifying these factors.

REFERENCES

Coutant, C. C. 1975. Responses of bass to natural and artificial temperature regimes. pp. 272-285. IN: Stroud, R. H., and H. Clepper (eds.), Black Bass Biology and Management. Sports Fishing Institute, Washington, DC. 534 pp.

Coutant, C. C., and D. K. Cox. 1976. Growth rates of subadult largemouth bass at 24 to 35.5 C. pp. 188-120. IN: Esch, G. W., and R. W. McFarlane (eds.), Thermal Ecology II. ERDA Symposium Series CONF-750425. National Technical Information System, Springfield, VA.

Fraenkel, G. S., and D. L. Gunn. 1961. The Orientation of Animals (revised edition). Dover Pub., Inc., New York. 376 pp.

Gibbons, J. W., J. T. Hook, and D. L. Forney. 1972. Winter responses of largemouth bass to heated effluent from a nuclear reactor. <u>Prog. Fish Cult. 34</u>(2):88-90.

Kitchell, J. F., J. F. Koonce, R. V. O'Neill, H. H. Shugart, Jr., J. J. Magnuson, and R. S. Booth. 1974. Model of fish biomass energetics. <u>Trans. Am. Fish. Soc. 103</u>(4):786-798.

McCauley, R., and N. Huggins. 1976. Behavioral thermoregulation by rainbow trout in a temperature gradient. pp. 171-175. IN: Esch, G. W., and R. W. McFarlane (eds.), Thermal Ecology II. ERDA Symposium Series CONF-750425. National Technical Information System, Springfield, VA.

McGarth, E. J., and D. C. Irving. 1975. Techniques for efficient Monte Carlo simulation. Vol. II. Random number generation for selected probability distributions. ORNL/RSIC-38 (Vol. 2). Oak Ridge National Laboratory, Oak Ridge, TN.

Moss, D. D., and D. C. Scott. 1961. Dissolved oxygen requirements of three species of fish. <u>Trans. Am. Fish. Soc. 90</u>(4):377-393.

Neill, W. H. 1976. Mechanisms of behavioral thermoregulation in fishes. pp. 156-169. IN: Sigma Research Inc. (ed), Report of a Workshop on the Impact of Thermal Power Plant Cooling Systems on Aquatic Environments. Electric Power Research Institute, Palo Alto, CA.

Peterson, S. E., and R. M. Schutsky. 1976. Some relationships of upper thermal tolerances to preference and avoidance responses of the bluegill. pp. 148-153. IN: Esch, G. W., and R. W. McFarlane (eds.), Thermal Ecology II. ERDA Symposium Series CONF-750425. National Technical Information System, Springfield, VA.

Reynolds, W. W., and M. E. Casterlin. 1976. Thermal preferenda and behavioral thermoregulation in three centrarchid fishes. IN: Esch, G. W., and R. W. McFarlane (eds.), Thermal Ecology II. ERDA Symposium Series CONF-750425. National Technical Information System, Springfield, VA.

Smith, S. F. 1972. Effects of a thermal effluent on aquatic life in an East Tennessee reservoir. Proc. 25th Annu. Conf. S. E. Game and Fish Comm., 374-384.

Stuntz, W. E., and J. J. Magnuson. 1976. Daily ration, temperature selection, and activity of bluegill. pp. 180-184. IN: Esch, G. W., and R. W. McFarlane (eds.), Thermal Ecology II. ERDA Symposium Series CONF-750425. National Technical Information System, Springfield, VA.

Warden, R. L., Jr., and W. J. Lorio. 1975. Movements of largemouth bass (*Micropterus salmoides*) in impounded waters as determined by underwater telemetry. *Trans. Am. Fish. Soc.* *104*(4):696-702.

APPENDIX: THE COMPUTER PROGRAM

```
      IMPLICIT REAL*4(A-H,O-Z)
C
C     *******************************************************************
C
C
C
C     THIS PROGRAM COMPUTES FISH DISTRIBUTIONS IN A BODY OF WATER.
C
C     WRITTEN BY D. L. DEANGELIS, 1977
C
C
C
C     *******************************************************************
C
      DIMENSION GRID(90,60),IPEG(40),IEND(40),TYPE(40)
      DIMENSION ARAX(50), ARAY(50)
      DIMENSION DHOR(100),DVER(100),RES(40)
      DIMENSION IA(40),JA(40),ATINDX(40)
      DIMENSION ADIR(40),DIR(3,3),RDIR(3,3),BDY(3,3),ATDIR(3,3),V(3,3),
     1SAVI(500),SAVJ(500),SPRESI(1),SPRESJ(1)
      DIMENSION IGR(90),SDF(40),AGP(100),AG(40),ERTIA(20)
      DIMENSION ITBEG(50),ITEND(50)          ,TDR(3,3)
      DIMENSION TEMPA(100),DISOX(100),FDP(3,3),HDR(3,3),DDR(3,3)
      DIMENSION FDALP(20),FDBET(20),FDNUM(20),FDIQ(20),FDJQ(20),
     1HBALP(20),HBBET(20),HBNUM(20),HBIQ(20),HBJQ(20)
      DIMENSION TEMSAV(100)
      COMMON/FINBLK/NFIN,NPEGP
      COMMON/NFBLOK/NFISH
      COMMON/DPAW/ARRAYX(50,50),ARRAYY(50,50)
      COMMON/THERM/KA,KB,NPTYP
C
      NSV = 0
      DO 3 I=1,100
      TEMSAV(I) = 0.0
    3 CONTINUE
C
C
C
C
C.....READ IN THE NUMBER OF HORIZONTAL AND VERTICAL GRID POINTS AND THE
C     NUMBER OF DISTINCT AREA TYPES
C
      READ(5,1000) NHOR,NVER,NREG
 1000 FORMAT(14I5)
      WRITE(6,2000)
 2000 FORMAT(1H1,10X,'FISH MOVEMENT IN A BODY OF WATER',///)
      WRITE(6,2001) NHOR,NVER,NREG
 2001 FORMAT(1H ,5X,'NUMBER OF HORIZONTAL GRID POINTS, NHOR = ',I5,//,
     1           6X,'NUMBER OF VERTICAL GRID POINTS, NVER = ',I5,//,
     2           6X,'NUMBER OF ENVIRONMENTAL REGIONS, NREG = ',I5,//)
C
C.....READ IN CARDS CONTAINING THE OUTLINE OF THE BODY OF WATER (LONGITUDE
C     VERSUS DEPTH)
C
      READ(5,1000) NREGP
      I = 1
      READ(5,1004)  (ARRAYX(I,J),J=1,NREGP)
      READ(5,1004)  (ARRAYY(I,J),J=1,NREGP)
```

```
 1004 FORMAT(7E10.0)
C
C
C.....READ IN CARDS SPECIFYING WHICH HABITAT EACH GRID POINT BELONGS TO
C
      DO 10 J=1,NVER
      READ(5,1001) IREG,(IBEG(I),IEND(I),TYPE(I),I=1,IREG)
 1001 FORMAT(I2,8X,6(2I2,F5.1,1X))
      DO 5  I=1,IREG
      IB = IBEG(I)
      IE = IEND(I)
      DO 5  K=IB,IE
      GRID(K,J) = TYPE(I)
    5 CONTINUE
   10 CONTINUE
C
C
C.....READ IN ITEM=0 AND IDISOX=0 IF TEMPERATURE AND DISSOLVED OXYGEN ARE
C      DESCRIBED BY MATHEMATICAL FUNCTIONS AND ITEM=1 AND IDISOX=1 IF THEY
C      ARE SPECIFIED POINT-BY-POINT IN SPACE
C
      READ(5,1000) ITEM,IDISOX
      IF(ITEM .EQ. 1) GO TO 12
      WRITE(6,2002)
 2002 FORMAT(1H ,5X,'TEMPERATURE IS DESCRIBED BY A MATHEMATICAL FUNCTION
     1',//)
      GO TO 14
   12 CONTINUE
      WRITE(6,2003)
 2003 FORMAT(1H ,5X,'TEMPERATURE IS READ IN GRID POINT-BY-GRID POINT',//
     1)
   14 CONTINUE
      IF(IDISOX .EQ. 1) GO TO 16
      WRITE(6,2004)
 2004 FORMAT(1H ,5X,'DISSOLVED OXYGEN AMOUNTS DESCRIBED BY A MATHEMATICA
     1L FUNCTION',//)
      GO TO 18
   16 CONTINUE
      WRITE(6,2005)
 2005 FORMAT(1H ,5X,'DISSOLVED OXYGEN AMOUNTS READ IN GRID POINT-BY-GRID
     1 POINT',//)
   18 CONTINUE
C
C
C.....READ IN THE TEMPERATURE VALUES AT EACH GRID POINT
C      EITHER FROM INPUT DATA OR AN EQUATION
C
      DO 25 J=1,NVER
      SJ = J
      IF(ITEM .EQ. 0) GO TO 22
      READ(5,1004) (TEMPA(I),I=1,NHOR)
   22 CONTINUE
      DO 25 I=1,NHOR
      SI = I
      IF(ITEM .EQ. 0) GO TO 23
      TEMP = TEMPA(I)
      GO TO 24
   23 CONTINUE
```

```
      TEMP =100000./(10000. + 0.8*(SI-85.)**2 + 6.*(SJ-55.)**2)
   24 CONTINUE
      LTEM = TEMP*10.
      TEMP = LTEM
      TEMP = 0.1*TEMP
      GRID(I,J) = GRID(I,J) + 0.01*TEMP
   25 CONTINUE
C
C.....READ IN DISSOLVED OXYGEN VALUES AT EACH POINT
C     EITHER FROM INPUT DATA OR AN EQUATION
C
      DO 30 J=1,NVER
      IF(IDISOX .EQ. 0) GO TO 27
      READ(5,1004) (DISOX(I),I=1,NHOR)
   27 CONTINUE
      DO 30 I=1,NHOR
      IF(ITEM .EQ. 0) GO TO 28
      DOX = DISOX(I)
      GO TO 29
   28 CONTINUE
      SJ = J
      DOX = 1.0 + 0.1*SJ
   29 CONTINUE
      LDOX = DOX*10.
      DOX = LDOX
      DOX = 0.1*DOX
      GRID(I,J) = GRID(I,J) + 0.000001*DOX
   30 CONTINUE
C
C.....READ IN OPTIMAL TEMPERATURE AND ITS ATTRACTIVE EFFECT ON FISH
C
      READ(5,1002) TEMPRF, TEMFOR
      WRITE(6,2006) TEMPRF, TEMFOR
 2006 FORMAT(1H ,5X,'PREFERRED TEMPERATURE, TEMPRF = ',F10.4,//,6X,
     1'FORCE OF ATTRACTION OF PREFERRED TEMPERATURE, TEMFOR = ',F10.4,//
     2)
C
C.....READ IN THE VALUE OF THE MINIMUM TOLERABLE DISSOLVED OXYGEN LEVEL
C     FOR THE FISH IN QUESTION ANF THE FORCE OF ATTRACTION OF HIGHER
C     DISSOLVED OXYGEN LEVELS
C
      READ(5,1004) DOXMIN,DOXFOR
      WRITE(6,2007) DOXMIN,DOXFOR
 2007 FORMAT(1H ,5X,'MINIMUM TOLERABLE DISSOLVED OXYGEN LEVEL, DOXMIN =
     1',F10.4,//,6X,'FORCE OF ATTRACTION OF HIGHER DISSOLVED OXYGEN LEVE
     2LS = ',F10.4,//)
C
C
C.....READ IN CARDS SPECIFYING THE EFFECTS OF THE ATTRACTION OF FOOD
C     DISTRIBUTED THROUGH THE BODY OF WATER ON THE MOVEMENTS OF FISH
C
      READ(5,1000) NFOOD
      READ(5,1002) FDATCT
      WRITE(6,2008) FDATCT,NFOOD
 2008 FORMAT(1H ,5X,'FORCE OF ATTRACTION OF GREATER FOOD AVAILABILITY, F
     1DATCT = ',F10.4,//,6X,'NFOOD = ',I5,//)
      IF(NFOOD .EQ. 0) GO TO 36
      WRITE(6,2009)
```

```
 2009 FORMAT(1H ,12X,'FOOD DISTRIBUTION COEFFICIENTS',/,6X,'FDNUM',12X,
     1'FDALP',12X,'FDBET',12X,'FDIQ',13X,'FDJQ',/)
      DO 35 I=1,NFOOD
      READ(5,1002) FDNUM(I),FDALP(I),FDBET(I),FDIQ(I),FDJQ(I)
      WRITE(6,2010)FDNUM(I),FDALP(I),FDBET(I),FDIQ(I),FDJQ(I)
 2010 FORMAT(1H ,5X,6(E15.8,2X))
   35 CONTINUE
   36 CONTINUE
C
C.....READ IN CARDS SPECIFYING THE EFFECTS OF THE ATTRACTION OF HABITATS
C     IN THE BODY OF WATER ON THE MOVEMENTS OF FISH
C
      WRITE(6,2020)
 2020 FORMAT(/)
      READ(5,1000) NHAB
      READ(5,1002) HBATCT
      WRITE(6,2012) HBATCT,NHAB
 2012 FORMAT(1H ,5X,'FORCE OF ATTRACTION OF HABITAT PREFERENCES, HBATCT
     1= ',F10.4,//,6X,'NHAB = ',I5,//)
      IF(NHAB .EQ. 0) GO TO 41
      WRITE(6,2011)
 2011 FORMAT(1H ,12X,'HABITAT DISTRIBUTION COEFFICIENTS',/,6X,'HBNUM',
     112X,'HBALP',12X,'HBBET',12X,'HBIQ',13X,'HBJQ',/)
      DO 40 I=1,NHAB
      READ(5,1002) HBNUM(I),HBALP(I),HBBET(I),HBIQ(I),HBJQ(I)
      WRITE(6,2010)HBNUM(I),HBALP(I),HBBET(I),HBIQ(I),HBJQ(I)
   40 CONTINUE
   41 CONTINUE
C
C.....READ IN BOUNDARY CROSSING FACTORS FOR KEEPING FISH IN THE BODY OF WATER
C
      READ(5,1002) (RES(I),I=1,NREG)
 1002 FORMAT(7E10.0)
      WRITE(6,2020)
      WRITE(6,2013) (RES(I),I=1,NREG)
 2013 FORMAT(1H ,5X,'BOUNDARY CROSSING FACTORS, RES(I) = ',4(F9.3,2X),//
     1)
      WRITE(6,2020)
C
C
C
C
C.....READ IN THE 'INERTIA' VALUE, OR TENDENCY TO CONTINUE MOVING IN SAME
C     DIRECTION
C
      READ(5,1002) (ERTIA(I),I=1,5)
      WRITE(6,2014) (ERTIA(I),I=1,5)
 2014 FORMAT(1H ,5X,'VALUES OF FORWARD INERTIA, ERTIA = ',5(F6.2,1X),//)
C
C
C
C.....READ IN RANDOM NUMBER GENERATOR INITIALIZATION
C     MMM INITIATES SUBROUTINE RANSET AND SHOULD BE LEFT AT THE VALUE BELOW
C
      READ(5,1000) IX
      WRITE(6,2015) IX
 2015 FORMAT(1H ,5X,'RANDOM NUMBER INITIATOR, IX = ',I5,//)
      MMM = 2147483647
```

```
              CALL RANSET(MMM,IX)
        C
        C
        C
        C.....READ IN THE NUMBER OF OF FISH IN THE BODY OF WATER AND THE NUMBER
        C     OF STEPS EACH TAKES
        C
              READ(5,1000) NFISH,NSTEPS
              WRITE(6,2016) NFISH, NSTEPS
         2016 FORMAT(1H ,5X,'NUMBER OF FISH IN BODY OF WATER, NFISH = ',I5,//,
             16X,'NUMBER OF STEPS EACH FISH IS ALLOWED TO TAKE, NSTEPS = ',I5,
             2//)
        C
        C
        C.....READ IN IPLOT=1 IF FISH PATHS ARE TO BE PLOTTED, IPLOT=0 OTHERWISE
        C
        C
        C.....READ IN ISOTH=1 IF ISOTHERMS ARE TO BE PLOTTED, ISOTH=0 OTHERWISE
        C
              READ(5,1000) IPLOT, ISOTH
              IF(IPLOT .NE. 1) GO TO 45
              WRITE(6,2017)
         2017 FORMAT(1H ,5X,'FISH PATHS ARE PLOTTED',//)
           45 CONTINUE
              IF(ISOTH .NE. 1) GO TO 47
              WRITE(6,2018)
         2018 FORMAT(1H ,5X,'ISOTHERMS ARE PLOTTED',//)
           47 CONTINUE
        C
        C.....READ IN THE MINIMUM AND MAXIMUM ISOTHERMS TO BE PLOTTED, AS WELL AS
        C     THE TEMPERATURE INTERVALS BETWEEN THEM
        C
              IF(ISOTH .EQ. 0) GO TO 59
              READ(5,1004) TEML,TEMH,TEMINT
              WRITE(6,2019) TEML,TEMH,TEMINT
         2019 FORMAT(1H ,5X,'MINIMUM ISOTHERM PLOTTED, TEML = ',F10.4,//,6X,
             1             'MAXIMUM ISOTHERM PLOTTED, TEMH = ',F10.4,//,6X,
             2   'DISTANCE BETWEEN ISOTHERMS, TEMINT = ',F10.4,//)
           59 CONTINUE
        C
        C
        C
              CALL PLOTT
        C
        C
        C.....CHOOSE AN INITIAL POSITION AND SENSE OF DIRECTION OF THE FISH RANDOMLY
        C
           60 CONTINUE
              ISV = 1
              NDIST = 0
              SHOR = NHOR
              SVER = NVER
           65 CONTINUE
              D = URAND(DUMY)
              DH = SHOR*D
              D = URAND(DUMY)
              DV = SVER*D
              ISTRT = DH
```

```
      JSTRT = DV
      IPAST = ISTRT
      JPAST = JSTRT
      SAVI(ISV) = ISTRT
      SAVJ(ISV) = JSTRT
      D = URAND(DUMY)
      FRAC = .125
      DO 80 I=1,3
      DO 80 J=1,3
      IF(I .EQ. 2 .AND. J .EQ. 2) GO TO 80
      IF(D .LT. FRAC) GO TO 85
      FRAC = FRAC + .125
   80 CONTINUE
   85 CONTINUE
      IDR = I
      JDR = J
      IPRES = ISTRT - 2 + IDR
      JPRES = JSTRT - 2 + JDR
      IF(GRID(ISTRT,JSTRT) .LT. 2.0) GO TO 65
C
C
C.....BEGINNING OF TIME ITERATION
C
  100 CONTINUE
C
C.....DETERMINE CURRENT TEMPERATURE AND DISSOLVED OXYGEN
C
      IF(GRID(IPRES,JPRES) .GT. 3.0) GO TO 105
      TEMP = (GRID(IPRES,JPRES) - 2.0)*1000.
      LTEM = TEMP
      STEM = LTEM
      DOX = (TEMP-STEM)*100.
      GO TO 107
  105 CONTINUE
      TEMP = (GRID(IPRES,JPRES) - 3.0)*1000.
      LTEM = TEMP
      STEM = LTEM
      DOX = (TEMP-STEM)*100.
  107 CONTINUE
      TEMP = 0.1*TEMP
      TDIFF = ABS(TEMP - TEMPRF)
      DDIFF = DOX - DOXMIN
      SJPAST = JPAST
      SIPAST = IPAST
      SISTRT = ISTRT
      SJSTRT = JSTRT
      SIPRES = IPRES
      SJPRES = JPRES
C
C.....DETERMINE CURRENT FOOD AVAILABILITY
C
      IF(NFOOD .EQ. 0) GO TO 111
      FOOD = 0.0
      DO 110 I=1,NFOOD
      DISTI = ABS(SIPRES-FDIQ(I))
      DISTJ = ABS(SJPRES - FDJQ(I))
      EXPARG = EXP(-FDALP(I)*DISTI - FDBET(I)*DISTJ)
      FOOD = FOOD + FDNUM(I)*EXPARG
```

```
  110 CONTINUE
  111 CONTINUE
C
C.....DETERMINE CURRENT HABITAT FAVORABILITY
C
      IF(NHAB .EQ. 0) GO TO 116
      HAB = 0.0
      DO 115 I=1,NHAB
      DISTI = ABS(SIPRES - HBIQ(I))
      DISTJ = ABS(SJPRES - HBJQ(I))
      EXPARG = EXP(-HBALP(I)*DISTI - HBBET(I)*DISTJ)
      HAB = HAB + HENUM(I)*EXPARG
  115 CONTINUE
  116 CONTINUE
C
C
C.....CALCULATION OF THE EFFECTS OF INERTIA OF FORWARD MOTION, THE EFFECTS
C      OF TEMPERATURE AND DISSOLVED OXYGEN GRADIENTS, AND THE INFLUENCE OF
C      SPATIAL FOOD DISTRIBUTION AND HABITAT PREFERENCES
C
      DO 200 I=1,3
      DO 200 J=1,3
      IPI = IPRES + I - 2
      JPI = JPRES + J - 2
      SIPI = IPI
      SJPI = JPI
C
C.....INERTIA EFFECTS
C
      SI = I
      SJ = J
      SIDR = IDR
      SJDR = JDR
      C = ABS(SI-SIDR) + ABS(SJ-SJDR)
      IF(C .GT. 0.0) GO TO 123
      IERT = 1
      GO TO 129
  123 IF(C .GT. 1.0) GO TO 124
      IERT = 2
      GO TO 129
  124 IF(C .GT. 2.0) GO TO 125
      IERT = 3
      GO TO 129
  125 IF(C .GT. 3.0) GO TO 126
      IERT = 4
      GO TO 129
  126 IF(C .GT. 4.0) GO TO 127
      IERT = 5
      GO TO 129
  127 IERT = 5
  129 CONTINUE
      DIR(I,J) = ERTIA(IERT)
C
C.....BOUNDARY EFFECTS
C
      IF(IPI .GE. NHOR .OR. JPI .GE. NVER) GO TO 60
      IF(IPI .LE. 0 .OR. JPI .LE. 0) GO TO 60
      IGRIDP = GRID(IPI,JPI)
```

```
          BDY(I,J) = RES(IGRIDF)
C
C
C.....EFFECTS OF FOOD ATTRACTION
C
          IF(NFOOD .EQ. 0) GO TO 141
          FOODA = 0.0
          DO 140 K=1,NFOOD
          DISTI = ABS(SIPI - FDIO(K))
          DISTJ = ABS(SJPI - FDJO(K))
          EXPARG = EXP(-FDALP(K)*DISTI - FDBET(K)*DISTJ)
          FOODA= FOODA+ FDNUM(K)*EXPARG
    140 CONTINUE
          IF(FOODA .LT. FOOD) GO TO 141
          FDR(I,J) = FDATCT
          GO TO 142
    141 CONTINUE
          FDR(I,J) = 0.0
    142 CONTINUE
C
C.....EFFECTS OF HABITAT PREFERENCE
C
          IF(NHAB .EQ. 0) GO TO 151
          HABA = 0.0
          DO 150 K=1,NHAB
          DISTI = ABS(SIPI - HBIQ(K))
          DISTJ = ABS(SJPI - HBJQ(K))
          EXPARG = EXP(-HBALP(K)*DISTI - HBBET(K)*DISTJ)
          HABA= HABA+ HBNUM(K)*EXPARG
    150 CONTINUE
          IF(HABA .LT. HAB) GO TO 151
          HDR(I,J) = HBATCT
          GO TO 152
    151 CONTINUE
          HDR(I,J) = 0.0
    152 CONTINUE
C
C.....TEMPERATURE AND DISSOLVED OXYGEN EFFECTS
C
          TDR(I,J) = 0.0
          IF(GRID(IPI,JPI) .GT. 3.0) GO TO 180
          TEMP = (GRID(IPI,JPI) - 2.0)*1000.
          LTEM = TEMP
          STEM = LTEM
          DOX = (TEMP-STEM)*100.
          GO TO 185
    180 CONTINUE
          TEMP = (GRID(IPI,JPI) - 3.0)*1000.
          LTEM = TEMP
          STEM = LTEM
          DOX = (TEMP-STEM)*100.
    185 CONTINUE
          TEMP = 0.1*TEMP
          TDIFFA = ABS(TEMP- TEMPRF)
          DDIFFA = DOX - DOXMIN
          IF(TDIFFA .GT. TDIFF) GO TO 190
          TDR(I,J) = TEMPOR
          GO TO 191
```

```
  190 CONTINUE
      TDR(I,J) = 0.0
  191 CONTINUE
      IF(DDIFF .GT. 0.0) GO TO 199
      DDR(I,J) = 0.0
      IF(DDIFFA .LT. 0.0) GO TO 195
      DDR(I,J) = DOXFOR
      GO TO 199
  195 CONTINUE
      DDR(I,J) = 0.0
  199 CONTINUE
  200 CONTINUE
C
C
C.....USING THE ABOVE CALCULATIONS TO OBTAIN THE PROBABILITIES FOR THE
C     DIRECTION OF THE NEXT STEP IN EACH OF THE EIGHT POSSIBLE DIRECTIONS.
C
      VSUM = 0.0
      DO 210 I=1,3
      DO 210 J=1,3
      V(I,J) =(1.0 + TDR(I,J) + DIR(I,J) + DDR(I,J) + FDR(I,J)
     1 + HDR(I,J))*BDY(I,J)
      IF(I .EQ. 2  .AND. J .EQ. 2) GO TO 210
      VSUM = VSUM + V(I,J)
  210 CONTINUE
      Y = URAND(DUMY)
      PER = 0.0
      DO 250 I=1,3
      DO 250 J=1,3
      IF(I .EQ. 2 .AND. J .EQ. 2) GO TO 245
      PER =(V(I,J)/VSUM) + PER
      IF(Y .GT. PER) GO TO 245
      GO TO 251
  245 CONTINUE
  250 CONTINUE
  251 CONTINUE
      IP = IPRES
      JP = JPRES
      IPRES = IPRES - 2 + I
      JPRES = JPRES - 2 + J
      IPAST = IP
      JPAST = JP
      IDR = I
      JDR = J
C
C
C.....COMPUTING THE DISTPIBUTION OF FISH
C
      NDIST = NDIST + 1
      IF(NDIST .GT. NSTEPS) GO TO 280
      IF(IPRES .LE. 0 .OR. JPRES .LE. 0) GO TO 280
      IF(IPRES .GT. NHOR .OR. JPRES .GT. NVER) GO TO 280
      ISV = ISV + 1
      SAVI(ISV) = IPRES
      SAVJ(ISV) = JPRES
      GO TO 100
  280 CONTINUE
      F1 = URAND(DUMY)
```

```
      F2 = URAND(DUMY)
      SIP = IPRES
      SJP = JPRES
      SPRESI(1) = SIP - 0.5 + F1
      SPRESJ(1) = SJP - 0.5 + F2
      CALL MARKER(1)
      CALL SCLPIC(.125)
      CALL CURVE(SPRESI,SPRESJ,1,-1)
      NSV = NSV + 1
      TEM = 0.0
      DO 285 I=1,80
      TEMPLU = TEM + 0.5
      IF(TEMP .LT. TEM .OR. TEMP .GT. TEMPLU) GO TO 284
      TEMSAV(I) = TEMSAV(I) + 1.0
  284 CONTINUE
      TEM = TEM + 0.5
  285 CONTINUE
      IF(IPLOT .EQ. 0) GO TO 290
      CALL CURVE(SAVI,SAVJ,ISV,0)
  290 CONTINUE
      IF(NSV .EQ. NFISH) GO TO 300
      GO TO 60
  300 CONTINUE
C
C.....PLOTTING OF ISOTHERMS
C
      TEM = TEML
      NK = (TEMH - TEML)/TEMINT
      KB = 1
      DO 400 K=1,NK
      SJ = 0.0
      KA = 0
      DO 350 J=1,NVER
      SJ = J
      ARGT = (400000.-(6*(SJ-55.)**2+10000.)*TEM)/(TEM*0.8)
      IF(ARGT .LE. 0.0) GO TO 320
      SI = 85. - SQRT(ARGT)
      IF(SI .LT. 1.0 .OR. SI .GT. 90.0) GO TO 320
      I = SI
      IF(GRID(I,J) .LT. 2.0) GO TO 320
      KA = KA + 1
      ARAX(KA) = SI
      ARAY(KA) = SJ
      GO TO 345
  320 CONTINUE
      IF(KA .EQ. 0) GO TO 340
      CALL CURVE(ARAX,ARAY,KA,0)
      KA = 0
      KB = KB + 1
  340 CONTINUE
  345 CONTINUE
      SJ = SJ + 1.0
  350 CONTINUE
      TEM = TEM + TEMINT
  400 CONTINUE
  401 CONTINUE
      CALL ENDPL(1)
      CALL DONEPL
```

```
C
C.....PLOTTING OF TEMPERATURE HISTOGRAM
C
      DO 500 I=1,80
  500 CONTINUE
      CALL HIST(TEMSAV)
      CALL DONEPL
      STOP
      END
```

```
      FUNCTION URAND(FRAN)
C
C
C.....E.J.MCGARTH AND D.C.IRVING.  1975. TECHNIQUES FOR EFFICIENT MONTE CARLO
C     SIMULATION. VOL. 2.  RANDOM NUMBER GENERATION FOR SELECTED PROBABILITY
C     DISTRIBUTIONS.  ORNL-RSIC-38
C
C
      COMMON/MIRNG/RAN(10),GEN(10),NWRD,BASE,MOD,FBASE,FMOD
      DIMENSION SUM(10)
      INTEGER RAN,GEN,BASE,CARRY,SUM,PROD,HPROD
      DO 30 IS=1,NWRD
   30 SUM(IS)=0.
      DO 1 IG=1,NWRD
      N2=NWRD-IG+1
      DO 1 IR=1,N2
      IS=IR+IG-1
      PROD=RAN(IR)*GEN(IG)
      HPROD=PROD/BASE
      LPROD=PROD-HPROD*BASE
      SUM(IS)=SUM(IS)+LPROD
      IF (IS.LT.NWRD) SUM(IS+1)=SUM(IS+1)+HPROD
    1 CONTINUE
      N2=NWRD-1
      DO 5 IS=1,N2
      CARRY=SUM(IS)/BASE
      SUM(IS)=SUM(IS)-CARRY*BASE
      SUM(IS+1)=SUM(IS+1)+CARRY
    5 CONTINUE
      SUM(NWRD)=SUM(NWRD)-MOD*(SUM(NWRD)/MOD)
      DO 20 IS=1,NWRD
   20 RAN(IS)=SUM(IS)
      FRAN=SUM(1)
      DO 10 IS=2,NWRD
   10 FRAN=FRAN/FBASE+SUM(IS)
      FRAN=FRAN/FMOD
      URAND=FRAN
      RETURN
      END
```

```
      SUBROUTINE RANSET (MAXINT,NSTRT)
C
C
C.....E.J.MCGARTH AND D.C.IRVING.  1975. TECHNIQUES FOR EFFICIENT MONTE CARLO
C     SIMULATION. VOL. 2.  RANDOM NUMBER GENERATION FOR SELECTED PROBABILITY
C     DISTRIBUTIONS.  ORNL-RSIC-38
C
C
      COMMON/MIRNG/ RAN(10),GEN(10),NWRD,BASE,MOD,FBASE,FMOD
      INTEGER RAN,GEN,BASE,CARRY,REM
      MAXI=MAXINT/4
      IB=0
      BASE=1
99    IF (BASE.GT.MAXI) GO TO 100
      BASE=BASE*4
      IB=IB+1
      GO TO 99
100   BASE=2**IB
      FBASE=BASE
      NWRD=47/IB+1
      REM=47-IB*(NWRD-1)
      MOD=2**REM
      FMOD=MCD
      DO 101 N=1,10
      RAN(N)=0
101   GEN(N)=0
      GEN(1)=5
      DO 200 I=1,14
      CARRY=0
      DO 190 N=1,NWRD
      GEN(N)=GEN(N)*5+CARRY
      CARRY=0
      IF (GEN(N).LT.BASE) GO TO 190
      CARRY=GEN(N)/BASE
      GEN(N)=GEN(N)-BASE*CARRY
190   CONTINUE
200   CONTINUE
      NSTART=NSTRT
      IF (NSTAPT.LE.0) NSTAPT=2001
      NSTART=2*(NSTART/2)+1
      DO 300 N=1,NWRD
      NTEMP=NSTART/BASE
      RAN(N)=NSTART-NTEMP*BASE
300   NSTART=NTEMP
      RETURN
      END
```

```
      SUBROUTINE PLCTT
      COMMON/FINBLK/NFIN,NREGP
      COMMON/DRAW/ARRAYX(50,50),ARRAYY(50,50)
      COMMON/THERM/KA,KB,NPTYP
      DIMENSION XX(500),YY(500)
      CALL CALCMF
      CALL BGNPL(-1)
      CALL PAGE(14.,11.)
      CALL TITLE(' FISH DISTRIBUTION$',100,'LENGTH',6,'DEPTH',5,10.,6.)
      CALL GRAF(0.,'SCALE',100.,0.,'SCALE',65.)
      XMAX = 100.
      XMIN = 0.0
      YMAX = 60.
      YMIN = 0.0
      I = 1
      DO 50 J=1,NREGP
      XX(J) = ARRAYX(I,J)
      YY(J) = ARRAYY(I,J)
   50 CONTINUE
      CALL CURVE(XX,YY,NREGP,0)
      RETURN
      END
```

```
      SUBROUTINE HIST(TEMSAV)
      DIMENSICN TEMSAV(100)
      DIMENSION CLASS(100),FREQ(100)
      COMMON/NFBLOK/NFISH
      SNFISH = NFISH
      NCLASS = 40
      NDAY = 1
      FRQMX = 1.0
      XSTEP = 2.0
      DO 10 I=1,40
      SI = I
      CLASS(I) = 20. + 0.5*SI
      FREQ(I) = TEMSAV(I+40)/SNFISH
   10 CONTINUE
      CALL BGNPL(-1)
      CALL PAGE(8.,11.)
      CALL TITLE('TEMPERATURE SELECTION$',100,
     1'TEMPERATURE$',100,'NUMBER OF FISH$',100,7.,7.)
      CALL XAXANG(45.)
      CALL GRAF(20.,XSTEP,40.,0.,'SCALE',FRQMX)
      CALL INTNO(NDAY,9.50,9.6)
      BWIDTH = 7./(NCLASS-1)
      CALL BARS(BWIDTH)
      CALL CURVE(CLASS,FREQ,NCLASS,0)
      CALL ENDPL(0)
      RETURN
      END
```

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