ISSN 0308 - 5589

MINISTRY OF AGRICULTURE, FISHERIES AND FOOD
DIRECTORATE OF FISHERIES RESEARCH

FISHERIES RESEARCH TECHNICAL REPORT No. 78

Fish pass design — criteria for the design and approval of fish passes and other structures to facilitate the passage of migratory fish in rivers

M. H. BEACH

LOWESTOFT, 1984

MINISTRY OF AGRICULTURE, FISHERIES AND FOOD
DIRECTORATE OF FISHERIES RESEARCH

FISHERIES RESEARCH TECHNICAL REPORT
NUMBER 78

Fish pass design — criteria for the design and approval of fish passes and other structures to facilitate the passage of migratory fish in rivers

M H BEACH

LOWESTOFT 1984

'Fish pass design - criteria for the design and approval of fish passes and other structures to facilitate the passage of migratory fish in rivers' by M. H. Beach. MAFF, Fisheries Research Technical Report No. 78, 1984

<u>Errata</u>

Page 20: Figure 15 - For dimension 0.2 m read 0.25 m

Page 34:	Left-hand column,	para 1,	line	8	- for 0.645 $m^3\ s^{-1}$ read 0.558 $m^3\ s^{-1}$
" "	" "	" "	"	9	- for 0.20 m read 0.25 m
" "	" "	" "	"	10	- for 0.100 $m^3\ s^{-1}$ read 0.129 $m^3\ s^{-1}$
" "	" "	" "	"	13	- for 42.87 m read 42.92 m
" "	" "	" "	"	18	- for 0.13 m read 0.15 m
" "	" "	" "	"	19	- for 0.100 $m^3\ s^{-1}$ read 0.129 $m^3\ s^{-1}$
" "	" "	para 3,	"	3	- for 0.745 $m^3\ s^{-1}$ read 0.558 $m^3\ s^{-1}$
" "	" "	" "	"	5	- for 0.745 $m^3\ s^{-1}$ read 0.558 $m^3\ s^{-1}$

The author:

M H Beach, BSc MSc AMIEE, is a Principal Scientific Officer in Research Support Group Section 2, of the Directorate of Fisheries Research and is based at the Fisheries Laboratory at Lowestoft.

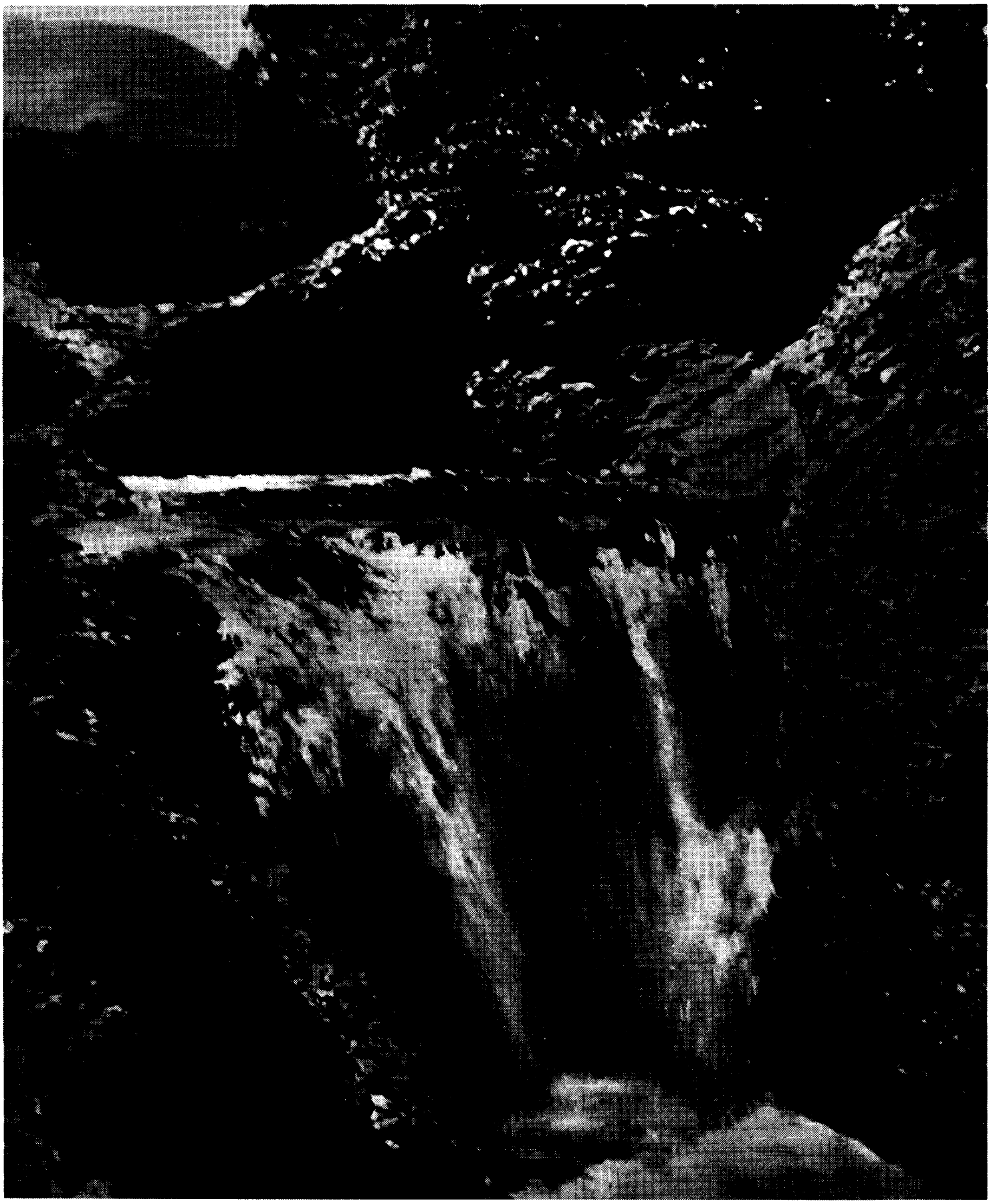
Fish. Res. Tech. Rep., MAFF Direct. Fish. Res., Lowestoft (78) 46 pp.

Foreword

A salmon or sea-trout's river passage to spawning gravels is often restricted by the structures and practices associated with water resource management for water supply and flood prevention: the attitudes of the biologist and the water engineer to river management are consequently somewhat different.

This report explains in simple terms how the fish and water control requirements can be reconciled and proposes design criteria to enable fish to negotiate structures such as sluice gates, weirs and fish passes. It also explains the Ministry's legal position with regard to obstructions in migratory fish rivers and gives examples of the procedures necessary to obtain Approval for satisfactory structures. The information on fish swimming speeds and endurance and the relation of these parameters to water control structures and fish passes is essential to the effective management of migratory fish in our rivers.

A Preston
Director of Fisheries Research



Frontispiece. A salmon on its way upstream leaps 3.65 m to clear the Orrin Falls in Ross-shire. However, the launch velocity of 8.46 m s^{-1} necessary to achieve this feat should certainly not be expected from every salmon! The brief but intense exertion here demands the equivalent of twice the fish's predicted 'burst speed' swimming maintained for a period of at least one minute. (Photo. Mills, 1971.)

CONTENTS

Page

Foreword

Frontispiece

1	**Introduction**	7
2	**Fish swimming capabilities**	7
3	**Flow control structures**	10
3.1	Flood relief channels	10
3.2	Sluices	10
4	**Flow measurement structures**	14
4.1	Crump weir	16
4.2	Flat-V weir	19
4.3	Other gauging weirs	19
5	**Fish passes**	19
5.1	'Pool and traverse' fish pass	19
5.2	Denil fish pass	21
6	**Approval of fish pass design**	28
6.1	Example of 'pool and traverse' pass	28
6.2	Example of a Denil fish pass	35
7	**Automatic fish-counters**	38
8	**Conclusions**	39
9	**References**	40

Appendices

1	Salmon & Freshwater Fisheries Act 1975, Chapter 51, Part II, Sections 9-18	42
2	Derivation of maximum swimming speeds for fish of different lengths	45
3	Derivation of endurance times for fish of different lengths	46

1. Introduction

Many of our rivers hold stocks of salmon (*Salmo salar* L.) and sea trout (*Salmo trutta* L.) and during most of the year some of the adult fish migrate upstream to the head waters where, with the advent of winter, they will eventually spawn. For a variety of reasons, including the generation of power for milling, improving navigation and measuring water flow, man has put obstacles in the way of migratory fish which have added to those already provided by nature in the shape of rapids and waterfalls. While both salmon and sea trout, particularly the former, are capable of spectacular leaps (see frontispiece) the movement of fish over man-made and natural obstacles can be helped, or even made possible, by the judicious use of fish passes. These are designed to give the fish an easier route over or round an obstacle by allowing it to overcome the water head difference in a series of stages ('pool and traverse' fish pass) or by reducing the water velocity in a sloping channel (Denil fish pass).

Salmon and sea trout make their spawning runs at different flow conditions, salmon preferring much higher water flows than sea trout. Hence the design of fish passes requires an understanding of the swimming ability of fish (speed and endurance) and the effect of water temperature on this ability. Also the unique features of each site must be appreciated to enable the pass to be positioned so that its entrance is readily located.

As well as salmon and sea trout, rivers often have stocks of coarse fish and eels. Coarse fish migrations are generally local in character and although some obstructions such as weirs may allow downstream passages only, they do not cause a significant problem. Eels, like salmon and sea trout, travel both up and down river during the course of their life histories. However, the climbing power of elvers is legendary and it is not normally necessary to offer them help, while adult silver eels migrate at times of high water flow when downstream movement is comparatively easy: for these reasons neither coarse fish nor eels are considered further.

The provision of fish passes is, in many instances, mandatory under the Salmon and Freshwater Fisheries Act 1975 (Great Britain Parliament, 1975; see Appendix I). This report is intended for those involved in the planning, siting, construction and operation of fish passes and is written to clarify the hydraulic problems for the biologist and the biological problems for the engineer. It is also intended to explain the criteria by which the design of an individual pass is assessed for Ministerial Approval.

2. Fish swimming capabilities

A major factor in the design of a fish pass is the swimming ability of the migratory fish in terms of speed and endurance. Fish swimming speed is often expressed in terms of body lengths per second ($BL\ s^{-1}$), but the more fundamental unit of metres per second ($m\ s^{-1}$) will be used in this report since this enables a direct comparison to be made with the speed of water flow. Fish swimming speeds are frequently described as being within a range of either 'cruising' speeds or 'burst' speeds and are attributed to the use of two different types of swimming muscle (Hudson, 1973; Webb, 1975; Wardle and Videler, 1980). The lower 'cruising' speeds, which can be maintained for long periods ($>$24 h), employ the dark or red muscle – perhaps better termed aerobic muscle – which contracts only when oxygen is available to the cells at a rate at least equal to that at which it is used. Any restriction in the oxygen supply limits performance. The faster 'burst' speeds employ white or anaerobic muscle which can contract rapidly and powerfully in the absence of oxygen and becomes exhausted only when all the glycogen stored in the white muscle cells is converted to lactic acid. Rebuilding of the glycogen store uses oxygen and can take relatively long periods (up to 24 h) if completely depleted (Wardle, 1978; Batty and Wardle, 1979).

A fish propels itself through the water using waves of contraction of the lateral muscle. Wardle (1975) contends that the limit to its forward velocity is set by the time it takes for a piece of muscle to shorten. Isolated muscle fibres when stimulated by a single electrical impulse take a characteristic time to shorten, so by measuring the contraction time of the isolated white swimming muscle the maximum swimming velocity can be predicted.

High-speed swimming is always associated with short endurance. In active fishing methods such as those using trawl and seine nets, all sizes of fish can be observed keeping station with the moving net (Hemmings, 1973). Small fish swimming near the net are seen to be moving with very rapid tail beats whereas large fish, moving at the same speed, are making slow tail sweeps. The small fish are moving close to their maximum speed and swim for only a short period before they drop back, but the larger fish can swim for long periods and have scope for much greater speed; therefore towing speed and duration of tow can affect the size range of fish caught. Recent findings have shown that maximum swimming speeds of most fish species are similar for fish of the same length and are surprisingly high. A 0.195 m rainbow trout (*Salmo gairdneri*, Richardson) can achieve a maximum velocity of 1.58 $m\ s^{-1}$ and a maximum acceleration rate of 32.6 $m\ s^{-2}$ (Webb, 1978). Such high burst speeds and fast start abilities are essential if migratory fish are to swim up or leap difficult waterfalls.

It is now well established that the swimming speed of a fish through the water is closely related to its tail beat frequency and that the distance moved during each body wave (stride length) is about 0.7 of the fish length. Wardle (1975) gives a general formula which relates the maximum swimming speed to the stride length;

$$U = 0.7L/2t \qquad (1)$$

where U is the maximum swimming speed, L the length of the fish and t the muscle twitch contraction time.

The twitch contraction time of the lateral swimming muscle is short for small fish and increases with fish size. Muscle contraction time is also sensitive to temperature: cold muscle contracts slowly and warm muscle contracts more rapidly as a result of the temperature dependence of the underlying biochemical and physiological processes (Wardle, 1980).

Maximum swimming speed is thus affected by both the length of the fish and the water temperature and it is possible to predict their effects (Figure 1) using an empirical formula (Appendix II) derived by Zhou (1982) from 276 measurements of muscle contraction time (Wardle, 1975). These measurements covered a temperature range of 2°C to 18°C and six species with a size range of 0.05 m to 0.80 m. Water temperature has a considerable effect on the maximum swimming speed, e.g., a 0.90 m salmon (7.8 kg) has a predicted maximum speed of only 2.5 m s^{-1} at 2°C but this increases to 9.6 m s^{-1} at 25°C.

Endurance is similarly determined by both body length and temperature and is governed by the amount of glycogen stored in the white muscle. This reserve is used once the fish exceeds its cruising speed and the rate of depletion depends on temperature. The endurance of a fish swimming at its maximum speed is predicted using another empirical formula (Appendix III) which examines performance in relation to a finite energy store (Zhou, 1982). Figure 2 relates endurance at maximum speed to fish length for a series of specific temperatures. The maximum speed equivalent to a particular endurance time in Figure 2 can be derived from Figure 1 using the length of the fish and the curve for the appropriate temperature.

Figure 2 shows that, for a given length of fish, an increase in temperature results in a dramatic reduction in endurance, and for a given temperature, an increase in fish length results in a large increase in endurance. The reduction in endurance at the higher temperatures results from the increased maximum swimming speeds and the consequent faster depletion in glycogen reserves, while the dramatic increase in endurance at a given temperature is simply a result of the larger fish having a greater glycogen store.

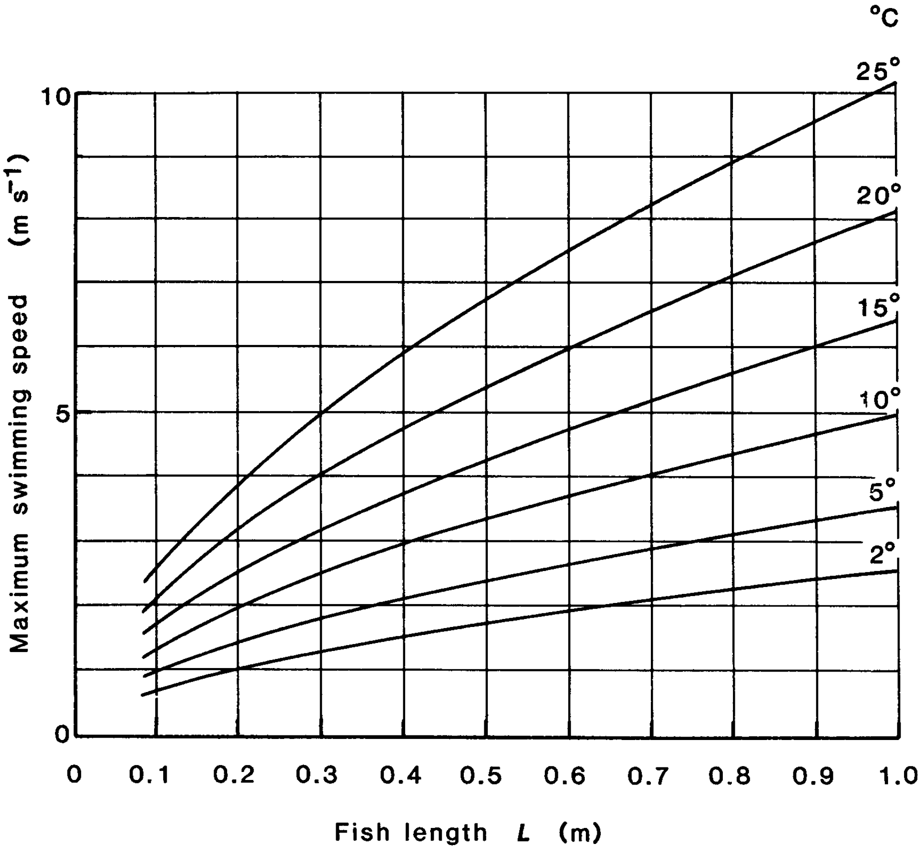


Figure 1 Maximum swimming speeds against fish length over a temperature range of 2°C to 25°C (see Appendix 2).

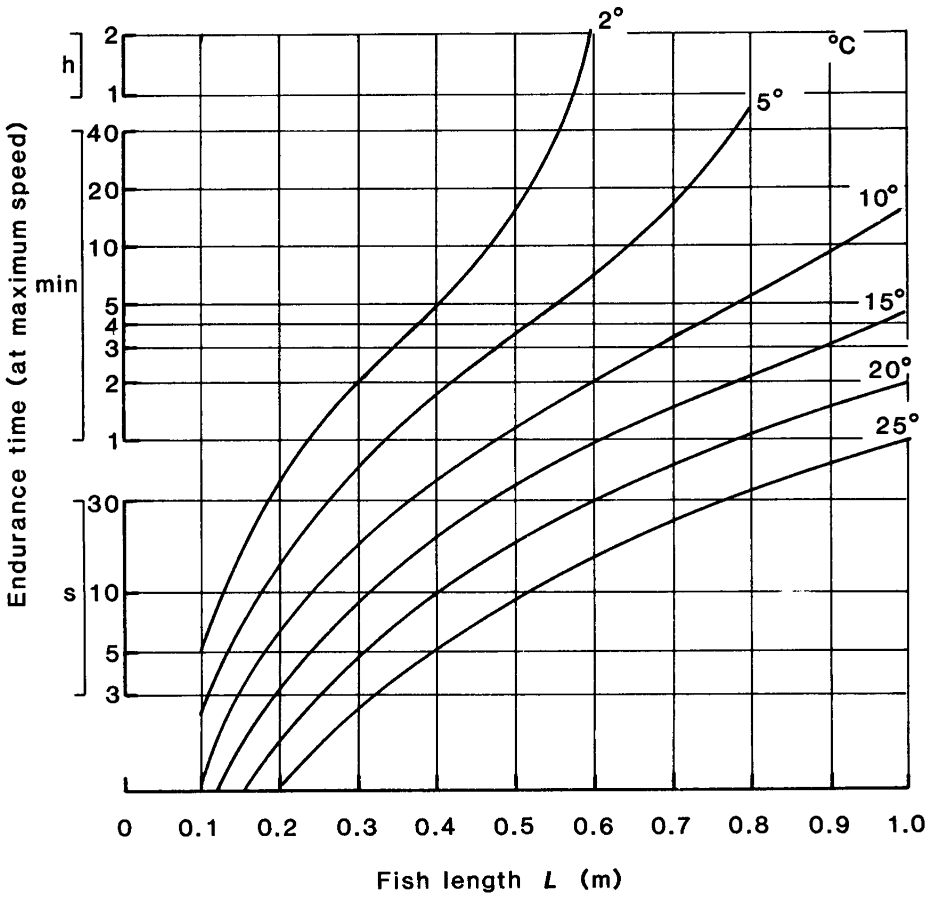


Figure 2 Endurance at maximum swimming speeds of various lengths of fish over a temperature range of 2°C to 25°C (see Appendix 3).

The swimming durations shown in Figure 2 should be taken as the absolute maxima to incur complete exhaustion, but unless a fish is being driven very hard, e.g. when played on a fishing line, it is unlikely to deplete its energy store completely. However, the spawning drive of a migratory fish to overcome difficult obstacles must make severe demands on its energy reserves and may well use some of its store of anaerobic glycogen.

River temperatures in the UK can range from 0°C to about 25°C. Table 1 shows the temperature range of five rivers at times of year significant to migratory fish movement (Water Resources Board and Scottish Development Department, 1974). Fish returning to their home river in June/July will encounter the highest temperatures and will thus be capable of achieving the high swimming speeds necessary to surmount many of the more difficult obstructions. Later migrants, returning in October, will be faced with lower temperatures and the earlier spring fish will encounter the lowest temperatures and thus have a much reduced maximum speed. It must be stressed that all burst speeds and endurance predictions are considered to be the maximum attainable with the fish in peak physical condition. Fish in poorer condition through injury, disease or being gravid would naturally have a reduced swimming capability.

Table 1. River temperatures at three seasons of the year (1970) significant to migratory fish movements. 1970 records are representative of continuous longer records, 4 to 11 years. (From Water Resources Board and Scottish Development Department, 1974.)

River	March			June/July			October		
	L	*H*	*M*	*L*	*H*	*M*	*L*	*H*	*M*
Wear, Northumberland	0	6	3	7	22	15	3	13	10
Itchen, Hampshire	5	10	8	13	21	17	8	17	13
Avon, Gloucestershire	3	8	7	17	22	19	9	17	13
Dee, Clwyd	3	9	5	13	19	17	8	14	12
Leven, Clyde	0	6	4	14	22	18	10	15	13

L = lowest temperature during period
H = highest " " "
M = mean " " "

Although high water velocities can prove difficult or even impossible for fish to overcome, they are considered to be a major factor for instigating the upstream movement of salmonids. Migrations are often initiated by freshets: the noise and turbulence associated with the increase of water velocity from freshets are thought to be the factors that enable a fish to find the main upstream route through a river system (Arnold, 1974), just as the current issuing from a river into the sea is thought to be an important guide to fish locating the river mouth (Mottley, 1933; Huntsman, 1934). The noise and turbulence of high velocity water below an obstruction can result in the standing wave or hydraulic jump (see section 4.1) that provides the 'lead' for fish and may stimulate them to move forward in readiness to leap over the obstacle (Stuart, 1962). However, the downstream approach to a structure should always be designed such that fish are encouraged to swim rather than to leap. An unsuccessful leap may not only be damaging but, whilst the fish is in the air, it may also attract the attention of potential enemies such as poachers.

3. Flow control structures

Structures are built in rivers to control or measure water flow, enabling the effects of spate or drought conditions to be mitigated and providing a head of water for milling or electricity generation. Where water flow velocity through, or over, a structure exceeds the 'burst' speed capacity of a fish it constitutes a barrier to fish ascent. Since the endurance of a fish at the 'burst' speed is very limited, it is crucial that the approach to the structure should be as easy as possible with adequate 'take-off' depth. High-speed flows of shallow water over long concrete aprons do not provide adequate access to the position where 'burst' speed has to be employed. The approach to a structure can also be made very difficult by a reduction in downstream water level caused by channel dredging or by scouring due to high flow rates and insufficient bed protection. Hence, when designing a flow-control structure likely to be an obstruction to migratory fish passage, it is important that the downstream water conditions be prescribed and recorded so that they can be maintained. A reduction in downstream water level can be very gradual and may only become evident when the number of fish in the river above the structure has been severely reduced, or when fish are observed being unsuccessful in their attempts to negotiate the obstruction. The presence of damaged fish in the river may also be an indication that an originally passable structure has become troublesome to fish.

3.1 Flood relief channels

These large channels, cut to provide an overflow route for a river in spate conditions, are a danger in that migrating fish attracted by the high flows – which may occur as infrequently as once in 10 years – may be stranded as the water subsides. A relief channel should be designed so that it can drain progressively as the flow reduces and afford fish an escape route. Usually the channel offers no route up the river since the velocities are very high and the flow control weir at its head is a total block to upstream migrants. Section 14 of the Salmon and Freshwater Fisheries Act 1975 (Great Britain Parliament, 1975) (Appendix 1) requires the provision of gratings across the exit of any channel that is likely to attract fish and then strand them.

3.2 Sluices

These are used to regulate water flow, are in a variety of shapes and are usually constructed from wood and/or metal. The majority are manually controlled but an increasing number are being automated, using water-level sensors and electric motors. There are three broad categories of sluice, namely undershot, overspill and radial.

The undershot type (Figures 3 and 4), as the name implies, effects its control by regulating the water flow under the sluice gate. The flow is approximately equal to the mean water velocity multiplied by the area of sluice gate open. The mean water velocity is equal to about $[2gh]^{0.5}$, where g is the acceleration due to gravity (9.81 m s^{-2}) and h the water head difference across the sluice. This is an approximation, because the velocity head (due to the velocity of approach to the sluice), coefficients of discharge and contraction, and frictional roughness effects are ignored; however, it is sufficient for fishery purposes. The shape of the open sluice aperture is relevant to fish passage: it is better to have the sluice gate either fully closed or well open than to have a narrow opening which provides a few centimetres of high velocity, squirting, 'leading' flow through which a fish cannot pass but may exhaust itself in trying. For fish passage the minimum aperture should be 0.30 m x 0.30 m with a water velocity not greater than about 3 m s^{-1}. As shown in Figures 1 and 2, such a 'burst' speed could be achieved by a 0.27 m fish at 15°C and maintained for 7 s, a 0.41 m fish at 10°C for 42 s, or a 0.76 m fish at 5°C for about 20 min. The velocity of 3 m s^{-1} would result from a head difference of 0.45 m and produce a flow through the 0.30 m square aperture of approximately 0.27 m^3 s^{-1} (5.13 Mgal d^{-1}).* Large automatic metal sluice gates often comprise a single massive gate allowing low flow control by providing an opening of a few centimetres only; this results in a noisy, squirting flow that is very attractive but, of course, completely impassable to migratory fish (Figure 5). To facilitate fish passage through an undershot sluice it is better to regulate flow by a number of adjacent sluices (Figure 6) only one of which need be open rather than by one large gate. Sluices should be designed to spill into a deeper area (stilling basin) with the sluice sill extended downstream so as to slope into this deeper area. There should be no base block in the sluice aperture and discharge should not be directed onto a raised concrete block.

---

*A water flow of 1 cubic metre per second (m^3 s^{-1}) is equivalent to about 19 million gallons per day (Mgal d^{-1})

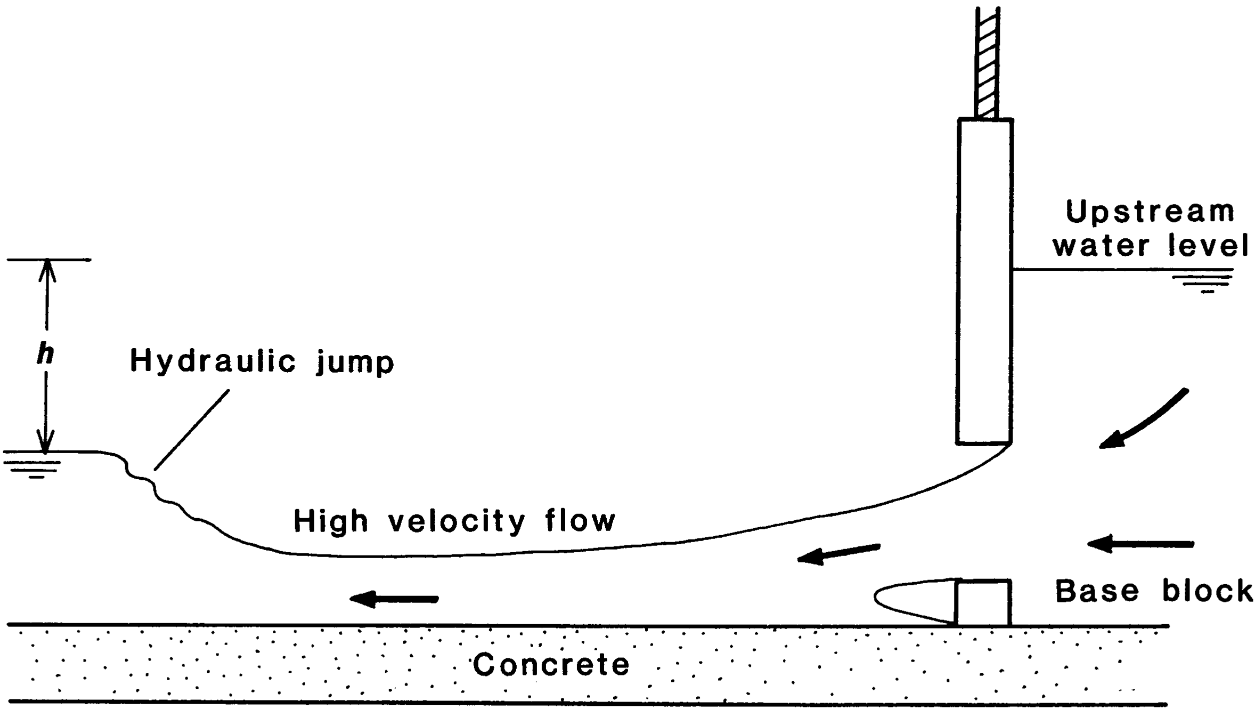


Figure 3 This form of undershot sluice makes fish passage very difficult, requiring both high speeds and long endurance times. The concrete base block enables a water jet to form, and the flat base allows the high velocity flow to persist over a considerable distance.

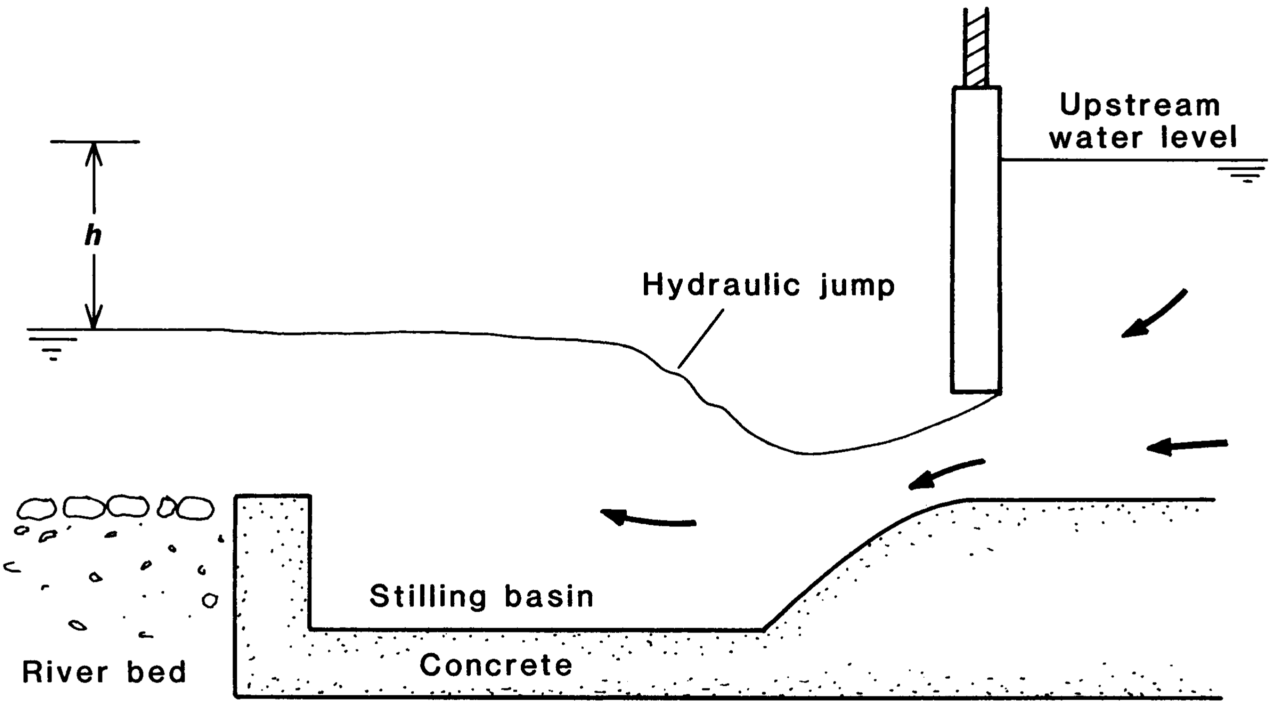


Figure 4 Fish passage is much easier at this arrangement of undershot sluice. The lack of obstruction below the sluice gate and graded approach to the stilling basin allow a rapid reduction of the high water velocity by forming the hydraulic jump close to the sluice gate.

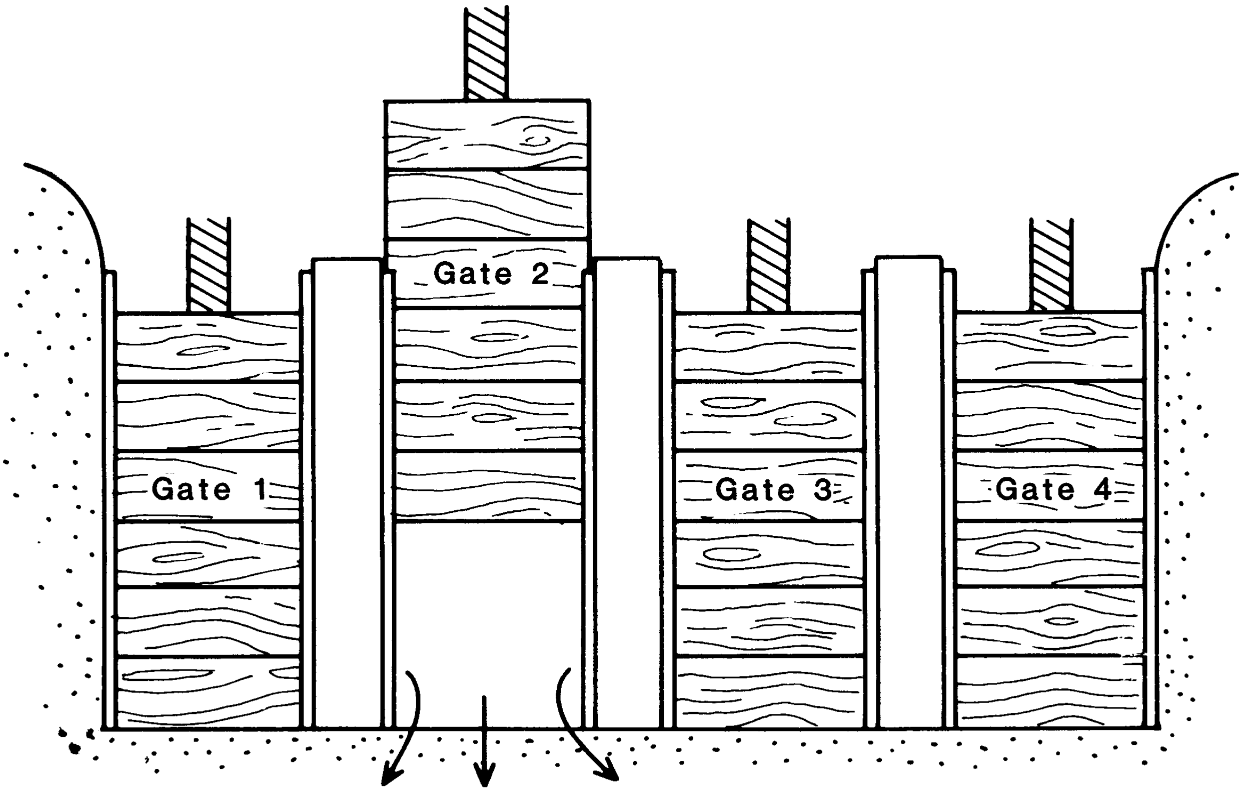


Figure 5 Undershot sluices with water flow controlled by four small gates. This enables a low discharge to be achieved using one gate only whilst still providing sufficient room for an ascending fish to pass under the gate.

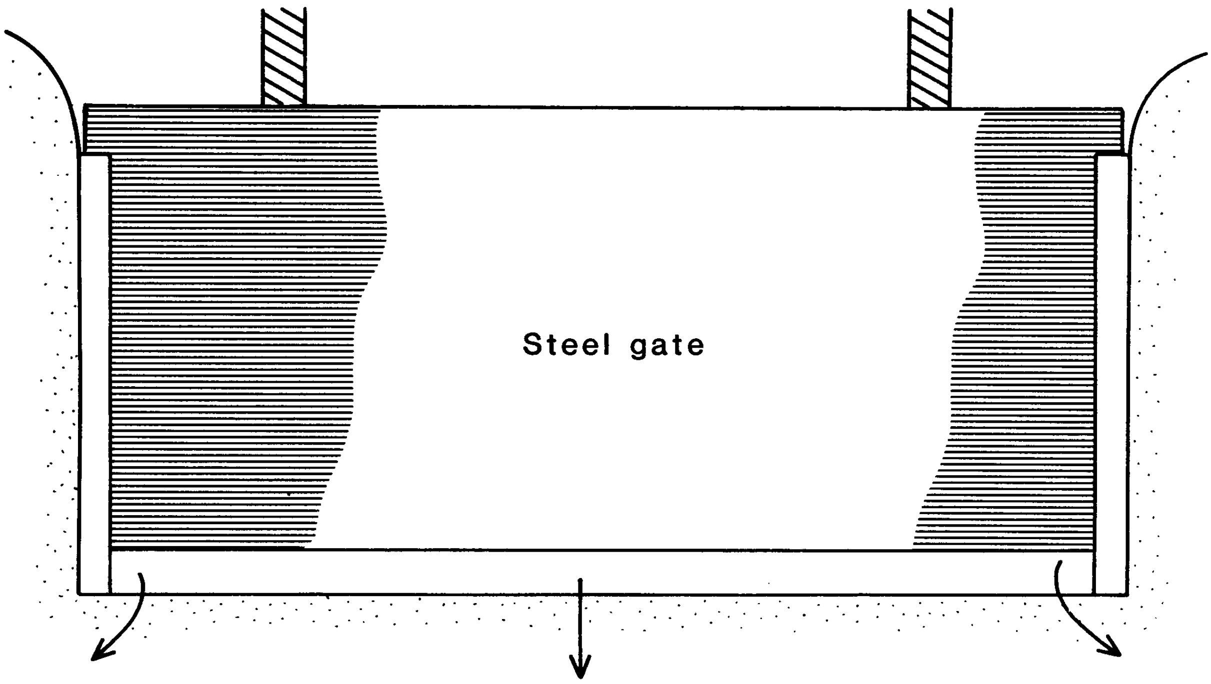


Figure 6 Undershot sluice with water flow controlled by one massive steel gate (often automated). A low discharge is achieved by providing a very small opening that is attractive to fish but completely impassable.

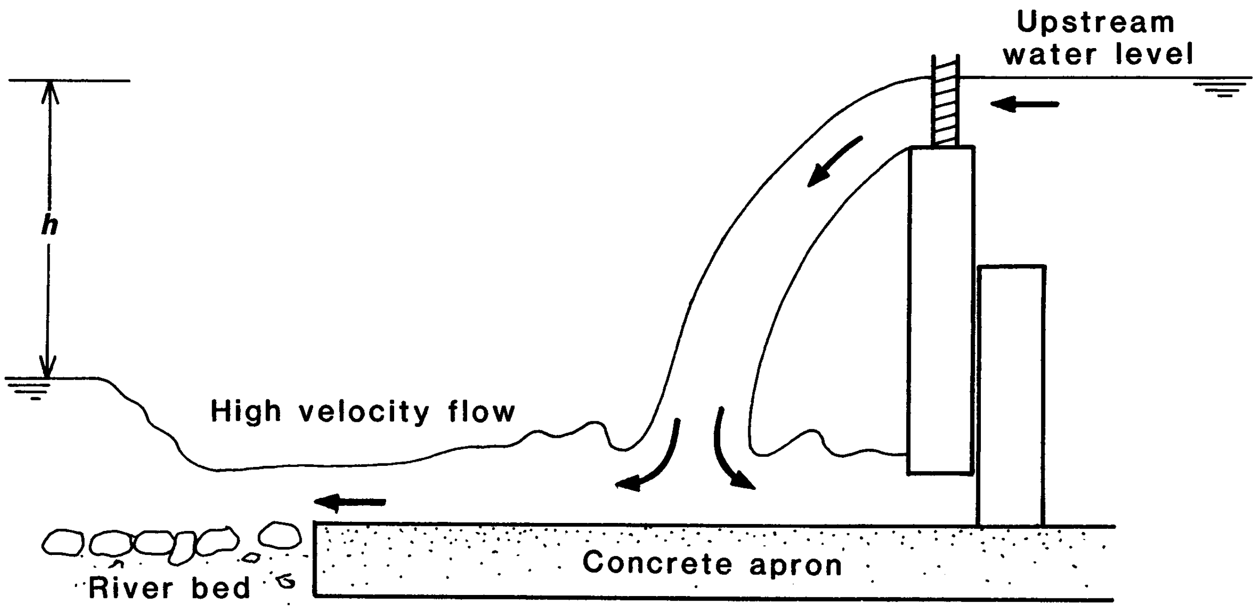


Figure 7 Overspill sluice with sharp edge and shallow water over concrete open; this produces difficult approach conditions for fish because of insufficient downstream water depth.

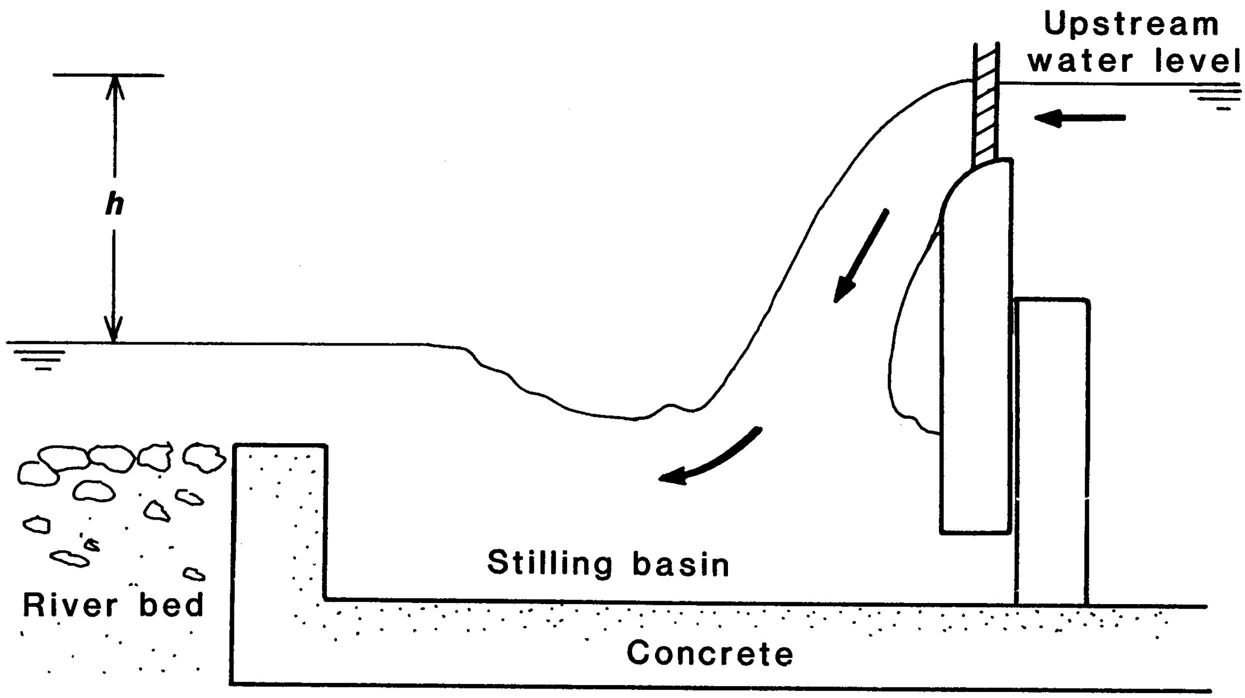


Figure 8 Overspill sluice with curved edge and stilling basin; this provides sufficient water depth for an easy approach and a smooth crest flow.

An overspill sluice (Figures 7 and 8) regulates the water head over the sluice gate. Here again, for the successful passage of fish an adequate 'take-off' depth of not less than 1 m on the downstream side should be ensured. This can be provided either by a maintained downstream water level or by a deeper pool immediately below the sluice; the sluice should never spill onto a raised concrete apron. In any overspill situation (sluice, traverse or weir) a curved or graded downstream edge should be provided (Figure 8), not a sharply truncated edge (Figure 7). This enables the overflowing sheet of water to adhere closely to the weir edge (adherent nappe), rather than to form a separate jet, and often gives fish the facility to swim over the obstruction. As in the 'undershot' sluice, the depth of water must be sufficient to accommodate the fish. It is better to effect water control with a number of narrow sluices with adequate water depth over each than to use one very wide gate with a few centimetres depth over it. The maximum recommended head is calculated in the same way as for the undershot type: a head difference of 0.45 m would produce a maximum velocity of about 3 m s^{-1}; the same minimum aperture is necessary (width 0.30 m) and would permit a flow of about 0.09 m^3 s^{-1}.

Radial sluice gates (Figure 9) are usually quite impassable, particularly when sited on a stepped base. The only situation in which a radial gate is passable is under flood conditions when the approach on the downstream side is deep, the steps are drowned and the gate is lifted high.

4. Flow measurement structures

These structures take many forms but usually attempt to relate the water head over the structure to the total river flow. Good hydraulic conditions are essential for accurate measurement, and the study of the necessary conditions and errors in measurement of flow is now sufficiently extensive to constitute an established science in its own right.

The structure is designed such that the flow conditions – the water velocity and depth – in the channel upstream of the structure are governed by the geometry of the structure and the approach channel, and by the physical properties of the water. Measurement structures are not affected by the conditions of flow downstream from the structure or by the roughness and geometry of the channel well upstream. For a well-designed structure there is a unique head: discharge relationship and critical flow conditions occur. The term 'critical flow' is used here in a general sense, meaning that for a given discharge the depth is such that the 'total head' is a minimum, or alternatively, for a given 'total head' the depth is such that the discharge is a maximum. The 'total head', which is measured in metres of water, is the total energy of the flow per unit weight of water. It is the sum of the potential head, the pressure head, and the velocity head and is calculated using the Bernoulli energy equation. The crest of the structure is generally taken as datum.

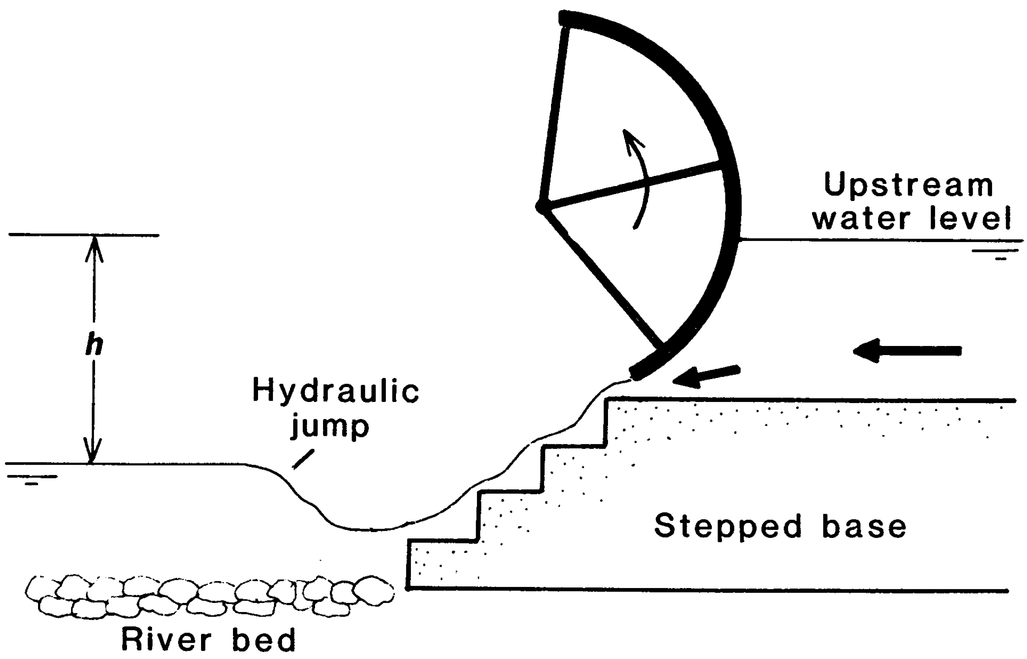


Figure 9 Radial sluice gate on a stepped base; this is impassable to fish in all conditions except very high flows when the gate lifted clear of the water.

Turbulent or skew approach flows are not conducive to accurate flow measurement since the purpose of the structure is to enable the head: discharge relationship to be described algebraically. However, even with the most regular of channels, streamlines are often curved in the region of the crest of the structure and the pressure distribution within the flow is not known. The coefficients of discharge of most types of structures are therefore derived empirically under rigorously controlled laboratory conditions. Numerous attempts have been made to derive a standard equation for full width weirs and recent tests by White (1975) at the Hydraulics Research Station (HRS), England yielded the following equation:

$$Q = 0.564\ [1 + 0.150\, h\,/\,P\,]\ b\, g^{0.5}\ [h + 0.001]^{1.5}, \ldots(2)$$

where, Q = discharge ($m^3\ s^{-1}$),
h = upstream gauged head (m),
P = crest height of weir above upstream mean bed level (m).
b = crest width (m),
g = acceleration due to gravity ($m\ s^{-2}$).

This equation fitted the Hydraulics Research Station data with a tolerance of ± 0.7% at the 95% confidence level. The limits of application set by the range of data are $h > 0.02$ m, $P \geqslant 0.15$ m, and $h/P \leqslant 2.2$, but accuracy diminishes when $h < 0.075$ m or $h/P > 1.8$.

The above introduction to metering weirs is superficial but is intended to stress the stringent conditions necessary to gauge water flow accurately. It will be appreciated that these precise engineering requirements are usually contrary to the natural requirements for fish passage. Fish prefer irregular channels with deep pools for cover and not straight trapezoidal concrete channels with sharp crested weirs having abruptly truncated downstream surfaces. However, since flow control and measurement are necessary and many weirs already exist, a compromise must be reached so that fish can swim over gauging structures.

The accurate gauging of a wide range of flows involves two conflicting requirements: high flows demand a large crest-breadth if head loss (afflux) is not to be excessive, whereas low flows demand a small crest-breadth in order that the sensitivity of the gauging structure does not fall below an acceptable figure. One solution to this problem is the compound weir in which low discharges are measured by containing the flow within a comparatively narrow crest section and high discharges are measured with a much wider crest section at a higher level. The low-level crest (which is usually separated from an adjacent higher-level crest by a pier) can be designed to afford fish easy passage at low flows. The 1:2, 1:5 profile weir (Figure 10) designed by

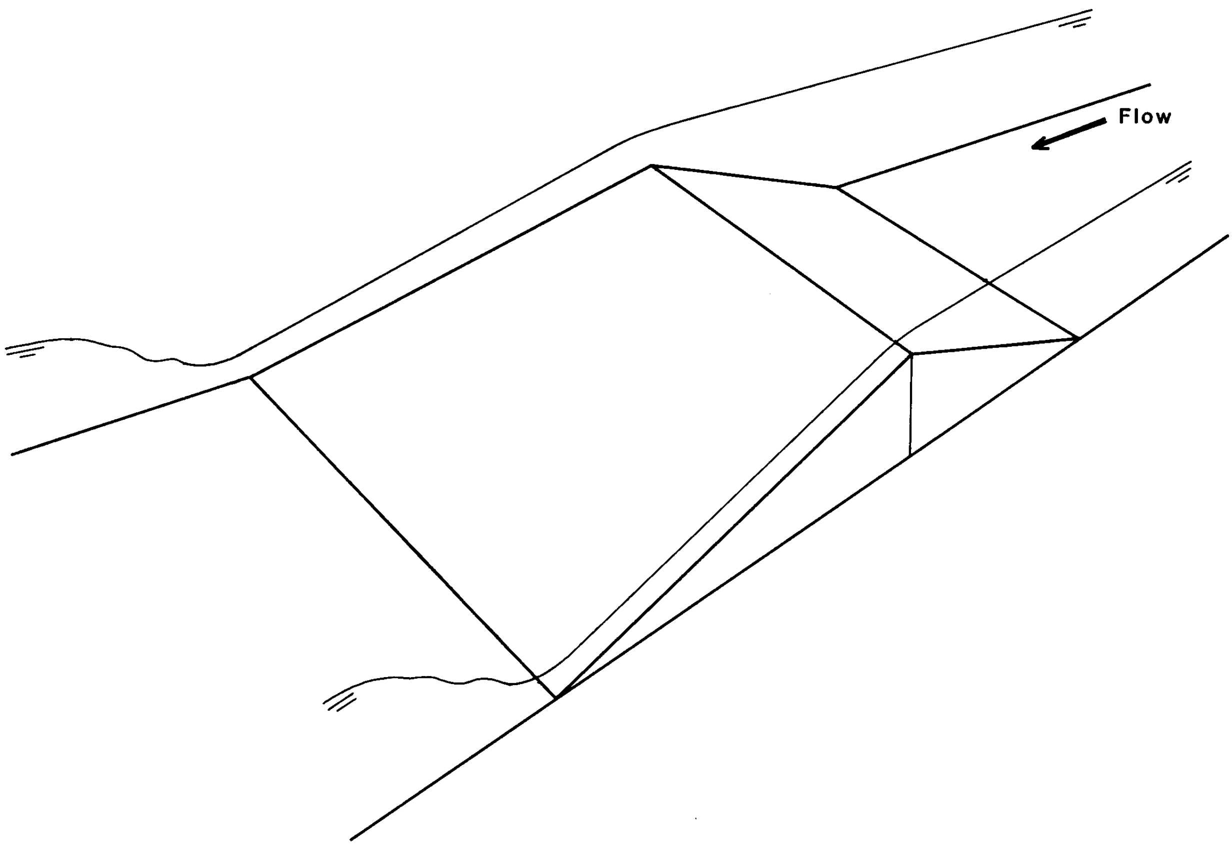


Figure 10 A Crump (1952) flow-gauging weir with upstream and downstream slopes of 1:2 and 1:5 respectively.

Crump (1952) is a popular gauging weir which is often compounded whereas the flat-V weir (Figure 11), with careful selection of crest breadth and cross-slope, can provide sensitivity at low flows without the need for dividing piers and also minimise head loss during flood conditions.

4.1 Crump weir

A Crump weir is a two-dimensional, triangular profile weir providing both an upstream measurement of hydrostatic head and a crest tapping for pressure measurement. By this method of double gauging and the choice of a triangular profile weir Crump showed, in tests carried out at HRS, that reliable flow measurement was possible with small afflux at high discharges. A diagram of a compounded Crump weir is shown at Figure 12 and a photograph of the Manley Hall compound Crump weir on the River Dee, illustrating the different elevation crests separated by dividing piers, is shown in Figure 13. A comprehensive treatment of the design of Crump weirs is given by Herschy *et al.* (1977) and sufficient detail will be given here to allow an appreciation of the hydraulic conditions only as they affect fish passage. Furthermore, only 'modular flow'* will be considered since under 'drowned flow' conditions passage by fish is considerably easier.

Well upstream of the weir the water in the river is flowing relatively slowly and obeying approximately the fundamental relationship: flow Q = cross-section area A x mean velocity U. As the water approaches the weir crest it is subjected to the 1:2 sloping face which reduces the available cross-section area and causes the water velocity to increase. The water then flows over the crest and down the 1:5 downstream face of the weir, converting its potential energy to kinetic energy. The depth of water on this downstream face decreases as the water accelerates under the action of gravity; the flow and velocity in this region being termed 'super-critical'. Downstream from the weir the river channel will be much the same in profile as that found above the weir, and the flow will be at about the same depth and sub-critical velocity as if the weir did not exist. Therefore, the shallow water on the downstream face of the weir travelling at super-critical velocity has to change its state back to deeper water at sub-critical velocity. This occurs quite suddenly in the form of a roller or standing wave below the weir, which is termed the 'hydraulic jump'. There is considerable turbulence within the hydraulic jump which can cause severe bed erosion below the weir if the jump does not occur over a firm, rocky base. It is common practice to provide a stilling basin below a weir to ensure that this energy is dissipated close to its foot in a concrete-lined pool.

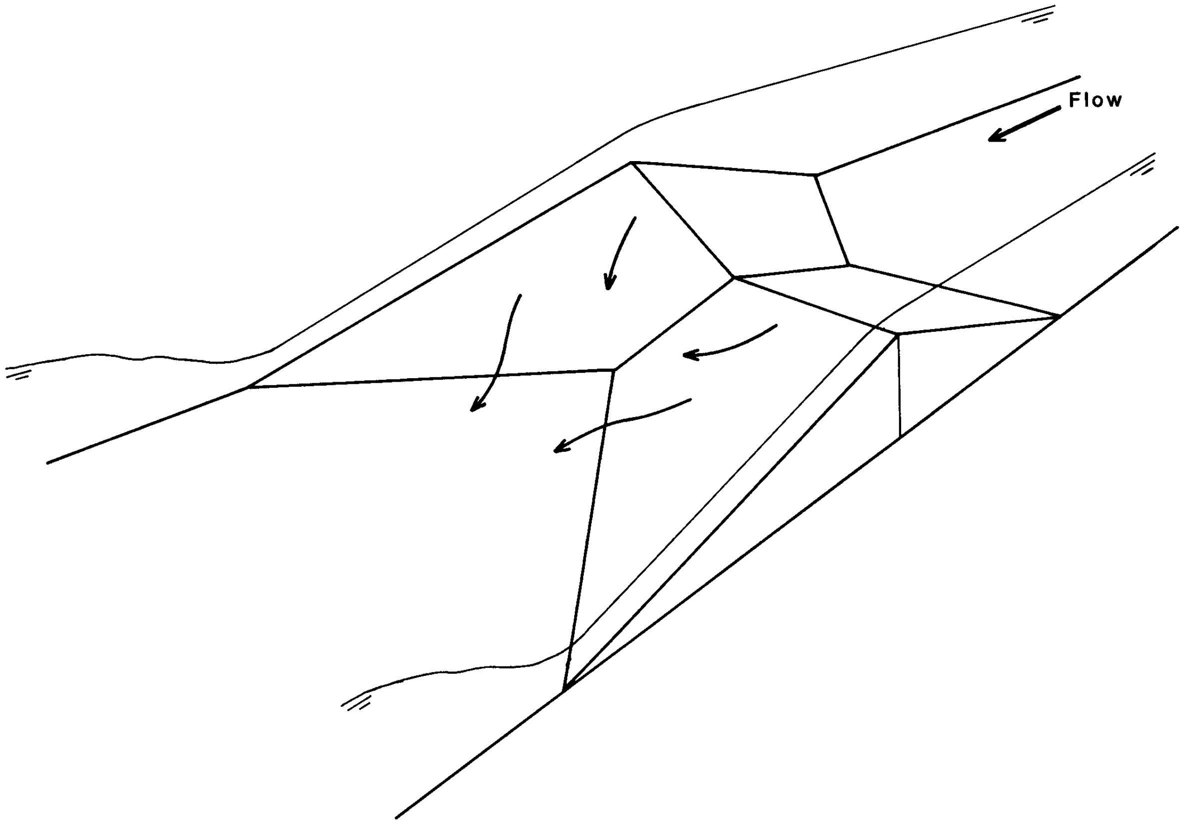


Figure 11 A 'flat-V' flow-gauging weir, with cross-section slopes 1:2/1:5 and traverse slopes of between 1:10 and 1:40.

* Modular flow occurs when the water level downstream from the weir does not affect the flow over the weir and there is thus a unique relationship between upstream water level and flow. If high tailwater conditions do affect the flow, the weir is said to be 'drowned' and two measurements are needed, one being the upstream state and the other the downstream state.

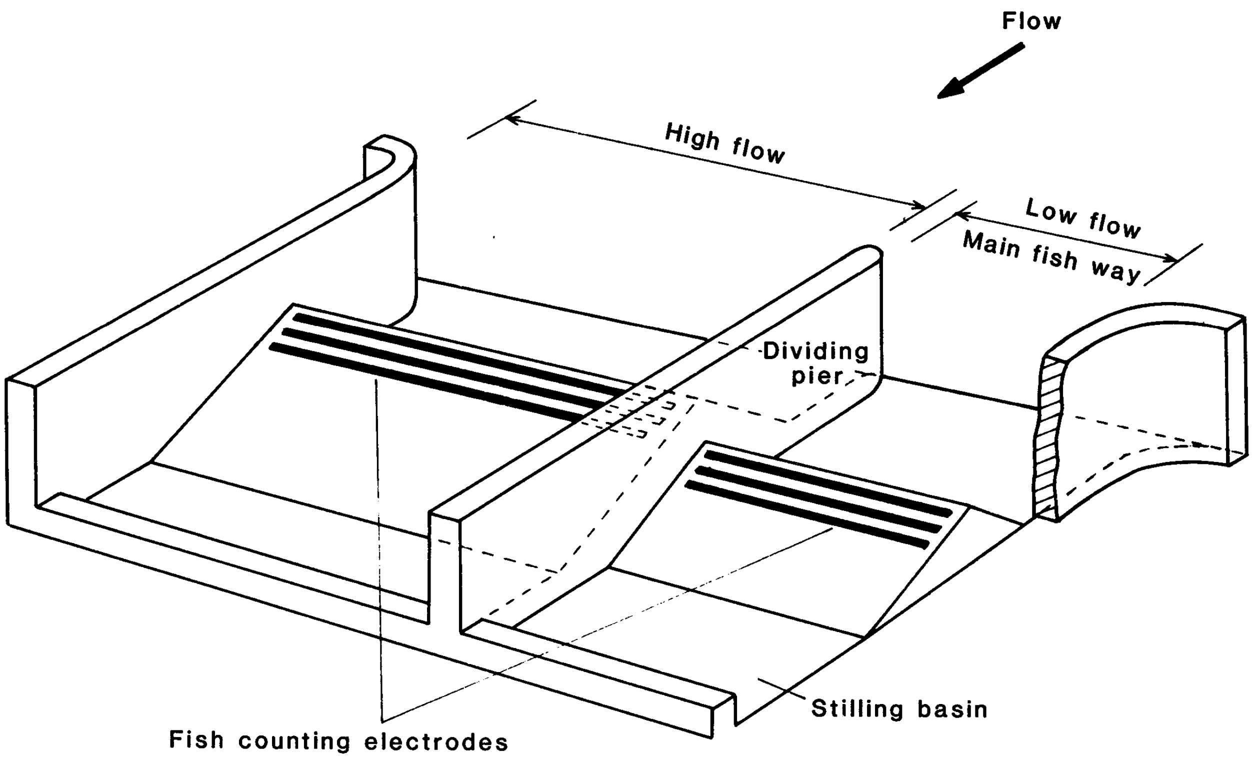


Figure 12 Diagram of a compound Crump weir showing the low flow section that provides the fish way and the high crest section for high flows. Note the automatic fish-counting electrodes on the 1:5 downstream weir face. (Diagram based on Bussell, 1978.)

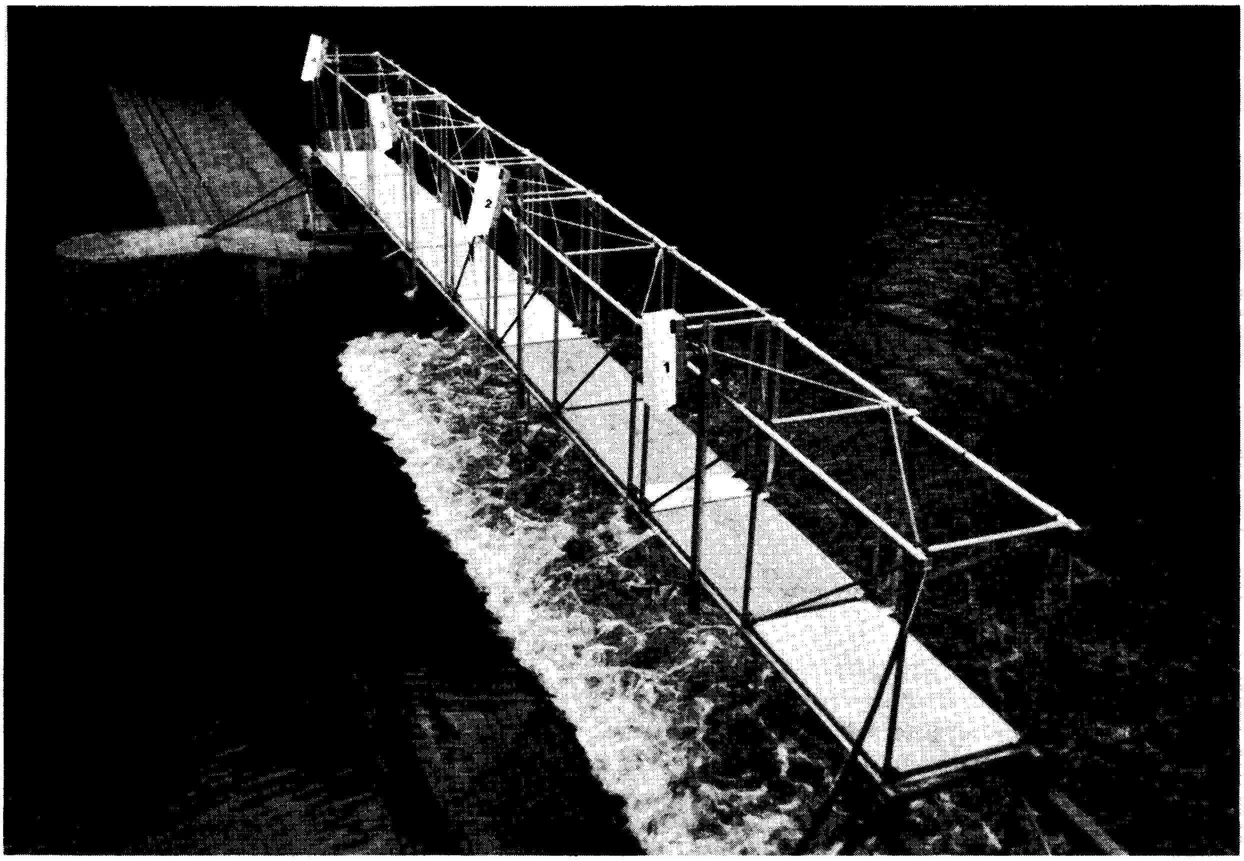


Figure 13 A view of the compound Crump weir at Manley Hall on the River Dee, Shropshire. The low crest section can be seen to be gauging water flow whilst the high crest section is dry. The bridge spanning the low-flow section is used to monitor the accuracy of an automatic fish-counting system (Beach, 1978b).

The degree of difficulty facing a migratory fish trying to ascend a flow-measuring structure can now be appreciated. It is attracted to the structure by the noisy turbulence of the hydraulic jump which it has to overcome before negotiating the long downstream face of the weir covered with water at shallow depth and flowing at super-critical velocity. The situation is often exacerbated by a tendency to truncate the downstream face of the weir sharply to minimise the amount of building materials used, since, if this truncation is not closer to the crest than about twice the maximum upstream total water head, the gauging accuracy will not be impaired. However, the sharp edge resulting from this truncation is often not submerged by the hydraulic jump and requires a fish to leap from a region of high turbulence onto a weir face thinly covered by water moving at high velocity and in which it may have to swim a distance of about 3.5 m to reach the weir crest.

The recommendations for the design of a Crump weir to allow fish passage derive from a consideration of the water velocities on its downstream face and require the submergence of any downstream truncated edge. Hence the stilling basin should be so designed that the hydraulic jump always forms on this downstream face. Figure 14 shows water velocity as a function of gauged head h for a range of weir heights P and distances Z downstream from the crest. Four weir heights are considered (P = 0.6 m, 0.7 m, 0.8 m, 0.9 m) and the water velocity is calculated at seven distances from the crest (Z = 0.5 m, 1 m, 1.5 m, 2 m, 2.5 m, 3 m, 3.5 m) using the appropriate coefficient of approach velocity for each value of P.

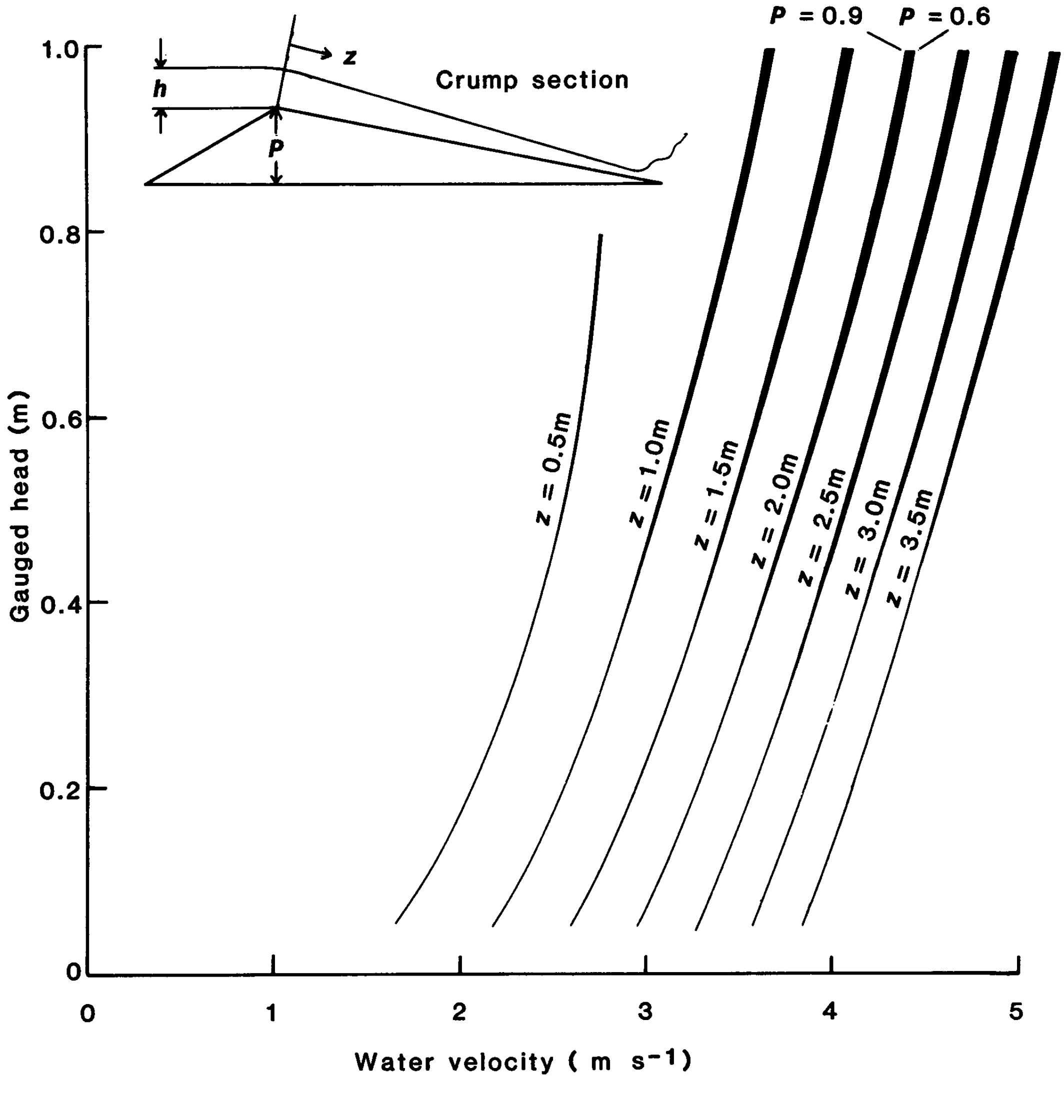


Figure 14 Mean water velocity at various distances Z from the crest of a Crump weir plotted against upstream gauged head h. The small inset section explains the nomenclature used. The height of the weir P has a greater influence on water velocity as the gauged head increases and is seen as a thickening of the appropriate Z curve. Values of P from 0.9 to 0.6 are given, the higher values causing a slight reduction in the mean water velocity. For example, at 2 m down from the weir crest at a gauged head of 1.0 m, a weir height of 0.9 m results in a mean water velocity of 4.4 m s^{-1} which increases by about 0.04 m s^{-1} as the weir height decreases to 0.6 m.

The maximum water velocity on a Crump weir, which occurs in the region of super-critical flow just above the hydraulic jump, should not exceed 3.5 m s^{-1}. This swimming velocity can be achieved, for example, by a fish of length 0.54 m in water of temperature 10°C and maintained for about 1.5 min before exhaustion. From Figure 14 it can be seen that this velocity occurs at about 2.5 m from the weir crest for a gauged head of 0.2 m (equivalent to a flow of 0.18 m^3 s^{-1} per metre of weir) or at about 1 m from the weir crest for a gauged head of 0.8 m (equivalent to a flow of 1.56 m^3 s^{-1} per metre of weir). A sloping distance of 2.5 m corresponds to a vertical distance of 0.5 m, so, since the zone of super-critical flow extends slightly below the downstream water level, the difference between the Crump weir crest level and the downstream water level must not exceed 0.5 m.

The channel conditions downstream from a Crump weir are very important both for the operation of the weir and for successful fish passage. Careful consideration must be given to the stilling basin design to ensure sufficient energy dissipation at high flows. Failure to do this will result in a continuation of super-critical and turbulent flows with water velocities so high as to make the approach to the weir by fish impossible.

4.2 Flat-V weir

A Flat-V weir (Figure 11) provides gauging sensitivity at low flows without the need for dividing piers and minimises head loss during flood conditions. Two cross-section profiles are common, 1:2/1:2 and 1:2/1:5 with traverse slopes of 1:10 to 1:40. Due to their downstream flow characteristics these weirs do not give easy fish passage. At low flows water is contained at the centre of the weir and issues as a squirting flow with circular side eddies. This is likely to present fish with very high velocities at the centre of the weir whilst causing disorientation at the sides. This type of weir lacks the horizontal crest necessary for automatic fish counting (see Section 7).

4.3 Other gauging weirs

A large variety of weirs and flumes have been used for several decades and many are still in use. The broad-crested weir was a weir of popular profile, the upstream edge of its flat horizontal crest being either 'sharp' or 'round-nosed'. It is now rarely installed because of its variable coefficient of discharge, and because the vulnerability of its upstream edge to damage affects the calibration characteristics. However, many are still in existence, so where an obstruction to fish passage occurs each weir should be assessed individually (using automatic fish count data if available) and appropriate remedial action taken. This might take the form of raising the downstream water level with a notched traverse or providing an effective fish pass round the structure.

5. Fish passes

Over the years many fish passes have been constructed to many designs and have achieved varying degrees of success. The assessment of the effectiveness of a fish pass is difficult. It is often based on observed aggregations of fish below a pass or a decline in the numbers caught above, but these indices ignore many other important factors such as the natural variation in the size of fish runs, the time of the run in relation to the water temperature and a possible size-selecting mechanism due to a more difficult passage for small fish. In 1940 McLeod and Nemenyi suggested that a fish pass should:

> *"Control water velocity below the swimming capacity of the fish; avoid rapid changes in flow pattern; provide physical and visual clearance; provide resting areas as required; operate without manual control; discharge enough water to attract the fish; possess a well located fish entrance; be economical to construct and maintain; operate without interference by sediment and debris; and, not require more water than is available or allocated".*

These diverse objectives are still being sought but there is now the opportunity to test the effectiveness of appropriate passes by using automatic fish counters (see section 7).

In England and Wales only two basic types of fish pass are now commonly installed: the 'pool and traverse' type with notched overflow weirs, and the Denil type. Other variants are in existence, e.g. B3 type and 'pool and traverse' with submerged orifices, but the first two are generally accepted as the most effective; thus, these will be the only types considered further in this report. The fish lift, e.g. Borland type, although worthy of mention, will also not be considered since it is intended primarily for large obstructions and is used mainly in Scotland to enable fish passage over high impounding dams. The Borland lift is described in some detail with examples of installations in both Scotland and Ireland by Aitken *et al.* (1966).

5.1 'Pool and traverse' fish pass

As the name implies, this pass consists of a series of traverses (cross walls) and pools which are arranged to circumvent an obstruction (natural or man-made) and afford fish a passage to the higher water level in easy stages (Figure 15). Ideally, the downstream entrance to the pass should be near the obstruction so as to be easily located by upstream migrating fish, and the upstream end should be close to the upper side of the obstruction so as to be easily located by downstream migrants (smolts and kelts).

The arrangement of pools and traverses is varied to suit a particular obstruction. A long, low obstruction (Figure 16) may require a pass of a similar shallow gradient cut into adjoining land, whereas a weir or dam (Figure 17) may require the pass to be tightly folded so as to position the entrance and exit close to the dam.

Recommended design requirements for a 'pool and traverse' fish pass are as follows:

(a) the change in water level across a traverse must not exceed 0.45 m;
(b) pools should have minimum dimensions of 3 m long x 2 m wide x 1.2 m deep;
(c) traverses should be 0.3 m thick with notches 0.6 m wide and at least 0.25 m deep;
(d) the downstream edge of both the notch and the traverse should be curved so as to reduce turbulence and provide an adherent nappe (not a free spurting jet);
(e) the pass entrance should be located easily by fish at all flows.

These recommendations are based on the Report of the Committee on Fish Passes (Anon. 1942) and on subsequent experience gained by MAFF, the pool size being the minimum to allow energy dissipation of the 0.45 m difference in water level and to provide adequate rest areas.

The design requirements listed above are the major ones examined when a fish pass is submitted for Ministerial Approval. They form the guidelines for assessment of effectiveness but are applied flexibly since each site is unique. For example, if the water available for a pass is always so low that the normally recommended minimum pool size is more than adequate for energy dissipation, a small reduction in size may be permissible. Similarly, the minimum notch size may be reduced provided the depth of water of flowing through it is never less than 0.25 m, and the width of the notch is not less than 0.3 m.

Particular attention should be given to the position of the entrance to the pass, since it must be readily located by fish under all flow conditions. A pass adjoining an impassable

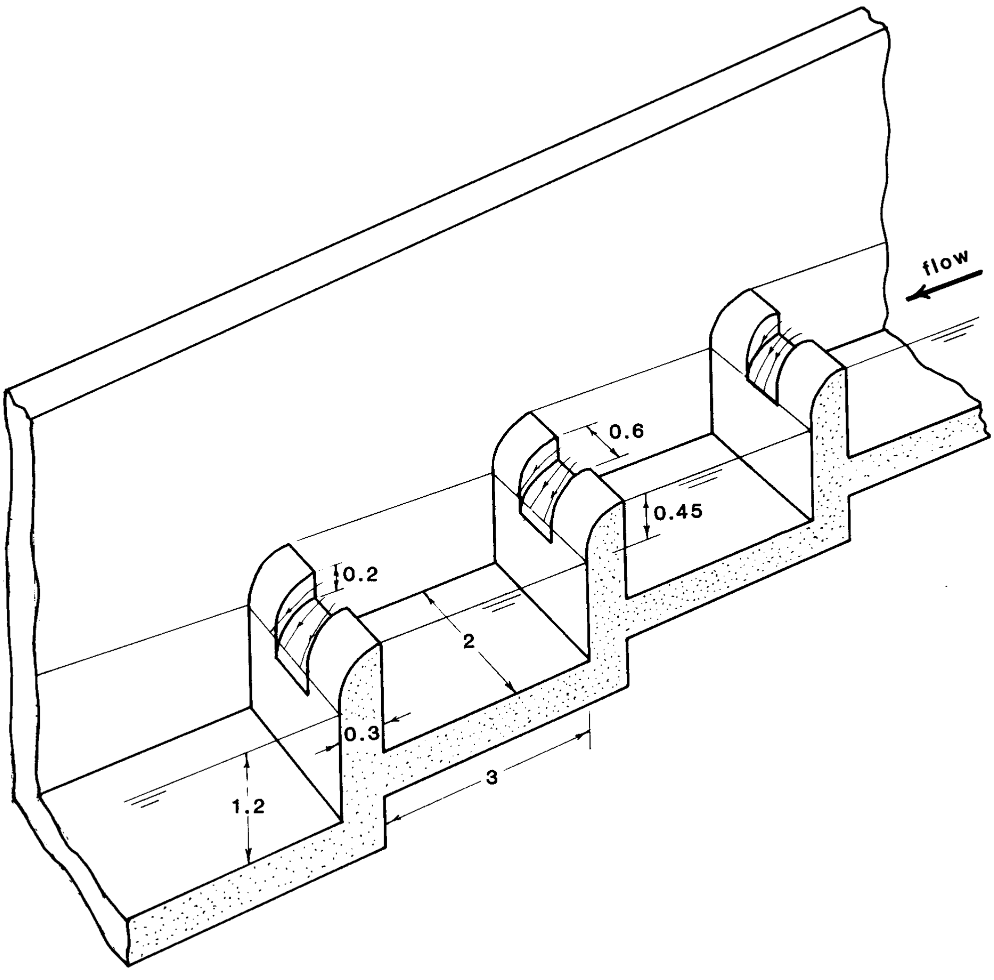


Figure 15 A schematic diagram of a 'pool and traverse' fish pass with notched traverses. The dimensions shown are recommended as the absolute minima. The head difference between pools should not exceed 0.45 m.

weir may be effectively blocked during high flows because of turbulence disorientating the fish or preventing its approach. Such flow conditions are often those that prompt salmon to make their spawning run. One solution to this problem is to ensure that, in addition to careful siting of the entrance, the pass always takes a fixed proportion of the flow over the main weir. Notches in the traverses should be arranged to take the correct proportion of the dry weather flow. The invert (or retention) level of the uppermost notch must always be lower than the adjoining weir crest so that the pass is preferentially supplied with water, instead of 'wasting' it over the crest of a long weir and thus attracting fish away from the pass.

Many hydraulic equations have been applied to the flow of water over weirs and notches, each proclaiming a greater degree of precision and usually involving a corresponding increase in complexity. For fishery purposes the Francis (1855) equation is sufficiently accurate and is usually simplified to:

$$Q = 1.84\,[b - 0.2h]\,h^{1.5}, \qquad (3)$$

where Q = flow ($m^3\ s^{-1}$),
b = weir breadth (m),
h = gauged water head (m).

Equation 3, although including the side contractions of a notch, ignores the velocity of approach. However, when dealing with a fish pass an accurate measure is neither possible nor necessary. If this equation is applied to the minimum size notch recommended (0.60 m wide by 0.25 m deep) an approximate flow of 0.13 $m^3\ s^{-1}$ would be required to ensure the notch runs full. Also the maximum water velocity resulting from the 0.45 m level difference across the pools would be 2.97 m s^{-1}. Such a speed could be achieved by a fish of length 0.41 m in a river of temperature 10°C and maintained for about 40 s, or a fish of length 0.27 m in a river of temperature 15°C and maintained for about 7 s.

5.2 Denil fish pass

The Denil fish pass is named after the Belgian engineer G. Denil whose studies in 1908 led to the first successful realisation of a channel fish pass using baffles for energy dissipation (Denil, 1936). The baffles are closely spaced and set at an angle to the axis of the channel (Figure 18) to form secondary channels whilst leaving a relatively large proportion of the channel for the straight main flow through which the fish pass. Flow re-entering from the secondary channels meets the main flow abruptly and

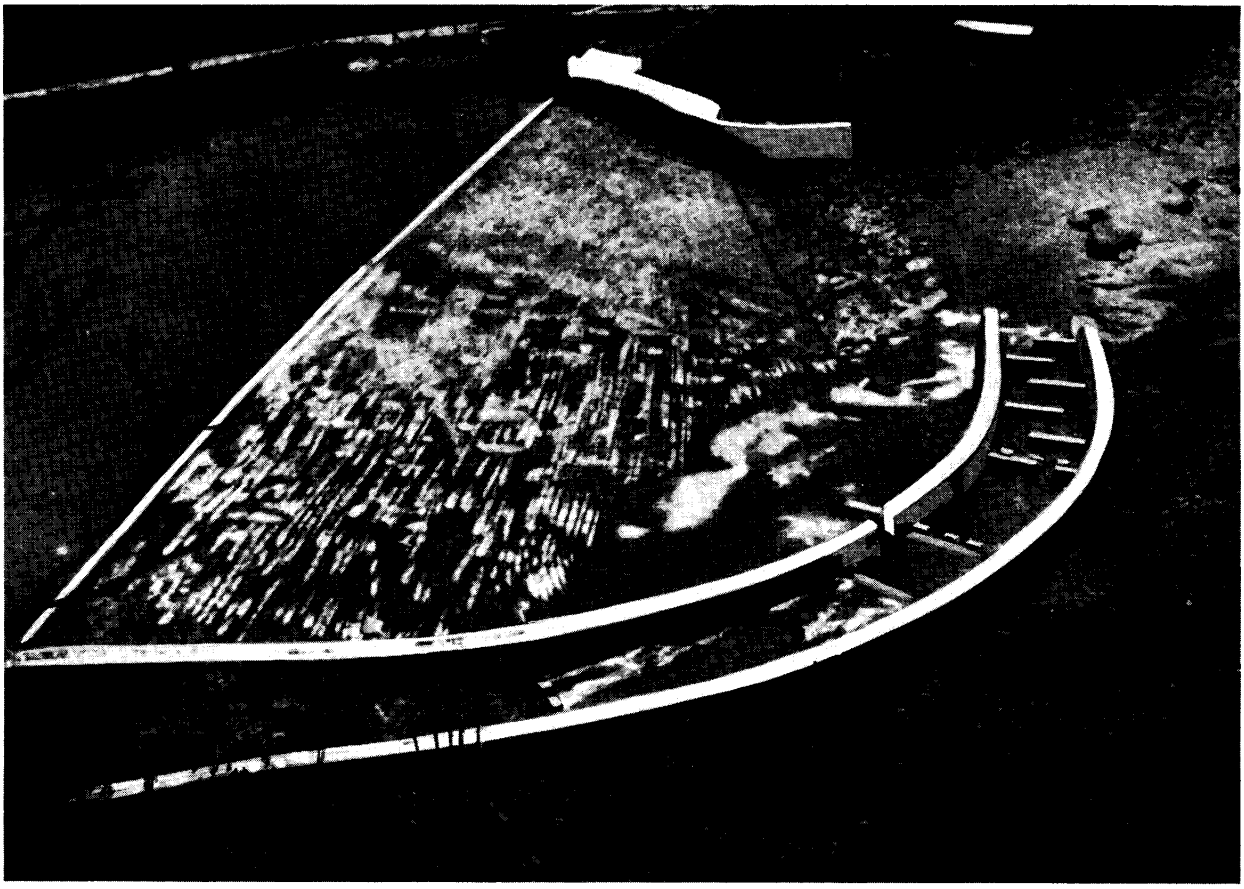
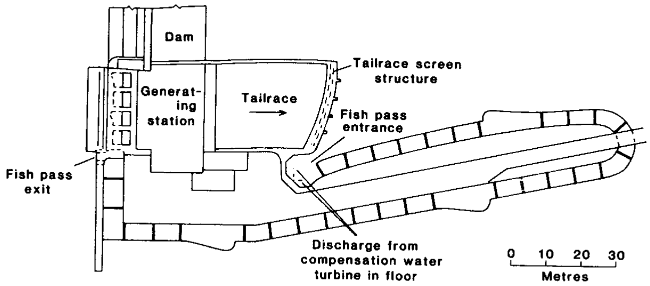


Figure 16 A 'pool and traverse' fish pass around Airthrey Dam on the River Allan, Strathallan. The pass discharges obliquely across the main river flow for easy location by fish at medium flows. Note the subsidiary entrance for use by fish attracted to this side of the dam at low flows. (Photo. Menzies, 1934.)



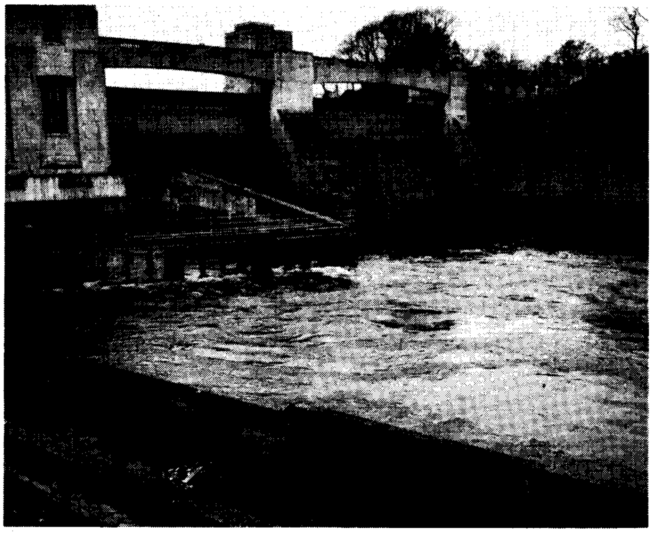


Figure 17 A plan (after Aitken *et al.*, 1966) and two views of the 'pool and traverse' fish pass circumventing the power station dam at Pitlochry on the River Tummel.

energy is dissipated by the large transfer of momentum and intense mixing; energy reduction is not due to the frictional effects of the numerous baffles (McLeod and Nemenyi, 1940) as is sometimes suggested. The surfaces of the secondary channels should be smooth and their entrances well streamlined to reduce frictional losses and to ensure that the secondary cross currents re-issuing into the main stream are vigorous and free from major eddies so that they effectively check the velocity of the main flow. It is in this connection that the shape, position and spacing of the baffles play such an important part. Denil's original design required baffles of a shape so complex that it was very difficult to reproduce. Simple single-plane baffles (Figure 18) are just as effective (McLeod and Nemenyi, 1940) and have been proved in operational passes in the UK, the Republic of Ireland, Canada, Denmark and elsewhere. A photograph of a Denil pass is shown at Figure 19.

In addition to the earlier work by Denil, 1936; McLeod and Nemenyi, 1940; Ziemer, 1962, and others, a recent detailed examination of practical Denil passes has been carried out by Lonnebjerg (1980) at Silkeborg in Denmark. His work examines in detail the hydraulics of the Denil pass and its effectiveness. He states that (in Denmark):

> *"In 1980 the number of dams and weirs preventing salmon from proceeding further up watercourse-systems is probably over 1,000 and fish passes have been built for very few of these".*

The need for an economical pass whose entrance is easily located and which must occupy minimal space suggests a pass with as steep a gradient as possible. However, the water velocity in a Denil pass increases approximately as the square root of the gradient, and the steeper pass allows a greater flow of water. Conversely, a reduction in the cross-section of the pass at a constant gradient will result in a lower flow, lower velocity and reduced building cost. The limit to the free passage through a Denil pass is set by the swimming space required by an ascending fish; McLeod and Nemenyi (1940) report that a catfish (weight about 11 kg) passed through a Denil pass having a passage width of only 0.25 m. The length of the fish was 0.84 m and the width of its head 0.23 m!

However long or steep the Denil channel, the water velocity must be such that neither the maximum speed nor the endurance of the fish is exceeded, due consideration being given to fish length and water temperature (Figure 1). A maximum water velocity of 3m s^{-1} is suggested as not being beyond the ability of any salmon and most sea-trout.

Denil considered the forces on a fish negotiating his passes to be composed of two elements, one due to the drag force necessary to overcome the water velocity and the other due to the need for the fish to lift itself against gravity. The first is defined by

$$F_D = 0.5\,K\rho U^2 A, \qquad \text{.........................(4)}$$

where F_D = drag force (N),

K = coefficient dependent on body shape,

ρ = fish density (kg m^{-3}),

U = mean water velocity (m s^{-1}),

A = maximum fish cross-section (m^2).

From a series of experiments Denil derived a value of 0.25 for K and Lonnebjerg substituted this value in equation 4 to give

$$F_D = 2.728U^2L^2 \qquad \text{.........................(5)}$$

where L is the length of the fish (m) and it is assumed that ρ = 1000 kg m^{-3} and $A = 0.02182\,L^2$.

The gravitational force, acting on a fish in an inclined channel, is given by

$$F_G = Mg \sin \alpha \qquad \text{...............................(6)}$$

where, F_G = gravitational force (N),

M = fish mass (kg),

g = acceleration due to gravity (9.81 m s^{-2}),

α = angle between channel slope and horizontal (degree).

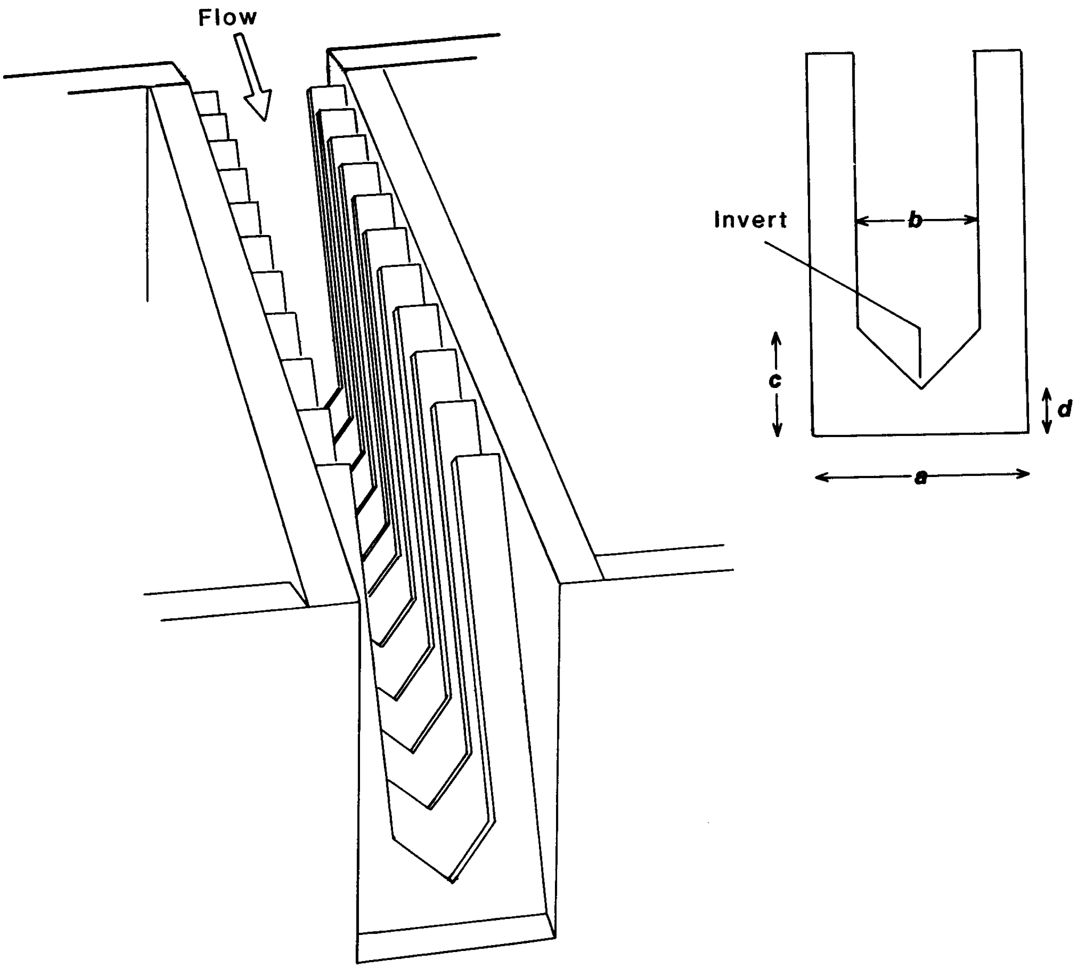


Figure 18 A schematic diagram of a Denil fish pass with single plane baffles. Inset is a diagram of a single baffle with the recommended proportions $a:b:c:d$ = 1:0.58:0.47:0.24; b is the fish free passage width, and the distance between consecutive baffles is 0.67 x a. (From Lonnebjerg, 1980.)

Figure 19 A view up part of the extensive Denil fish pass complex at Ennistyman on the River Inagh in the Republic of Ireland.

Assuming the following relationship between salmon mass and length (W.M. Shearer, personal communication):

$$M = 10.836\,L^{2.964}, \qquad \text{.............................(7)}$$

then,

$$F_G = 104.64\,L^{2.964}\sin\alpha\,. \qquad \text{.............................(8)}$$

As the total force acting on the fish is

$$F = F_D + F_G, \qquad \text{...........................(9)}$$

then from equations (5) and (8)

$$F = 2.728\,U^2L^2 + 104.64\,L^{2.964}\sin\alpha\,. \qquad \text{...........(10)}$$

Denil proposed that salmon and sea-trout exert a force equivalent to 0.6 and 0.7 times their respective weights when swimming energetically against a water flow. Thus, if a 0.80 m salmon (mass 5.59 kg, from equation 7) is to be able to swim up a pass having a water velocity of 3 m s^{-1} and a gradient of 1:5 ($\sin\alpha = 0.20$) with a relative velocity of 0.3 m s^{-1}, it must exert a total force of 32.51 N (equation 10). This total force is equivalent to a mass of 3.31 kg x g and is 0.59 times the fish's weight.

If the total force on a salmon is not to exceed 0.6 of its weight, the maximum water velocity permissible in the Denil pass can be calculated using equation (10) to give

$$U = 6.19\,L^{0.482}\,[0.61 - \sin\alpha]^{0.5}\,. \qquad \text{................(11)}$$

These maximum velocities are shown in Figure 20 against fish length for three gradients of Denil pass (1:3, 1:4 and 1:5). A strict comparison with the burst speeds from Figure 1 is impossible since Denil did not take water temperature into account when arriving at his drag figure of 0.6 times the weight of a salmon. However, there is sufficient correlation to allow Figures 1 and 2 to be used to assess the ability of a salmon to negotiate a particular Denil pass if the mean water velocity and channel length are known.

The design of a Denil fish pass requires a knowledge of the relationship between flow and depth. Very few data on this relationship are available, and those which do exist relate to a variety of pass designs which makes comparison difficult. Lonnebjerg (1980) investigated the effects of slope and dimension on flow using models and concluded that the significant forces are those due to inertia and gravity. Using Froude's law of scale he proposes the following approximate equations for mean water velocity and flow:

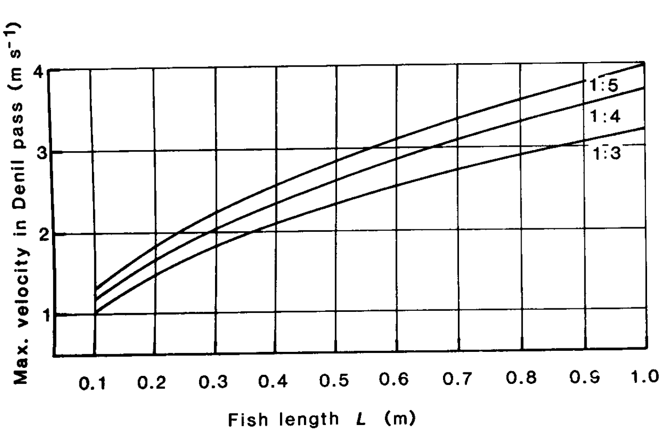


Figure 20 Maximum water velocity at three gradients of Denil fish pass equated to speed achievable by fish of various lengths, based on the drag force for a salmon being proportional to 0.6 of its body weight. (Subtract 0.3 m s^{-1} to allow fish to progress through the pass at this rate.)

$$U_F/U_M = \lambda^{0.5} \text{ and} \qquad \text{..................(12)}$$

$$Q_F/Q_M = \lambda^{2.5}, \qquad \text{......................(13)}$$

where λ is the scale ratio L_F/L_M, L_F is a dimension in the full size pass, and L_M is the equivalent dimension in the model pass.
As the water velocity in a Denil pass increases in proportion to the square root of the gradient,

$$U_F/U_M = [\alpha_F/\alpha_M]^{0.5}, \qquad \text{............................(14)}$$

where α is the sine of the slope angle as before.

The Report of the Committee on Fish Passes (Anon, 1942) proposed a practical Denil pass with a channel width of 0.91 m and baffles set a distance apart equal to two-thirds the width of the channel (about 0.60 m) and sloping upstream at an angle of 45° to the channel bed, the slope of which should not exceed 1:4 (i.e. sin $\alpha \leqslant 0.25$). Large resting pools for fish (3 m long x 2 m wide x 1.2 m deep) should be provided at vertical intervals of 2 m. A test channel was constructed in concrete with metal baffles as defined above, by the Committee on Fish Passes. The length of channel between resting pools was 9 m and the gradient 1:5. A continuous flow of 0.60 m^3 s^{-1} was obtained with a mean water velocity of only 1.8 m s^{-1} and a water depth of 0.91 m. At the lower flow of 0.28 m^3 s^{-1} (corresponding to a water depth of 0.61 m) it was claimed that there was still sufficient room for fish to swim the channel. In fact, in the Republic of Ireland fish have been observed swimming up Denil passes with a total water depth of 0.30 m which is equivalent to only 0.15 m depth over the invert of the baffle (see Figure 18).

Lonnebjerg (1980) reports that in 1945 at Herting in Sweden a single-plane Denil pass was built to the same proportions as suggested by the Committee on Fish Passes, but scaled up by 50% and the channel slope decreased from 1:5 to 1:6. A flow of 1.4 m^3 s^{-1} was measured using hydrometric vanes, but unfortunately no data are given on water depths. Following the success of the pass at Herting the Fish and Wildlife Service of the Department of the Interior (USA) decided to build a similar pass at Dryden Dam on the Wenatchee River, Washington and to monitor its performance more fully; its flow was measured to be 0.85 m^3 s^{-1} at a depth of 0.91 m. Calculations based on Froude's law of scale (equations 12, 13 and 14) and the Committee on Fish Passes' figure of 0.60 m^3 s^{-1} predict a flow of 1.05 m^3 s^{-1}, which shows reasonable agreement with the measured flow, particularly as a change of scale and slope is involved and the passes are similar but not identical.

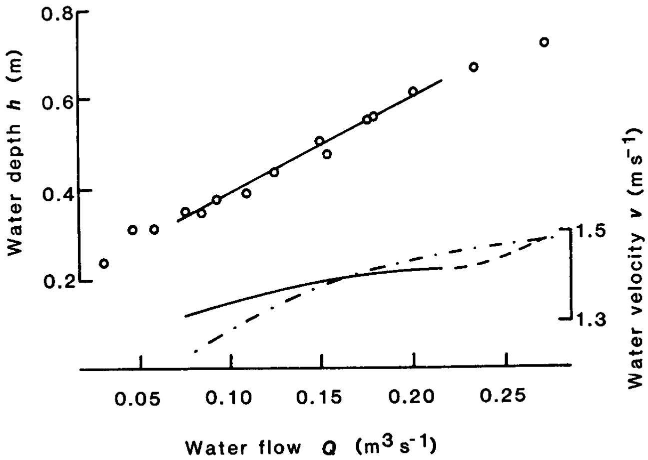


Figure 21 Flow measurements in the Denil fish pass at Årup-Mølle on the River Rohden-Årum, Denmark (slope 1:4): top curve is flow Q against depth h; bottom curves are flow Q against velocity U (solid line indicates measured values, broken line predicted values). (Lonnebjerg, 1980.)

Lonnebjerg also supervised a project at Horsens in Denmark in 1978 which included model trials on a Denil-type pass. The conclusion from these trials corroborated Denil's original findings in that the best incline for the baffles was found to be 45° and the best distance between the baffles was 67% of the channel width. A pass was subsequently constructed incorporating these design criteria at Årup Møllе, Denmark on the Rohden-Årum River with a channel width of 0.57 m and free passage of 0.33 m. The slope was 1:4 (sin $\alpha = 0.25$) and the length 9.4 m. Comprehensive flow measurements were made at this pass and the results are shown graphically in Figure 21; the water depth h was measured from the bottom of the channel and so the water height above the invert of the baffle was about 0.12 – 0.13 m less than h. An approximately linear relationship between flow and depth exists over the range of water

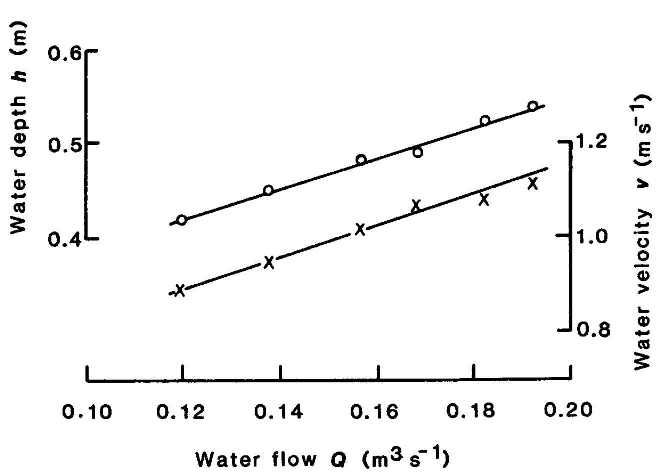


Figure 22 Flow measurements in the experimental section of Denil fish pass at Hesselvig Enggärd on the River Skjern, Denmark (slope 1:5): top curve is flow Q against depth h; bottom curve is flow Q against mean water velocity U. Note that since there are no bottom baffles, h represents the water depth above the channel. (from Lonnebjerg, 1980.)

depths of 0.35 m to 0.65 m; the mean water velocity varies only between 1.32 m s^{-1} and 1.42 m s^{-1}. In trials with fish, sixteen brook trout (*Salvelinus fontinalis* (Mitchill)) and two rainbow trout (*Salmo gairdneri* Richardson) were released immediately downstream from the pass: after 7.5 hours, eight of the brook trout and both of the rainbow trout had negotiated the pass, the smallest fish being a 0.25 m brook trout.

The success of the Denil pass at Årup Mølle resulted in Lonnebjerg becoming involved with the recently installed Denil pass at the hydroelectric power station at Tange on the Gudenå River, Denmark. The structure comprised seven resting pools and eight Denil flights each 6.55 m long with a gradient of 1:5, the total rise being about 10 m. In order to predict the performance of this ambitious project it was proposed that a single Denil flight be tested prior to field construction. Consequently a section of width 0.57 m, free passage 0.32 m and distance between baffles of 0.32 m was erected at a gradient of 1:5 at a fish farm on the Skjern River at Hesselvig Enggård, Denmark. In this pass the baffles occupied the sides of the channel only, but in spite of the lack of bottom baffles – and the consequent higher water velocities at low flows – the pass showed good energy-reducing properties with Chezy coefficients* between 5.9 and 7.1. This type of baffle arrangement was suggested by the Committee on Fish Passes (Anon, 1942) as being particularly suitable for large variations in water head. Flow and velocity measurements for this pass are shown in Figure 22, where it can be seen that a change in head from 0.42 m to 0.53 m resulted in a change of flow from 0.12 m^3 s^{-1} to 0.19 m^3 s^{-1} over which range the velocity increased from 0.90 m s^{-1} to only 1.12m s^{-1}.

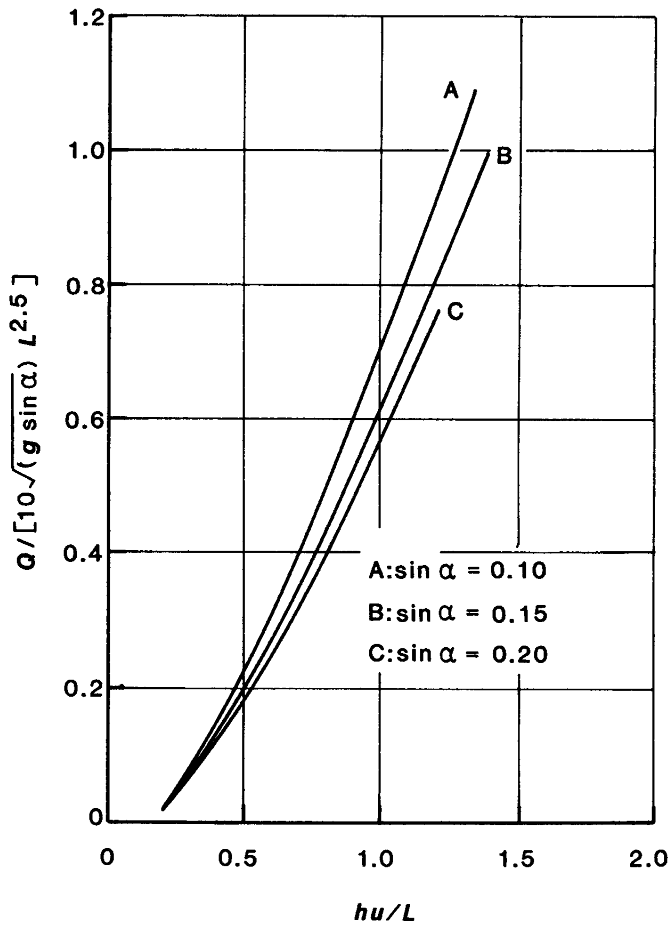


Figure 23 The flow Q in a Denil channel of width L related to upstream river level h_u at each of three channel gradients ($\sin \alpha$ = 0.10, 0.15, 0.20). (Redrawn from Larinier, 1983.)

Additional information on the flow characteristics of a Denil fish pass with the baffle arrangement as in Figure 18 is given by Larinier (1983). The relation between the water flow and the upstream head h_u over the invert of the top baffle is given in Figure 23, and the relation between the flow and the depth h in the pass (normal to the channel) in Figure 24. The measurements were made at three gradients ($\sin \alpha$ = 0.10, 0.15 and 0.20) and provide a useful addition to the limited data available for this type of pass.

The energy-reducing property of the Denil pass and its relatively low water demand has been put to novel use by the Alaska Department of Fish and Game (Ziemer, 1962): for the installation of passes at remote locations prefabricated Denil sections (approximately 3 m long) are attached to the floats of light aircraft and flown to the sites. Up to three such sections are then bolted end-to-end and leant against the rim of the obstruction. The design of fish pass used is designated 'Model A' by the Alaska Department of Fish and Game and is an adaptation of a modified Denil pass developed by McLeod and Nemenyi (1940). The baffle arrangement is complex and difficult to visualise but a small diagrammatic section is shown in Figure 25 and a view through such a section is shown in Figure 26.

*The Chezy coefficient is a measure of the effect of the roughness of a channel on the velocity of water flow through it. A glazed surface would have a coefficient in excess of 100, whereas a river channel choked with weeds and boulders and having hollows in its bed and banks, and sharp bends would have a coefficient of about 30.

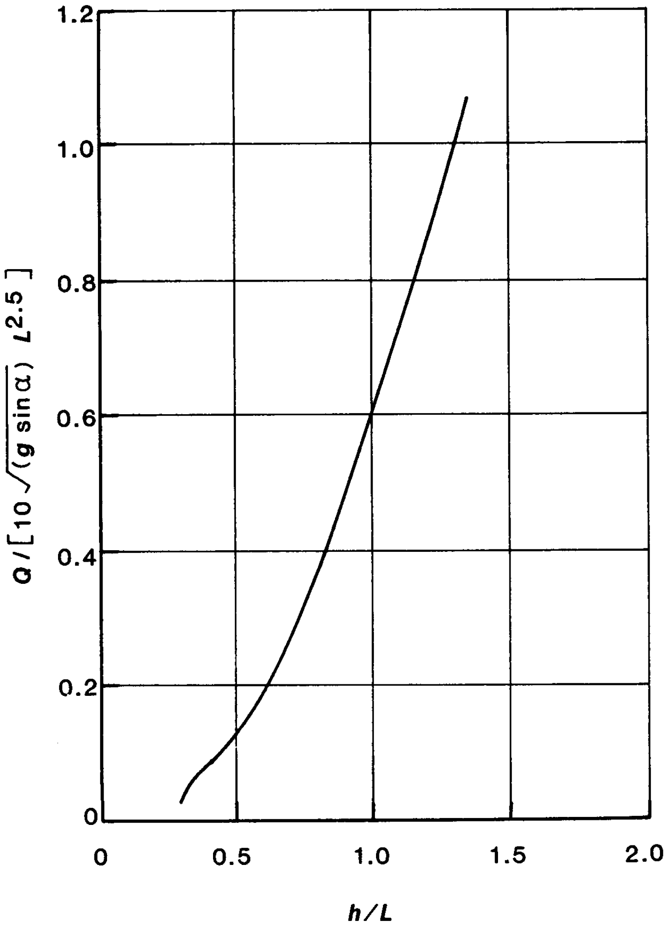


Figure 24 The relationship between the flow Q and the water depth h in a Denil channel of width L at three gradients ($\sin \alpha = 0.10, 0.15, 0.20$). The best line has been drawn through the experimental points for all three channel gradients. (Redrawn from Larinier, 1983.)

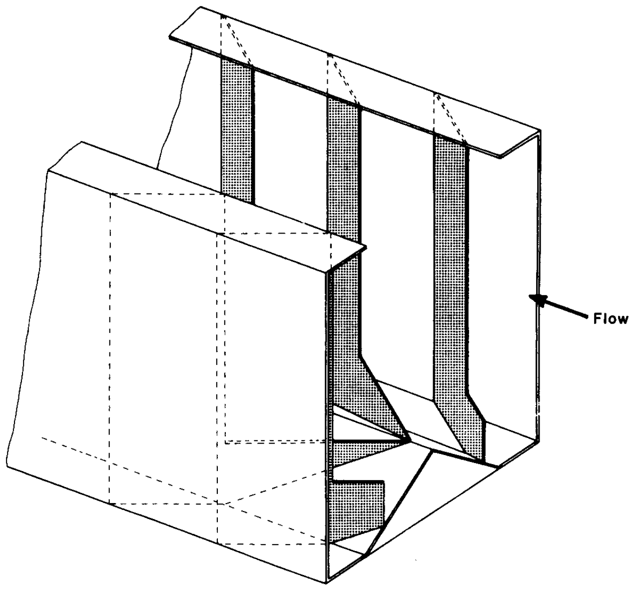


Figure 25 Cut-away sectional diagram of the Alaskan 'Model A' Denil fish pass prefabricated from steel in 3 m lengths with a channel width of 0.56 m and channel depth of 0.69 m.

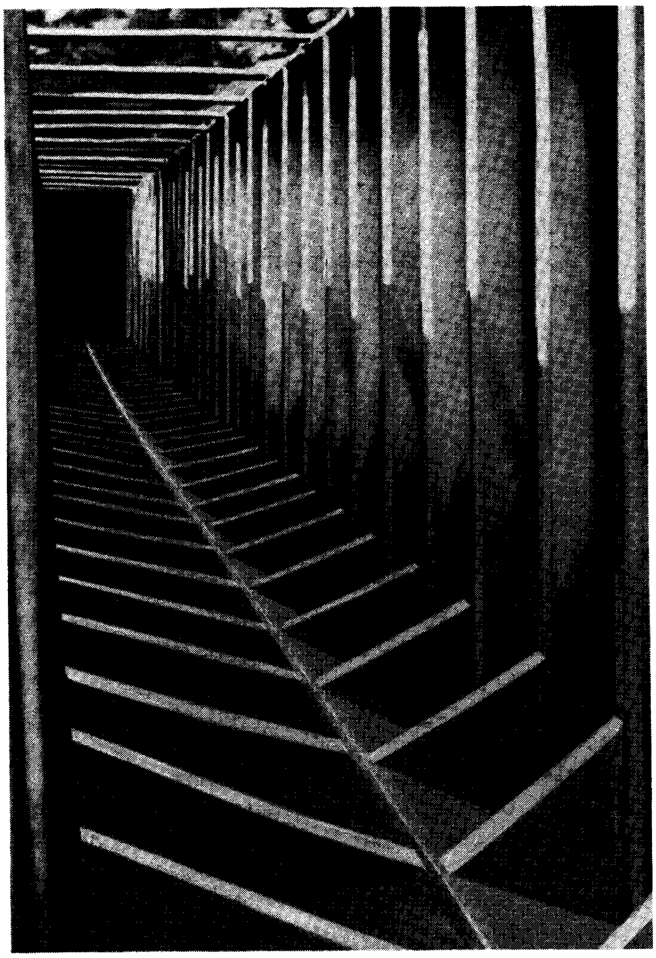


Figure 26 A view through the prefabricated Alaskan 'Model A' Denil fish pass.

A 2.31 m high obstruction to the passage of salmon at Gretchen Creek on Afognak Island, Alaska was surmounted in 1959 using three sections of the 'Model A' Denil channel at an inclination of about 1:4. The following account of its performance is given by Ziemer (1962):

"Construction was accomplished under force account procedures at a total cost of $6,654. Thirty lineal feet of steep pass was installed on a 26.2% grade to span a vertical rise of 7.6 feet for a unit cost of $876 per foot of rise. All the materials used in this project were flown to the shoreline of a lake 3,000 feet distant using a two-place plane on floats and then man-packed to the site. The first red salmon migrant† arrived at the fish pass entrance two days after its completion, entered without pause, exited almost immediately and continued up the creek without stopping. During the 1960 season the biologist estimated that 3,500 red salmon passed through this steep pass."*

*Equivalent to the UK gradient of 25.3%. The UK uses the sine of the small angle to give gradient, whereas the USA uses the tangent of the angle.

† The salmon migrant referred to is the red salmon (*Oncorhynchus nerka* (Walbaum)).

6. Approval of fish pass design

The Salmon and Freshwater Fisheries Act 1975 (Great Britain Parliament, 1975) requires that proposed new obstructions in migratory fish rivers and certain alterations to existing obstructions *must* be approved by the Ministry of Agriculture, Fisheries and Food. Initially, a detailed proposal should be submitted to the Inspector of Salmon and Freshwater Fisheries at the Ministry as early as possible. The detail should include:

(a) a location plan with Ordnance Survey reference;
(b) full engineering drawings of the existing obstruction (natural, weir, sluice, etc) including plan, side and sectional elevations;
(c) datum levels (preferably referred to Newlyn – the Ordnance Survey datum) of all crests and inverts, and upstream and downstream water levels;
(d) a water flow/frequency graph applicable to the flow at the structure;
(e) any operating regime (e.g. water draw-off, sluice gate manipulation, etc.) that may affect the flow available for the fish pass;
(f) information on the migratory fish stocks (species, length range, timing of main spawning run, etc.) and water temperature; and
(g) any general information that may relate to the structure (design constraints, complex ownership arrangement, water abstraction or fishing rights, etc.).

The details submitted are examined and an occasional site visit undertaken. If the site of the proposed fish pass is not in the ownership of the water authority that authority is required under section 18(2) of the 1975 Act (see Appendix 1 Page 44) to serve notice of their application, together with a plan and specification of the proposed work, on the owner and occupier of the site. When considering an application for "provisional approval" the Ministry must take into account any objections made by the owner or occupier.

If the proposals are considered satisfactory by both the Ministry, the local water authority Fishery Officer, and, where appropriate, the consulting engineers the authority should then seek official 'provisional approval' from the Ministry. This requires 3 complete sets of plans (4 sets if the site is privately owned) which *must* specify the location of the site, the specification of the structure, the range of water levels, and other items of relevant information as listed above. When provisional approval is given each set of plans is 'sealed' (Figure 27), two sets being retained by the Ministry, one sent to the relevant water authority and if appropriate, one sent to the owner of the site of the proposed structure. Construction of the pass can then proceed.

After an agreed period, usually about 3 years, the Ministry will contact the water authority for information on the operating effectiveness of the structure and its ability to afford fish easy passage. If the authority is satisfied with the operation of the pass it may apply for 'final approval' enclosing any supporting evidence that illustrates the effectiveness of the pass. If this is satisfactory the Ministry will approve and certify the pass.

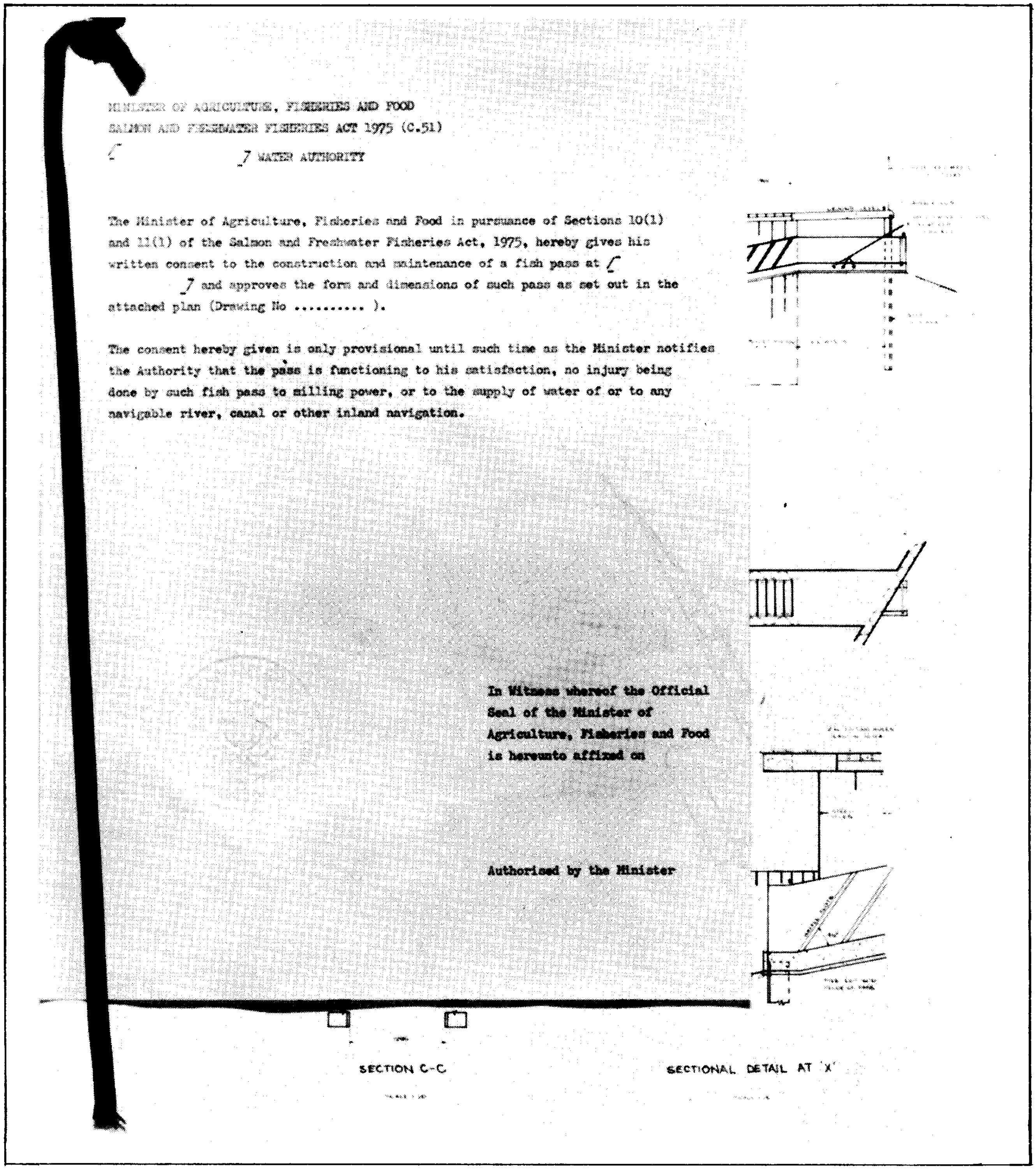
However, it may happen that modifications to the pass prove to be necessary between provisional and final approval stages and in such cases the Ministry should again be consulted. When agreement is reached on revised plans the original provisional approval will be revoked and, after 90 days, a new 'provisional approval' given on the basis of the revised plans. The Ministry should of course be notified if any changes are made to a fish pass after final approval has been given.

6.1 Example of 'pool and traverse' fish pass

The following example of the way in which a proposed scheme for a 'pool and traverse' fish pass is evaluated is based on Figure 28 which refers to a proposal and approval of 20 years ago. This pass should not be considered ideal, nor applicable to all situations, but merely an example to illustrate the aspects examined for an effective fish pass. It should be noted that although the drawings in Figure 28 have been reduced considerably, sufficient detail is available for discussion and the rest readable with magnification. Although the original information presented in Figure 28a and b is in Imperial units, all the dimensions in the following text are in metric units.

The inset key plan (scale 1:2500) in Figure 28a shows the fish pass site in relation to the local town. The site is not marked but its position can be seen on the larger scale section to be where the flood channel rejoins the main river. A large central buttress protects the west bank from the flood channel outflow and a radial gate (not shown) and weir link this buttress to the west bank. The radial gate and weir together constitute an impassable barrier at most of the range of river flows and it is proposed to construct a pass around it with seven pools. Two of the pools can be seen to be larger than the others. A small river flows into the main river just downstream from the pass. The upstream arrangement and its relation to the river is a little confused.

Figure 28b shows a detailed plan, side elevation and sectional elevations of the pass and weir. Here again the upstream exit is not clear and no detail of the radial gate is apparent. To describe the pass from top to bottom, the upstream exit from the pass is through a rectangular side notch (0.61 m wide x 0.76 m deep) from a square pool of length about 3 m. The next two pools are 3.05 m long x 1.83 m wide below which is another square pool of length



MINISTRY OF AGRICULTURE, FISHERIES AND FOOD
SALMON AND FRESHWATER FISHERIES ACT 1975 (C.51)

[ ] WATER AUTHORITY

The Minister of Agriculture, Fisheries and Food in pursuance of Sections 10(1) and 11(1) of the Salmon and Freshwater Fisheries Act, 1975, hereby gives his written consent to the construction and maintenance of a fish pass at [ ] and approves the form and dimensions of such pass as set out in the attached plan (Drawing No ....).

The consent hereby given is only provisional until such time as the Minister notifies the Authority that the pass is functioning to his satisfaction, no injury being done by such fish pass to milling power, or to the supply of water of or to any navigable river, canal or other inland navigation.

In Witness whereof the Official Seal of the Minister of Agriculture, Fisheries and Food is hereunto affixed on

Authorised by the Minister

Figure 27 The form of the Approval certificate given by the Minister of Agriculture, Fisheries and Food to an acceptable set of plans for a fish pass scheme.

3.05 m. The next two pools are again 3.05 m long x 1.83 m wide and connected to the lowermost entrance pool. This pool has a rectangular notch (again 0.61 m wide x 0.76 m deep) positioned in its most downstream corner and the opposite corner is faired to provide good flow characteristics and to enable the 90^{o} course change required of fish entering the pass. Below this pool is a stilling basin to dissipate the energy of the water discharged by the radial gate and weir, entry to this being by two 0.61 m wide x 0.46 m deep notches. Wooden boards are used to adjust the various water levels throughout the pass, there being grooves for these in the three lowermost notches and the most upstream notch.

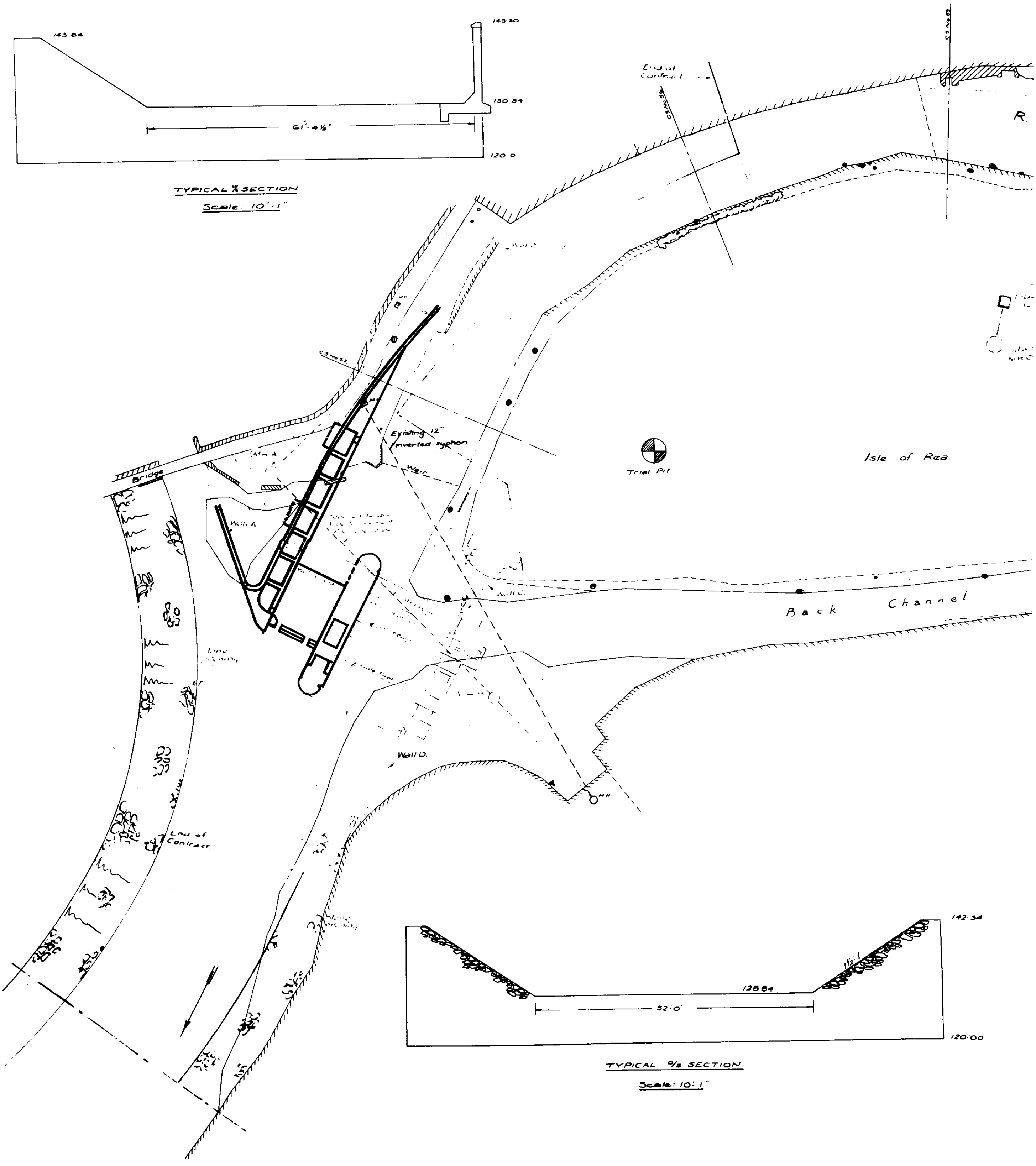
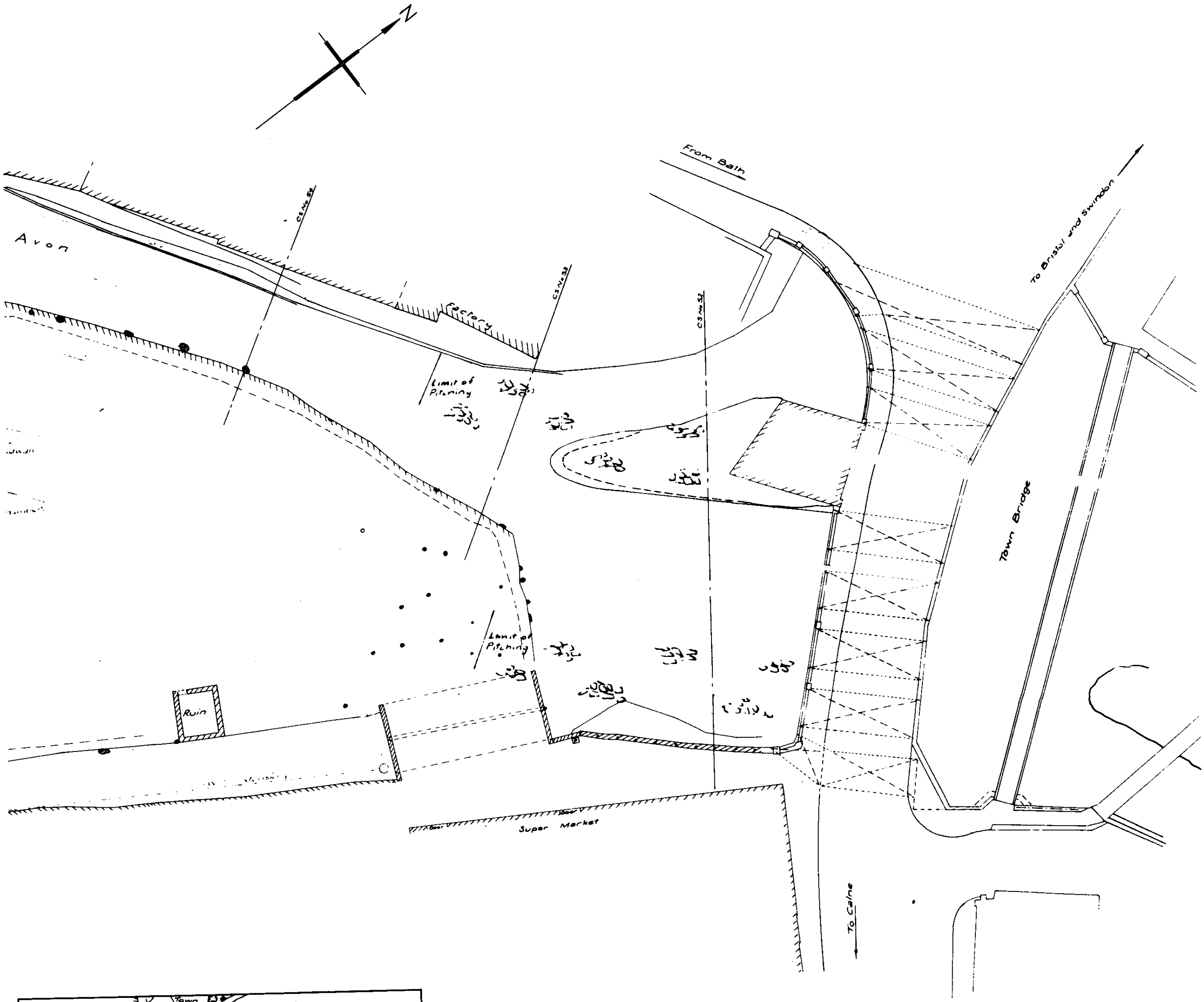
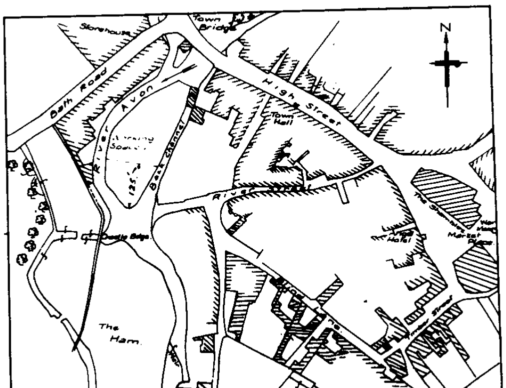


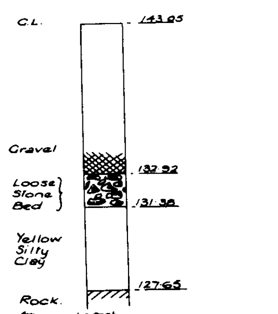
Figure 28a Plan of proposed 'pool and traverse' fish pass. Inset is a map of the site location.





KEY PLAN

Scale 1/2500.



Details in Trial pit. Nov/Dec '63

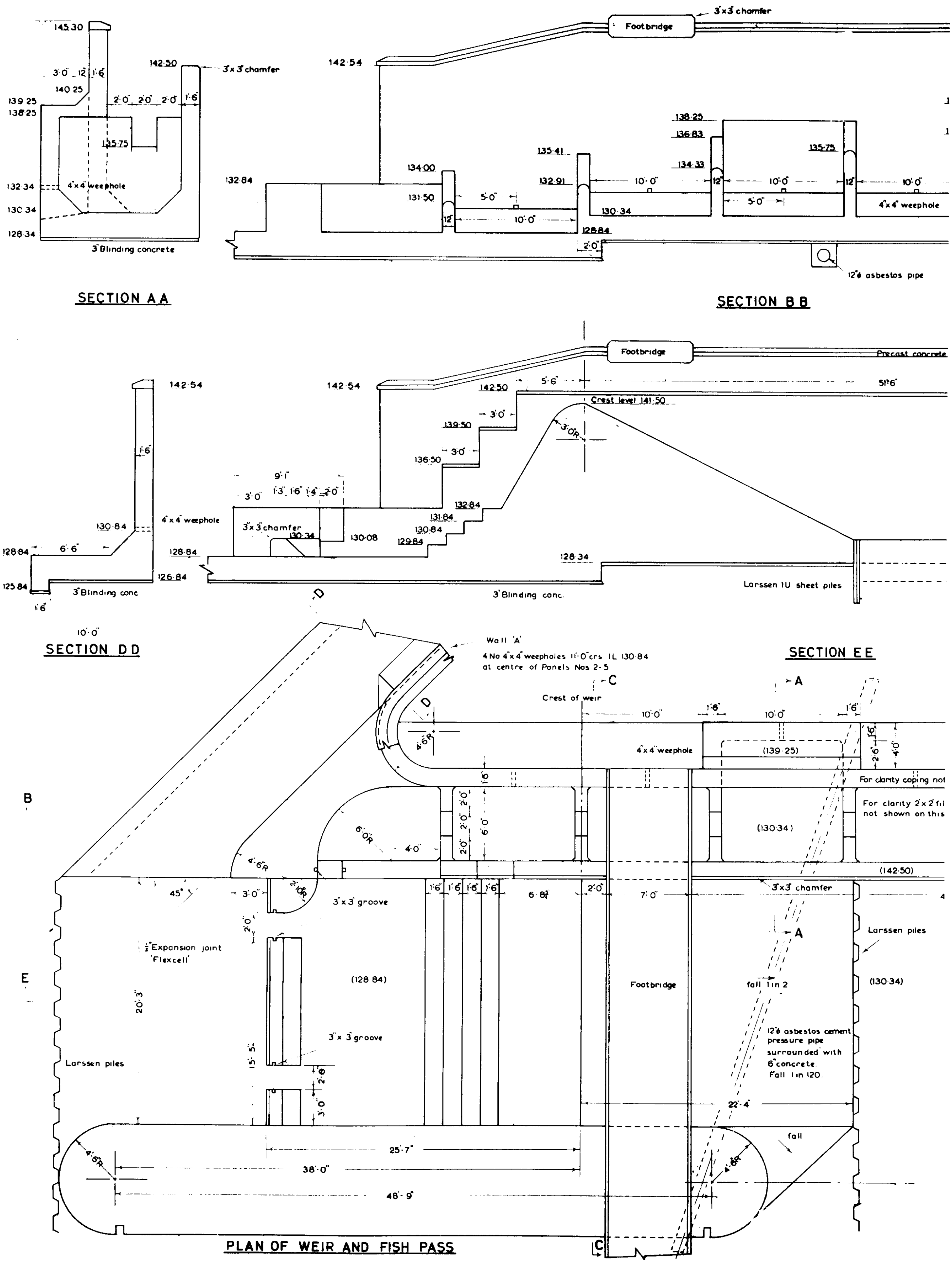
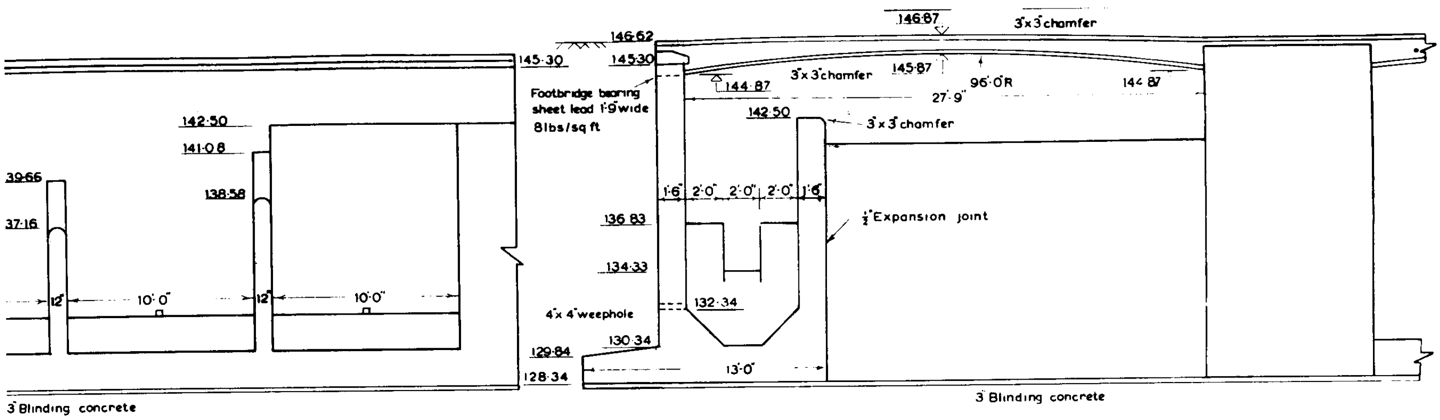
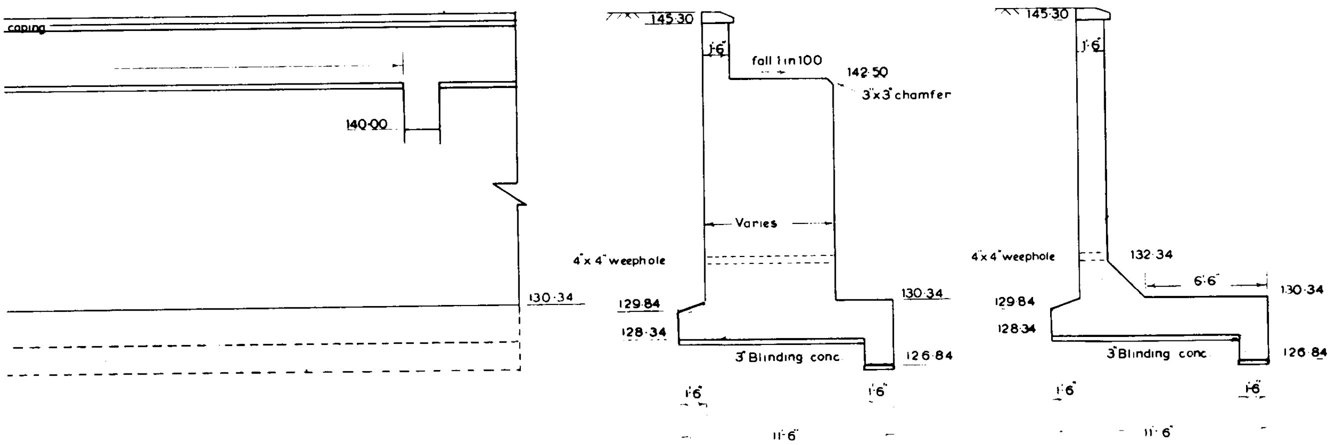


Figure 28b Detailed engineering layout of proposed 'pool and traverse' fish pass, including plan, side and end elevations and specific sectional drawings (dimensions in feet; ordnance datum levels referred to Newlyn).



SECTION CC

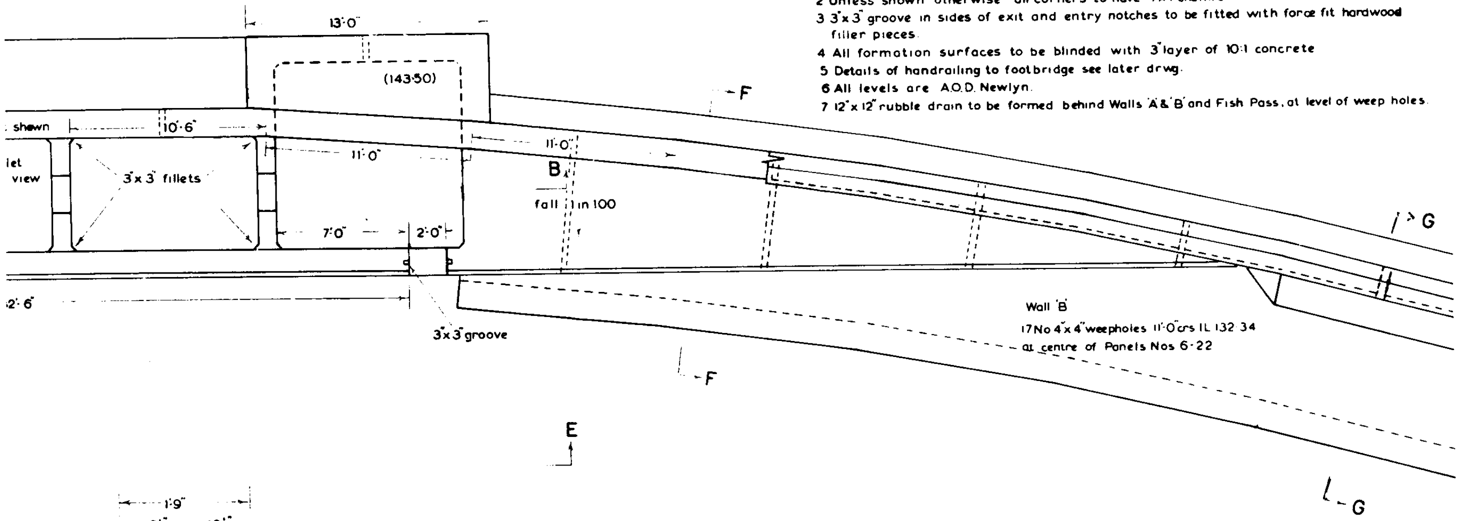


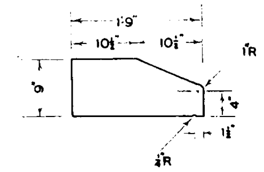
SECTION FF

SECTION GG

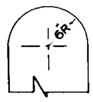
NOTES

1 This drwg to be read in conjunction with 2724/16 and 2724/20
2 Unless shown otherwise all corners to have 1"x 1" chamfer
3 3"x 3" groove in sides of exit and entry notches to be fitted with force fit hardwood filler pieces.
4 All formation surfaces to be blinded with 3" layer of 10:1 concrete
5 Details of handrailing to footbridge see later drwg.
6 All levels are A.O.D. Newlyn.
7 12"x 12" rubble drain to be formed behind Walls 'A' & 'B' and Fish Pass, at level of weep holes.

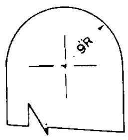




SECTION OF PRECAST CONCRETE COPING



SECTION THROUGH CROSS WALL NOTCH



SECTION THROUGH ENTRY AND EXIT NOTCH

Water depths in the two lowermost pools and the stilling basin, at the minimum flow just sufficient to fill the notches, would nowadays be considered too low to conform with present recommendations (see section 5.1); they are 0.78 m, 0.81 m and 0.46 m respectively, whereas 1.2 m is now recommended. An approximate water flow through the notches is calculated using the Francis formula (equation (3), section 5.1) and at notch full would be about 0.645 $m^3\ s^{-1}$. At a notch depth of about 0.20 m (the absolute minimum recommended) the flow would be 0.100 $m^3 s^{-1}$. The invert level of the upstream notch is 42.67 m above the ordnance datum at Newlyn (A.O.D.) and thus the upstream river level must not be allowed to fall below 42.87 m A.O.D. if this minimum notch depth is to be maintained throughout the pass (all notches being the same size). The water flow from the stilling basin is by way of two 0.61 m wide notches which would serve to reduce the already inadequate depth of 0.46 m to only 0.13 m at the minimum flow of 0.100 $m^3\ s^{-1}$. Hence, the upstream river level must be maintained at 43.43 m A.O.D. (the notch full condition) to ensure the maximum depth in the stilling basin.

However, if the upstream river level increases above the notch full condition of 43.43 m A.O.D., water will spill sideways into most of the fish pass. This could have disastrous consequences to the direct flow through the pass and disorientate ascending fish so as to cause them to jump unsuccessfully at the side walls. Hence the upstream river level must not exceed the notch full condition if side spill is to be prevented and the maximum stilling basin depth preserved. Also, excess water cannot be taken through the pass but must be drawn off through the radial gate where it will create a competing 'lead' for fish at the entrance to the pass and a turbulent situation in the stilling basin.

A flow/frequency graph for this river (not included) would indicate the percentage of time the flow exceeds the necessary 0.745 $m^3\ s^{-1}$ and is spilled through the radial sluice, and also the percentage of time when the flow is lower than the ideal 0.745 $m^3\ s^{-1}$. It is critical to the appraisal of this pass that the operating regime of the radial gate, and its effect on the upstream water level, be fully understood and documented. Information must also be submitted on the fluctuations in the downstream water level so that the access by fish to the two notches at the bottom of the stilling basin can be assessed.

A summary of the examination of Figure 28 would be as follows:

(i) Plan dimensions of all pools satisfactory.

(ii) All water level changes between pools (0.43 m) acceptable except for that at the entrance to the pass from the stilling basin which is too great at 0.76 m because it exceeds the difference in water level of 0.45 m recommended in section 5.1.

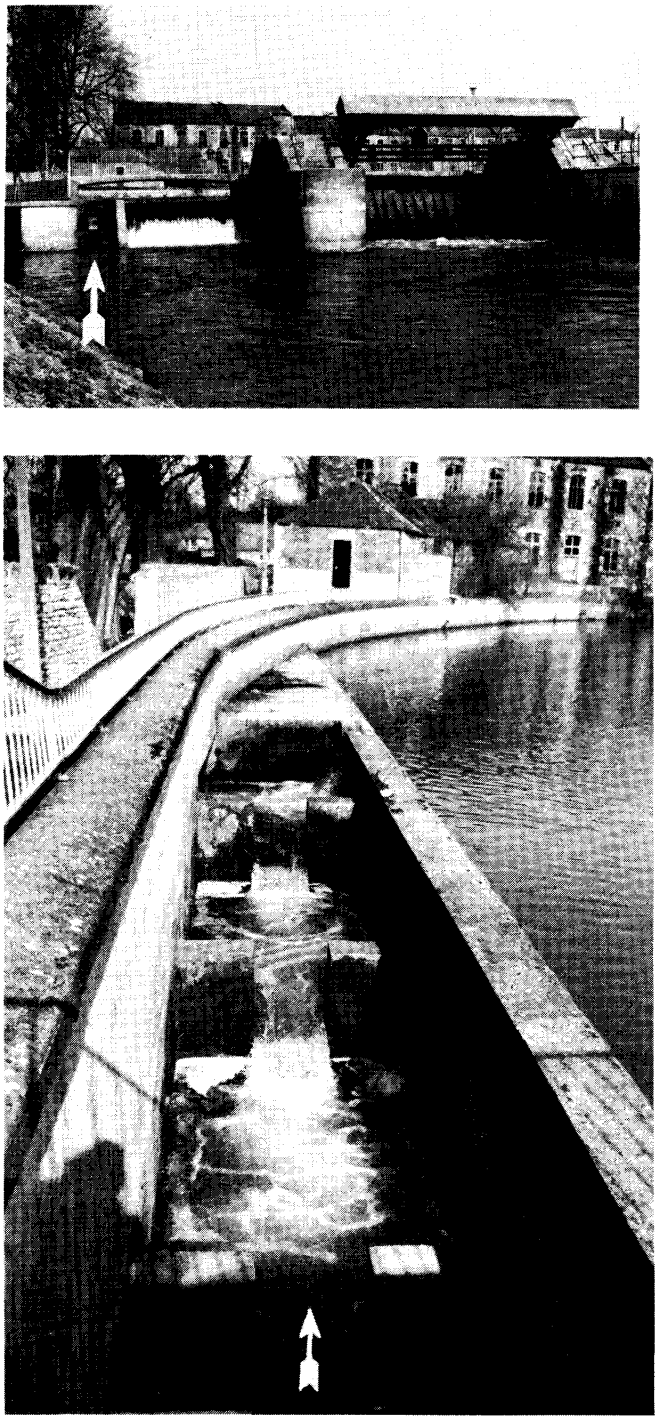


Figure 29 Two views of the completed 'pool and traverse' fish pass (arrowed) based on plans in Figure 28, showing detail inside the pass and its relation to an adjoining weir and radial sluice gate.

(iii) The pass is unable to cope with changes in upstream river level: too high a level and side spillage results, too low a level and the water depth in the downstream pools becomes grossly inadequate.

(iv) A competing flow from the radial gate and the turbulent condition in the stilling basin would adversely affect the finding by fish of the pass entrance.

(v) No information is supplied on the dimensions of the radial gate or its operating regime.

(vi) No information is supplied on the downstream water level to be maintained and the access to the notches in the stilling basin.

(vii) The pass would be improved if the height of the wall dividing the pass from the main river (presently at 43.43 m A.O.D.) were enhanced along all pools upstream from the weir except the uppermost pool. This would enable the pass to take more water, reduce the competitive 'lead' from the radial gate discharge, and give more latitude to the control of the upstream river level.

(viii) The stilling basin situation must be improved to provide greater water depth and reduce the water level change into the lowermost pool of the pass.

It must be stressed that, although this pass was in fact Approved, this occurred almost 20 years ago when less was known of the swimming capabilities of migratory fish, and when this river was not yet supporting a migratory fish run. Also, substantial alterations to the course of the river and adjoining banks now make the original plan (Figure 28a) unrecognisable. Figure 29 shows views of the site and pass as it is today. The latest information shows that, whilst used by coarse fish (there are still no migratory fish in the river), the entrance is confused by the discharge from the adjoining weir and radial sluice gate and by the outflow from a brook which discharges into the river immediately downstream from the weir stilling basin.

6.2 Example of a Denil fish pass

Part of a recent proposal for a Denil fish pass at Wood Mill on the River Itchen, Hampshire is shown at Figure 30. Considerable background information was available on this scheme since the site contains the oldest Approved fish pass – it was officially Approved in 1862. Changes in downstream water levels had rendered the original pass impassable: a finding which was confirmed recently using an automatic fish counter and camera system. Fish obstruction at this site was due to a battery of sluice gates which control the discharge of the river into a tidal pool. In addition to the several ancient, manually-operated, wooden sluice gates, a single large automatic steel sluice was used. This, when just raised, provided a very good lead for fish but was clearly impassable (see Figure 6).

Figure 30a shows a site plan (reduced to approximately 43% of the size original submitted) on which the proposed Denil pass has been marked. The river flows through the sluices shown into the Salmon Pool and then out under Woodmill Lane. Although the line of the proposed pass is shown on the site plan, it is not in sufficient detail to convey the complex arrangement of pool and river. Also the sluice arrangement is complicated and would require more detailed information than is given here. This was a situation where both photographs and a site visit were found to be necessary. The plan also refers to the highest point to which medium tides flow and indicates the presence of a bench mark (BM 13.7, equivalent to 4.01 m) on Woodmill Lane. A small river, Monks Brook, flows into the Salmon Pool: information on whether this brook supports a migratory fish population that might be affected by the discharge from the newly sited Denil pass should be sought. Little more information can be gained from Figure 30a but there is a need to know the use to which the slipway is put and whether the turbulence generated by the new pass would affect this.

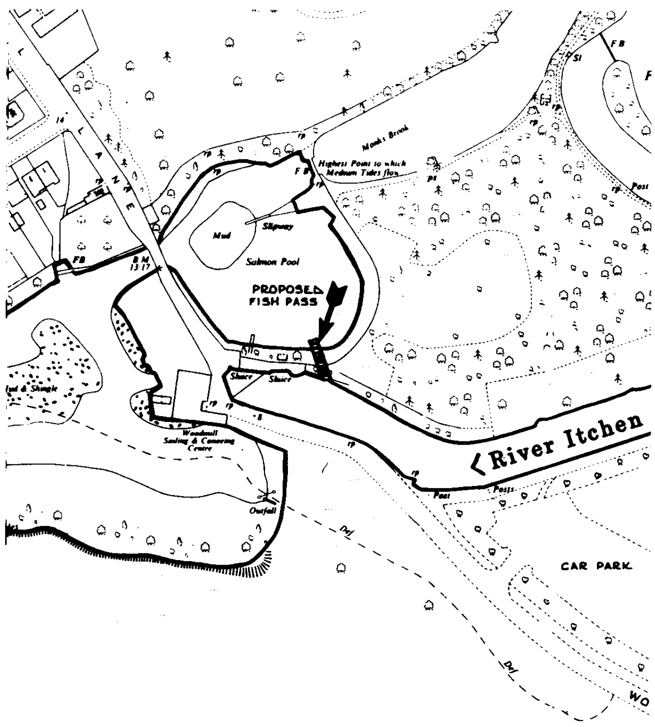


Figure 30a Large-scale map giving location of proposed Denil fish pass (arrowed).

Detailed engineering plans are shown in Figure 30b. The important features with regard to fish passage are the actual dimensions of the Denil channel and baffles, the entry and exit arrangements, and the upstream and downstream water levels. A view of a single baffle is shown and alongside it, for comparison, a view of Denil's original design. The dimensions of the baffles, their distance apart and the slope of the channel are satisfactory. A.O.D. levels are marked on sectional view B-B: as the scale is given, any additional levels can be calculated. The upstream river level is shown as a maintained level and is set at the top of the uppermost Denil baffle. This should be acceptable, but extra detail on the capability of the regulating sluices and the minimum summer drought river level and its frequency would allow a better assessment to be made. The down-

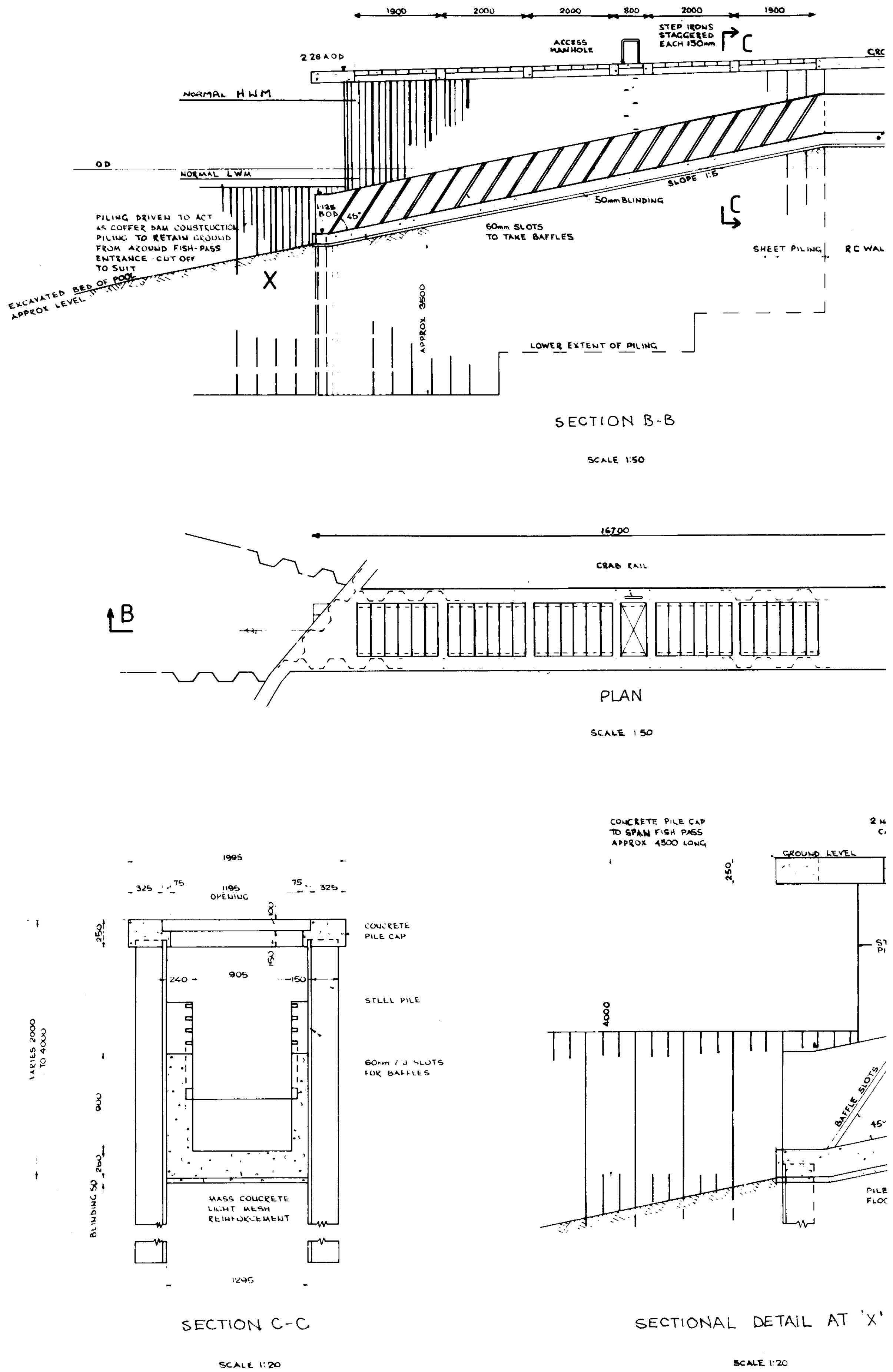
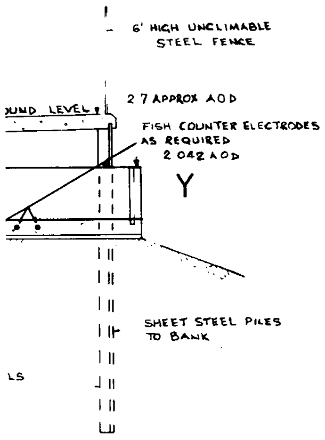
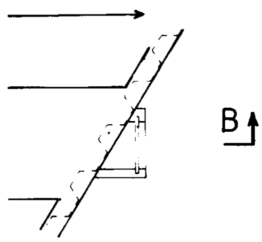
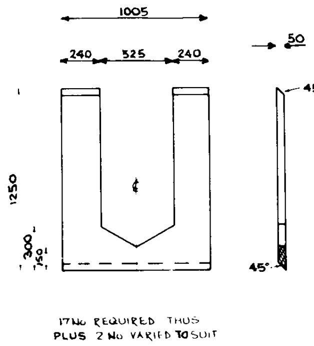


Figure 30b Detailed engineering layout of proposed Denil fish pass. The important details of entry and exit arrangements, baffle dimensions and range of water levels are included.

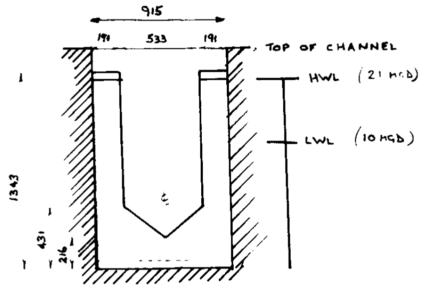






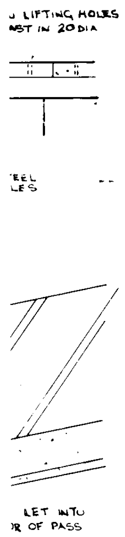
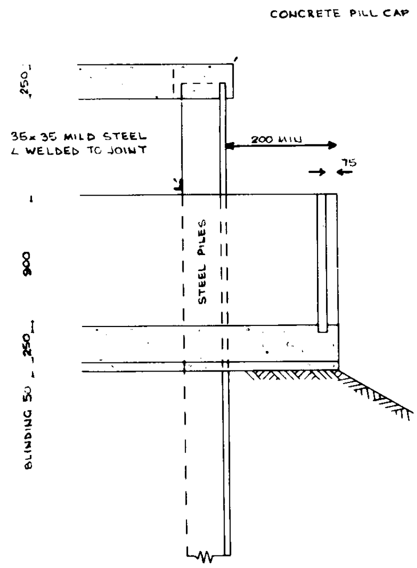
BAFFLE DETAIL

SCALE 1:20



DENIL'S ORIGINAL DESIGN

SCALE 1:20

SECTIONAL DETAIL AT 'Y'

SCALE 1:20

stream pool levels are shown as 'normal LWM' (low water mark) and 'normal HWM' (high water mark). Here it can be seen that at normal HWM the pass will be inundated and at normal LWM fish will have easy access. However, the situation at low spring tides is not specified and thus it is not clear if the lowermost baffle will still be accessible to fish. Judging by the number of baffles submerged at normal LWM it is highly probable that this aspect has been considered carefully, but it should be documented. Extra detail of the pass entry and exit arrangements is shown by larger-scale elevation views at 'X' and 'Y'. These are useful and, because of their larger scale would be better views on which to show upstream and downstream water level ranges. A relevant flow/frequency diagram with sufficient explanation should have been included. Fish-counter electrodes are shown in the upstream channel of the pass and precautions must be taken against the incursion of salt water when the pass floods at high tides since this will generate false fish-count data. (An automatic fish-counter (see Section 7) relies on the relatively low conductivity of fresh water for its operation).

A summary of the examination of Figure 30 is as follows:

(i) Water datum levels given are insufficient to show range of upstream level to be maintained.
(ii) Water levels for downstream full tidal excursions are not given.
(iii) The head difference between the normal LWM and the upstream maintained level is 2.267 m which is acceptable for the one Denil flight proposed. However, the tidal variation in the Salmon Pool, which is influenced both locally and by Southampton Water, is such that for about one third of the total time a near-maximum water level difference occurs between the Salmon Pool and the upper river. Also, neither the minimum water-retention level in the Salmon Pool nor the effect of extra-low spring tides on the access to the Pool are specified. From the above it can be seen as most important that the depth of submersion at all times of the lower end of the Denil be documented.
(iv) The Denil baffles are correctly proportioned with sufficient extra width to allow engagement in the recesses in the sides of the channel.
(v) Attention should be given to the fish-counter channel since the water velocity may be too low for reliable fish counts. A low weir to increase the water velocity in the vicinity of the counter electrodes should be considered. Electrical insulation under the electrodes may be necessary if the concrete construction of a low counting weir involves reinforcing steel close to the surface. Other points in connection with access to the counter electrodes and photographic surveillance need to be discussed further.

It must be emphasised that the figures used in this example were only a small part of the total information made available. Sometimes the information is available on an alternative drawing and must be extracted and annotated on the fish pass plans: this occurs because a full set of engineering drawings for a large project comprises hundreds of plans, only a few of which are considered relevant to the fish pass and so sent to the Ministry. However, the present procedure of selecting drawings, with its occasional omission, is preferable to the Ministry being required to search through hundreds of irrelevant engineering plans for pertinent information.

This pass has now received full Approval after a satisfactory Provisional Approval period; photographs of the operational pass are shown in Figure 31.

7. Automatic fish-counters

The number of migratory fish using a fish pass or traversing a gauging structure can be obtained automatically if fish are constrained to swim close to three stainless steel electrodes either fixed inside a tube or attached to the downstream face of a weir (open channel counter) and connected to an electronic fish-counter. The field from the three electrodes defines two water volumes whose effective resistances are constantly monitored. When these volumes are penetrated successively by a migratory fish their effective resistances change in turn because the conductivity of a fish's body is greater than that of the fresh water it displaces. The magnitude of the changes and the order in which they occur give information on the size of the fish crossing the electrodes and its direction of passage respectively. The open channel counter has an advantage over the original tube arrangement (Lethlean, 1951) in that debris can flow freely over the structure and down the river, and it does not require a series of grids to constrain the fish to swim through a tube.

It is essential that, because fish detection is achieved by conductivity change, each fish passes not only through the counting zone but also as close to the electrodes as possible. Hence, if a complete count is to be obtained, the electrode structure must be positioned where all fish are compelled to cross it at all conditions of river flow. Also, an increase in water velocity must be made to occur in the vicinity of the electrodes to encourage fish not to loiter in the counting zone, as loitering may give rise to false counts. Joint experiments with the Department of Agriculture and Fisheries for Scotland on the River North Esk at Montrose (Beach *et al.*, 1981) have shown that the majority of fish moving upstream swim very close to the electrodes whereas fish going downstream swim anywhere in the available water column.

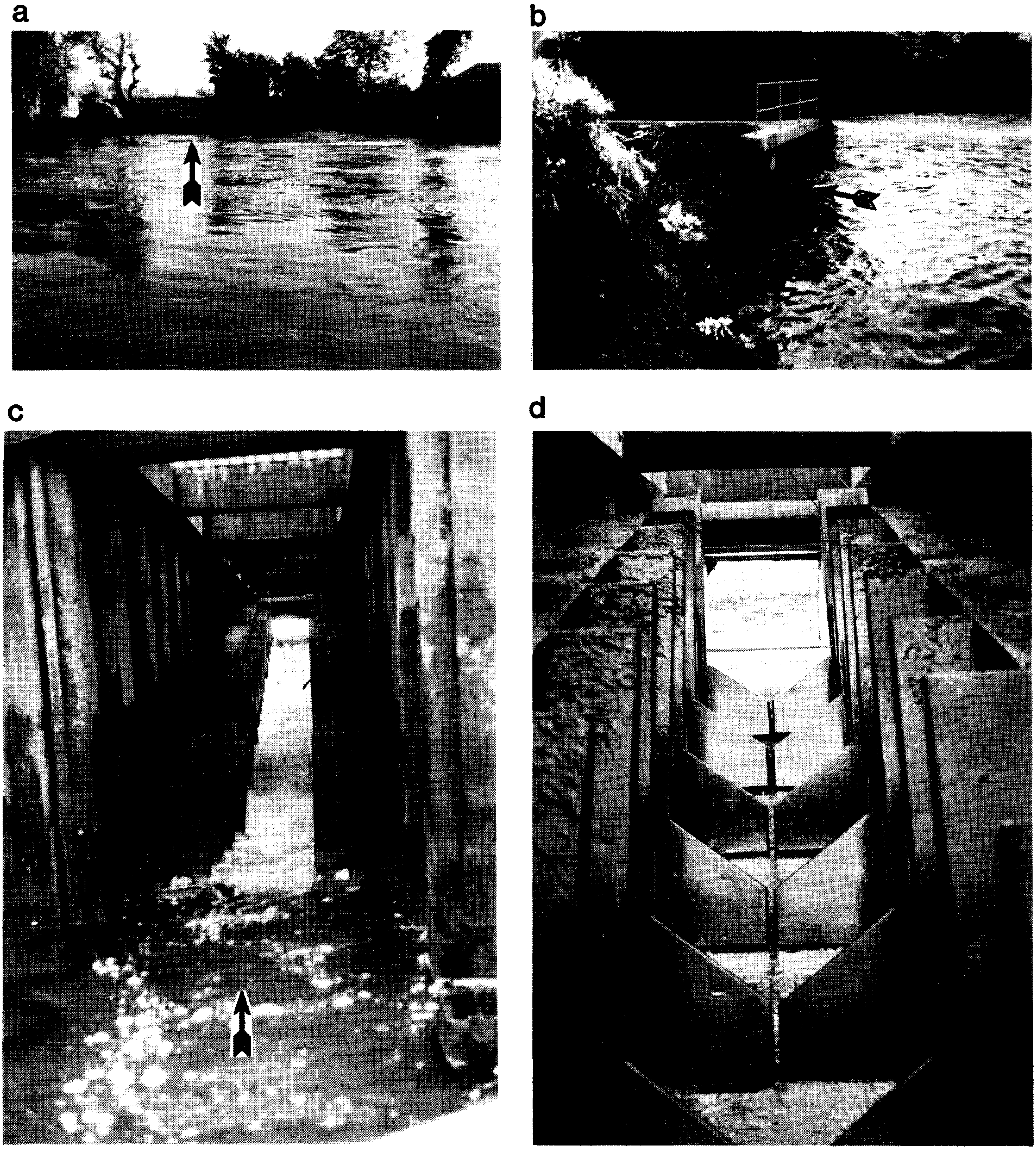


Figure 31 The completed Denil fish pass (arrowed) at Wood Mill. Views are (a) across the Salmon Pool to the pass, (b) the lower entrance, (c and d) the baffle arrangement inside the pass.

8. Conclusions

(1) The swimming speed and endurance times given in Figures 1 and 2 should not be exceeded. It is stressed that they are considered the maximum attainable and presume the fish to be in peak physical condition.

(2) Flow control structures such as flood relief channels should be designed so as to drain progressively and not strand fish. The minimum opening for a sluice aperture should be not less than 0.30 m x 0.30 m and the water velocity not greater than about 3 m s^{-1}; this corresponds to a water head difference of about 0.45 m and a flow of approximately 0.27 m^3 s^{-1}.

(3) The water head over a Crump flow-measurement weir should be such that excessive velocities do not occur on its downstream face; any truncated section should always be submerged. The maximum water velocity, which occurs just above the hydraulic jump, should not exceed

3.5 m s^{-1}. This velocity is attained at about 2.5 m from the weir crest for a gauged head of 0.2 m (equivalent to a flow of 0.18 m^3 s^{-1} per metre of weir) or at about 1 m from the weir crest for a gauged head of 0.8 m (equivalent to a flow of 1.56 m^3 s^{-1} per metre of weir). Since a slope of length 2.5 m corresponds to a vertical distance of 0.5 m, the difference between the Crump weir crest and the downstream water level (for the 0.2 m gauged head) should not exceed 0.5 m.

(4) The basic design requirements for a 'pool and traverse' type of fish pass to gain Ministry 'Approval' are:

- (a) the change in water level across a traverse should not exceed 0.45 m;
- (b) pools should have minimum dimensions of 3 m long by 2 m wide by 1.2 m deep;
- (c) each traverse should be 0.3 m thick with the notch 0.6 m wide and at least 0.25 m deep;
- (d) the downstream edge of both the notch and the traverse should be curved so as to reduce turbulence and provide an adherent nappe;
- (e) the pass entrance should be located easily by fish at all flows. An approximate flow of 0.13 m^3 s^{-1} would be required to ensure the notch runs full, and the 0.45 m change in water level would result in a maximum velocity of 2.97 m $^{-1}$.

(5) The original design of Denil fish pass required baffles of complex shape, but single-plane baffles have been shown to be very effective and are used in successful fish passes in many countries. The recommended proportions for a Denil pass (Figure 18), based on the Report of the Committee on Fish Passes (Anon, 1942), require a channel width of 0.91 m with baffles set 0.60 m apart and sloping upstream at an angle of 45 degrees to the channel bed, the slope of which should not exceed 1:4. Large resting pools (3 m long x 2 m wide x 1.2 m deep) should be provided at vertical intervals of 2 m. Through such a channel, of length 9 m and gradient 1:5, the flow was measured as 0.6 m^3 s^{-1}, the mean water velocity 1.8 m s^{-1}, and the mean depth 0.91 m. A shallower depth of 0.61 m gave a flow of 0.28 m^3 s^{-1}, and fish have been observed swimming up a Denil pass with a water depth as shallow as 0.30 m. Approximate formulae presented allow water flow and velocity to be estimated for passes built at different slopes and to different scales, and graphs presented allow flow and water depth to be estimated.

(6) As the Minister of Agriculture, Fisheries and Food is legally required to Approve many fish pass proposals, detailed site and engineering plans must be submitted. These should show all crest and invert datum heights, the expected range of upstream and downstream water levels, and the water flow/frequency at the site. Ancilliary information on factors effecting the operation of the fish pass should also be included, e.g. operation of adjacent sluice gates, type and behaviour of migratory fish, water temperature, ownership, fishing rights, etc. A satisfactory proposal for a fish pass, which requires three complete sets of plans (four sets if the site is privately owned), is given Provisional Approval. After an agreed period (usually about 3 years) the effectiveness of the pass is assessed and, if it is satisfactory, full Approval is given.

Acknowledgements

The manuscript was read in whole by Dr G.P. Arnold, Mr B. Stott, Dr D.J. Solomon, Dr M.G. Pawson, Mr J.R. Chandler, and in part by Dr C.S. Wardle, Dr W.R. White, Mr E. Whitehead and Mr M. Amey. I am very grateful to them all for their help and advice, but I wish to thank Dr G.P. Arnold and Mr B. Stott in particular.

I gratefully acknowledge permission to reproduce illustrations from D. Mills (Frontispiece), R.B. Bussell (Fig. 12), N. Lonnebjerg (Figs.18, 21 and 22), and M. Larinier (Figs 23 and 24). I am grateful to the Southern Water Authority for help in obtaining photographs (c) and (d) in Figure 31.

9. References

AITKEN, P.L., DICKERSON, L.H. and MENZIES, W.J.M., 1966. Fish passes and screens at water power works. Proc. Instn civ. Engrs, *35*: 29-57.

ANON, 1942. Report of the Committee on Fish Passes. Instn civ. Engrs, London, 59 pp.

ARNOLD, G.P., 1974. Rheotropism in fishes. Biol. Rev., *49*: 515-576.

BATTY, R.S. and WARDLE, C.S., 1979. Restoration of glycogen from lactic acid in the anaerobic swimming muscle of plaice, *Pleuronectes platessa* L.J. Fish Biol., *15*: 509-519.

BEACH, M.H., 1978a. The use of infra-red light and closed circuit television to validate records from automatic fish counters. J. Fish Biol., *13*: 639-644.

BEACH, M.H., 1978b. Determination of the accuracy of two types of fish counter employing the principles of (i) conductivity change and (ii) acoustic reflection. Appendix B. pp. 1-27. To 'Fish Counting Stations: Notes for Guidance in Their Design and Use', (ed.), Bussell, R.B. Department of the Environment, London, 70 pp.

BEACH, M.H., DUNKLEY, D.A. and SHEARER, W.M., 1981. Fish counters and reality. Proc. Inst. Fish. Mgmt, *12:* 25-34.

BUSSELL, R.B., 1978. Fish Counting Stations – Notes for Guidance in Their Design and Use. Department of the Environment, London, 70 pp.

CRUMP, E.S., 1952. A new method of gauging stream flow with little afflux by means of a submerged weir of triangular profile. Proc. Instn civ. Engrs, *1*: 223-242.

DENIL, G., 1936. La mécanique du poisson de riviére. Annls Trav. publ. Belg., *37*: 507-583.

FRANCIS, J.B., 1855. Lowell hydraulic experiments. Little, Brown and Company, Boston, Mass., 156 pp.

GREAT BRITAIN PARLIAMENT, 1975. Salmon and Freshwater Fisheries Act 1975. HMSO, London, 43 pp.

HEMMINGS, C. C., 1973. Direct observation of the behaviour of fish in relation to fish gear. Helgoländer wiss. Meeresunters, *24*: 348-360.

HERSCHY, R. W., WHITE, W. R. and WHITEHEAD, E., 1977. The design of Crump weirs. Technical Memorandum, D.O.E., Water Data Unit, Reading, (8), 73 pp.

HUDSON, R. C. L., 1973. On the function of the white muscles in teleosts at intermediate swimming speeds. J. exp. Biol., *58*: 509-522.

HUNTSMAN, A. G., 1934. Factors influencing return of salmon from the Sea. Trans. Am. Fish. Soc., *64*: 351-355.

LARINIER, M., 1983. Guide pour la conception des dispositifs de franchissement des barrages pour les poissons migrateurs. Bull. fr. Piscic., numéro spécial, 39 pp.

LETHLEAN, N. G., 1951. An investigation into the design and performance of electric fish screens and an electric fish counter. Trans. R. Soc. Edinb. *62*: 479-526.

LONNEBJERG, N. 1980. Fiskepas af modstrømstypen. (Fishways of the Denil type.) Meddr Ferskvandsfiskerilab. Danm. Fisk.-og Havunders., Silkeborg, (1) 1980, 107 pp.

McLEOD, A. M. and NEMENYI, P., 1940. An investigation of fishways. Bull. Iowa St. Univ., Ames, Iowa, *24*: 1-72.

MENZIES, W. J. M., 1934. Salmon passes – their design and construction. 1. At smaller obstructions. Fishery Bd Scotl., Salmon Fisheries, 1934, *1*: 1-29.

MILLS, D., 1971. Salmon and Trout. Oliver and Boyd, Edinburgh, 351 pp.

MOTTLEY, C. McC., 1933. The spawning migration of rainbow trout. Trans. Am. Fish. Soc., *63*: 80-84.

STUART, T. A., 1962. The leaping behaviour of salmon and trout at falls and obstructions. Freshwat. Salm. Fish. Res., Dept. Agric. Fish. Scotl., (28), 46 pp.

WARDLE, C. S., 1975. Limit of fish swimming speed. Nature, Lond., *255*: 725-727.

WARDLE, C. S., 1978. Non-release of lactic acid from anaerobic swimming muscle of plaice *Pleuronectes platessa* L. : a stress reaction. J. exp. Biol., *77*: 141-155.

WARDLE, C. S., 1980. Effects of temperature on the maximum swimming speed of fishes. pp. 519-531. In 'Environmental Physiology of Fishes', (ed.) Ali, M. A. Plenum Press, New York and London, 723 pp. (NATO Advanced Study Institute Series (A), Vol. 35).

WARDLE, C. S. and VIDELER, J. J., 1980. Fish swimming. pp. 125-150. In 'Aspects of Animal Movement' (eds.) Elder, H.Y. and Trueman, E.R. Cambridge University Press, Cambridge, 250 pp.

WATER RESOURCES BOARD AND SCOTTISH DEVELOPMENT DEPARTMENT, 1974. Graphical presentation of monthly data of selected river temperature stations. pp. 114-116. In 'The Surface Water Year Book of Great Britain 1966-70.' HMSO, London, 160 pp.

WEBB, P. W., 1975. Hydrodynamics and energetics of fish propulsion. Bull. Fish. Res. Bd Can., (190), 1-158.

WEBB, P. W., 1978. Fast-start performance and body form in seven species of teleost fish. J. exp. Biol., *74*: 211-226.

WHITE, W. R., 1975. Thin plate weirs: an investigation into performance characteristics. Rep. Hydraul. Res. Sta., Wallingford, (INT 152), 1-10.

ZHOU, Y., 1982. The swimming behaviour of fish in towed gears; a reexamination of the principles. Scott. Fish. Work. Pap., Dept. Agric. Fish. Scotl., (4), 1-55.

ZIEMER, G. L., 1962. Steeppass fishway development. Inf. Leafl., Alaska Dept. Fish. Game, Div. Engng Serv., (12), 1-32.

Appendix 1 Salmon and Freshwater Fisheries Act 1975, Chapter 51, Part II, Sections 9-18.

Section 9. *Duty to make and maintain fish passes*

(1) Where in any waters frequented by salmon or migratory trout –

(a) a new dam is constructed or an existing dam is raised or otherwise altered so as to create increased obstruction to the passage of salmon or migratory trout, or any other obstruction to the passage of salmon or migratory trout is created, increased or caused; or

(b) a dam which from any cause has been destroyed or taken down to the extent of one-half of its length is rebuilt or reinstated,

the owner or occupier for the time being of the dam or obstruction shall, if so required by notice given by the water authority for the area and within such reasonable time as may be specified in the notice, make a fish pass for salmon or migratory trout of such form and dimensions as the Minister may approve as part of the structure of, or in connection with, the dam or obstruction, and shall thereafter maintain it in an efficient state.

(2) If any such owner or occupier fails to make such a fish pass, or to maintain such a fish pass in an efficient state, he shall be guilty of an offence.

(3) The water authority may cause to be done any work required by this section to be done, and for that purpose may enter on the dam or obstruction or any land adjoining it, and may recover the expenses of doing the work in a summary manner from any person in default.

(4) Nothing in this section –

(a) shall authorise the doing of anything that may injuriously affect any public waterworks or navigable river, canal, or inland navigation, or any dock, the supply of water to which is obtained from any navigable river, canal or inland navigation, under any Act of Parliament; or

(b) shall prevent any person from removing a fish pass for the purpose of repairing or altering a dam or other obstruction, provided that the fish pass is restored to its former state of efficiency within a reasonable time; or

(c) shall apply to any alteration of a dam or other obstruction, unless –

(i) the alteration consists of a rebuilding or reinstatement of a dam or other obstruction destroyed or taken down to the extent of one-half of its length, or

(ii) the dam or obstruction as altered causes more obstruction to the passage of salmon or migratory trout than was caused by it as lawfully constructed or maintained at any previous date.

Section 10. *Power of water authority to construct and alter fish passes*

(1) Any water authority may, with the written consent of the Minister, construct and maintain in any dam or in connection with any dam a fish pass of such form and dimensions as the Minister may approve, so long as no injury is done by such a fish pass to the milling power, or to the supply of water of or to any navigable river, canal or other inland navigation.

(2) Any water authority may, with the written consent of the Minister, abolish or alter, or restore to its former state of efficiency, any existing fish pass or free gap, or substitute another fish pass or free gap, provided that no injury is done to the milling power, or to the supply of water of or to any navigable river, canal or other inland navigation.

(3) If any person injures any such new or existing fish pass, he shall pay the expenses incurred by the water authority in repairing the injury, and any such expenses may be recovered by the water authority in a summary manner.

Section 11. *Minister's consents and approvals for fish passes*

(1) Any approval or consent given by the Minister to or in relation to a fish pass may, if in giving it he indicates that fact, be provisional until he notifies the applicant for approval or consent that the pass is functioning to his satisfaction.

(2) While any such approval or consent is provisional, the Minister may, after giving the applicant not less than 90 days' notice of his intention to do so, revoke the approval or consent.

(3) Where the Minister revokes a provisional approval given to a fish pass forming part of or in connection with a dam or other obstruction, he may extend the period within which a fish pass is to be made as part of or in connection with the obstruction.

(4) The Minister may approve and certify any fish pass if he is of opinion that it is efficient in all respects and for all purposes, whether it was constructed under this Act or not.

(5) Where a fish pass has received the approval of the Minister, and the approval has not been revoked, it shall be deemed to be a fish pass in conformity with this Act, notwithstanding that it was not constructed in the manner and by the person specified in this Act.

Section 12. *Penalty for injuring or obstructing fish pass or free gap*

(1) If any person –

(a) wilfully alters or injures a fish pass; or

(b) does any act whereby salmon or trout are obstructed or liable to be obstructed in using a fish pass or whereby a fish pass is rendered less efficient; or

(c) alters a dam or the bed or banks of the river so as to render a fish pass less efficient; or

(d) uses any contrivance or does any act whereby salmon or trout are in any way liable to be scared, hindered or prevented from passing through a fish pass, he shall be guilty of an offence, and shall also in every case pay any expenses which may be incurred in restoring the fish pass to its former state of efficiency; and any such expenses may be recovered in a summary manner.

(2) The owner or occupier of a dam shall be deemed to have altered it if it is damaged, destroyed or allowed to fall into a state of disrepair, and if after notice is served on him by the water authority in whose area the dam is or was situated he fails to repair or reconstruct it within a reasonable time so as to render the fish pass as efficient as before the damage or destruction.

(3) If any person –

(a) does any act for the purpose of preventing salmon or trout from passing through a fish pass, or takes, or attempts to take, any salmon or trout in its passage through a fish pass; or

(b) places any obstruction, uses any contrivance or does any act whereby salmon or trout may be scared, deterred or in any way prevented from freely entering and passing up and down a free gap at all periods of the year,

he shall be guilty of an offence.

(4) This section shall not apply to a temporary bridge or board used for crossing a free gap, and taken away immediately after the person using it has crossed.

Section 13. *Sluices*

(1) Subject to subsection (3) below, unless permission in writing is granted by the water authority for the area, any sluices for drawing off the water which would otherwise flow over any dam in waters frequented by salmon or migratory trout shall be kept shut on Sundays and at all times when the water is not required for milling purposes, in such manner as to cause the water to flow through any fish pass in or connected with the dam or, if there is no such fish pass, over the dam.

(2) If any person fails to comply with this section, he shall be guilty of an offence.

(3) This section shall not prevent any person opening a sluice for the purpose of letting off water in cases of flood or for milling purposes or when necessary for the purpose of navigation or, subject to previous notice in writing being given to the water authority, for cleaning or repairing the dam or mill or its appurtenances.

Section 14. *Gratings*

(1) Where water is diverted from waters frequented by salmon or migratory trout by means of any conduit or artificial channel and the water so diverted is used for the purposes of a water or canal undertaking or for the purposes of any mill, the owner of the undertaking or the occupier of the mill shall, unless an exemption from the obligation is granted by the water authority for the area, place and maintain, at his own cost, a grating or gratings across the conduit or channel for the purpose of preventing the descent of the salmon or migratory trout.

(2) In the case of any such conduit or artificial channel the owner of the undertaking or the occupier of the mill shall also, unless an exemption is granted as aforesaid, place and maintain at his own cost a grating or gratings across any outfall of the conduit or channel for the purpose of preventing salmon or migratory trout entering the outfall.

(3) A grating shall be constructed and placed in such a manner and position as may be approved by the Minister.

(4) If any person without lawful excuse fails to place or to maintain a grating in accordance with this section, he shall be guilty of an offence.

(5) No such grating shall be so placed as to interfere with the passage of boats on any navigable canal.

(6) The obligations imposed by this section shall not be in force during such period (if any) in each year as may be prescribed by byelaw.

(7) The obligations imposed by this section on the occupier of a mill shall apply only where the conduit or channel was constructed on or after 18th July 1923.

Section 15. *Power of water authority to use gratings etc. to limit movements of salmon and trout*

(1) A water authority, with the written consent of the Minister –

(a) may cause a grating or gratings of such form and dimensions as they may determine to be placed and maintained, at the expense of the authority, at a suitable place in any watercourse, mill race, cut, leat, conduit or other channel for conveying water for any purpose from any waters frequented by salmon or migratory trout; and

(b) may cause any watercourse, mill race, cut, leat, conduit or other channel in which a grating is placed under this section to be widened or deepened at the expense of the authority so far as may be necessary to compensate for the diminution of any flow of water caused by the placing of the grating, or shall take some other means to prevent the flow of water being prejudicially diminished or otherwise injured.

(2) If any person –

(a) injures any such grating; or

(b) removes any such grating or part of any such grating, except during any period of the year during which under a byelaw gratings need not be maintained; or

(c) opens any such grating improperly; or

(d) permits any such grating to be injured, or removed, except as aforesaid, or improperly opened;

he shall be guilty of an offence.

(3) A water authority, with the written consent of the Minister, may adopt such means as the Minister may approve for preventing the ingress of salmon or trout into waters in which they or their spawning beds or ova are, from the nature of the channel or other causes, liable to be destroyed.

(4) Nothing in this section shall –
- (a) affect the liability under this Act of any person to place and maintain a grating; or
- (b) authorise a grating to be so placed or maintained during any period of the year during which under a byelaw gratings need not be maintained; or
- (c) authorise any grating to be placed or maintained so as to obstruct any conduit or channel used for navigation or in any way interfere with the effective working of any mill;

and nothing in subsection (3) above shall authorise the water authority prejudicially to interfere with water rights used or enjoyed for the purposes of manufacturing or for milling purposes or for drainage or navigation.

Section 16. *Boxes and cribs in weirs and dams*

(1) Any person who uses a fishing weir or fishing mill dam for the taking of salmon or migratory trout by means of boxes or cribs shall be guilty of an offence unless the boxes or cribs satisfy the requirements specified in subsection (2) below.

(2) The requirements mentioned in subsection (1) above are –
- (a) the upper surface of the sill of the box or crib must be level with the bed of the river;
- (b) the bars or inscales of the heck or upstream side of the box or crib –
  - (i) must not be nearer to each other than 2 inches;
  - (ii) must be capable of being removed; and
  - (iii) must be placed perpendicularly;
- (c) there must not be attached to any such box or crib any spur or tail wall, leader or outrigger of a greater length than 20 feet from the upper or lower side of the box or crib.

Section 17. *Restrictions on taking salmon or trout above or below an obstruction or in mill races*

(1) Any person who takes or kills, or attempts to take or kill, except with rod and line, or scares or disturbs any salmon or trout –
- (a) at any place above or below any dam or any obstruction, whether artificial or natural, which hinders or retards the passage of salmon or trout, being within 50 yards above or 100 yards below the dam or obstruction, or within such other distance from the dam or obstruction as may be prescribed by byelaws; or
- (b) in any waters under or adjacent to any mill, or in the head race or tail race of any mill, or in any waste race or pool communicating with a mill; or
- (c) in any artificial channel connected with any such dam or obstruction,

shall be guilty of an offence.

(2) Nothing in this section shall apply to any legal fishing mill dam not having a crib, box or cruive, or to any fishing box, coop, apparatus, net or mode of fishing in connection with and forming part of such a dam or obstruction for purposes of fishing.

(3) Where a fish pass approved by the Minister is for the time being attached to a dam or obstruction, this section shall not be enforced in respect of the dam or obstruction until compensation has been made by the water authority to the persons entitled to fish in the waters for that right of fishery.

Section 18. *Provisions supplementary to Part II*

(1) If any person obstructs a person legally authorised whilst he is doing any act authorised by section 9, 10 or 15 above, he shall be guilty of an offence.

(2) The Minister shall not give a water authority his consent –
- (a) to the construction, abolition or alteration of a fish pass or the abolition or alteration of a free gap in pursuance of section 10 above; or
- (b) to the doing of any work under section 15 above,

unless reasonable notice of the authority's application under the relevant section has been served to the owner and occupier of the dam, fish pass or free gap, watercourse, mill race, cut, leat, conduit or other channel, with a plan and specification of the proposed work; and the Minister shall take into consideration any objections by the owner or occupier, before giving his consent.

(3) If any injury is caused –
- (a) to any dam by reason of the construction, abolition or alteration of a fish pass or the abolition or alteration of a free gap in pursuance of section 10 above; or
- (b) by anything done by the water authority under section 15 above,

any person sustaining any loss as a result may recover from the water authority compensation for the injury sustained.

(4) The amount of any compensation under section 10, 15 or 17 above shall be settled in case of dispute by a single arbitrator appointed by the Minister.

(5) In any case in which a water authority are liable to pay compensation under this Part of this Act in respect of injury or damage caused by the making or maintaining of any work, compensation shall not be recoverable unless proceedings for its recovery are instituted within two years from the completion of the work.

Appendix 2 Derivation of maximum swimming speeds for fish of different lengths

(a) The general formula relating maximum swimming speed to muscle twitch contraction time is given by Wardle (1975) as

$$U = 0.7L/2t \qquad \text{A1}$$

where U is the maximum swimming speed, the factor 0.7 is a coefficient defining the distance moved through the water for each body wave (stride length), L is the length of the fish, and t is the muscle twitch contraction time.

(b) The empirical formula relating muscle-twitch contraction time to length of fish was obtained by Zhou (1982) after analysing 276 measurements of muscle contraction times. Six species were included with lengths ranging from 0.05 m to 0.80 m, and temperatures ranged from 2°C to 18°C (maximum 30°C).

$$t = 0.1700L^{0.4288} + 0.0028 \log_e T - 0.0425L^{0.4288} \times \log_e T - 0.0077 \qquad \text{A2}$$

where T is the muscle temperature (°C).

Equation A2 gives the shortest possible muscle contraction time and thus, when used with equation A1, the maximum possible swimming speed. Figure 1 in the text was drawn using equations A1 and A2.

References

Wardle, C. S., 1975. Limit of fish swimming speed. Nature, Lond., *255*: 725-727.

Zhou, Y., 1982. The swimming behaviour of fish in towed gears; a reexamination of the principles. Scott. Fish. Work. Pap., Dept. Agric. Fish. Scotl., (4), 1-55.

Appendix 3 Derivation of endurance times for fish of different lengths

The endurance of fish at various swimming speeds is predicted by relating performance to a limited energy store (Zhou, 1982). As the speed exceeds the maximum cruising speed the glycogen store begins to be depleted. An endurance time is calculated by dividing the total energy store E by the difference between the potential chemical power P_c required to drive the fish through the water at the required speed, and the power P_r being supplied by the red muscle taking oxygen from the water.

Measurements have shown that the total energy store, or glycogen level, in most rested teleost fish can be as high as 10 gram per kilogram of muscle. The metabolism of glycogen by anaerobic glycolysis to lactic acid releases 558 joules for each gram of glycogen, so the maximum value of E is 5580 J kg^{-1}. If it is assumed that the average fish has about 50% of its weight as muscle, the maximum value of E becomes 1790 J kg^{-1} of fish. The total energy store is related to the length of a salmon by using the length/weight relationship of W. M. Shearer (personal communication). $M = 10.836\,L^{2.964}$. Thus,

$$E = 1790 \times 10.836\,L^{2.964} \qquad \text{A3}$$

where L is the length of the fish (m).

The chemical power P_c is calculated for a particular fish length, speed and water temperature using the empirical equation developed by Zhou (1982) which also takes the drag force and efficiency of propulsion into account:

$$P_c = 0.9751 \times e^{-0.00522.T} \times U^{2.8} \times L^{-1.15}, \qquad \text{A4}$$

where, P_c = chemical power (W),

U = swimming speed (m s^{-1}),

T = muscle temperature (°C).

The maximum oxygen uptake rate for salmon is given by Brett (1965; 1972) as 800 mg O_2 kg^{-1} h^{-1} * (the weight unit referred to is fish weight not muscle weight). One milligram of oxygen can release 20 joules of energy, so that the power supplied by red muscle in aeorobic swimming is 4.44 watts per kilogram of fish weight; hence

$$P_r = 4.44 \times 10.836\,L^{2.964}, \qquad \text{A5}$$

where, P_r = power from oxygen uptake (W).

The endurance time t_m is calculated from

$$t_m = E/[P_c - P_r], \qquad \text{A6}$$

where, t_m = endurance time (s).

Maximum cruising speed U_c is important since it determines the point at which aerobic swimming is no longer possible and the glycogen store begins to be depleted. It is the highest speed, theoretically, that can be maintained *ad infinitum*, and is estimated by Zhou (1982) using the following empirical equation:

$$U_c = 1.0091\,e^{0.001904.T} \times L^{0.4107} \times P_r^{\,0.357} \qquad \text{A7}$$

where U_c is the maximum cruising speed (m s^{-1}) and the other symbols are as defined above.

Figure 2 in the text was drawn using equation A6.

References

Brett, J. R., 1965. The swimming energetics of salmon. Scient. Am., *213*: 80-85.

Brett, J. R., 1972. The metabolic demand for oxygen in fish, particularly salmonids and a comparison with other vertebrates. Resp. Physiol., *14*: 151-170.

Zhou, Y., 1982. The swimming behaviour of fish in towed gears; a reexamination of the principles. Scott. Fish. Work. Pap., Dept. Agric. Fish. Scotl., (4), 1-55.

* It is customary now to express oxygen consumption in terms of milligrams of oxygen since gaseous exchange is not involved at gill surfaces. At NTP,
1 mg O_2 = 0.70 cm^3 O_2 or 1 cm^3 O_2 = 1.43 mg O_2.