AN INVESTIGATION OF FISHWAYS

by

A. M. McLeod
and
Paul Nemenyi

Conducted for the
Iowa State Conservation Commission
by the
Iowa Institute of Hydraulic Research

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AN INVESTIGATION OF FISHWAYS
INTRODUCTION

In December, 1937, the Iowa Conservation Commission requested that research, tests, and investigative work be carried on by the Iowa Institute of Hydraulic Research, a division of the State University of Iowa, on the problem of developing types of fishways more effective under Iowa conditions than those now in use. A limited program was set up which is now complete and this report presents the results and conclusions. The report, while it by no means covers the whole fishway problem, does give definite results, and does suggest designs which are of proved value. An attempt has been made to present the whole picture so that the present status of the problem can be understood.

The first approach was to compile a bibliography of existing literature on the subject so as to avoid repetition of the work of other investigators, and to find suggestions for definite types of fishways to be studied. This bibliography is not included in the present report. It is hoped that it will be published shortly as a separate bulletin.

Definition

Fishways are channels, series of pools, or similar hydraulic structures, installed to aid fish in overcoming obstacles in migrating. The obstacles may be natural or artificial, including waterfalls, rapids, or dams. Some of the most successful fishways, as, for example, the Ballysadare fishway in Ireland (built in 1856) and several Norwegian salmon passes assist the fish over natural obstacles, opening up river reaches seldom or never visited before. The great majority of fishways, however, were built to overcome artificial obstacles and in many regions are now required by law and considered as indispensable at any dam. The present paper deals with fishways for upstream migration only.

Motivation of Fish Migration

Migrating fish are usually classed in three main groups: salmonides (salmon, trout), spawning in the fall; cyprinides (carp family and allied fishes), spawning in the summer; and young eels. For the salmonides, upstream migration is unquestionably closely connected with the maturation of the sex glands and the approaching period of propagation, although it is not certain whether the salmonides’ efforts are directed toward definite spawning grounds or whether their positive rheotropism (tendency to respond to the stimulus of water flow by swimming against it) awakened in this particular biologic state explains their efforts. The migration of young eels is, on the whole, opposite in direction to that of the salmon; the young eels appear to seek definite feeding grounds in rivers and lakes, far from their native place in the ocean; and they return to the ocean before the spawning period. Least clarified of all seems to be the motivation of the cyprinides. Their

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3Some biologists think that in most cases the same spawning grounds are sought from which they originate.
movements are known to be restricted to rivers, often to comparatively short sections, and their migration is believed not to be directly connected with propagation activities. That they try to reach definite river reaches or lakes as feeding grounds does not seem likely. These fish, it is simply assumed, having been swept a good many miles downstream by the current in the autumn or winter, when they are weak, make efforts to return in the late spring and early summer, when the warmer water reawakens their vitality.

**Fishway Requirements**

The requirements of fishways for all summer-spawners and salmonides are basically the same, in spite of considerable quantitative differences caused by the sizes of fish as well as by differences in the motivation, intensity, and time period of the migrating effort. These basic common requirements may be stated as follows:

1. The size of the free cross-section (particularly free breadth) of fishways must be sufficient for unhampered swimming movements, considering the size and number of fish using the fishway. It appears from experience in Belgium, Holland, and France that if this condition is satisfied, fish will seldom be injured by the baffles even if they are very sharp.

2. The hydraulic conditions must be of such a nature that the passage of the fish up the fishway does not overtax the energy of any but the weakest individual fish. Also no large-scale vortex or whirlpool effect should be present.

3. The quantity and character of the flow and the placement of the fishway, should be such that the downstream end will be easily accessible and also easily discovered by the fish.

Additional requirements to be fulfilled are: (a) ability to withstand weathering, and (b) ability to withstand the impact of floating ice and logs; (c) such a flow that the fishway remains free from debris and excessive sedimentations; (d) such economy as to be economical in its construction and maintenance and also in the use of water; (e) and finally such accessibility as will permit of easy inspection and repair. All these conditions, however, are obvious and apply to other hydraulic structures as well as those here considered. The fishway designer should therefore give his attention primarily to size, negotiability, and attraction to the fish at the downstream end.

**Approaching the Problem**

The number of completely or almost completely unsuccessful designs of fishways is surprisingly large. Landmark of Norway stated many years ago, and it is probably still true today, that the majority of unsatisfactory results are due to failure to attract the fish. Here no generally accepted rule can be given as to exactly where the downstream end of the fishway should be placed, and it is doubtful whether such a specific rule can be formulated. On the contrary, almost all experts agree today that the best guide in this respect is the observa-

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1Passes for young eels have not been considered, not only for local reasons, but also because the manner of movement of young eel is different from that of all other fish.
tion of the actual behavior of the migrants at the particular site. This does not solve the problem, however, in the case of the construction of a new dam since the hydrographic and hydraulic conditions at its foot may be altered to such an extent that the fish may fail to search for passage at the same place as before. For this reason the Norwegian fishery authorities have made it a rule not to design or place a fishway until the new dam is ready and in operation and actual fish behavior has been observed for a sufficient period. Similarly, no reliable general rule is known for the quantity of water necessary to attract the fish; this also depends upon various conditions, mostly local. The species of fish which run simultaneously and the cross section required for unhampered swimming movement of an individual fish are fairly well known from recent research, so that the shape and size of the free cross section of the fishway can be determined with comparative ease and certainty.

The study of fishways from the point of view of the effort required of the fish may be approached by two methods: The first method is to gather empirical data at actual fishways with satisfactory entrance conditions, as to the passage of the fish; the percentage of fish failing to pass; and the apparent effort of those which complete the passage. The second approach is aimed at a deeper insight into the problem, the three main phases of which may be defined as follows:

a. A study of the hydraulic properties of various fishways by measurements and observations on small models as well as on full-scale fishways with application of the general laws of fluid mechanics.

b. A study of the relation of fish effort to the properties of the flow.

c. Determination of the limit of effort of which each different species is normally capable.

The phase (a) is purely a question of fluid mechanics or hydraulics, and phase (c) is purely biological, while phase (b) is a combined problem. The concept of "effort" must be defined quantitatively on the basis of physiological considerations before the problem can be treated as one of fluid mechanics. If the flow properties of a fishway are such that the effort required remains well under the limit of the capability of the fish, it is satisfactory from this standpoint; its merit can then be compared with other satisfactory solutions. Consideration should then be given to its economy, sturdiness of structure, and other accessory properties.

Obviously the second approach has considerable merits. However, its difficulties are great. Before the present research as herein reported can be related to the above research program, a few remarks on the history of fishway construction and research will be necessary.

Historical Background

The construction of fishways in Europe is a very old branch of hydraulic practice. Lachadenede mentions regulations for the construction of fishways in the French province of Bearn in the 17th century.
and describes the early fishways. There are reasons to believe that in the other European countries fishways were built very early. For example, the way in which Norway's old mill dams and minor natural obstacles in streams are fitted with fishways of simple design, usually in wood, indicates that the construction of fishways is old and firmly rooted in tradition in that country.

However, a stronger development in the design and construction of fishways came with the more modern methods of water-power utilization by turbines; because as a result of this activity much larger and higher dams were constructed and the need for fishways became more urgent. In the second half of the last century, therefore, fishway design gradually became a recognized branch of hydraulic engineering, both in Europe and in America.

Two designers and authors stand out among a number of men active at this time. An American, MacDonald, was the first to attempt to direct part of the flowing water of a fishway into secondary channels, returning it to the main channel in a manner calculated to reduce the energy of the main flow. But the particular design in which MacDonald incorporated his excellent idea was so incomplete that his fishway was considered a failure and was eventually abandoned. However, the Frenchman, Camere, probably influenced by MacDonald's idea, designed his well-known fishways, a few of which proved very successful. In these the "extra water" impinging upon the main flow was taken not from the fishway but directly from the headwater of the dam. An unsuccessful fishway of Camere's was the starting point for later work by Denil (a Belgian) whose studies led him in 1908 to a type which may be considered the first successful realization of the ideas of MacDonald. Denil gradually improved his early design and eventually constructed the most effective energy dissipators known not involving moving parts.

Simultaneously with MacDonald, Landmark in Norway found a solution for the fishway problem which was less radical and more immediately successful. He improved upon the traditional pool fishway by making baffles perpendicular to the bottom but oblique to the axis and by placing a simple jet deflector close to the opening left by the baffles (see Fig. 1). The jet is deflected in a horizontal plane, as in most of the pool fishways, but close to its issue. His design is superior in many ways to the fishways prior to his work, and has with slight modifications been used in Norway and Sweden even up to the present time.

Although Landmark's observations were careful and extensive and his whole approach rational, he does not appear to have made a systematic scientific investigation of the problem. The first important work of this kind was probably that which was started by Denil in 1908 and continued, with some interruptions, for a period of 30 years. His latest publication appeared in 1936-38.

Denil's research included extensive observations and fish counts on

2La Mechanique du Poisson de Riviere.
actual fishways and also hydraulic measurement on small-scale models and on actual fishways. However, many of his generalizations concerning the relation of fish effort to hydraulic conditions are not sufficiently evidenced. His investigations were restricted primarily to the Denil type of fishway and to a few of the fishways conventional in western Europe.

Other research workers and societies in western Europe have undertaken fish counts and engaged in experimental research in some aspect or other of the fishway problem in the last ten or fifteen years. However, most of this laboratory research was restricted in scope compared with that of Denil. For example the research planned by the Fishpass Committee of the Swiss Federal Association for Water Utilization (Schweizerische Wasserwirtschaftsverband) and undertaken by Meyer-Peter and Schmassmann, concerns one particular form of the pool-and-jet fishway. Another interesting modification of the pool and submerged-jet fishway was investigated by Kreitman, and Lachadenede investigated a new and extremely simple fishway based on Denil's ideas.

These four investigators took it for granted that the only quantitative factor determining the effort required of the fish is the velocity it has to face, whereas Denil's recent research indicates that it is likely that two fishways with the same velocity of flow may require a different degree of effort from the same fish depending upon the slopes, or if pool fishways are compared, according to the elevation differences between two consecutive pools. This question is obviously of great importance, particularly if quantitative rules are to be established for rational fishway design. In an investigation sponsored by the Institution of Civil Engineers, London, Nemenyi and White investigated this controversial question with results strongly supporting Denil's new criterion of effort required. In addition they proposed a number of new designs, and tested them on the basis of this criterion.
In the United States, although interest in conservation problems in general and in fishway design in particular has greatly increased in the last few years, research work has usually been limited to definite projects, as for example, the large fishway system at the Bonneville Dam. The present investigation seems to be the first major research project in this country undertaken for the advancement of rational fishway design in general.

**Purpose and Scope of Present Research**

The ultimate purpose of the present research is to study the whole problem of fishway design in the sense in which it has been defined in the first sections of this introduction. The bulletin deals with the hydraulics of models and the gathering of empirical data from observations of fish movement.

It appeared to be an economically sound plan to start this research with small-scale laboratory tests of a large number of fishways. Although the authors are aware that velocity measurements in models in themselves do not give a sufficient basis for quantitative rules of design for a definite type of fishway, they believe that these velocity tests are valuable as a basis of comparison. Laboratory tests were made therefore on about 40 models from October, 1938, to June, 1939. Many of the models tested were of old fishway types in common use. A second group of models were of modern European fishways. The last and largest group tested were made from designs developed in this laboratory, either as entirely new tentative designs or new designs suggested by recent European developments. The latter were modifications mostly in the direction of simplification and of sturdier structure. In addition to the studies of the flowing water many of the hydraulic tests were supplemented by tests with small fish.

After the laboratory work was completed those designs showing good energy-dissipating qualities and suitable properties in other respects were reproduced in full-scale, and used for actual fish count in the outdoor experimental set-up in the Iowa River at Iowa City. These full-scale fishways operated in pairs give a direct comparison of the value of two different types since there were no differences due to location.

The fish counts yielded numerous data concerning the migratory habits of fish. The value of the information is increased by simultaneously recording the climatic, hydrographic, and hydrological data. The present research does not attempt any biological generalizations because the fish counts were restricted to a single season, April to October, 1939, and because the authors do not consider themselves competent in this field. However, certain practical implications of these fish counts became apparent and have been evaluated and are discussed briefly in this report under “Observations of Fish Behavior.”

**Local Conditions**

Game fish such as trout, bass, wall-eyed pike, and northern pike are found in the better Iowa streams. Pan fish such as crappies, bluegill, perch, and sunfish are common throughout the state. Other species
are found in considerable numbers, and all except a few are sought by the sportsman and small commercial fisherman. However, all of them are prevented from migrating by a number of dams, most of which are not passable even in extreme floods. The construction of suitable fishways at these dams would greatly increase the migrating range of the fish, improving feeding and spawning conditions. In a number of streams the pollution has been great enough in the past so that only rough fish remain. Owing to the removal of many of the sources of pollution, however, the water quality in certain Iowa streams is now more suited to game fish than a few years ago. With the solution of these pollution problems, the construction of fishways is made more feasible on these streams than it was formerly.

We know that in addition to the diversity of species, another local condition should be taken into account, namely, the distance of the site of the investigation from the starting point of the migrants. This factor is of importance for long-distance migrants such as the salmon; it probably has some significance for other species as well.

In spite of the quantitative limitations at any site, the comparison between the different types of fishways has general validity. Also some methodic aspects of the work, e.g., the methods applied in the fish count recording, are probably of importance beyond the special conditions in this state.

I. MODEL STUDIES

Object

The investigation of fishways by using small models was not attempted with the aim of obviating studies of full-scale fishways. It was seen rather as a means of easily and inexpensively checking a large number of old and new ideas and pointing the way for efforts to be made in the study of larger models. Inasmuch as the laws of hydraulic similarity are fairly well established, it is possible to predict the hydraulic characteristics of large fishways with considerable accuracy from the study of small models.

The possibility of predicting the action of adult fish in large fishways from a study of fingerlings or small fish in the model fishway is by no means well established. The idea was tried for what it might prove to be worth. Denil and others in Europe and some investigators in the United States have observed and counted adult fish in actual full-scale fishways, but no model studies with fish are on record.

Hydraulic Studies

General set-up: The apparatus used in the hydraulic investigations of the models is shown in Fig. 2. The flume was about 30 feet long, 2 1/2 feet wide, and 3 feet deep. The central test section had glass sides which facilitated observations for many of the tests. A wooden bulkhead was constructed the full height of the flume with openings at the top for attaching the models. A tail gate operated by a small winch controlled the tailwater level, while another winch was used to vary the slope of the models.
The models were about 8 by 8 inches in cross-section and 5 to 10 feet in length. They were constructed of wood or sheet metal or a combination of both materials. In many models the channel was built of wood with baffles of sheet metal. This proved to be a satisfactory combination, easily constructed and easily changed when variations of baffle spacing or shape were desired. Furthermore, when a particular design proved wholly unsatisfactory the baffles could be removed and the wooden channel used again. In several cases, however, wooden baffles were used to simulate heavy construction.

The model fishways were placed in the test flume with the upper end resting on a support and the lower end suspended on the winch cable. The upper end of the model was sealed against leakage by using inner-tube rubber to attach the model to the wooden bulkhead. This set-up was very flexible since all required changes could be made quickly and easily.

Operating technique: The hydraulics of the model fishway were studied in the following manner. Each model was tested at three different slopes (15 per cent, 25 per cent, and 35 per cent) and at two or three depths of flow for each slope. The maximum flow was the greatest depth of flow the model would carry without undue splashing over the sides. The minimum depth of flow was intended to be the lowest flow at which the baffle system was still operating with fair efficiency.

For each set of conditions outlined, the mean depth of flow, the rate of flow, and the maximum velocity head were recorded. The depth of flow was obtained by placing a thin scale perpendicular to the channel bottom or bottom baffles, and estimating the mean depth. An accurate estimate of mean depth was difficult in most cases because of the uneven water surface produced by the action of the baffles. The rate of flow was determined by diverting the discharge from the supply pipe into a calibrated tank and timing with a stop watch. The distribution of velocity in the cross section of each model was roughly determined by means of a pitot tube. The magnitude and location of the maximum

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velocity head and other pertinent items concerning the character of the flow were noted. Particular attention was given to unfavorable velocity distribution, strong vortices, and surging.

Analysis of data: Most of the channel type models and a few others were compared on the basis of the Chezy coefficient, in the following manner.

Plate I—Testing Model Fishways
The Chezy formula $V = C \sqrt{RS}$ was used taking the free cross section as the channel in question. The terms are as follows:

- $C =$ Chezy coefficient
- $V =$ Average velocity in free cross section
- $R =$ Hydraulic radius
- $S =$ Slope of fishway

Thus for a fishway with a rectangular free cross section 5½ inches wide, on a 25 per cent slope, discharging 0.45 cubic feet per second at a flow depth of 5 inches, the Chezy “C” is computed as follows:

- Area of free cross section = $\frac{5.5 \times 5}{144} = 0.191$ square foot.
- Average velocity in free cross section = $\frac{0.45}{0.191} = 2.36$ feet per second.
- Hydraulic radius = $\frac{\text{area}}{\text{wetted perimeter}} = \frac{0.191 \times 12}{15.5} = 0.148$ foot.
- Slope = 25 per cent = 0.25 feet per foot.

$$C = \frac{V}{\sqrt{RS}} = \frac{2.33}{\sqrt{0.148 \times 0.25}} = 10.4 \text{ ft./sec.}$$

Therefore 10.4 is the Chezy coefficient of this channel for the conditions outlined. If the Chezy “C” abruptly increases at a certain flow depth the model in question ceases to be efficient at that point. If the coefficient is low for a wide range of depths and slopes it indicates that the model is an excellent energy dissipator. Thus the Chezy “C” can be used to investigate a single model or as a basis of comparison between models.

For this reason the Chezy “C” has been represented as a function of depth for two or three slopes for many of the fishway models as shown in Figs. 4, 5, and 10. The Chezy coefficient is not generally used for the type of roughness found in these models. Nevertheless it is a convenient means of comparison of channel type fishways involving steady, fairly uniform flow.

The flow in pool-type fishways, though steady, is extremely non-uniform. The relative magnitudes of the velocity and static heads vary from point to point within the pools. Therefore the Chezy “C” cannot be applied to these models. Accurate measurement of total head and static head must be made at several points within the pools as was done for Models 20-b and 20-c (shown in Fig. 7).

Mechanical resistance encountered by the fish in pool type fishways is a composite quantity which must be computed from the diagram of the static and velocity heads. If this total resistance is moderate and fairly constant along the fish passage it indicates a good pool-type fishway.

In any case because of the many geometric, hydraulic, and biological factors influencing the efficiency and economy of fishways, neither the Chezy “C” nor any other single numerical characteristic is sufficient for a final comparison of the various fishway types. The final test is the success and economy of the fishway when it is put into actual use.

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Model Studies with Small Fish

In the first studies with fish, about 150 rainbow, speckled brook, and German brown trout, ranging in length from 4 to 10 inches, were used. In later studies, suckers, crappies, catfish, quillback, carp, buffalo, and others were used.

A number of the fish were placed in the fish compartment of the test flume upstream from the wooden bulkhead. All handling was done with a fine dip net and the fish compartment of the flume was small so that the fish could be caught quickly without tiring them. Care was exercised to minimize handling and prevent injuries. Originally there was no approach channel at the lower end of the models and fish were held in the dipnet at the foot of the fishways in an attempt to start them up. This was not successful and resulted in injuries. Approach channels were then constructed and placed as shown in Figure 2 and Plate I. When placed in the approach channel, the fish immediately faced upstream but usually lay for 20 to 30 seconds before attempting to ascend the fishway, although some ascended immediately and others stayed in the approach channel unless driven out. The fish were easily induced to climb by lowering the tailwater level and making the flow in the approach channel shallow and swift. Usually the fish entered the fishway after making a "run for it" from the downstream end of the approach channel. If the fishway was easily negotiable, the fish went rapidly upward and into the upper pool. If the fishway was not negotiable or if the fish became confused, they were carried down by the flow and sometimes injured by the baffles. It was noted quite generally that once a fish had given up it made no further attempt to right itself and continue up the fishway. Furthermore, after being frustrated a few times it refused to enter the fishway regardless of what was done to induce it to do so.

The slope of the models and the depth of flow were varied and the effect upon the action of the fish was noted.

Discussion of results: A general discussion of the studies and conclusions follow:

1. Slope. Most of the models were easily negotiable when placed at a mild slope. By starting at mild slopes and gradually increasing a point was reached where even the strongest fish could not swim up. This limiting slope varied considerably for different models, being by far the greatest for the Denil type and was not predictable from the results at mild slopes. The maximum slope achieved was 1:2 by a rainbow trout in a Denil-type model.

2. Depth of flow. The flow depth was varied from less than one inch to 6 or 7 inches depending on the model. The overfall types were most affected by deep flow. Because of the resulting increase in velocity or surging the fish were often unable to pass the overfall models at deep flow even at moderate slopes. The overfall types were also most affected by shallow flow. The Denil and the paired-obstacle types were easily negotiated by the fish throughout a wide range of flow depths.
Trout as large as 10 inches sometimes climbed when the flow depth was less than 1 inch.

3. *Placing of baffles.* In general the fish preferred a straight channel requiring uniform effort in one direction. In fishway types having notches or orifices in a staggered position the fish often struck the obstacles, sometimes with such force as to stun them. If the variation in the effort required was great the fish seemed to be disturbed even though the passage was straight. Bottom baffles having a wide spacing disturbed the fish in much the same manner as was noted for variation in required effort. The fish tended to follow the bottom and passing over bottom obstacles slowed them down and made their travel very jerky. A combination of swift and zigzag flow was by far the worst condition. The swiftness of the flow caused the fish to make strenuous efforts and the zigzag flow caused them to lose control.

4. *Speed of travel.* The fish were timed with a stop watch in climbing the fishways. The maximum speed of travel was 4 feet per second against a water velocity of about 3 feet per second. Thus their speed relative to the water was about 7 feet per second. Since the fishways used with varying slope were very short the effect of slope on speed was difficult to determine. The above noted speed was attained at a slope of about 30 per cent. However, the average speed was cut down when the fishways were made longer. One fixed set-up with a 20-foot length of model at a 6 foot height of rise was used to check speed. The average speed in this set-up was 3 feet per second or only three-fourths of that achieved in the shorter models.

5. *Height of dam.* The highest model dam was 6 feet as noted in the previous paragraph. This was apparently far from the limiting height.

**Discussion of the Various Fishway Types.**

Denil system and its derivatives: The Denil or channel type of fishway consist of a straight channel with closely spaced baffles set at an angle with the axis of the channel. The baffles with parts of the channel walls and bottom form "secondary channels," while they leave free a relatively large proportion of the channel for the straight "main flow" through which the fish pass.

The principle implicit in more or less all Denil fishways but incorporated with particular perfection in some of his more recent designs is that the baffles are shaped and arranged in such a manner as to make the entrance of the water into the secondary channels and its passage through them easy. The flow reentering from the secondary channels into the main flow, meets the latter abruptly, i.e., at an angle not far from 90 degrees.

An analysis of the mechanical process by which the energy dissipation is attained has been published recently. Here suffice it to state that the greater part of energy dissipation is accomplished at the re-
issue of the secondary currents by the large momentum transfer and intense mixing occurring there. It is necessary to emphasize this because even in recent literature we find statements to the effect that the superior energy dissipating efficiency of Denil fishways is due largely to the friction along the surfaces of the numerous baffles forming the secondary channels. Hardly any conceivable interpretation of the mechanics of the Denil system could be less correct. The close spacing of baffles is desirable only in order to give a definite lead to the secondary currents. Only to the extent that the secondary channel surfaces are smooth and their entrances well "streamlined" causing the flow between them to be nearly frictionless will the secondary current reissuing into the main stream be vigorous and free from major eddies and capable of effectively checking the velocity in the main flow.

It has been asserted that the Denil fishways give too high a degree of energy dissipation and that therefore the velocities become too small, the total flow insufficient to attract the fish, and that the intricate baffles are too expensive. This criticism, however, is justified for only a few Denil fishways and does not in any way affect the value of the principle. In fact if circumstances require an unusually large cross section the most efficient Denil fishway will perhaps be the most economical; whereas for ordinary conditions, the designer can make the secondary channels simpler and less streamlined, thus incorporating any degree of energy dissipation that the local conditions require. Such more or less simple baffles based upon Denil's ideas have been suggested by Lachenede in France, by Nemenyi and White in London and by the present writers. Denil's studies, as well as those of the other investigators mentioned, have proved that the Denil system is adaptable to any required shape of cross section and, still more important, to great headwater fluctuations. This wide adaptibility of the system is probably its greatest advantage.

It may appear that even in the much simplified fishways based upon this principle the necessarily large number of baffles would make economical construction impossible. However, for a given free cross section for the passage of the fish, the total cross section of the channel in the Denil system is so small compared to other types of fishways that this advantage in most cases more than compensates for the extra expense in consequence of the close spacing of baffles.

It has been asserted, but not proved, that the fish are disturbed by the secondary currents impinging upon them. Lachenede says that this disturbance exists in the Denil fishways in which the secondary currents fall upon the back of the fish. However, as this type was used with good results in our full-scale studies the criticism of Lachenede is disproved insofar as the species encountered in our tests are concerned.

The Denil system of fishways and its manifold derivatives should be noted by hydraulic engineers in all fields of hydraulic practice where a high degree of uniform energy dissipation along a conduit is required, such as in spillways, in timber floating channels, and in the regulation of mountain rivers and damping pipes of surge tanks.
Photos and diagrams of the models studied are shown in Plate II and in Fig. 3. Of these designs Model 1 is a copy of one of the oldest fishways designed by Denil and Model 6 is a copy of a design by Nemenyi and White. All other designs were made in this laboratory; some being only slightly modified Denil designs, while in others essentially new considerations are combined with Denil's general principle.

Model 1. Early Denil fishway—1908.

\[1\] Nemenyi and White, London, 1938.
This old design has been exactly reproduced and retested. It is discussed here because of its historic interest. Although an exact comparison of the results was not made it has been found that our tests made with a 25 per cent slope agree with Denil's model tests in 1908. The Chezy coefficient indicates that although this elaborate design of fishway is fairly efficient, it is substantially less so than the recent more simple designs. The advantage of the latter seems to be mainly that the entrance resistance of the secondary channels has been greatly reduced, an improvement which was first used in Denil's elaborate fish-
ways of about 1920 but which has been more recently incorporated in extremely simple designs also. This early Denil design is obsolete and should no longer be used.

Models 2 and 3. Symmetrical modified Denil fishways for medium depths.

Model 2 represents probably the first attempt to make a fishway design on the basis of the Denil principle yet using baffles of simple sturdy triangular cross section. Sturdy baffles are of particular value
at installations where it is difficult to keep floating timber out of the fishways. Such floating material would easily damage thin or finely shaped baffles. The new design was made with the view of construction either in timber or concrete, possibly in precast units.

Theory shows that other conditions being equal, the effectiveness of a Denil fishway is in proportion to the size of cross section of the secondary channels. Therefore, the authors did not expect so high efficiency with this model as in similar Denil fishways with thin baffles. However, the results found were very favorable. This is probably due to the fact that use was made of the possibility of forming well "streamlined" entrances to the secondary channels when using the triangular shape of baffle cross section. In judging the economy of this design we should also keep in mind that the ratio between the free cross section and the total cross section is larger in this model than in most other designs.

In order to better clarify the role of the baffle cross section a direct comparison was made between Models 2 and 3, the latter being in all essentials the same design but having thin sheet-metal baffles. The results of the tests indicate that Model 3 is only 15 per cent better than Model 2 as measured by the Chezy coefficient. Both designs can be recommended for use.

Models 6 and 7. Unsymmetrical modified Denil fishways for medium depths.
Probably the simplest fishway based upon the ideas of Denil is one in which each baffle is in a single plane. This leads to an unsymmetrical arrangement of baffles and an unsymmetrically shaped channel cross section as was used in the fishway designed by Nemenyi and White in London. The London tests have shown it to have excellent energy dissipating ability. In the present study a copy of the London design was tested. In both tests the average of the Chezy coefficient is 11. Therefore this very simple type is superior as an energy dissipator, for example, to Denil fishway Model 1. From a visual inspection of the baffles it would appear that the water would move in a sharp longitudinal vortex which would no doubt be disturbing to the fish. However, as shown by theory as well as by experimental study of the flow this assumption is erroneous, the flow being, predominantly, straight and free of large scale vortices. The small trout readily ascended this model.

Model 7 is essentially an imitation of Model 6 but with relatively smaller and much more sturdy baffles. Although such a modification should not have serious difficulties, Model 7 did not prove quite successful because the upstream baffles are too short, with the result that the main flow at the side of these baffles is somewhat too rapid. This fault could be corrected by extending these upstream baffles.

Models 8 a, b, c, d, and 9 a, b. Deep channels for variable headwater.

Circumstances often require that a fishway must operate under a wide range of headwater conditions. Denil designed a special pattern of zigzag side baffles for such cases and suggested that the bottom of the channel should be flat because bottom baffles are hydraulically effective for only a limited range of water depth. The zigzag baffle system hinted at by Denil seemed to the authors to be unnecessarily complicated. It appeared that plane, parallel baffles at the sides might give a very satisfactory solution if they were at an angle with both the side walls and the bottom. In order to easily make a variety of tests with the same baffles two removable sidewalls with attached baffles of the kind described were constructed. With these two sidewall baffle units four essentially different symmetrical models were built and tested. These are shown in Fig. 3 as Models 8a, b, c, d. Plate II shows the model with one sidewall unit removed and shown separately.

The results have shown that two out of the four possibilities are good energy dissipators. These are Models 8a and b, both of which are characterized by the fact that the baffles project upstream in the plan view. In the side view of 8a they project in the downstream direction and of 8b in the upstream direction. Model 8a is a superior energy dissipator whereas 8b is only a good energy dissipator but has a flow free from surging even for extremely small depths.

It is interesting to note the extremely low efficiency of the same baffle systems with reversed slope. (Tests c and d.) In fact it seems to be a common property of highly efficient (in Denil’s expression “super-active”) baffle systems that with reversed flow they tend to become almost inactive or at least less active than ordinary perpendicular baffles of the same height.
A slight modification of Model 8a has been tried out, the thin steel baffles having been replaced by carefully shaped wood baffles. Two variants of this design were made, the one having the free breadth the same as the steel models, the other 50 per cent wider (Models 9a and b). In spite of the restricted cross section of the secondary channels even the latter model gave satisfactory results, in fact practically to the extent as in the thin baffle models. This result is probably due to the good shaping of the baffles at the entrance to the secondary channels.

Models 10 and 11 are analogous to Models 9a and 9b but are different in two essential points. The baffles have a triangular cross section and the channel cross section is trapezoidal rather than rectangular. It can hardly be doubted that good designs could be found in this direction. However, Designs 10 and 11 were not very successful. The triangular baffle cross sections were not well chosen as they offer entrance for only weak secondary currents.

Model 4. Simple symmetrical fishway for relatively shallow depths.
This extremely simple new design is characterized by a trough-like channel having bottom baffles formed from oblique and perpendicular parts. The system has proved extremely efficient, the average velocities and the Chezy coefficient being the smallest of all models tested. This is probably due to the trough-like cross section which make particularly good entrance conditions to the secondary channels and also to the fact that the reissue of the secondary currents is in the region where the greatest velocities would otherwise occur. The velocities in the greater part of the channel breadth are extremely moderate. Only near the side walls at the entrance to the secondary channels are the velocities large. As these narrow strips can easily be avoided by the fish, they do not affect the efficiency of the design as a fishway. It is likely that the channel could be used for greater depths than those used in the tests.

A longitudinal vertical dividing wall equal in height to that of the baffles was placed on the axis of the channel. Such a wall prevents the secondary currents coming from both sides from impinging upon each other and thus directs all their impetus upward into the main flow, checking it effectively. However the cross section of the main flow becomes too strongly convex so that this center baffle cannot be recommended except possibly for deep flow.

Model 5. Pipe fitted with energy dissipators.
In case of exceptionally high headwater fluctuations it might be desirable to form part of a fishway as a closed conduit. Denil has suggested that in such a case a resting pool should be used, the closed conduit connecting the lowest headwater elevation with the resting pool while downstream an ordinary fishway can be used. However, Denil believed that intense energy dissipation in closed conduits could be attained only if the conduit had a rectangular cross section and was fitted with twisted baffles.

Starting from the trough-like open channel (Model 4) the authors have succeeded in showing that a circular pipe can be fitted with very
simple baffle systems not containing any twisted elements yet having all the properties of a highly efficient energy dissipator. The idea is that by combining a circle as a total cross section with a regular polygon as a free cross section the remaining space is particularly suited to the arrangement of several highly efficient sets of baffles.

Model 5 has a square inner cross section and the preliminary test results show it to be fully satisfactory. There can be no doubt that other regular polygons would offer good solutions. It seems certain also that the use of longitudinal radial walls, similar to that described for Model 4, would further improve the system. The baffle system and its entrance conditions are essentially the same as in Model 4 and the effect is reproduced as many times as the polygon has sides. Since the conduit is closed, the resulting check upon the main current is even more complete than in the open channel. In further research these predictions will have to be verified by detailed tests.

Pool and jet fishways: The pool-and-jet fishway consists of a series of pools in a stepped arrangement from tailwater to headwater. The pools may be connected by short sloping channels, as would be the case if the fishway were cut in rock, or they can be formed by a series of obstacles or dams placed in a sloping channel. In the latter case the flow from pool to pool may be over solid obstacles, or through notches or orifices in the obstacles, or a combination of these two types may be used.

Each pool affords a more or less adequate resting place for the ascending fish according to the size and design of the pools. The effort required of the fish is intermittent, alternating between exertion and partial rest. When the obstacles have submerged orifices, the fish generally prefer to use them, thus avoiding exposure. In negotiating an ordinary overfall the fish usually swim up the falling jet. The tendency to jump from pool to pool is limited to certain species of fish and is caused by inadequate conditions for swimming such as exist when the overfall jet is too shallow. According to Denil, passing from pool to pool the fish must work against two forces; first, against the velocity of the jet or overfall; second, against a “threshold resistance” encountered in entering an orifice or passing over an obstacle. In the case of an overfall the fish must raise itself from one pool elevation to the next and in the case of an orifice the fish must work against the difference in the static pressures on the two sides of the orifice.

The pool and jet fishway in its many variations is probably the oldest and most widely used of all types. It has been investigated extensively and in its common forms is found to be suitable for mild slopes only. However, the overfall type has the advantage of being attractive to the fish. Where submerged orifices are used, they are ordinarily staggered, i.e., they are placed on opposite sides of successive obstacles. This disposition of orifices is not desirable from the standpoint of the fish, but it is more effective hydraulically than a straight-line disposition if the common vertical obstacles are used. However, a successful pool and submerged-orifice fishway has been developed which has all the orifices on the center line.

Figure 4
Photos and diagrams of the pool-and-jet models tested are shown in Plate III and in Fig. 6.

A. Ordinary Pool and Jet Fishways

Model 12 is a conventional overfall whereas Model 13 is a slight modification of, and also a slight improvement over, Model 12. Both are limited to use at very mild slopes and with small fluctuations in headwater.

Model 14 is a copy of a design recommended by John Spencer. It has been used in many installations in the United States. These tests showed it to be slightly less effective hydraulically than the straight overfall, but is preferred somewhat more by the fish because the deeper jets allow passage without exposure. The same can be said of Model 18, which, although originating in the laboratory, was found later to be similar as to disposition of pools to a fishway in use in Scotland. We do not expect that the spiral layout will find general application, but rather that it will be suited to use where space is extremely limited or where the particular topography of a site lends itself to such a disposition. Model 19 also is intended to conserve space.


The Cail fishway of the proportions of Model 15 was found by these tests to be the best of the conventional pool-type fishways studied. It is effective at greater slopes and for greater variations in headwater. It affords the possibility for the fish to be out of sight and also has fair hydraulic conditions. However, Model 16 with the stepped bottom and the longer pools, copied from a U. S. B. F. design of about 1898, was entirely unsuccessful in the studies with small fish and no hydraulic tests were made.

Model 17. Pool and overfall—submerged jets on center line.

This model was entirely unsuccessful.

B. Pool Fishways Based Upon Abrupt Deflection of a Jet Immediately at Its Issue

Models 20, a, b, c, d. Pool and jet—submerged jets on center line.

Ordinary pool-and-jet fishways with staggered orifices are usually low in efficiency. In fact, if the jets are strongly deflected in the horizontal plane, a vortex or whirlpool of great intensity would be formed, which would disorient the fish. If, on the other hand, the jet deflection is moderate the energy dissipation will also be moderate, and in consequence the slope would have to be very small. Denil suggested therefore that the cross walls of an ordinary pool fishway be given a slight slant downstream in order to secure a certain amount of jet deflection in the vertical plane and thus improve the energy dissipation of the pass as a whole. Nemenyi and White (London), made a new design based upon strong jet deflection in the vertical plane; thus eliminating the feature of a tortuous passage, which is, apart from other shortcomings, doubtless a cause of additional effort for the fish. This simple new design is characterized by cross walls slanted strongly downstream with submerged orifices in axial disposition. Design 20d, the fifth in a series of trials, satisfied all requirements and has been recommended by its designers for fairly large salmon passes of 1/5 slope. For small fishways it can probably be used with somewhat steeper slopes. A qualitative explanation of the fluid mechanics of this fishpass is given in the report of the London study. Here suffice it to state that the broadening of the jet in itself does not secure the

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1John Spencer, "Fishways in California," 1932.
energy dissipation; this is accomplished rather by the "friction" be­tween the broadened jet and the water in the pool. Therefore the sys­tem is efficient only insofar as at least part of the broadened jet sur­face is submerged.
It appears likely that the energy dissipating effect will be stronger if the jet produced by the orifice is as free as possible from vorticity and large-scale turbulence. If this assumption is correct, a certain amount of improvement upon the London design would be possible by giving the orifice either a gradually convergent form, or an abruptly

Model 15

Model 16

Model 17
Figure 6—Details of Fishway Models—Pool and Jet Types
divergent one. In the former case the downstream edges of the orifice would issue a "healthy" convergent stream; in the latter case, the jet would separate at the upstream edges and show the convergent contracted form characteristic of a free jet. On the basis of these considerations, three modified forms of the London design were made, the modification being restricted to the orifice and the adjoining details of the baffles. See Fig. 6 and Plate III.

A comparison between these designs was made by constructing sections of the same model channel according to the three designs. It was found that baffles type "a" of the three modified designs is appreciably, though not substantially, superior to the other two. As this design is somewhat elaborate, the two others were investigated in more detail. Fig. 7 shows the main results of this test. The two designs may be considered about equally effective with a very slight difference in favor of baffle type "c"; although the best conditions for each are not the same. An indirect comparison with the London results\(^1\) indicates that neither one of these two designs is appreciably better than the original.

A better understanding of the fluid mechanics of a fishpass can often be gained by comparing the flow when the pass is in its proper position with that which takes place if the tailwater and headwater ends are interchanged. Such a comparison was made for the baffle type "b" and "c," with a slope of 20 per cent and a discharge of 10.6 lb./sec.

The main results are:

<table>
<thead>
<tr>
<th>Fishpass Model</th>
<th>Fishpass Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>in Proper</td>
<td>in Reversed</td>
</tr>
<tr>
<td>Position</td>
<td>Position</td>
</tr>
<tr>
<td>Depth of water in pools</td>
<td>6 in.</td>
</tr>
<tr>
<td>Greatest velocity head</td>
<td>2 in.</td>
</tr>
<tr>
<td>Greatest velocity</td>
<td>3.27 ft./sec.</td>
</tr>
</tbody>
</table>

The difference is very striking. It indicates once more that the "size" and distance of "obstacles" is only part of their description; their particular shape and position with respect to the flow direction being at least an equally important condition of their efficiency. It illustrates also the essential irreversibility of dissipative processes in fluid motion.

Alternate obstacle fishways: The alternate baffle fishway consists in general of a straight rectangular channel with obstacles or baffles placed alternately along the sides producing a jet deflection in the horizontal plane. This type of fishway has been built in an almost unlimited variety of baffle shapes, spacings, and angles. The flow is confined to a zigzag path which is much longer than the fishway. The width of passage is effectively less than its measured width because of its tortuous form. Velocities are sharply localized and are often in such a direction as to strike the fish from the side. The water depth is usually irregular and there are many whirlpools or vortices. Few of the forms used provide adequate resting places for the fish. Baffle

\(^1\)The comparison is not direct because in the London tests the slope was 28% while in the present tests 15, 20, and 25% slopes were used.
Velocity Head Distribution
Along Axis of Channel
Model 20
Baffle Type b — Baffle Type c —

Slope of Fishway
20%
Depth of Flow
7.5"  
Slope  20%
Depth 6"
Slope  20%
Depth 4.25"
Slope  15%
Depth 7.5"  
Slope  15%
Depth 5.2"
Slope  15%
Depth 3.3"

Figure 7
arrangements can be made which minimize these difficulties and pro-
vide a fair passage for fish if the slopes used are mild. However, most
fishways of this type are unsatisfactory.

The models of this type studied are shown in Plate IV and Fig. 8.
Models 22, 23, and 24 are copies of types in common use whereas Model
21 resulted from a series of trials to determine the best length, angle,
and spacing of baffles for this type. However, the results were not
promising and the search was abandoned with the form shown. Pre-
liminary tests of Models 23 and 24 showed them to be inferior types
and no hydraulic tests were made. However, Model 22 which was copied
from the installation at Coralville, Iowa, was studied more thoroughly
and proved to be a very effective design for this type; but owing to
the very tortuous path the fish have to follow the favorable hydraulic
conditions should not lead to an overestimation of the possibilities of
this type.

**Paired-obstacle fishways:** The paired-obstacle fishway consists of a
sloping rectangular channel with baffles or obstacles in opposed pairs
spaced along the channel at intervals about equal to the channel width
and with a straight free passage between them. The free passage is
considerably restricted, one-half to five-eighths of the channel width
being taken up by the obstacles. The floor of the free passage is usu-
ally flat, although small bottom obstacles may be used. The flow is
relatively deep as it passes the restricted area between a pair of ob-
stacles; but the jet flattens and spreads on the channel floor and a
large part of it is intercepted and reversed in direction by the suc-
ceeding pair of baffles. In effect, the flow is a series of pools and ori-
fices; and although the free passage is straight, it cannot be considered from the hydraulic standpoint a true channel type fishway. The effort required of the fish varies, being a maximum at the obstacles. The wide spacing of the pairs of obstacles along the channel gives the fishway the hydraulic function of a pool and jet type fishway but since the pools are divided by the central flow they do not afford much of a resting place except to the smaller fish. This type of fishway adapts

Plate IV
Paired-Obstacle Fishway Models
itself to a considerable range of headwater elevation with little change in flow characteristics. However, the flow was unstable in the full-scale fishway. This unstable condition has been found in other hydraulic tests where pairs of obstacles were placed symmetrically in a stream.

The models of this type studied are shown in Plate IV and Fig. 9. All designs originated in the laboratory.

Although the full-scale fishway of this type studied was unsuccessful because of the instability of the flow, a few of the better designs will be pointed out because of the particular success of the models with the small trout. Furthermore it may be possible to stabilize the flow in an unsymmetrical pattern by slightly offsetting some of the baffles, an expedient which has been successful where similar instability was encountered.

Figure 8—Details of Fishway Models—Alternate-Obstacle Types

Model 21

Model 22

Model 23

Model 24
Models 26 and 28 have fairly strong circulation in the side pockets or channels formed by the baffles, a condition which causes a large amount of water to be thrown back against the jet formed by the preceding pair of obstacles. The type of energy dissipation which takes place is similar to that described for Model 20, a submerged-orifice fishway.
II. FULL-SCALE STUDIES

Object

The object of this study was to compare various designs of full-scale fishways using fish actually migrating, and to maintain as large a degree of control as possible over the conditions under which the comparisons were made.
General Set-up

The layout of the Hydraulics Laboratory of the University of Iowa is particularly suited to a study of this type. The University dam on the Iowa River is 120 feet upstream from the laboratory and has a head at low-water flow of about 9 feet, which can be increased about 1 foot by the use of flashboards. It is the first dam on the Iowa River above the Mississippi (70 miles away), and cannot be negotiated by fish except possibly at very high flows which occur only rarely. An alternate obstacle fishway was built with the dam, but it is no longer in operation.

Figure 11 shows the layout of the dam and the laboratory channels. The fishways were placed in a channel 10 feet wide and 10 feet deep that starts at the dam, passes through the laboratory and enters the

Details Of Fishway Models
Paired Obstacle Types
Figure 9

http://ir.uiowa.edu/uisie/24
river about 350 feet downstream. Flow in the channel is controlled by a motor operated headgate.

In previous use of the channel for hydraulic tests other than fish-way studies during fish-migration periods, large numbers of fish entered the channel. For this reason it was thought to be a likely place for studies of this type, although a point so far downstream from the dam would usually not be considered proper for a fishway entrance.

A bulkhead 8 feet high was placed in the channel 30 feet downstream from the dam. Two openings were cut in the bulkhead at 6-foot height to receive the fishways, which were operated in pairs for comparison.
All fishways were 24 feet long and set at a 1:4 slope. This constant slope was one of the chief limiting factors in the scope of studies.

A depth of flow of about 2 feet was maintained in the channel below the fishways. In the spring, the river stage was high enough so that backwater from the river maintained this depth. As the river stage dropped, it was necessary to install a series of low baffles in the channel downstream from the fishways to maintain the proper depth. During the summer and fall the flow from the fishways was augmented by...
flow under the bulkhead and auxiliary flow from the large channel on the east side of the laboratory.

**Fish Counting Arrangement**

In order to keep a record of the fish which passed the fishways, a net was placed on the top of each fishway. These nets were cubical frames 5 feet on a side covered with galvanized hardware cloth. Traps were placed at the entry to the nets to prevent the fish from returning down the fishways. At first the tops of the nets were not covered, but it was found necessary to cover them because of the large number

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**Plate V—Views of Full-scale Fishways**
of carp which escaped by jumping out into the headwater. The nets were hoisted with a block and tackle for removal of fish or for inspection.

Periodic checks of the fish in the approach channel was made by seining, after placing barriers across the channel at both ends of the laboratory. The fish were returned to the approach channel after being counted. In the early part of the studies a daily check was made but later checks were made only occasionally.
Operating Technique

The fish were taken from the nets at two-hour intervals during the period of greatest activity and about three times daily throughout the balance of the season. In a few cases the count was continued through the night. The rough fish were removed and all others placed in the river above the dam.

The following test data was recorded:

1. The types of fishways in place and their position, i.e., east or west side of the channel.
2. The date and time of day.
3. The flow conditions in the fishways.
4. The number and approximate size of each species of fish in each trap.

In addition complete climatological data was gathered and notes were made of peculiarities of the weather and the muddiness of the river.

Fifteen comparisons of fishways were made over a period of 75 days or an average of five days for one pair or comparison. Of these 15 comparisons, some were repeated comparisons in which the fishways were reversed in position to determine whether or not the fish tended to follow one side of the approach channel and thus favor the fishway on that side. The conclusion was that there was no such tendency.

The operating range of each fishway was studied by varying the flow depth and noting the effect on the efficiency as determined from the resulting fish counts. The size of fish, the apparent effort of the fish in climbing and the appearance of the flow were noted in this connection.

However, a single set of conditions or a small range of conditions does not suffice to adequately evaluate a fishway. In these tests, for example, assuming that equal numbers of fish approach each of two fishways and the requirements of each fishway are within the normal ability of the fish, an equal count would probably result indicating that the fishways were of equal efficiency, which might be far from the truth. Other decisive factors such as slope and height of dam which were not varied in these tests must be studied to give the whole picture.

Discussion of Full-scale Fishways and Results

The full-scale fishways studied were (1) conventional types in general use as reported by the various Fish and Game Commissions, (2) modern European types, and (3) types developed in our laboratory tests. Inasmuch as the pool and jet fishways are most widely used in this country, several variations were studied. One alternate-obstacle fishway was included because of its extensive use in this region. Only one definitely new type resulting from the laboratory tests was used. Of the others some are copies, the rest modifications of modern European fishways.

A. Pool and Jet Fishways

1. Pool-and-overfall jet (6 variations)
   (a) Straight obstacles (shown in Fig. 12).
   Straight channel 30 inches wide, 36 inches deep, 24 feet long. Ob-
Obstacles 2 feet high spaced 3 feet along channel. Obstacles hinged at bottom. Slope of fishway 1 to 4.

This fishway was very sensitive to headwater changes. If the flow over the baffles was less than 4 inches deep, the fish were unable to climb. If the flow was more than 6 inches deep, there was periodic surging and large "slugs" of water moved down the fishway. To maintain flow within this narrow range it was necessary to vary the height

![Diagram of fishway details](http://ir.uiowa.edu/uisie/24)

Figure 12—Details of Full-scale Fishways
of the top baffle. Even with close attention given to flow regulation it was very difficult to maintain proper flow. With a 3-foot spacing of baffles and a slope of 1 to 4, the difference in elevation between consecutive pools is 9 inches. Longer pools would necessitate greater heights between pools unless the slope was reduced. Closer spacing of the baffles is not recommended since the 3-foot pool length used is thought to be about minimum. From the results obtained, even a 9-inch rise appears to be large.

Within the narrow range of 4 to 6 inches depth over the baffles, the appearance of the flow was quite good. The energy from each overfall

![Diagram of fishways](http://ir.uiowa.edu/uisie/24)

*Figure 12—Details of Full-scale Fishways*
was dissipated in the succeeding pool and there was upstream flow on the surface of the pools.

The baffles were first installed vertically but it was observed that the fish had difficulty in passing over the square edge of the baffle. Because of this difficulty and also for the purpose of increasing the circulatory motion in the pools, the baffles were tilted upstream 5 inches. The fish rested in the pools, sometimes for periods of half an hour or more. The attraction at the foot of the fishway is particularly good. However, more carp than other fish were attracted.

This fishway was compared with the Denil type (Full-scale No. 6) and also with the submerged-orifice fishway (Full-scale No. 3). The fish using the submerged fishway outnumbered those using the overfall fishway more than four to one, whereas those using the Denil type outnumbered it almost eight to one. One-half to two-thirds of the carp, but practically no other fish, used the overfall fishway.

(b) Notched obstacles (shallow notches)—one side only).
(c) Notched obstacles (shallow notches—alternate).

Same description as No. 1-a except baffles are notched. Notches 6 inches deep, 1 foot wide.

As with the straight overfall, these fishways are sensitive to changes in elevation of the headwater and close control was necessary. The results were found to be best when the notch flowed full and when there was no flow over the top of the baffle. A slight circulatory motion was noticed in the pools, and the flow did not carry over from pool to pool if carefully controlled. The notching of the obstacle tended to cut down the jump height; and although the effort required is probably no less than for the straight overfall, the fish are less exposed in passing an obstacle.

The attraction to the fish is fairly good and the water required is less than for the straight overfall (Full-scale No. 1-a). Except for the direction of the eddies in the pools there was very little difference in the action in the two shallow-notched overfall fishways.

These fishways were compared consecutively with the Denil type fishway (Full-scale No. 6) for brief periods. One-half of the carp used the shallow notched overfalls, but 7 out of 8 of all fish used the Denil type.

(d) Notched obstacles (deep notches—alternate).
(e) Notched obstacles (deep notches—one side).

Same description as for No. 1-a except baffles are notched. Notches 1 foot deep, 1 foot wide.

With the 1-foot depth of notch, the flow is quite strong and the difference in action caused by having the notches on one side or on alternate sides is quite marked. The general appearance is not particularly good. However, these fishways are less sensitive to headwater changes than the straight overfall or the shallow-notch types. Because of the depth of the notches, the water surface approaches a slope rather than being a series of overfalls. The velocity of flow is quite high but the
fish pass through the notches without an abrupt change in the position of their bodies with respect to the horizontal.

In the alternate notch fishway the eddies in the pools are strong. In moving from pool to pool the fish must pass diagonally through a high velocity jet. However, when they have passed the jet they enter water that has an upstream motion.

With the notches on one side the flow proceeds down the notched side with fairly high velocity. The circulation in the pools is slight, indicating that little energy is dissipated there. Resting conditions are excellent; on the other hand, passing through the jet is difficult since the fish must project itself diagonally into the high-velocity stream and turn again to get out of it. However, the greater depth of the notch seems to somewhat offset the other difficulties, probably because the fish need not expose themselves in passing the obstacles.

These two fishways were compared consecutively with the Denil type (Full-scale No. 6) with almost identical results. In each case about one-half of the carp, one-half of the catfish and one-quarter of the quillback used the notched overfalls. The ratio of preference of all fish for the Denil type was 3 to 1. It will be noted that as the notches were deepened, resulting in less of a "jump," fish other than carp used the overfall type in increasing numbers. The catfish were the first to follow the carp in negotiating the overfall types and the quillback were most reluctant. Other species were not present in quantity but the general preference was for the Denil type.

(f) Notched obstacles (deep notch—on center).

Same description as for No. 1-a except baffles are notched. Notches 1 foot deep, 1 foot wide, on center line.

As was observed in the fishway with the deep notches on one side, there is a carry-over of flow between pools with little energy dissipation in the pools. The rest pools are divided and thus have no value. However, this condition could be improved somewhat by widening the channel. The sensitivity of this fishway to headwater changes is about the same as that of the previously discussed deep-notch types. That is, it is less sensitive than the straight overfall or shallow-notch types but is still appreciable. With the notches flowing full the rate of flow is rather large.

This fishway was compared with the Denil type (Full-scale No. 6) for a four-day period. The preference for the Denil was about seven to one, or about the same ratio as was found in the comparison of the straight overfall and shallow-notch types with the Denil. There was no marked selection as to species. About one-fifth of the carp used the overfall, but this was the largest proportion for all species.

2. Cail types (shown in Fig. 12)

Straight channel 30 inches wide, 36 inches deep, 24 feet long. Baffles 2 feet high, spaced 3 feet along channel. Submerged orifices staggered, graduated in size. Downstream orifice 8.5 inches by 8.5 inches. Upstream orifice 12 inches by 12 inches.

This Cail-type fishway is the result of modifications made during the
tests of a commonly used Cail design. The pools were first made 6 feet in length but it was found that they could not be maintained full except at high flows. That is, the water passed directly from orifice to orifice. It appears that the pools should be about square in order to produce the desired circulatory motion. The flow was kept even with the tops of the baffles and all flow was through the orifices, as this appeared to be about right for best operation. The circulation in the pools was moderate and the resting facilities were excellent. However, in passing between pools it was necessary for the fish to pass diagonally through the jet. Once they had passed the jet they were in the upstream movement of the eddy in the next pool which allowed them to rest immediately.

Fish were able to ascend this fishway even when the flow was low enough to expose the orifices but they found much better flow at baffle depth (2 feet). The action at very high flows is not definitely known. The only check on this is that during one short flood peak, which occurred during the night, practically no fish ascended the Cail fishway whereas many were found to have used the Denil type (Full-scale No. 6) with which it was being compared.

This fishway was compared with the Denil type for three days in the latter part of May and again for nine days in June and July. In the first comparison the preference for the Denil type was two and one-half to one and in the second case it was four and one-half to one. There was no particular selection as to species except that slightly fewer quillback used this fishway.

3. Pool and submerged orifice (with abrupt jet deflection) (shown in Fig. 12)

Straight rectangular channel 30 inches wide, 30 inches deep, 24 feet long. Baffles at right angles to flow, spaced 36 inches along channel sloped downstream, angle with bottom 55 degrees. Orifices on center line 10 inches wide, 12 inches deep.

The full-scale fishway used in this investigation was the first of this design to be built. The results fully justify the expectations based upon the London laboratory results and the present model tests. No variation from the model characteristics was noted except for full flow. When the flow is even with the top of the baffles the rolling motion in the pools is quite strong. This is probably the least favorable condition of flow because fewer fish used the fishway under these conditions. However, it operates well throughout a wide range of headwater elevation. For small depths of flow when conditions for energy dissipation for this type are less favorable, this fishway still continues to be passable to a considerable extent. Apparently even with the shallow flow the obliqueness of the jet tends to decrease the "threshold resistance" which, according to Denil's investigation of ordinary pool-orifice fishways, is about three-fourths of the total force the fish must overcome. Thus the minimum depth for effective operation is determined by depth necessary for swimming, depending on the size of the fish rather than the mechanical effort.
The tailwater end when submerged has no attraction other than the underwater current. To increase the attraction, this end of the fishway was raised until the jet was partly exposed. By comparing fish counts it was concluded that medium flow with the lower jet partially exposed gave the best results and that the medium to low-flow range was better than the medium to high-flow range.

This fishway was compared in the early part of the study with the straight overfall. The ratio of preference for the submerged orifice fishway was more than 4 to 1. The flow was even with the top of the baffles throughout most of the period. The submerged orifice fishway was later compared with the Denil type under average conditions for both and the results for each we found to be the same in the total number of fish, the catfish, however, tending to favor the Denil type.

This design can be recommended either in its original form or with the slight modifications used in the model tests. As the foregoing full-scale tests were made with a copy of the original London design and gave good results, either this or the simplest of the three modifications (20-c) should be used in practice.

B. Paired-obstacle Fishways

4. Angle obstacle (shown in Fig. 12)


This design was selected from several models of the same type studied in the laboratory. It has a straight free passage but is not a strict channel type because the flow is similar to a series of orifices. Although it is intended that fish make continuous passage, the effort required is not uniform, since the effort must be greater when passing between the obstacles. This is the type of effort required to overcome the "threshold resistance" in the usual pool and overfall fishways. The pools, being halved by the flow, are not adequate resting places except for the smaller fish.

Although the model of this type showed excellent hydraulic properties, the full-scale fishway was unsatisfactory because the flow was unstable, with waves traveling down the fishway in a zigzag path. This phenomenon has been observed by other experimenters when working with symmetrically placed obstacles\(^1\); these results indicate that the flow could probably be stabilized in an unsymmetrical pattern by a slight unsymmetry in the baffle placing or form. But the unsymmetrical flow pattern would reduce the other advantages of this type. When the water depth was 18 inches to 2 feet the flow was somewhat more stable, but this range is relatively small.

This fishway was compared with the Denil type (Full-scale No. 6) for a seven-day period in June. The ratio of preference for the Denil was approximately five to one. The particular feature of the compari-

son was that no catfish used the paired-obstacle fishway. The shad, however, used the two fishways in about equal numbers.

C. Alternate-obstacle Fishways

5. Coralville copy (shown in Fig. 12)


The proportions of this fishway were taken from one installed at the Iowa City Power & Light Company dam at Coralville, Iowa. The slope of 1 to 4 used during the tests was, however, somewhat less than that of the fishway copied.

When a reasonable slope is used, the flow has a good appearance for a fishway of this type. Slight eddies form near the center line, while the high velocity flow swings toward the sides. The fish must follow a zigzag path which is generally considered to be unfavorable, and they must pass diagonally through a jet of relatively high velocity. The pockets formed by the baffles are only partially effective as resting places since they are relatively small and are occupied in part by high velocity flow.

At very shallow flow the conditions tend to change, i.e., the center flow becomes swift at the same time that the pools improve. At such low flows large fish cannot negotiate the fishway, although small fish can pass from pocket to pocket. The action in the fishway is not destroyed even when the flow is so high as to overtop the baffles and as a result the allowable range of headwater variation is fairly large.

This fishway was compared with the Denil (Full-scale No. 6) for a five-day period in June and again for a six-day period in July. About equal numbers of fish used the two fishways in each period. There was no particular selection as to species except that more catfish (two to one) used the Denil type and more quillback used the alternate obstacle fishway.

D. Modified Denil Fishways

6. Small Denil (shown in Fig. 12)


This fishway is a slight modification of a Denil fishway, selected from the models studied in the laboratory. It was designed for construction either in concrete or wood. The character of the flow was the same for all depths and conditions as observed in the model.

There is little apparent change in flow characteristics or in velocity with a change in flow depth. It is not affected by headwater and tailwater conditions so long as the fish can enter the fishway, and so long as there is sufficient water flowing. Strong overtopping does not reduce its effectiveness. The fish were not visible when ascending, although in clear water Denil claims the fish have good access to light.
This fishway was compared with all other fishways used during the tests. It serves therefore as an index of comparison for the complete series. Reviewing the data already presented in connection with the various full-scale fishways, we see that the ratio of preference for the Denil type was about 7 to 1 when compared with the straight overfall fishway, the two shallow-notched overfall fishways, and the center-notched fishway. When compared with the paired-obstacle fishway, the preference for the Denil type was about 4.5 to 1. When compared with the two deep-notched overfall fishways and with the Cail fishway, the preference for the Denil was about 3 to 1. The preference for the small Denil over the large Denil was about 1.75 to 1. The preference for the submerged orifice and the alternate-baffle fishways when compared with the Denil fishway gave equal results as to numbers. The catfish, however, tended to favor the Denil type.

One interesting occurrence during the tests was the use of the small Denil fishway by a catfish weighing about 25 pounds and measuring 33 inches and 9 inches across the head. The channel width of this fishway was 10 inches only.

7. Large Denil (shown in Fig. 12)


This fishway is essentially the same as the small Denil but increased 50 per cent in cross-section breadth. The general character of the flow is the same as described for the small Denil, but the velocities are higher and the larger secondary streams make the water surface rougher. According to Froude's law, the velocities should be greater than those in the small Denil type by an amount equal to the square root of the number of times the size is increased. In this case they would be about 1.2 times larger.

The larger fishway of this design was made because it was thought that possibly the smaller one was too small for good results. However, the preference for the smaller fishway was found to be 1.75 to 1. Most fish, but particularly the catfish, definitely favored the small Denil type; whereas the carp tended to use the large Denil fishway. The carp swim with a wide side motion which may account for their choice of the larger fishway.

III. OBSERVATIONS OF FISH BEHAVIOR

Information concerning fish activity was collected incidental to the study of the efficiency of fishways. For example, the daily and hourly records which were made primarily for a comparison of the fishways serve as a record of fish movement during the same periods. When it became apparent that the study could serve a dual purpose, additional effort was made to observe and record pertinent data.

Data Recorded

A large number of agencies at Iowa City keep accurate daily weather
and stream-flow records which are available for comparison with the fish activity records. A brief sample of these records is shown in graphical form in Fig. 13 and includes river stage, muddiness, river-water temperature, air temperature, cloudiness, precipitation, and barometric pressure. On the same time scale is plotted the hourly rate of movement of the various species of fish and also the hourly rate of the total number of fish using the fishways. The total graphical record

<table>
<thead>
<tr>
<th>AM</th>
<th>MAY 8</th>
<th>PM</th>
<th>AM</th>
<th>MAY 9</th>
<th>PM</th>
<th>AM</th>
<th>MAY 10</th>
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</table>

**Rate of Fish Movement Up Experimental Fishways**

IOWA RIVER, IOWA CITY, IOWA 1939

Fig. 13
covers the period of May 3 to July 11, during which time the full-scale studies of fishways were in progress. However, the fishways remained in place and the records were continued throughout the season. Fig. 14 shows the season's run (all species) in a brief graphical form compared with the river-water temperature. The lower graph shows the accumulative percentage of the total seasonal run of fish.

Analysis of Data

No particular effort was made to analyze these records. However, from a brief examination of the charts and tabular data it is observed that practically no fish moved up the fishways until the water temperature had reached 65 degrees F. in the spring, and practically no fish used the fishways after the water temperature had dropped below 65 degrees F. in the fall. This is in agreement with the results obtained by Schmassman in Switzerland. There is considerable evidence to indicate that the fish travel when the stage rises. Further correlation between weather variables and fish travel is not immediately apparent or would require several seasons of study for determination.

Seining Approach Channel

In order to determine whether some species were not negotiating the fishways the approach channel was seined periodically and the fish counted. It was found in general that the fish in the approach channel compared in number and species to the fish found in the nets; and no species appeared in the channel that was not found in the nets, thus indicating that the conditions of the test were within the limits of ability of all species present. However, during a brief period in May, large numbers of catfish were found in the channel, although few used the fishways where earlier they had been very active. Normal balance was restored about the middle of May and no other marked variation was noted.

Most species were found in the approach channel at least a week before they were found in the traps above the fishways. In the case of the quillback a period of one month elapsed between their first appearance and the time of use of the fishways, whereas some species climbed immediately upon arrival. At least a few of most species appeared as early as April 27 and used the fishways soon after, although the main period of activity for some of these species was much later. Examples were the sheephead perch and yellow catfish, their activity starting about one or two months respectively after the first were found in the nets. This was also true of the bullheads, but they were too few in number to be considered.

Throughout the entire season, the largest catches of fish by the many fishermen below the dam occurred at times of greatest fish activity in the fishways. The correlation was noted in both number and species, strengthening the general impression that when no fish are caught it is likely that few fish are present in the area.

Rate of Movement

The maximum rate of fish movement up the fishways occurred on
May 25 between 12 noon and 4 p.m. and directly preceding a sudden electric storm. The average hourly rate for the four-hour period was 78 per hour, and the maximum hourly rate is believed to have been well over 100 per hour. Directly following the storm the number returned to near normal.

The maximum daily run was 580 and occurred on May 21. Other high daily runs occurred on May 27 and 25 and were 573 and 557 respectively.
The period of greatest activity, considering all species, is the last two weeks in May as is shown by Fig. 14. The accumulative graph shows that 50 per cent of the season's total run had passed the fishways by June 1, and that a two-month period ending July 15 accounted for 80 per cent of the run.

Records of Individual Species

The records of the individual species have been compiled so far as possible and are shown in Table I. Where the data is insufficient or doubtful the record is left blank. Furthermore it must be kept in mind that the table represents a single season and that it possibly differs considerably from the average of several seasons. However, it does give a brief picture of some factors of the full-scale studies.

![Rate of Fish Movement up Fishways](http://ir.uiowa.edu/uisie/24)

![Accumulative Percentage of Total Number of Fish Passing up Fishways](http://ir.uiowa.edu/uisie/24)
Tagging Tests
On May 11, 66 carp, quillback, and catfish were tagged and placed in the river about one-half mile downstream. One tagged carp returned on May 16. In the five months that the count was continued after this date no other tagged fish were found in the nets. Although tagging of fish is a recognized method for migration studies this attempt was too limited to give any useful conclusions.

Figure 15

Rate of Fish Movement
Up Fishways
Quillback
Cottfish
Carp
Shad
Herring
Perch
Buffalo
<table>
<thead>
<tr>
<th>Species</th>
<th>Total Number</th>
<th>First Seen</th>
<th>First in Traps</th>
<th>Main Run</th>
<th>Last Seen</th>
<th>Size Range (Inches)</th>
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<tr>
<td>Quillback</td>
<td>7,285</td>
<td>Mar. 28</td>
<td>May 4</td>
<td>May 18 to May 27</td>
<td>Oct. 5</td>
<td>5 to 14</td>
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<tr>
<td>Channel Catfish</td>
<td>1,991</td>
<td>Apr. 25</td>
<td>Apr. 28</td>
<td>May 18 to May 27</td>
<td>Sept. 16</td>
<td>4 to 20</td>
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<tr>
<td>Carp</td>
<td>1,446</td>
<td>Apr. 29</td>
<td>May 3</td>
<td>May 18 to May 27</td>
<td>Sept. 26</td>
<td>8 to 24</td>
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<tr>
<td>Gizzard Shad</td>
<td>434</td>
<td>Apr. 27</td>
<td>May 7</td>
<td>May 20 to June 10</td>
<td>Sept. 20</td>
<td>4 to 12</td>
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<td>Mooneyed Herring</td>
<td>312</td>
<td>May 24</td>
<td>May 24</td>
<td>June 3 to July 28</td>
<td>Sept. 25</td>
<td>4 to 14</td>
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<tr>
<td>Buffalo</td>
<td>232</td>
<td>Apr. 20</td>
<td>May 7</td>
<td>Sept. 25</td>
<td>5 to 20</td>
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<tr>
<td>Sheephead Perch</td>
<td>129</td>
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<td>May 24</td>
<td>Sept. 18</td>
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<tr>
<td>Yellow Catfish</td>
<td>14</td>
<td>Apr. 27</td>
<td>Apr. 27</td>
<td>June 30 to July 12</td>
<td>July 12</td>
<td>14 to 23</td>
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<tr>
<td>Redhorse and Common Sucker</td>
<td>10</td>
<td>Apr. 26</td>
<td>Apr. 25</td>
<td>July 17</td>
<td>10 to 14</td>
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<tr>
<td>Chub</td>
<td>3</td>
<td>Apr. 27</td>
<td>Apr. 27</td>
<td>July 17</td>
<td>10 to 14</td>
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<tr>
<td>Bullhead</td>
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<td>Apr. 27</td>
<td>May 26</td>
<td>May 27</td>
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<td>Walleyed Pike</td>
<td>1</td>
<td>May 6</td>
<td>May 6</td>
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<td>Pickerel</td>
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<td>May 10</td>
<td>June 19</td>
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<td>Eel</td>
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<td>Aug. 9</td>
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<td>Aug. 9</td>
<td>14</td>
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<tr>
<td>Sunfish</td>
<td>2</td>
<td>May 27</td>
<td>May 27</td>
<td>June 9</td>
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### OF INDIVIDUAL SPECIES

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<tr>
<th>Fishway Type</th>
<th>Preferred</th>
<th>Avoided</th>
<th>Concealed Swimming</th>
<th>Concealed Swimming Preferred</th>
<th>Prefers Jump</th>
<th>Locomotive Power*</th>
<th>Breadth Required for Locomotion**</th>
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<tr>
<td>Small Denil</td>
<td>Pool and overfall, Full-scale 1-a</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Average</td>
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<tr>
<td>Small Denil</td>
<td>None</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Average</td>
<td>Average</td>
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<tr>
<td>All pool and overfall types</td>
<td>None</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Strong</td>
<td>Broad</td>
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<tr>
<td>All pool and overfall types</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Strong</td>
<td>Average</td>
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<tr>
<td>Small Denil</td>
<td>All others</td>
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<td>No</td>
<td>No</td>
<td>Strong</td>
<td>Weak</td>
<td>Narrow</td>
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<tr>
<td>All pool and overfall types</td>
<td>Paired obstacle</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Strong</td>
<td>Weak</td>
<td>Narrow</td>
</tr>
</tbody>
</table>

*Compared with species listed only.

**Relative to breadth of fish.
Injuries

Injured fish were never found when only a few were in the nets. From this it is concluded that no injuries resulted from climbing the fishways. However, when large numbers accumulated in the nets many quillback and some carp were found to be injured. Injuries to other species were very rare, and in no case was an injured catfish seen. Denil's studies also showed that even very sharp-edged obstacles do not injure the fish if the breadth of passage is adequate.

Obviously the injuries to the carp resulted from their vigorous attempts to escape from the nets; the quillback could not stand the crowded conditions and died quickly when handled.

Behavior of Fish in Model Tests

Some observations of the behavior of the fish used in the model tests are of interest. The trout were kept in the laboratory river channels where the water temperature was about 34 degrees F. and were transferred to the test flume a few at a time when needed. Since the water temperature in the test flume was 59 degrees F., it was necessary when transferring the fish to put them in a container and gradually change the water temperature until it was near that of the test flume water.

After a few days in the test flume the fish became sufficiently acclimated to be used in the tests. Attempts to use the fish for tests before a two or three-day conditioning period were almost always unsuccessful. The trout displayed a very nervous disposition. They even seemed to change in color when upset by a radical change in conditions.

The water in the test flume was aerated to provide oxygen and produce motion. The fish were fed daily with chopped pork liver. When not fed they displayed cannibalistic tendencies. The rainbow trout were the most vigorous and hardy and dominated the others, while the German brown trout seemed weakest and least aggressive. Each trout was readily identified by his individual characteristics and habits. Each fish had its own place in the fish compartment and was usually forced to remain there by one large rainbow trout.

The ability of the several individual fish became known from repeated ascensions of the models. One of the techniques of testing a model was to choose succeedingly weaker individuals in order to better determine the suitability of the flow conditions to the passage of fish. In like manner succeedingly smaller fish were used to find the limiting size of fish that could negotiate a particular model. Thus the use of fish was an aid to a more thorough knowledge of the characteristics of the models and an indication of their suitability to actual use. Of course, further verification of these results by full-scale tests was necessary.

It appeared that the fish learned to climb. A certain few performers could always be depended upon to negotiate the fishways whereas fish just introduced from the storage channels were not dependable even though they had passed the usual acclimating period.
IV. CONCLUSIONS AND RECOMMENDATIONS

As indicated in the introduction, the present research can be considered as but the preliminary stage of a thorough investigation of the problem. Accordingly most of the results admit only more or less tentative conclusions and serve merely as a starting point for further studies.

However, sufficient evidence has already accumulated to justify the following general conclusions and specific recommendations:

Method of Testing

Although questions of dynamic similarity were beyond the scope of the first stage of this study the following results have been well established.

Small models with a free breadth of a few inches are an extremely commendable device for preliminary, exploratory work. The results of hydraulic measurements, together with the observation of the behavior of small fish in these model fishways, form a fairly reliable basis for predicting the success of the design in full-scale, provided that the type of flow is the same in the model and in the full-scale fishway. However, as it has been found that symmetrically paired obstacles may give rise to a stable jet in the model but to an unstable one in full-scale, no positive final recommendation can be based upon small scale studies alone, particularly not if the type in question has a symmetrical disposition. On the other hand, a design showing unsatisfactory results in the model study can be rejected.

General Recommendations of Fishway Types

No single fishway type can claim to yield the complete and general solution of the fishway problem. However, the ideas of energy dissipation which were first incorporated in successful designs by G. Denil are the most efficient so far known and are sufficiently general to be freely adaptable to almost any particular set of local conditions and requirements. Nevertheless, in most cases, another type of fishway—old or modern—should be considered along with a fishway derived from the Denil principle as a possible solution. The selection will depend mainly upon a comparison of costs; it may also depend upon the opinion of the designer, e. g., whether or not he considers it more desirable that the fish should have a submerged passage rather than one close to the water surfaces. Any fishway type, however perfect, has definite limitations.

Specific Recommendations Concerning the Various Types of Fishways

The Denil type (Full-scale No. 6) and the pool and submerged-orifice type (with abrupt jet deflection) (Full-scale No. 3) showed up well in the full-scale studied and in the sizes used in these studies can be recommended for slopes up to 25 per cent and heights of dam up to 6 feet. Since the ascent under these conditions was made with comparative

1This last statement appears to be, at first glance, superfluous. However, so many complete failures are caused by too steep a slope for otherwise good fishways that the authors wanted to emphasize this point by including it in the general conclusions. The specific recommendations give details as to the limitations.

2Design by Nemenyi and White, London.
ease this is probably not the limit, but must be considered so for the present.

If the size of the cross section of a fishway is increased, other conditions remaining the same, the velocity would increase and the fishway would become more difficult to pass. By a proper reduction of the slope, the increase in size can be compensated.

Also, an increase in height of a fishway tends to make the passage somewhat more difficult for the migrants, because their exertion must extend over a longer period. It seems to be a reasonable and even conservative assumption that the influence of the increase in height is not greater than the effect of increasing the size of cross section; that, for example, doubling of the head difference of a fishway does not necessitate a more substantial reduction of slope than would the doubling of the breadth. If this hypothesis is accepted, the aforementioned method can also be used for the computation of slope reduction for fishways at high dams.

If the headwater fluctuations are large, the new narrow channel type (Model No. 8a and 9a Denil derivatives) can be used if the conditions of use are kept within the limits outlined for the first two recommended types. Although this recommendation is based on small-scale experiments, it is believed to be conservative considering the comparative excellence of the results obtained with models of this type.

The alternate-baffle fishway (Model No. 22, Full-scale No. 5, Coralville copy) although generally considered to be an inferior type, showed up favorably in this investigation. For sizes not exceeding the full-scale fishway used in these studies and for heights up to 6 feet this fishway can safely be recommended for slopes not exceeding 20 per cent.

For larger cross sections and for greater heights, slope reduction is necessary according to the following tables, computed by the method mentioned above.

**Period of Use for Fishways**

Even allowing for yearly hydrographic and climatic variations, we should judge from the results obtained that fishway use can be restricted to a period sufficiently brief to warrant the consideration of closing devices at installations where the water supply is not plentiful. In most cases, at least within the state, there should be no conflict between water usage by fishways and water-power plants because the important period of fishway use coincides in general with the period of ample supply of water.

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1Method shown in author's original copy.

2Although this fishway appeared to work satisfactorily at a 25% slope the conservative recommendation of 20% has been made because the information concerning actual fishways of this type is, on the whole, very unfavorable, and accurate data of their installation are not known. Further investigations may perhaps warrant recommendation of this simple type for a wider range of conditions.
TABLE II—SLOPE MODIFICATION

For fishways with normally admissible slope of 25 per cent.

<table>
<thead>
<tr>
<th>Height of Dam (ft.)</th>
<th>Number of Times Width of Fishway Tested Is Increased</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Slopes in Per Cent</td>
<td></td>
</tr>
<tr>
<td>Six</td>
<td>25.0</td>
</tr>
<tr>
<td>Nine</td>
<td>20.0</td>
</tr>
<tr>
<td>Twelve</td>
<td>16.7</td>
</tr>
<tr>
<td>Fifteen</td>
<td>14.6</td>
</tr>
<tr>
<td>Eighteen</td>
<td>12.5</td>
</tr>
</tbody>
</table>

For fishways with normally admissible slope of 20 per cent.

<table>
<thead>
<tr>
<th>Height of Dam (ft.)</th>
<th>Number of Times Width of Fishway Tested Is Increased</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Slopes in Per Cent</td>
<td></td>
</tr>
<tr>
<td>Six</td>
<td>20.0</td>
</tr>
<tr>
<td>Nine</td>
<td>16.0</td>
</tr>
<tr>
<td>Twelve</td>
<td>12.8</td>
</tr>
<tr>
<td>Fifteen</td>
<td>11.6</td>
</tr>
<tr>
<td>Eighteen</td>
<td>10.8</td>
</tr>
</tbody>
</table>

N. B.: If a fishway has large resting pools giving complete resting possibilities, the difference between their levels can be substituted for "Height of Dam."

V. SUGGESTED PROGRAM FOR FURTHER RESEARCH

Although the investigation herein reported touches upon many of the more important aspects of the fishway problem, few of them could be sufficiently treated to admit of final conclusions. This was due to the limited scope of the investigation and to the complexity of the problem, which consists of hydraulic, biological, and combined factors. Therefore it is proposed to clarify the various aspects by making thorough hydraulic measurements, fish counts, and observations of fish effort on a limited number of promising fishway types rather than by studying a large number of models. Some model studies are suggested but the bulk of the investigation should be on full-scale fishways.

Proposed Model Studies

Continued model investigations of highly efficient designs for steep slopes probably would not yield important results and extended checks of conventional types would be even less promising. Therefore it is proposed to study models of extremely simple types for moderate slopes utilizing the momentum transfer principles inherent in the highly developed fishways. Such solutions should be sought because the problem at many sites is best solved by the use of fishways with moderate
slopes. To this end we recommend investigating designs with obstacles of a more longitudinal position.

Proposed Full-scale Studies

In the full-scale studies we see the advantage of investigating the following fishways:

a. Types proved to be most efficient by the present model and full-scale studies.

b. The new types for large headwater fluctuations as suggested in the conclusions.

c. The Landmark fishway and its modification suggested by C. Schmidt.

d. Promising fishway types if such are obtained from the further model studies.

The procedure to be followed is to test simultaneously two fishways situated in such a manner that the downstream entrances of both can be reached and discovered by the fish with equal ease. One of the two fishways will be a "control" fishway, that is, apart from its use for comparison with climatic and hydrographic conditions, it will indicate whether any fish are trying to pass. The other fishway will be varied in type, size, and slope.

This procedure will enable us to determine for each fishway type studied the limiting slope for any cross section size which may be necessary for a given size of fish, and possibly, also, for large fish runs. This laboratory is uniquely situated for this study: It unites the advantages of a full-scale field study with the possibility to replace the fishways by others, to conveniently modify the slope, to study two or three fishways simultaneously and to register all data, hydrographic and climatic, which can be of significance.

In addition to these important possibilities, the facilities available at this laboratory would also enable us to increase substantially the total height of the rise, a factor which so far has been studied but little, although it might have considerable importance.

In order to secure the information outlined above for all fishway types which are promising for Iowa conditions, the study will probably have to be extended over two seasons.

Incidental to determining definite heights and slopes that the fish can climb, fundamental information will be gained concerning the resistance to the fish in climbing, and also the swimming strength of the fish. These would in turn serve as a basis for judging the possibilities of any situation where a fishway is proposed in the future.

Thus while the research in its first stage has led to the recommendation of new designs and to preliminary results concerning energy dissipation and fish migration, the second or proposed stage is intended mainly to obtain general quantitative rules for the proper economic design of these fishways, and to clarify those problems of mechanical

*For an explanation of the principles of this procedure see the introduction.
resistance and fish effort which are essential for the understanding of the success or failure of a fishway.

NOTE

The original paper is on file at the Iowa Institute of Hydraulic Research and at the Iowa State Conservation Commission. It contains, in addition to more detailed records of the tests, a deduction of the rules for slope modification and a more detailed scheme of the proposed program for further research.

ACKNOWLEDGMENTS

The investigation herein reported was carried out at the Iowa Institute of Hydraulic Research under the general supervision of Prof. E. W. Lane, Associate Director in Charge. The test work was started early in 1938 by Edward Soucek and Victor A. Koelzer, members of the Institute staff at that time, and some of their results have been used in the present report. Since late in 1938 the present authors were in charge of the investigation although the junior author was absent in the spring of 1939 when most of the full scale studies were conducted. Marion F. Thorne, graduate assistant, aided in the planning and final wording of the report.

The writers wish to acknowledge the encouragement, helpful suggestions and cooperation received from M. L. Hutton, Director of the Iowa Conservation Commission, W. W. Aitken, State Biologist, and Ed Sybil, Conservation Officer.

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Workmen of the Professional and Service Division of the Works Progress Administration contributed materially to the success of the project by constructing the models, full-scale fishways and auxiliary equipment; also by counting and classifying the fish passing through the fishways.
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