EVALUATION OF THREE TYPES OF FISH REARING PONDS

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EVALUATION OF THREE TYPES OF FISH REARING PONDS

INTRODUCTION

Artificial propagation subjects salmon and trout to abnormal conditions. Confinement of large numbers of fingerlings in relatively small volumes of water may create an environment definitely detrimental to optimum growth and development. The several types of fish-rearing ponds now in use differ both in the manner of maintaining the fish and in efficiency of operation.

A study of the hydraulic, biological, and physical characteristics of several types of ponds was undertaken with the ultimate objective of either improving present types or developing new designs. This paper is concerned only with the first phase of the investigation, namely, the development of methods of evaluating fish ponds based on their hydraulic characteristics. The paper will show that biological and physical conditions in ponds are dependent on the hydraulic characteristics, and further, that the hydraulic characteristics can be predicted by the use of models.

Three types of ponds were selected for test : the Foster-Lucas, the circular, and the raceway. These particular types were chosen, not because they were considered either the best or the worst, but because more actual operating information and more experimental data have been accumulated for them than for some of the other types. They also are more or less typical of the fish-rearing ponds in general use. Each of these types has been constructed in various sizes and with considerable variation in the basic design. On the assumption that trial and error would have eliminated impractical alterations, the ponds tested were selected from large groups recently constructed. Small rearing ponds on the Grand Coulee project supplied the Foster-Lucas type of rearing pond used during these investigations and the Little White Salmon Station (Wash.), the raceway—both constructed by the U. S. Fish and Wildlife Service. The Marion Fork Station of the Oregon State Fish Commission provided the circular type of pond. Thus, although the findings of this study with regard to each type of rearing pond apply only to the specific modification of the type studied during this investigation, minor alterations in design and operation do not alter the basic characteristics sufficiently to invalidate general comparisons.

In the hydraulic studies, the flow patterns in both ponds and models were determined by the use of floats and dyes. Comparisons of the degree of mixing and short circuiting were ascertained by the injection of dye into the influent and the measurement of the time of appearance and the concentration of the dye in the effluent. The biological and physical characteristics of the three types of ponds were determined from experiments conducted at the Salmon-Cultural Laboratory, Entiat, Wash., and from evaluations made by other investigators.

Model studies were incorporated in these investigations to determine the model size necessary to reproduce the hydraulic characteristics of fish-rearing ponds, and to facilitate various portions of these and future studies. The use of scale models will eliminate the necessity for the construction of full-sized ponds to evaluate new pond designs and the alterations necessary for the improvement of established types.

The design and scale drawings of the models were prepared by Scott Bair. Trevor Watson constructed the pond models. Dr. Robert Rucker and Charles Wagner assisted in the hydraulic and chemical evaluations.

Results of this investigation are presented in two parts : The first is concerned with determination of the hydraulic conditions which exist in the three types of ponds studied and the degree to which these conditions can be duplicated in models ; the second correlates hydraulic conditions with known biological and physical characteristics of the ponds.

DETERMINATION OF HYDRAULIC CONDITIONS

By HARRY H. CHENOWETH

FACTORS INFLUENCING MODEL STUDIES

From their previous experience with ponds and similar pools of water and knowledge of other investigators' findings, it was logical for the present writers to assume that criteria could be established for evaluating the biological and physical performance of fish-rearing ponds from their hydraulic characteristics. Therefore, they simultaneously sought such criteria and developed model techniques that could be used to determine the hydraulic characteristics of either altered ponds or new designs. A study of the flow pattern in each type of pond was required for both the correlation of the hydraulic and biological characteristics and the determination of the degree to which a model would reproduce the hydraulic characteristics.

Many problems concerning the flow of fluids are too complicated to be solved by mathematical analysis alone, and scale models were developed to solve these problems. The structure which the model represents is called the prototype. The model should be geometrically similar to the prototype (in certain cases a distortion in the vertical direction may be desirable), but this geometrical similarity is not enough to ensure that the fluid motion of the prototype will be accurately reproduced in the model. If the direction of flow and the relative velocities are the same at corresponding points in both the model and its prototype, the flow is said to be kinematically similar. The force required to change the direction of a moving streamline depends on the mass as well as the velocities of the particles composing the fluid. If densities and velocities are proportional, the model is said to be dynamically similar to the prototype. The dynamic forces are often the predominant forces, but sometimes viscous drag and surface tension are not negligible.

Complete similitude requires that all of the properties of the fluid in the model be related correctly to the corresponding properties of the fluid in the prototype. The proper density, viscosity, et cetera, of the fluid in the model depends on the geometric scale ratio between model and prototype, and on the density, viscosity, et cetera, of the fluid in the prototype. It is apparent that with the limited number of fluids available for use in the model complete similarity is practically impossible. Fortunately, absolute similitude is not necessary to obtain practical results. In any particular hydraulic problem, one law is usually the dominating one and other effects may be ignored if they are small, or the results of following the major law can be adjusted to take care of the secondary influences.

DETERMINATION OF MODEL SIZE

The flow pattern in fish-rearing ponds is governed principally by inertial forces and, hence, models of these ponds should follow Froude's law (essentially, the velocities should be reduced by the square root of the scale ratio) . If Froude's law is to be followed, the velocity in the model should be to the velocity in the prototype as the square root of the linear dimensions of the model is to the square root of the linear dimensions of the prototype. For example, if the model is one-ninth the size of the prototype, the velocities in the model should be the square root of one-ninth, or one-third the velocities in the prototype. The velocities in a 1: 10 scale model should be adjusted so that they are 0.316 times those in the prototype. The flow, being the product of velocity and area, would be proportional to the 2.5 power of the linear-dimension ratio. The flow through a 1: 10 scale model should therefore be 0.00316 times that through the prototype.

The largest of the secondary influences on fluid motion is viscous drag and, unfortunately, this influence is not negligible. If viscosity affects the flow pattern in the prototype, any model smaller than the prototype will have a distorted flow pattern. If the flow in the prototype is fully turbulent (i. e., all velocities high enough that viscosity is not a factor), there is a critical model size above which no appreciable distortion occurs and below which a gradually increasing distortion of the flow pattern results as the model size is decreased.

In certain regions of all fish ponds, velocities are low enough that viscosity affects the flow pattern. Because of these viscous effects, the flow is not fully defined by geometry throughout the prototype, and hence there is no critical model size. The smaller the model, the greater is the effect of viscous drag. A scale ratio of 1: 10 was selected as the most practicable for these model studies although it was known in advance that some distortion of the flow pattern would occur due to viscosity. Models which were exact replicas of the Foster-Lucas, circular, and raceway prototypes were constructed one-tenth normal size.

DESCRIPTION OF PROTOTYPES

The prototypes selected for study were of modern construction and incorporated the best features of each of the pond types. Great variation existed in shape, size, and water inflow between the three types of ponds.

FOSTER-LUCAS POND

The Foster-Lucas pond was roughly oval-shaped, and had a center partition wall. The inside measurements of the prototype tested were 76 by 17 feet. The pond was operated with a mean depth of 3 feet, and its capacity was 28,000 gallons. During the tests, the flow was adjusted to 202 gallons per minute, which approximated normal operating conditions. The water circulated around the center partition wall, and finally passed out through screens located on each side of the partition wall near the center of the pond. In the particular Foster-Lucas pond studied, water entered through perforated influent pipes running transverse to the major axis of the tank. Water was introduced through eighteen %6-inch orifice holes drilled in each of the two 4-inch standard-weight influent headers. The headers were rotated so that the axes of the jets were depressed 45° below the horizontal. Figure 1 illustrates the model of the Foster-Lucas pond used in this study.

CIRCULAR POND

The circular pond tested had a 25-foot inside diameter and a flat bottom. The depth of water was 31½ inches, making the capacity of the pond 9,630 gallons. Water was admitted through a single nozzle that delivered 105 gallons per minute, and was directed tangentially to the peripheral wall but tilted downward at an angle of 35° to the horizontal. The outlet

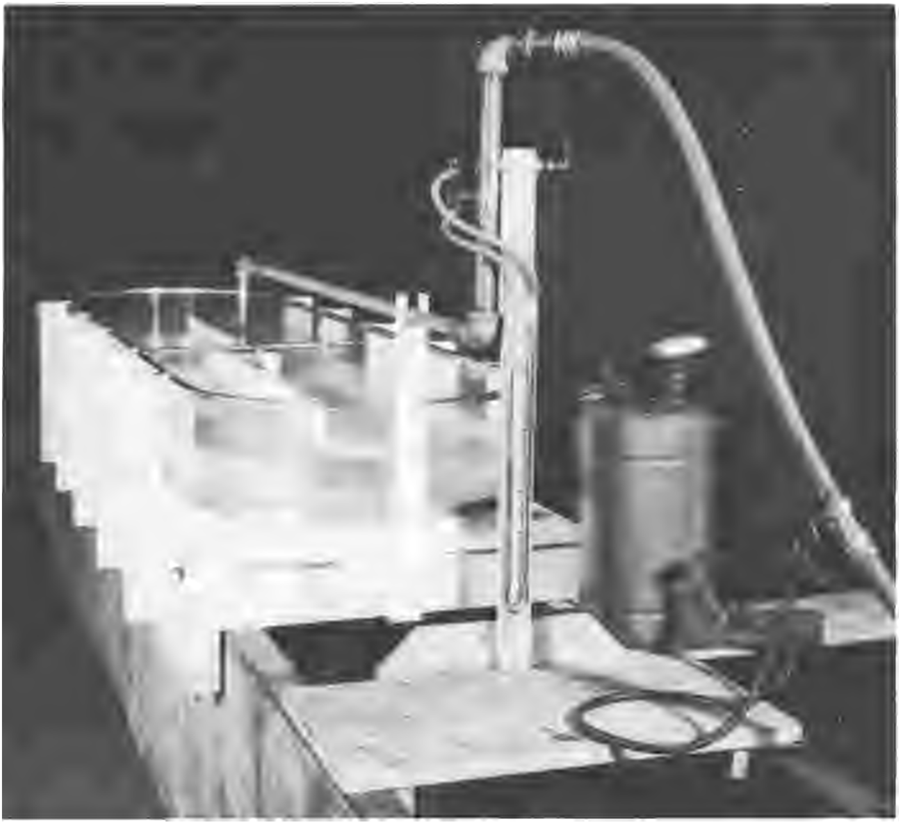


Figure 1.—Model of the Foster-Lucas pond showing the dye-injection tank and mercury differential gage. The gage is connected across a diaphragm orifice, and is used to set flow to the desired quantity.

screens were located at the center of the pond. The circular pond model is shown in figure 2.

RACEWAY POND

The raceway pond tested was 8 feet wide, 80 feet long, and averaged 2 feet deep. The capacity of this pond was 9,650 gallons. The bottom had a very slight slope toward the outlet end to facilitate drainage when the pond was being cleaned. Water was admitted to the pond through slots between boards along the side of an elevated flume header. Each side of the pond was fed by a separate slot. The total inflow to the pond was 490 gallons a minute. Figure 3 shows the raceway pond model.

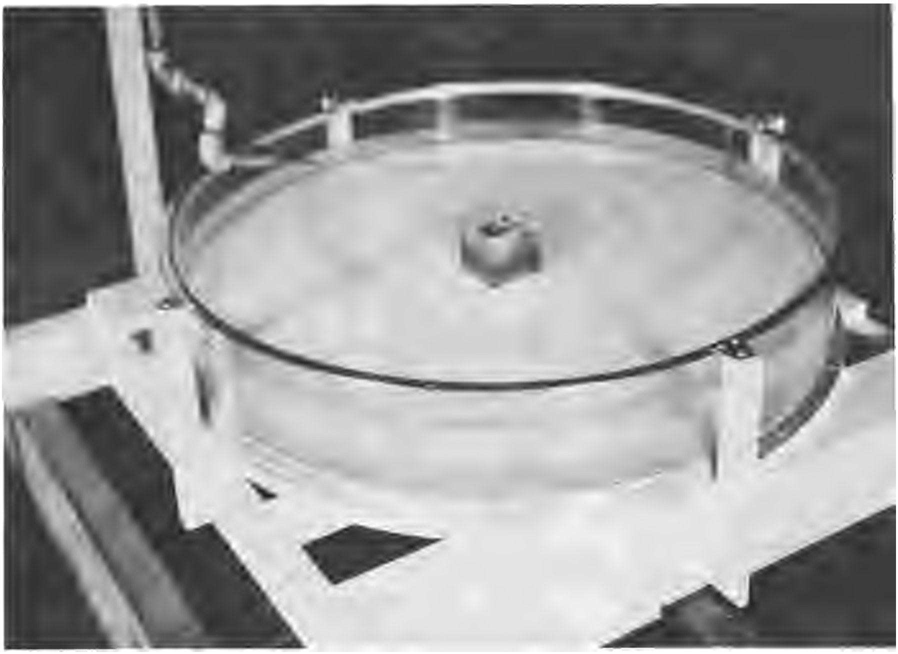


Figure 2.—Model of the circular pond.

Figure 3.—Model of the raceway pond. The two plastic plates in the foreground were added to facilitate capture of the effluent.

FLOW PATTERNS IN MODELS AND IN PROTOTYPES

When the models were operated at the same Froude number as the prototypes, the same general patterns of flow were observed. The greatest discrepancies were in those regions where velocities were low. These regions were more sluggish in the models than in the prototypes. This behavior is explained by the fact that in low-velocity regions of the models inertial forces were relatively small, and hence viscosity of the fluid readily dampened out eddies and even hindered their formation. Dye injected in these regions of the model was pulled into nonturbulent streamlines, or streaks. Although this typical phenomenon of viscosity was also observed in the same regions of the prototype, the tendency was not so pronounced. Low-velocity regions in the prototype will be relatively lower in the model, and conversely, when predicting the flow characteristics of a proposed prototype from observations made on a model, one should expect a little less difference in relative velocities in the prototype than in the model.

Before proceeding to a detailed discussion of the flow pattern in each type of pond, a few remarks dealing with flow characteristics in open conduits or channels are in order. At very low velocities, the flow is nonturbulent. The movement of the fluid down the conduit may be thought of as being laminar, or a sliding of layer on layer, although this concept is somewhat of an oversimplification. The velocity profile is parabolic. Velocities at the fixed boundary are zero, but increase rapidly with the distance from the boundary until the maximum is reached a short distance under the free surface, and then decrease slightly because of surface tension.

At higher mean velocities, the flow becomes turbulent except for a thin layer near the bottom (see fig. 4). The velocity profile is somewhat the same as in nonturbulent flow except that the velocities near the fixed boundary are relatively larger. The velocities at the fixed boundary are still zero, however. If the velocity in the conduit is gradually increased, this laminar layer next to the fixed boundary will become thinner, and if the velocity becomes great enough, the laminar layer will disappear altogether. The flow is then said to be fully turbulent.

Since in fully turbulent flow the velocity against the fixed boundary is a relatively large percentage of the mean velocity in the conduit, wall roughness becomes an important factor. If fully turbulent

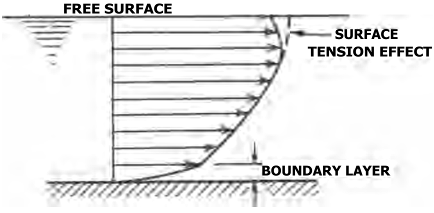


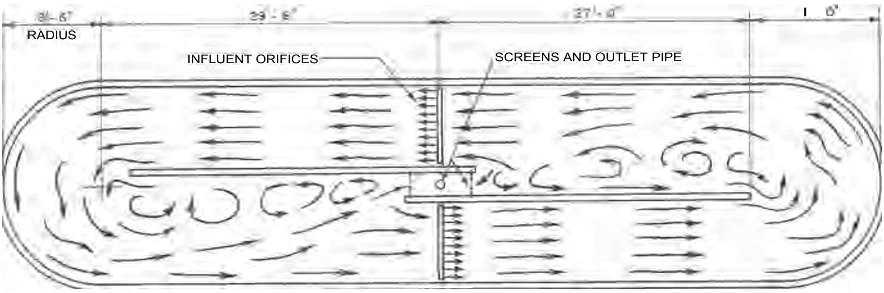
Figure 4.—Velocity distribution in partially turbulent flow.

flow is to be expected, then the roughness of the wall of the model should be a scale reproduction of the prototype's roughness. It should be pointed out that the three modes of flow (degrees of turbulence) just described are typical of straight conduits. Curvature, obstructions, sudden changes in section, et cetera, will alter the flow pattern locally. These local phenomena are likely to be a major item in shaping the flow pattern of most fish-rearing ponds.

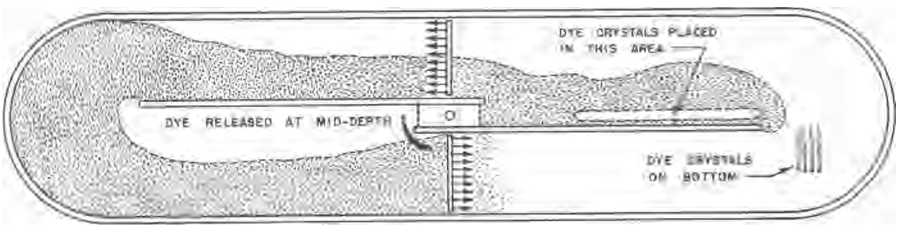
Flow pattern in the Foster-Lucas pond.—In the particular Foster-Lucas type pond used in these studies, the momentum imparted to the water by the 36 influent jets caused the water to circulate around the pond with a maximum velocity of about 0.8 feet per second. The general flow pattern is shown in figure 5, a. The flow pattern near the ends of the ponds was unstable since observations over a period of time revealed continuously changing details. The high velocities near mid-depth in the reach just upstream from the turn carried through to the wall, causing a roll off the end wall. Streaks from the dye crystals placed at the bottom, as shown at the right in figure 5, b, were straight across the pond rather than on a curved path paralleling the curved end wall. After making the bend at the end of the pool, the main flow was near the outside wall. The bulk of this outer stream was carried on around the pond, but some of the flow found its way to the outlet screen and some of it turned into a large eddy behind the partition wall. A spoonful of dye crystals was scattered in this area and the resulting coloration clearly defined the extent of the eddy (see fig. 5, b). The similarity of flow in the model and prototype observed near the end of the center partition wall is shown in figure 6.

The study of the flow pattern in the Foster-Lucas pond revealed three undesirable conditions: A large eddy behind the partition wall, short circuiting, and a roll at each end of the pond. The eddy was primarily objectionable because of the low velocities in the area. The mixing action in the eddy contributed to short circuiting, although the rolling of the water at the ends of the pond and the introduction of the influent by a series of orifices extending completely across the width of the pond probably played a more important role in the short-circuiting action.

Flow pattern in the circular pond.—Water admitted at the periphery of the circular pond through the tangentially placed nozzle should flow spirally around the pond gradually approaching the screen and outlet located at the center of the pond. The actual flow pattern in the circular pond under study was quite different. The outer zone, near the wall, was a region of high velocity and intense mixing. Inside this outer zone, the main flow was circular with a secondary spiral motion superimposed (see fig. 7, d). While the main flow revolved around the vertical axis of the tank, a slow twisting motion carried the water near the bottom inwardly toward the screen. Some of the water carried in by this sec-



A) GENERAL FLOW PATTERN IN FOSTER-LUCAS POND



B) SOME FLOW PATTERN DETAILS

Figure 5.—Flow pattern in Foster-Lucas pond. a. General flow pattern; b. Some flow pattern details.

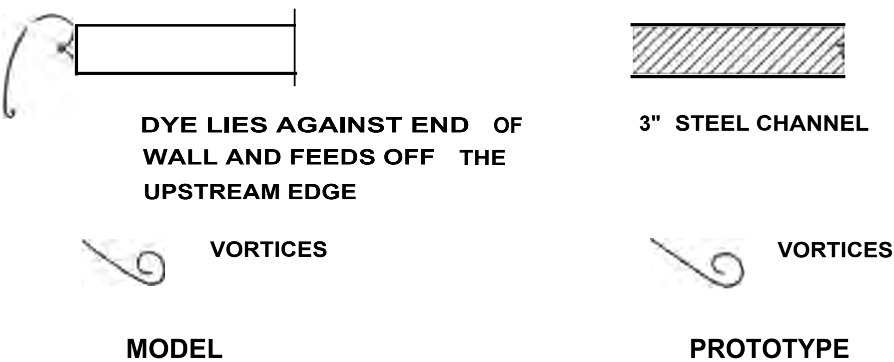


Figure 6.—Comparison of flow patterns in model and prototype near the end of the central partition wall of the Foster-Lucas pond.

ondary spiral passed through the screen and thence to the outlet. The greater portion, however, rose as it revolved around the screen (see fig. 7, b).

While the inward flow along the bottom contributed to short circuiting, in this particular case short circuiting may be advantageous. Settling matter is picked up by this inward current and is carried to the screen. The objectional hydraulic features of this circular pond were the large peripheral mixing zone and the torus-shaped (doughnut-shaped) dead region. The circular axis of this torus lay roughly midway between the bottom of the pond

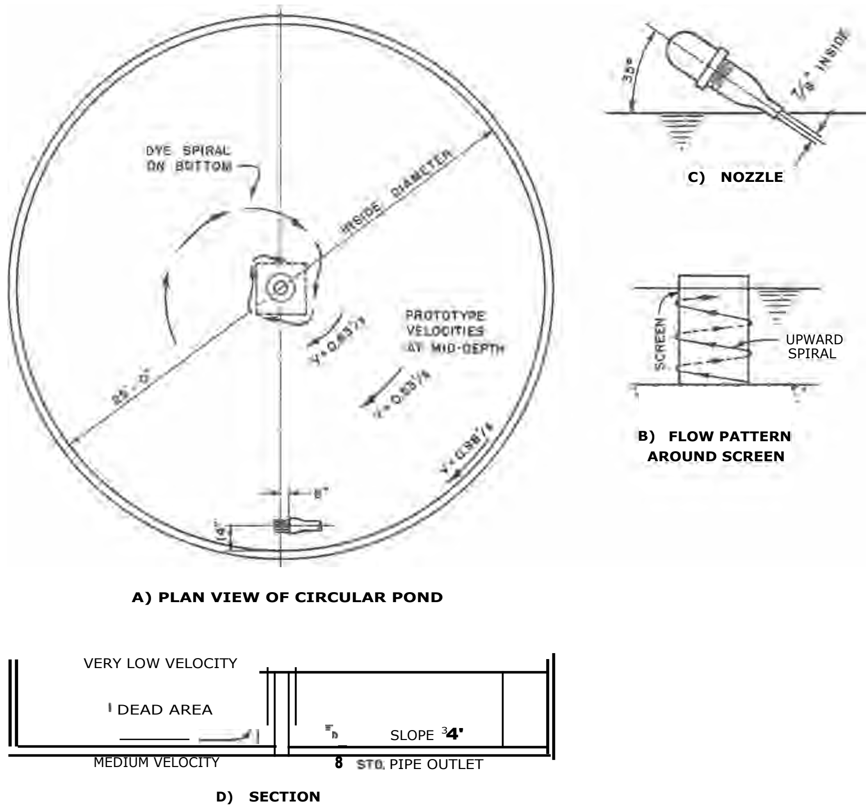


Figure 7.—Flow pattern in circular pond. a. Plan view; b. Flow pattern around screen; c. Nozzle; d. Section.

and the free surface and about a third of the radius out from the center of the pond, as shown in figure 8. This region is described as dead because of the lack of interchange of water between it and the rest of the pond, rather than a lack of actual motion. This entire region revolved around the central axis of the pond at a reasonably high velocity, though this velocity was less than that near the pond wall or near the screen (see fig. 7). Since this was a relatively sluggish area in the prototype, this tendency toward low velocity was accentuated in the model. Figure 9 shows the model a short time after the flow of dye had been stopped. Clear water had moved from the outer mixing zone to the screen by passing under the torus-shaped area. Much of the dye that finally found its way into the dead area was held there and the area shows dark on the photograph.

The driving force of the tangential jet must be transmitted over a relatively long distance by shear stresses in the fluid to reach this region. Making the pond smaller in diameter or deeper should tend to

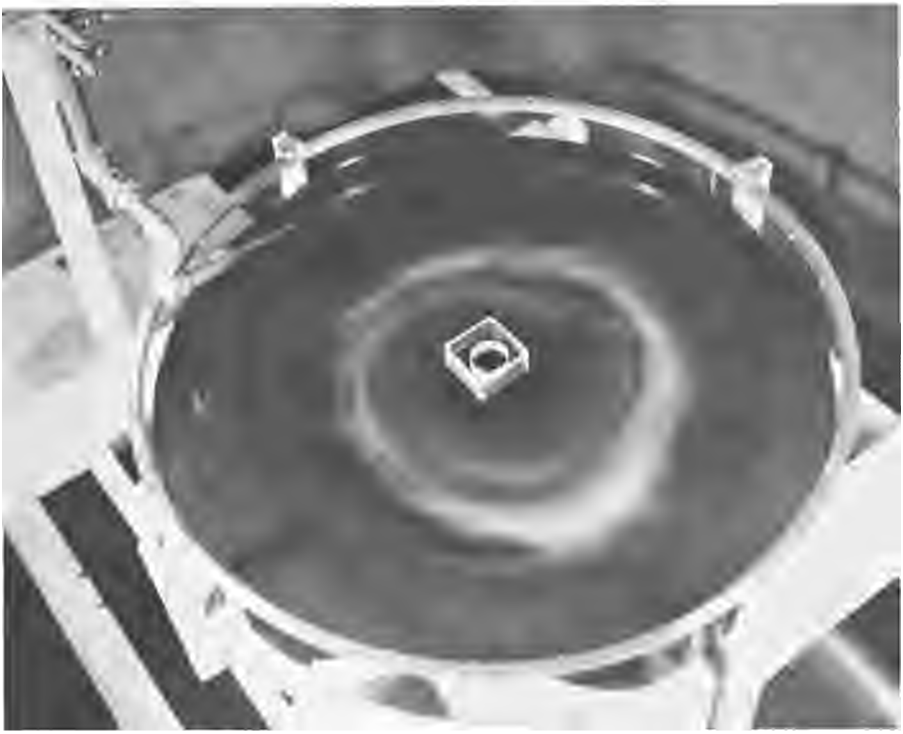


Figure 8.—Model of the circular pond photographed shortly after dye had been added to the influent. Note the dead area that did not color and the typical viscous streaks near the central .... n

alleviate the sluggishness in this region. Because of the retarded boundary layer, the velocity distribution is less uniform in shallow ponds than in deep ones. Since a moving mass will travel in a straight line rather than a curved path unless acted upon by some external force, the high velocity above mid-depth tends to travel tangentially to the curved path and thus tends to move to the outside wall. Because the momentum of the water near the top is greater than that near the bottom, this top water is deflected downward at the wall and then moves in against the low-velocity water at the bottom. This action explains the secondary roll observed in the model and the prototype.

Flow pattern in the raceway pond.—The only available raceway pond was one of a battery of 20 ponds. Unfortunately, the flow pattern of the pond studied was not typical of that in the other ponds. It was estimated that one slot was delivering about twice the flow of the other (see fig. 10, d). This lack of symmetry of the influent stream caused an unsymmetrical flow pattern in the pond (see fig. 10, a). The unsymmetrical intake was duplicated in the model and a similar flow pattern was observed. The influent slots were about 3½ feet above the water surface of the pond

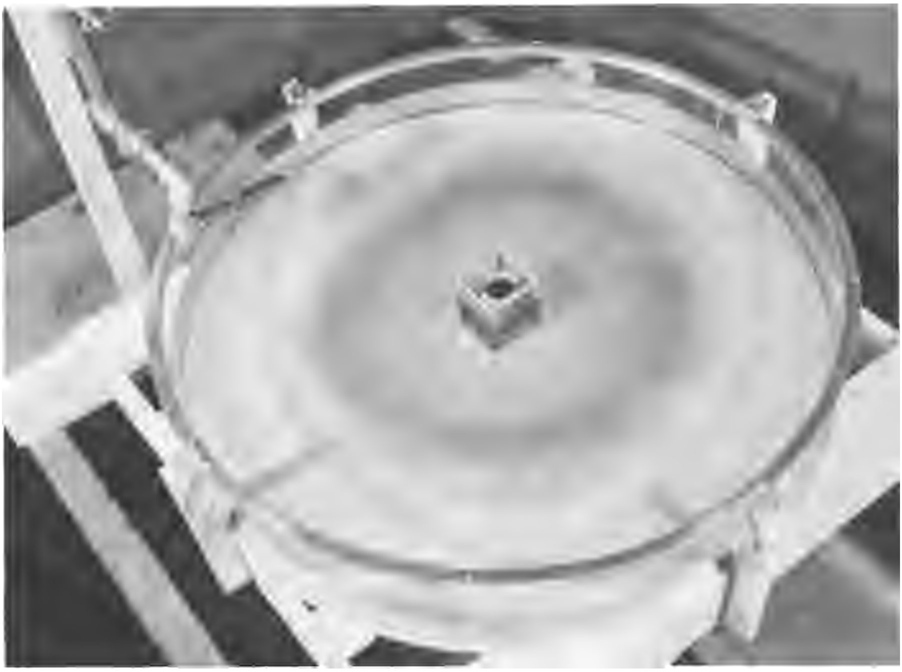


Figure 9.—Photograph of circular pond taken 45 minutes after the dye-injection period. Note that the dead area shown in figure 8 as clear now contains an appreciable amount of dye.

(see fig. 10, c), and so the falling sheet of water struck the surface with a velocity of about 15 feet per second. The turbulence created was still evident slightly below the mid-length of the pond. The bottom velocities were directed upstream. The influences of viscosity were clearly noticeable in the region just upstream from the screen in the prototype, and for a relatively greater distance in the model. It was thought that a more distinctive flow pattern could be obtained for model-verification purposes if water were admitted from one slot only. This was done and the flow pattern is diagrammed in figure 10, b.

Since the raceway pond does not have the advantage of recirculation as do the Foster-Lucas and circular ponds, its mean velocity will be low unless an extremely large quantity of water is available. High inlet velocities at the upper end of the raceway type of pond contribute to short circuiting, but they can easily be eliminated by the use of a suitably baffled intake. Such a baffle added to the intake of the model resulted in a definite improvement.

COMPARISON OF FLOW PATTERNS

The location of a dead region may be more important than the extent. A raceway pond fed through a well-baffled intake will have dead areas only at the fixed boundaries. If the quantity of water passing through the pond is large, this boundary layer will be thin. If the flow through the race-

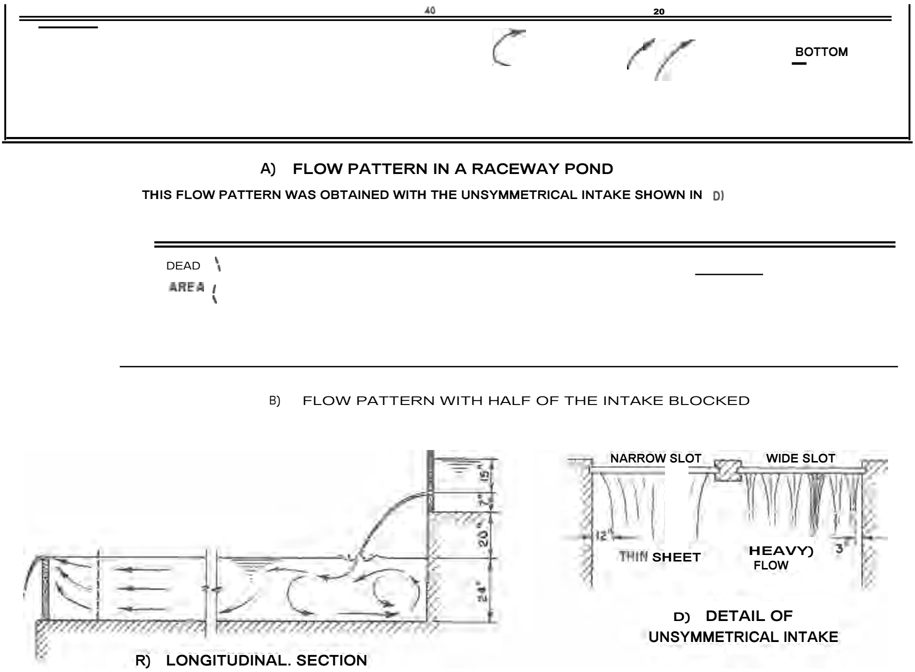


Figure 10.—Flow pattern in raceway pond. a. Flow pattern in raceway pond with unsymmetrical intake; b. Flow pattern with half of intake blocked off; c. Longitudinal section of pond; d. Detail of unsymmetrical intake.

way is small, the boundary layer may be of consequential thickness and, unfortunately, would extend the full length of the pond.

The doughnut-shaped dead area in the circular pond lies above a layer of water that is moving toward the screen with a medium velocity. Settling solids that drop out of the dead region may be picked up by the undercurrent and carried toward the screen. This desirable feature is somewhat offset by the accessibility of this dead area to all fish and by its remoteness from the outlet screen.

The dead regions behind the center partition wall in the Foster-Lucas pond are about as accessible and as remote from the screens as in the circular pond, but the region extends from the top to the bottom of the pond. Furthermore, the dead area is fed by water coming from the direction of the outlet screen, and water that has passed through the dead area is picked up by the main flow and is carried around to the intake on the opposite side of the wall (see fig. 5, b). The mixing zones in the raceway and circular ponds are confined primarily to the inlet region, whereas in the Foster-Lucas pond there is considerable mixing at the intake, the turn at each end of the pond, and at each end of the large eddies behind the center wall.

SHORT CIRCUITING IN MODELS AND IN PROTOTYPES

If efficient use is to be made of the water in a fish-rearing pond, the influent water should pass through all parts of the pond before reaching the outlet. If water passes quickly from the inlet to the outlet without circulating to all parts of the pond, short circuiting is said to take place. Short circuiting is exhibited by all ponds to some degree and is due to differences in velocities and lengths of the stream paths, and it is accentuated by high inlet velocities and by mixing due to eddies. Short-circuit studies are usually made on model ponds operated in accordance with Froude's law. A quantity of dye or salt is injected into the influent and the concentration of the added substance in the effluent is observed at the end of various time intervals until virtually all the substance has passed from the pond. From the data thus obtained a curve of concentration against time may be plotted. If these curves are plotted in dimensionless form (see fig. 11), they are a means of comparing the hydraulic characteristics of ponds of different shapes.

The abscissa for a point on the dimensionless curve is the relative time, i. e., the actual time divided by the theoretical detention time. The ordinate is the relative concentration computed by dividing the observed concentration by the concentration that would be obtained if the dye or salt injected at the intake were instantaneously dispersed throughout the pond volume. This type of plot is independent of the amount of dye or salt used and is also independent of the detention time of the pond.

The ideal pond would have a relative-concentration, relative-time curve as shown in figure 12. Any actual curve will depart considerably from this ideal shape, but the less its departure the better the pond from a hydraulic standpoint. If duplicate runs made under the same conditions yield different curves, the flow pattern of the pond is unstable. The more unstable the flow pattern, the more unpredictable are the hydraulic properties of the pond. Instability will lead to erratic performance, and is therefore undesirable. Low velocities in a pond are conducive to instability. If there are dead spaces in which the liquid plays little or no part in the general displacement through the pond, the effective pond volume will be less than the true volume. Consequently, the effective detention time will be less than the theoretical detention time, and the relative time to the centroid of the area under the relative-time, relative-concentration curve will be less than unity. Since the relative time to the centroid is unity except for ponds with dead spaces, the relative time to the centroid is an indicator of the amount of dead space in the ponds. If there is any interchange between the dead spaces and the main flow, there will be a long "tail" on the end of the curve. The relative time to the center of the area under the curve is usually less than unity and decreases the greater the short circuiting. The actual time to the center of the area is the

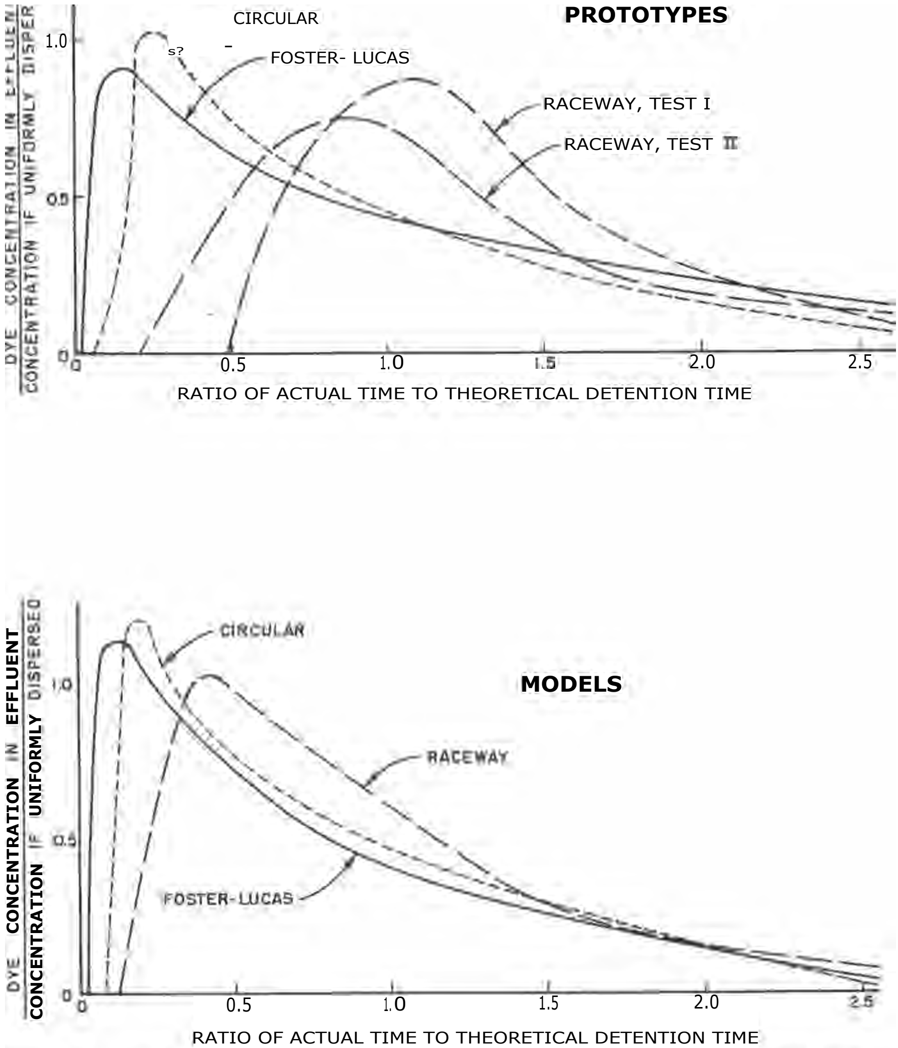


Figure 11.—Relative time-concentration curves for the prototype (above) and models (below).

probable flowing-through time, since half the particles of fluid move through the pond in less time than this and half pass through in more time than this.

Attention is called to the fact that the terms "centroid" and "center" are not synonymous. For convenience, centroid may be thought of as the center of gravity, whereas center means that there is as much area on one side of a given point as there is on the other. A line through the center divides the area into two equal parts, while a line through the centroid may or may not divide the area into equal parts. The centroidal axis is a balancing

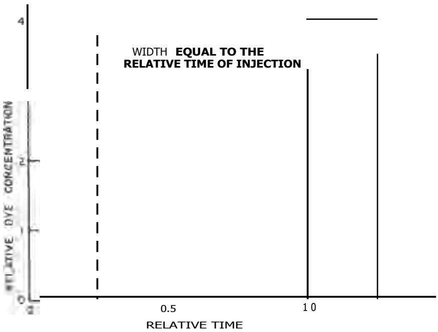


Figure 12.—Dye-concentration-time curve of an **ideal fish-rearing pond.**

axis and its position depends on the distribution of the area as well as its magnitude. The relative time of the initial appearance of the dye or salt is also a measure of short circuiting.

Tests both of models and of prototypes were made in which gentian-violet dye was injected in the influent by means of a small pressure tank, a converted weed burner (see fig. 1). The concentration at the outlet was determined with a photocolorimeter. Theoretically, dye-injection time should be infinitesimal. Actually this is not possible, nor for that matter, desirable. All ponds are at least slightly unstable, and a finite dye-injection time gives a somewhat average picture, which is desirable unless instability is being studied. The injection period for the models was 30 seconds; for the prototypes it varied from 5 to 9 minutes. The large amount of dye necessary in the tests of the prototypes made a shorter period impractical. The fact that the relative injection times in the models and in the prototypes were slightly different and that the dye was injected somewhat closer to the influent nozzles in the prototypes may explain some of the variation between the model curves and the corresponding prototype curves. Since the observed time started with the beginning of the dye-injection period, one-half the injection time was subtracted from the probable flowing-through time and from the effective detention time shown in table 1.

Table 1.—Relative flowing-through time in the **three types of ponds.**

[Time for ideal pond taken as 1]

	Foster-Lucas	Circular	Raceway
Time of first appearance of dye at outlet	0.023	0.055	[illegible]
Effective detention time	.83	.88	1.11
Probable flowing-through time	.57	.58	.92

The ideal pond would have a relative time of unity for each item shown in table 1, and the smaller the actual value the worse the hydraulic performance from the standpoint of short circuiting. Stability is also an important hydraulic characteristic, but statistical data on stability are expensive to obtain. Some instability was observed in all of the ponds when the flow pattern was traced. As previously mentioned, theoretical considerations indicate that instability will be greatest ill low-velocity ponds, and so one would expect the greatest instability in the raceway type of rearing pond. The values shown in the table are the averages of several tests and although the deviations from the average values were greatest in the raceway pond, all the relative times from the individual tests were larger than those obtained for the circular pond or the Foster-Lucas pond. The comparisons made in the table, therefore, seem valid. A relative effective detention time greater than unity for the raceway pond may be explained partly by the instability of this pond due to its low velocity.

Comparison of each of the model curves with the corresponding prototype curve shows that invariably the maximum concentration of dye reaches the outlet in a relatively shorter time in the models than in the prototypes, and that the relative concentration of dye is higher in the models. This condition means that the relative size of the dead spaces is larger and that the short circuiting is worse in the models, as is to be expected, because of the relatively greater influence of viscosity in the case of the models. This condition agrees with the results found in tracing flow patterns. An important point to note in predicting the characteristics of a proposed prototype from the type of tests under discussion is that the predicted curve should be sketched slightly to the right and with ordinates of about 90 percent of those for a 1: 10 scale model.

Short circuiting in the *Foster-Lucas* pond.—Direct observation of the flow pattern in the Foster-Lucas pond revealed serious short circuiting. Studies in the dye-concentration-time relationship gave a quantitative evaluation of this characteristic. Both the relative time of the first appearance of the dye at the outlet and the relative effective detention time are measures of the short circuiting. As shown in the table, both of these criteria mark the Foster-Lucas pond as hydraulically inferior to either the circular or the raceway pond. The relative probable flowing-through time is a measure of the extent of the dead areas. The extent of these regions was about the same in the Foster-Lucas and circular ponds, but the fact that the relative effective detention time was greater for the Foster-Lucas pond indicated more interchange between these dead regions and the regions of main flow. This increased interchange is further substantiated by the long tail on the Foster-Lucas curves.

Short *circuiting* in the circular pond.—Studies in the dye-concentration-time relationship confirmed the existence of a large dead area in the circular pond (the observed doughnut-shaped region) and, furthermore, showed this region to occupy about the same percentage of the pond volume as did the dead areas in the Foster-Lucas pond. While the short circuiting was considerably more in the circular pond than in the raceway pond, it was less than that in the Foster-Lucas pond by both criteria shown in the table. It should be remembered that much of the short circuiting in this pond occurred along the bottom and was directed to the outlet. This assisted in making the circular pond self-cleaning and, therefore, was not entirely undesirable.

Short circuiting in the raceway pond.—Considerable difficulty was encountered in injecting the dye evenly across the slots of this pond. The other two prototypes and all of the models were fed by pipes into which dye could be injected easily. The influent slots of the raceway pond were fed by a large open channel, but during the dye-injection period of the first test on the prototype most of the dye entered the pond through one slot. Therefore, a second test was run. Most of the dye entered through the other slot at the beginning of this run but was fairly evenly distributed during the latter part of the injection period. This difficulty was not experienced when testing the models, and both the prototype and model tests indicate that the dead regions in this type of pond are smaller than in the other two types tested. The dead areas are confined principally to the quite stable boundary layers. Dye trapped in these regions is held for some time resulting in a fairly *long* tail on the concentration-time curves (see fig. 11). Despite the unfavorable intake characteristics of the raceway pond tested, the superiority of this type of pond in regard to short circuiting and dead areas is clearly shown by the curves.

CONCLUSIONS

The hydraulic characteristics of fish-rearing ponds may be studied satisfactorily by 1: 10 scale models. The data obtained from the model should be corrected for the minor influence of viscosity when predicting the performance of the prototype.

The three specific types of ponds studied during the investigation have serious hydraulic defects of such a nature that only major changes would correct them. Were the intake of the raceway pond modified by baffling, the low initial cost of this type of pond might justify its use where a large quantity of water is available. Rarely will velocities be high enough to make the raceway pond self-cleaning.

Since the natural path of a moving mass is a straight line, and since the flow against any fixed boundary is retarded, it is difficult to see how any circular pond having recirculation can be freed of short circuiting and mixing. The curved ends of the Foster-Lucas pond gave characteristics similar to the circular pond and the eddies behind the partition wall were even more serious.

It is, of course, easy to find fault with existing ponds, but much harder to offer improvements. The authors felt that before they could undertake the task of searching for improvements, they should determine and study the faults of existing ponds and develop criteria that could be used in the development of better fish-rearing ponds.

CORRELATION OF HYDRAULIC CONDITIONS WITH PHYSICAL AND BIOLOGICAL CHARACTERISTICS

By ROGER E. BURROWS

The actual operating characteristics of established types of fish-rearing ponds have become known over the years. Most of the reports on pond operations in the literature, however, are not accompanied by comparative data from which accurate evaluations of the ponds can be made. As a result, comparisons of operating characteristics of various types of ponds under comparable conditions are practically unobtainable. Despite the dearth of comparative data, certain conclusions and assumptions have been made and criteria established by which rearing-pond types have been evaluated. In this section of the report, the hydraulic conditions determined for the three types of ponds used in this study—the Foster-Lucas, the circular, and the raceway—will be correlated with the known biological and physical characteristics of each pond, and criteria established by which alterations in pond design may be evaluated.

FACTORS AFFECTING EFFICIENT POND OPERATION

Carrying capacity, disease-inhibiting qualities, food-distribution characteristics, and cleaning efficiency, have been selected as the major criteria to be used in evaluating the efficiencies of the three types of ponds. The carrying capacity of a pond includes both the inflow measured in gallons per minute and the concentration expressed as pounds of fish per cubic foot of water. Disease inhibition is evaluated on the basis of the differential in resistance of the fish to diseases endemic to the water supply, which under normal operating conditions require routine prophylaxis for control. The food-distribution characteristic is defined as the ability of a pond to distribute the food throughout its area. Cleaning efficiency is determined by the disposition of excrement and debris in relation to the outflow and the effort required to remove this material from the pool. Although other factors also influence pond efficiency it is believed that they are closely associated with one or more of these four major criteria.

CARRYING CAPACITY

In a comparison of the carrying capacity of the raceway and circular types of pools, Cobb and Titcomb (1930), Surber (1936), Prévost (1941), and Davis (1946), all state that the circular pond is superior to the raceway both with regard to the inflow of water required and the pounds of fish that may be carried per cubic foot of water. Experiments conducted by this laboratory cast some doubt on their conclusions. If the gallons-per-minute inflow is used as the criterion, then the circular pond can carry more fish per cubic foot of water, but if the inflow is ignored the carrying capacity of the raceway appears to be superior to that of the circular pool.

The hydraulic conditions that exist in a raceway are very similar to those in a deep trough, as indicated by model studies. Experiments conducted in deep troughs with blueback salmon as the test animals indicated that the carrying capacity of this type of trough was in excess of 5 pounds per cubic foot for this species. In these tests, the water inflow was increased as the load increased. Actually, physical factors such as screen and drain capacities were overtaxed by the increased water inflow required to meet the oxygen demand and forced abandonment of the experiment before a reduction in growth rate was attained. The poundage per trough in the heaviest stocking was in excess of 100 pounds (more than 5 pounds of salmon per cubic foot) when the experiment was abandoned. Davis (1946) found that rainbow trout had a normal growth rate in shallow troughs at poundages in excess of 5 pounds per cubic foot.

Experiments with chinook salmon to determine carrying capacities of circular ponds indicated that the capacity of the circular pond studied was slightly in excess of 1 pound of fish per cubic foot of water. Contrary to popular belief, carrying capacity did not increase with larger fish but was purely a function of weight and volume. Pond capacities were determined for fish ranging from 280 to 40 per pound.

Species differences may invalidate this comparison between raceways and circular pools, although the work of Johnson and Gastineau (1952) and Palmer et al. (1952) indicate that the growth of chinook salmon is not inhibited in circular tanks. It is not anticipated that raceways could carry loads of 5 pounds per cubic foot unless the normal input of water was very greatly increased. It may be expected, however, that loads in excess of 1 pound of fish per cubic foot could be exceeded providing the inflow, screen area, and drainage facilities were adequate. Rodgers (1949) mentions stocking a particular type of raceway at the rate of 1.6 pounds of fish per cubic foot, but he made no comparisons between this raceway and other types of ponds.

No actual comparisons of the Foster-Lucas pond with either the raceway or the circular pool have been possible. Another factor—that of disease—has prevented the carrying of fish loads of more than one-third pound per cubic foot in Foster-Lucas ponds available for test on the Grand Coulee project. It is doubtful, however, if this type of pond would approach the carrying capacity of a circular pool under even the most favorable conditions.

Elements which influence the carrying capacity of a pond are believed to be the available oxygen, carbon-dioxide content, and accumulation of metabolic waste products. Oxygen content of the water is affected by the amount of inflowing water, the path of water flow through the pond, and possibly the distribution of the fish in the pond. The amount of oxygen available to the fish is limited by the oxygen contained in the water supply and the amount of water introduced, plus the surface area of the pond. Ellis et al. (1946) state that 'an oxygen content of 5 p. p. ni. is adequate for fish life and that of 3 p. p. m. is lethal. Davis (1946) points out that the oxygen requirement of a fish varies with its activity and is correlated with feeding. If the water inflow is limited or the oxygen content reduced, there is danger of an oxygen depletion approaching the lethal level that may well be a limiting factor in the carrying capacity of a pond.

The path of water flow also may affect the amount of oxygen available to the fish. In the hydraulic determinations, the path of water was measured by the amount of short circuiting that occurred. If the inflowing water is not completely available to all the fish, but is following a shortened path to the outlet screens, obviously the available oxygen will not be utilized efficiently. This condition appears to be particularly true in both of the recirculating types of ponds tested. Short circuiting appeared to be at its minimum in the raceway type of pool under the conditions of the test. It should be emphasized, however, that a reduced flow through the raceway aggravates short circuiting because of the dead areas that develop along the sides and bottom of the pond. The raceway and circular pools had almost identical water capacities, but were not comparable with respect to the amount of water introduced. Five times the amount of water required by the circular pool was used in the raceway under actual operating conditions. On the basis of water path alone, under the conditions of these tests, the raceway was superior to the circular pond and the circular pond was superior to the Foster-Lucas pond.

Davis (1946) states that, because of the more even distribution of fish in the circular pool, they have a better opportunity to extract oxygen from the water and that this factor is responsible for the greater carrying capacity of the circular pool. This may very well be true, but it should not be considered in terms of the available oxygen but rather in terms of the inhibiting effect of oxygen absorption produced by accumulations of metabolic waste products. Irvin et al. (1941) and Black and Black (1950) have demonstrated that increases in carbon-dioxide content inhibit the absorption of oxygen. Brockway (1950) has shown the same effect for ammonia. The oxygen content at the outlet of a pond may not necessarily be a measure of the available oxygen in view of the inhibiting effect of metabolic wastes on absorption of oxygen. An even distribution of the fish may provide a better opportunity for the dissipation of the metabolic products, particularly carbon dioxide, and consequently result in a more efficient utilization of oxygen. The extent and position of eddies in a pond affect not only the disposition of the fish, but also the accumulation of metabolic waste and the utilization of oxygen.

Carbon dioxide may be present in the water supply of a pond, and in large quantities assumes significance. Such a condition, however, is rare in most water supplies except in instances of multiple reuse of water without adequate aeration. Under these circumstances, the picture again is confused by the presence of metabolic products other than carbon dioxide. Powers (1938) attributes mortalities in trout to the inability of the fish to accommodate themselves to abrupt and repeated changes in carbon-dioxide tension. Marked differences in carbon-dioxide tensions might be present in any of the types of ponds tested, particularly if extensive eddies are created, as in the Foster-Lucas pond. The raceway pond, which is best adapted to the reuse of water, could produce marked changes in carbon-dioxide tension between surface and bottom areas in the specific instance of inadequate water inflow. The circular pool, with its sweeping current along the bottom, would be the least subject to marked variations in carbon-dioxide tension. Whether Powers' premise that the inability of fish to accommodate to changes in carbon-dioxide tension is the cause of mortality, or the Bohr effect (the inhibition of oxygen absorption) is the cause, the fact remains that high carbon-dioxide concentrations can be detrimental to the well-being of fish.

The accumulation of metabolic waste products can produce an unfavorable environment in rearing ponds which does not necessarily result in the death of the fish, but is indicated by their reduced growth rate or lowered resistance to disease. Brockway (1950) described the effects of accumulations of metabolic products measured by ammonia concentrations. Here again, reuse of water and inadequate inflows caused unfavorable conditions for the fish. Although not specifically stated, Brockway's description of conditions indicates that raceways were the type of pond in which he observed high ammonia concentrations.

The reduction in water level that Brockway recommends is not necessarily designed to increase the rate of interchange, but to prevent formation of dead areas along the sides and bottom of the pond. In the circular-type pond, the sweeping action of the current along the bottom of the pond prevents high concentrations of metabolic products. Even the torus eddy is not susceptible to a buildup of waste products, because as the products of metabolism settle in the eddy they are picked up by the bottom current and carried to the screens. The current pattern, therefore, may be an effective substitute for water inflow in some types of ponds.

In the Foster-Lucas pond, location of the eddies is such that movement of the water out of the eddies is directed, not toward the screens, but into the main current of the pond. This type of current pattern is conducive to the accumulation rather than the dissipation of metabolic waste products.

It may be concluded from the preceding discussion that the carrying capacities of the three types of ponds cannot be compared without certain qualifications. Under optimum operating conditions with an adequate water supply, the hydraulic and biological determinations indicated that the raceway is superior to the circular pond and it, in turn, is superior to the Foster-Lucas pond. With a limited water supply utilized at maximum efficiency, the circular pool is superior to either the raceway or Foster-Lucas ponds. The reuse of water does not appear advisable, but when such a procedure is necessary the circular pool would be superior to the raceway type if the installation could be such as to secure adequate head between ponds. The Foster-Lucas pond is not adaptable to the reuse of water.

DISEASE INHIBITION

It has been demonstrated in actual production operations that under comparable conditions certain types of ponds are more resistant to disease development than are others. In experimental tests, the raceway exhibited a greater inhibitory effect on disease than did the circular pool, and the circular pool a greater inhibitory effect than the Foster-Lucas pond. These tests were conducted at the Leavenworth Station (Wash.), where bacterial gill disease appears to be endemic in the water supply and routine weekly prophylaxis is necessary to prevent the disease from reaching epidemic proportions in Foster-Lucas ponds. Under normal operating conditions without weekly prophylaxis at temperatures approximating 60° F. and with fish loads approximating one-third pound per cubic foot, blueback salmon (*Oncorhynchus nerka*) contracted gill disease in epidemic proportions in 2 weeks' time. Under comparable conditions, but with stockings of approximately 1 pound of fish per cubic foot, 3 weeks were required for an epidemic to develop in an 18-foot circular pool. In an improvised raceway and in deep troughs with sufficient water inflow to prevent stratification and poundages not in excess of 1 pound of fish per cubic foot, the disease did not reach epidemic proportions and treatments for the control of the disease were not necessary. If water inflows had been reduced in the raceway type proportional to those in the circular or Foster-Lucas ponds—which inflows were comparable—stratification would have developed in the raceway and the disease-inhibition characteristic of this type would have been altered.

The principal factors responsible for disease inhibition appear to be isolation of the infected fish and rapid elimination of disease organisms from the pond. Flow pattern and the extent and location of dead areas influence the disease-resistance characteristics of a pond. In recirculating ponds of the circular and Foster-Lucas types, there is little opportunity for the infected fish to isolate themselves from the healthy stock. Active fish move freely throughout these ponds and pass through the eddies in which the sick fish concentrate. In the raceway type, healthy fish concentrate principally in the area of inflowing water, while infected stock tend to collect near the outlet. As the disease organisms are usually waterborne, the possibility of infection of healthy stock is materially reduced in the raceway pond because of the isolation of the sick fish—assuming, of course, that the water is not reused and that the inflow is sufficient to prevent stratification.

The extent and location of eddies are of particular importance in the evaluation of the disease-inhibition characteristics of a pond type. Infected fish and disease organisms tend to concentrate in these eddies. If the flow pattern is such that water from the eddy moves directly to the outlet, the chances of the infection reaching epidemic proportions are materially reduced. Under optimum conditions of water inflow, the raceway pond has the smallest amount of dead area of any of the three types tested and this area is located at the bottom and toward the lower end of the pond. In the circular pool, the large torus-shaped eddy does not extend to the bottom of the pond, and the sweeping action of the bottom current toward the screen tends to discourage the accumulation of waterborne disease organisms. The eddy in the circular pond is also a true eddy in that the water is in rapid motion, which is unfavorable for concentration of sluggish fish. The Foster-Lucas pond has the largest dead area, located adjacent to the center wall with the interchange from this eddy feeding into the main path of water flow and over the normal concentration points of healthy fish. This eddy has an imperceptible current and is a collection point for infected fish and a concentration point for disease organisms.

The hydraulic characteristics of a pond and its disease-inhibition characteristics appear to be closely correlated. Alterations in present pond designs or development of new pond types may be evaluated with respect to disease resistance by determination of the hydraulic characteristics of the structure in model studies.

FOOD DISTRIBUTION

Food distribution in a pond is primarily a function of current velocity. In general, recirculating types of ponds develop a higher current velocity than raceway ponds, and are more efficient in food distribution. Palmer et al. (1951), in experiments on frequency of feeding, concluded that concentrations of fish and food are the principal factors responsible for food wastage when large fingerlings are fed. Ponds that have the fish concentrated in one particular area and that do not have sufficient current to distribute the feed rapidly should be fed at more frequent intervals and more slowly than ponds that have the fish more evenly distributed and that have sufficient water currents to distribute the feed more rapidly, if food wastage is to be reduced to a minimum.

A current of 0.8 to 1 foot per second will distribute most sinking feeds throughout the periphery of a circular pool and throughout the narrow section of a Foster-Lucas pond. Both of these ponds had currents of this magnitude. The raceway had a current of less than 0.1 foot per second. In such a current, sinking feeds drop to the bottom immediately, and food distribution must be accomplished artificially by introducing the food along the length of the pond. This procedure is more timeconsuming and, therefore, less efficient.

Floating foods present a slightly different problem in that it is desirable to keep them from coming in direct contact with the turbulence of the inflow to prevent their excessive leaching. In the circular pool, floating foods are introduced at a single point at the periphery of the pond where the food will make almost a complete revolution before it is subjected to the action of the inflow. About 8 minutes are required for a single revolution and during this period the bulk of the food is consumed. Two points of introduction are used in the Foster-Lucas pond, downstream from each header pipe. In this manner, the food is consumed before it passes under the opposite inflow pipe. In the raceway, with its inflow spill, the food should be introduced below the point of excessive turbulence and for at least 20 feet downstream to ensure adequate distribution. Because of the slow current, there is little distribution even of floating foods in the raceway type of pond.

The more effective the food distribution by the pond the less time is required for feeding, and the more efficient is the pond. Using this criterion, the circular pool is superior to the Foster-Lucas pond, and the Foster-Lucas in turn is superior to the raceway.

CLEANING EFFICIENCY

The cleaning efficiency of a pond is governed by current velocity, flow pattern, and location of the eddies. A tremendous difference in cleaning efficiency was found to exist between the three ponds studied.

Current velocities of 0.8 to 1 foot per second, or more, carry excrement and all but the heaviest debris. As the velocity decreases, the heavier particles settle out until at about 0.1 foot per second all but the most semibuoyant particles are deposited. In the circular pool, current velocities were sufficiently high so that no deposition of excrement or debris occurred, except at the screens. The Foster - Lucas pond had a range in current velocity from 0.8 foot per second to practically zero, and debris was deposited in these areas of low velocity. In the .raceway, except in the area of turbulence at the inflow, the current velocity averaged less than 0.1 foot per second. As a result, a continuous settling action occurred along practically the entire length of the pond.

If the flow pattern in a pond is such that the eddies are located adjacent to the outflow or the current sweeps the material dropped by the eddies into the outflow, the self-cleaning characterists of the pond are not sacrificed. In the circular pool, the latter case was true; the sweeping action of the bottom current picked up the debris as it settled from the torus-shaped eddy and deposited it at the screens. The flow pattern of the Foster-Lucas pond was such that the debris and excrement were deposited in the large eddy adjacent to the center wall with the principal deposition at the maximum distance from the outflow. When the pond was drawn down during cleaning, the sediment was picked up by the main-current flow and recirculated. The most effective method of cleaning this pond was to keep the debris stirred up and rely on the drawdown to remove it. Such a procedure proved both slow and inefficient in that it was impossible to remove all the material at one cleaning. The raceway had little self-cleaning action because of the low current velocity, but the material could be brushed toward the screens as the pond was drawn down. With large fish it was possible to reduce the water depth for cleaning and rely on the increased current and swimming action of the fish to clean the upper portion of the pond. Neither the raceway nor the Foster-Lucas ponds had the self-cleaning characteristics of the circular pool, but of the two the raceway was superior.

COMPARATIVE POND EFFICIENCIES

To determine the efficiency of any pond type, it is necessary to consider the pond in relation to each of the four criteria that have been discussed. In table 2, the relative standing of the three types, together with their relative efficiencies, has been enumerated. No attempt has been made to weight the standings, because different water supplies present different problems. In regions where endemic diseases jeopardize operations, the disease-inhibition characteristic would be of prime importance in the selection of a pond type. The amount of water available and the desired output of the station also influence the selection. In this instance, an attempt has been made to rate the types under conditions of optimum inflow and comparable inflows. With optimum inflow, the circular and raceway types are approximately equal in efficiency, according to this arbitrary rating. If disease problems were anticipated, the raceway would be selected. Should

Table 2.—Comparative efficiency ratings of three pond types

Pond	Carrying capacity		Disease inhibition		Food distribution	Self-cleaning	Efficiency	
	Optimum water supply	Comparable water supply	Optimum water supply	Comparable water supply			Optimum water supply	Comparable water supply
Raceway	1	2	1	2	3	2	1.75	2.25
Circular	2	1	2	1	1	1	1.50	1.00
Foster-Lucas	3	3	3	3	2	3	2.50	2.75

the water supply be limited and maximum output desired, the circular pool would be the type selected.

Several fallacies in this method of comparative ratings are apparent if the time element is considered. In recirculating types of ponds, the time required for feeding and the frequency of feeding for optimum food utilization are nearly comparable. In the raceway, both the time required for feeding and the frequency of feeding would be at least twice that in the recirculating ponds. The time required for cleaning the circular pool is one-third that for the Foster-Lucas pond. The time consumed in cleaning the raceway is slightly less than in the Foster-Lucas, but much greater than in the circular pond. On the other hand, where weekly or biweekly prophylaxis can be eliminated, the saving in time would be considerable. The time element is, in a sense, an intangible factor in that the operational policy of a station determines the time spent on these various items.

The results of these investigations indicated that none of the pond types studied even approaches perfection. Neither can one type of pond be recommended as superior to the others under all circumstances. One fact is evident : the Foster-Lucas type of pond is inferior in every instance to either raceway or circular pools when measured by the four criteria used in making these evaluations.

These studies have demonstrated that the physical and biological characteristics of new pond designs or alterations in established types of ponds may be evaluated from the hydraulic characteristics of the pond. Models may expedite the determination of these hydraulic characteristics.

SUMMARY AND CONCLUSIONS

Hydraulic investigations were conducted on three types of rearing ponds. Models were constructed of the three prototypes to determine hydraulic similitude. The flow patterns in the models and prototypes were observed by the use of floats and dyes. The degree of short circuiting and mixing, and the apparent detention time and flowing-through time were determined by injecting dye in the inflow and measuring both the time of its appearance and its concentration at the outflow.

Flow-pattern determinations in the models and prototypes disclosed the following differences in character between pond types:

1. In the Foster-Lucas pond studied, there was a recirculating current of 0.8 foot per second, a large eddy behind the partition wall, a roll at each end of the pond, and short circuiting.

2. In the circular pond, there was a recirculating current of 1 foot per second at the periphery, a large, peripheral mixing zone, a torus-shaped eddy, and an inflowing bottom current that contributed to short circuiting.

3. In the raceway pond, there was no recirculating current, a

mean current velocity of less than 0.1 foot per second, turbulence at the inflow caused by a high inlet velocity, and a high water demand to prevent stratification.

Studies in dye-concentration time produced the following comparative evaluations :

1. The Foster-Lucas and circular ponds had dead areas comparable in extent. In the raceway, these dead areas were much reduced.

2. There was more interchange between the dead areas and the main current in the Foster-Lucas type than in the circular pond.

3. Short circuiting was greatest in the Foster-Lucas, less in the circular, and least in the raceway type of pond.

Model studies indicated that the hydraulic characteristics of fish-rearing ponds may be studied satisfactorily in 1: 10 scale models.

Hydraulic conditions in the three types of ponds were correlated with carrying capacity, disease inhibition, food distribution, and cleaning efficiency, as follows:

1. Carrying capacity was correlated with the available oxygen, carbon-dioxide content, and the accumulation of metabolic waste products.

(a) The amount of available oxygen was affected by the volume of water inflow, the flow pattern, short circuiting, and distribution of the fish.

(b) The carbon-dioxide content in the ponds not associated with metabolic waste was correlated with inadequate aeration and the reuse of water. Changes in carbon-dioxide tension in a pond were influenced by the location and extent of the dead areas.

(e) The accumulation of metabolic waste was affected primarily by the extent and location of dead areas.

2. The disease-inhibition characteristic of the three pond types was correlated with the degree of isolation of infected stock as influenced by the flow pattern, and the rapid elimination of disease organisms as affected by the extent and location of the dead areas.

3. Distribution of food in a pond was indicated to be primarily a function of current velocity.

4. The great variation in cleaning efficiency of the three ponds studied was attributed to differences in current velocities, flow patterns, and location of the eddies.

Of the pond types studied, no single type could be considered superior under all conditions of fish-cultural operations. The Foster-Lucas type, however, was definitely inferior to either the raceway or circular pond.

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