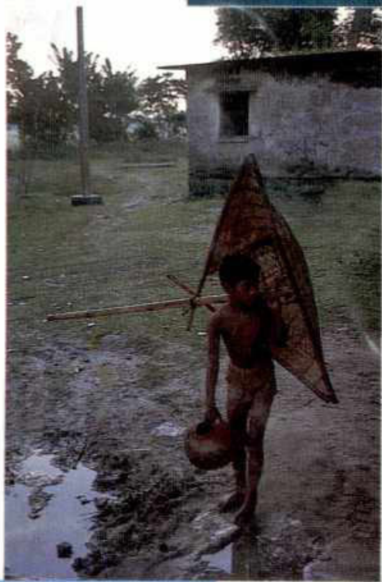
Government of the Peoples Republic of Bangladesh
Flood Action Plan

FAP 17

Fisheries Studies and Pilot Project



FINAL REPORT

(Draft)

JUNE 1994

Special study

Supporting Volume
No. 23

THE USE OF PASSES AND WATER REGULATORS TO ALLOW MOVEMENTS OF FISH THROUGH FCD/I STRUCTURES

ODA
Overseas Development Administration, U.K.

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Special study.

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The Use of Passes and Water Regulators to Allow Movements of Fish Through FCD/I Structures

FAP 17
FISHERIES STUDIES
AND PILOT PROJECT

June, 1994

Funded by ODA in conjunction with the Government of Bangladesh

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EXECUTIVE SUMMARY

1 The effects of flood control structures on the migration of fish in Bangladesh has previously been overlooked during planning. Considering the importance of these movements in the life cycles of fish, this issue should be addressed in future plans.

2 To allow the passage of fish, fish passes can be constructed at regulators which create significant head height differences between the upstream and downstream (or inside and outside) water levels and where interference with migration routes is apparent. This is particularly important in the North East Region of Bangladesh, where head differences commonly exceed three metres and where the carp fishery may be in jeopardy due to obstruction of migration pathways by flood control structures. The installation of fish passes should also be considered when large main river barrages are planned. Passes can be designed in the light of experience gained elsewhere in the world.

3 Throughout Bangladesh, small and intermediate scale regulators are affecting the movement of fishes to and from the floodplain. Efficient flood control produces benefits for agriculture, but can damage floodplain fisheries. Regulators can be modified simply to improve their "fish-friendliness", prevent fish kills, minimise physical harm to fish and avert detrimental changes in behaviour. It may therefore be possible to compromise between the needs of fish and rice, to optimise the production of both.

1 INTRODUCTION

Flood control schemes in Bangladesh, prior to the Flood Action Plan (FAP), have previously not considered nor proposed mitigation against the negative impacts on the floodplain fisheries. One of the most important prerequisites for the life cycle of many fishes is the ability to move between the different habitats required for growth and reproduction. If this is obstructed by FCD/I schemes, then not only is the fishery constrained by the physical boundaries, but the interruption of the life cycle can severely reduce the production of fish.

The effectiveness of flood control schemes is dependent upon embanking an area of the floodplain and installing regulators, through which water is channelled in and drained out at appropriate times. Embankments along river banks alter the flow pattern and velocity of current in the river and consequently may effect the response of fish migrating upstream.

With the construction of full riverside embankments, the overbank spillage of river water is changed from a continuous slow seepage across the floodplain during peak floods to a powerful surge of water through narrow canals and sluices. As a result fish actively moving onto the floodplain to breed and feed are swept with the current, disorientating them and possibly causing physical damage.

In the NE Region of Bangladesh, Indian major carps are thought to overwinter in *haors* (large flooded areas) and pass into the rivers around April, when they are stimulated to move by run-off from rainfall in the hills of India. Embanking haor areas blocks the passage of carp and narrows the escape routes to the rivers. Where submersible embankments are present, delay in the overbank flooding affects the movement of adults and may delay the drift of fry onto the floodplain.

The effects of regulators on the drift of hatchlings is unclear, although densities of fish upstream and downstream of structures are often different. The hydrostatic pressure caused by head differences across regulators may sometimes be sufficient to kill hatchlings, but studies by FAP 17 have so far not recorded such kills (FAP 17 Interim Report, 1993). Hatchling studies are continuing at a number of regulators in the NE and NW regions of Bangladesh.

It is possible to partially mitigate the negative impacts due to restriction of river bank overspill, through structural additions and/or modifications to flood control schemes. Fish passes can be installed to assist both adult upstream migration and to facilitate active downstream movement of adults and passive drift of hatchlings.

There is no experience in construction and use of fish passes in Bangladesh, and very little information on the swimming characteristics of the fish species of Southern Asia. In order to predict likely responses to various types of fish passes extrapolation from information gathered in other parts of the world is therefore necessary. Before the design and operational characteristics of a fish pass can be decided upon, those aspects of the migratory response which are to be accommodated need to be identified.

This report presents information from several expert sources. The experiences of hydraulic engineers on the interaction between migrating fish and flood regulating structures has been drawn upon. The timing and pathways of fish migrations in Bangladesh were considered by fisheries biologists, as were the characteristics of migrations of comparable species elsewhere in the world. Work on fish passes implemented in other countries was also reviewed, as a guide to FAP planners. Ongoing and completed surveys in Bangladesh, conducted by FAP 17 and other FAP projects, were reviewed.

The conclusions and recommendations presented here should not be considered final, as investigations in progress will yield a greater understanding of the migration of native species, the distribution of fry and hatchlings, and the effect of flood control upon young fish.

The migration patterns of groups of fish from other rivers elsewhere in the world are chronicled because so little has been published about the behaviour of native species. Knowledge about fish movements is necessary to formulate sensible advice for planners.

A discussion of the possible designs of fish passes that may be suitable for use in FCD/I schemes is provided. "Fish-friendly regulators" are proposed, with a detailed discussion of how regulators affect fish and how modifications to the designs and operation can be made to minimise harmful effects. Some other FAP projects have looked at the effects of flood control on movement of fishes, and their recommendations on how this might be considered in future plans have been reviewed. Recommendations and suggestions for future investigations are included, and it is hoped this report will stimulate discussion amongst interested parties.

2 FISH MIGRATION

Few flood river fish are confined to one habitat throughout the year. The species that reside on the floodplain and *beels* during the dry season tend to be those with adaptations to withstand limiting conditions (such as desiccation, isolation and deoxygenation) in the dry season pools. The majority of species, however, are migratory. Of these, some are restricted to a small geographical area and make only short migrations (20-30 km). Some, however, migrate substantial distances, up to several thousand kilometres, between widely different habitats.

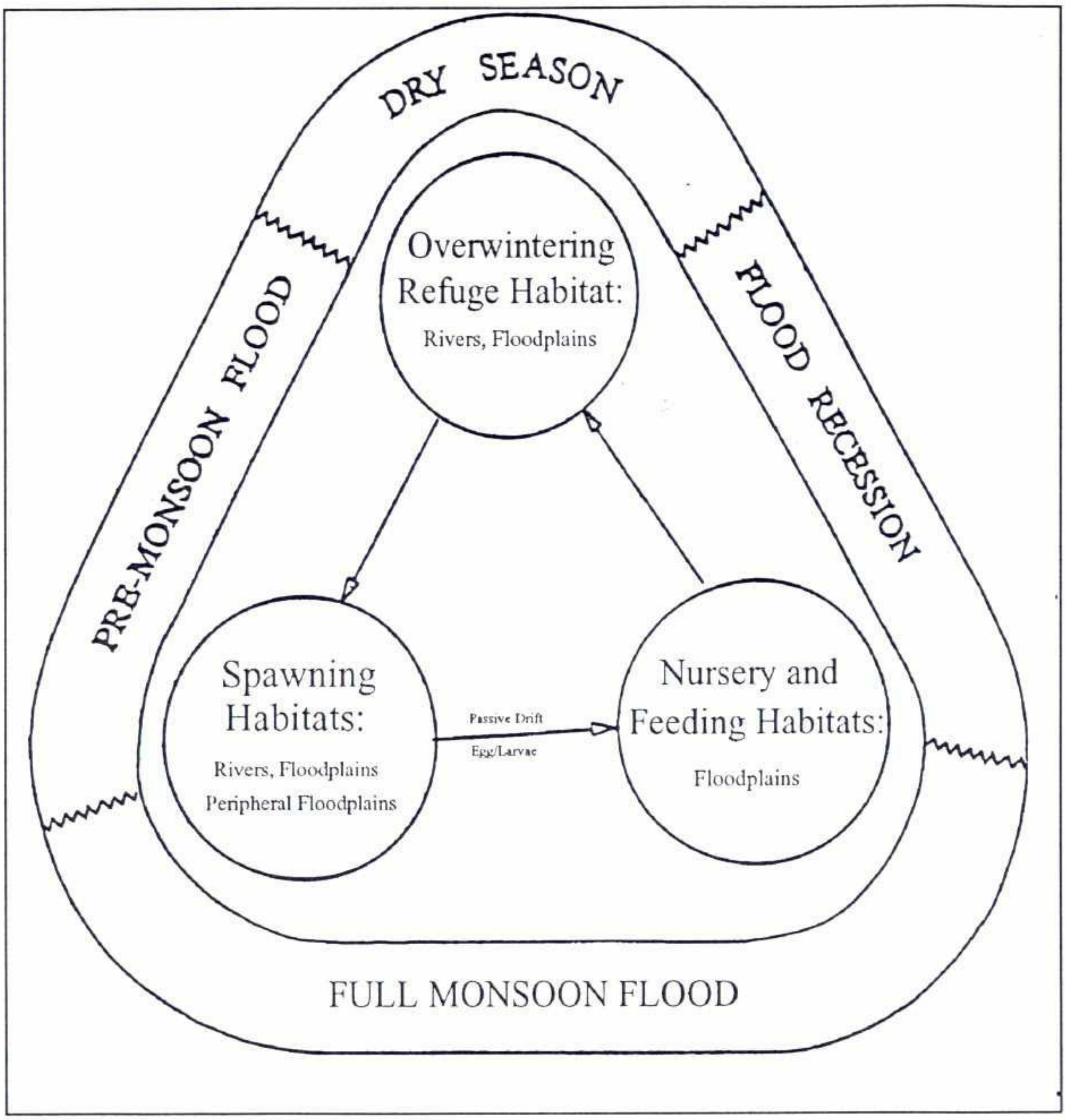
For fish inhabiting seasonal floodplain river systems, the optimum habitat for feeding is rarely the same as that for breeding, and migrations between the two habitats are undertaken. The breeding grounds are often upstream of the feeding grounds, so that the relatively passive eggs and hatchlings can drift downstream towards the feeding grounds. The developing fish are transported and dispersed with the floods through smaller river systems and canals, and by the time they reach the floodplains are at a stage of development able to exploit the rich food resources.

Fish migration is most commonly brought about by a behavioural response to currents. However, the nature of this response can change during the life cycle of the species. The most fundamental change is between active upstream migration, usually undertaken by adults moving to their spawning grounds, and the passive or combined active/passive downstream migrations of juveniles. For the fish population to be maintained, both phases need to be possible (Figure 2.1).

Whilst this is the basic pattern, species of fish differ greatly in the extent of their movements. The fish communities of Southern Asia have been divided into the "black fishes" which are essentially resident on the floodplain and the "white fishes" which show some distinct migration within the river system, usually associated with spawning.

The "black fishes" are those which would normally retreat into the *beels* or other residual water bodies after the floods have receded. They are commonly taken in the kua or fish-pits, which trap the last remnants of the floodplain waters. They include for example, *Anabas testudineus, Heteropneustes fossilis, Channa spp., Mastacembellus spp., Colisa spp.* and some species of *Puntius*.

Figure 2.1 Basic pattern of migration between feeding, spawning and nursery habitats



The "white fishes" can be divided into three categories depending on the extent of their migrations:

(i) Those with considerable longitudinal migrations, which may be followed by lateral migrations onto the floodplain (e.g. *Pangasius pangasius*, *Tor putitora*);

(ii) Those with limited longitudinal migrations followed by lateral migrations onto the floodplain (e.g. major carp species, *Clarias batrachus*); and

(iii) Those species which are truly anadromous, moving from the sea into freshwater to breed (e.g. *Hilsa ilisha*).

Few direct observations of the migration of fishes in the rivers of Bangladesh have been published. It is necessary, therefore, to infer the most probable pattern of events from observations elsewhere in the Gangetic or Brahmaputra systems or from other regions with hydrological conditions which are essentially tropical. The mahseers, such as *Tor putitora*, which in India move considerable distances into headwater streams to spawn (Talwar and Jhingran, 1992), are of the first category of migratory species. However, it appears that by far the greatest number of migratory species in Bangladesh exhibit category (ii) migrations. Observations in India suggest that *Catla catla* (Jhingran, 1968), *Labeo rohita* (Khan and Jhingran, 1975) and *Cirrhinus mrigala* (Jhingran and Khan, 1979) all show only local movements upstream, and primarily migrate laterally onto the floodplain after spawning along the margin adjoining the river. Though it has been suggested that the major carps carry out long distance migrations beyond the borders of Bangladesh to spawn (Tsai and Ali, 1985), evidence of fry catches along the banks of the Padma (Nabi and Hossain, 1982) suggest that there might be more local spawning grounds.

The migratory behaviour of the catfishes of Bangladesh is unknown. In Africa many of the catfishes such as *Clarias*, *Schilbe* and *Eutropius spp.* show local migrations plus the lateral movement onto the floodplain as outlined in category (ii), (Lowe McConnell, 1975). The catfish *Clarias batrachus* has been mentioned as migrating onto the floodplain (Talwar and Jhingran, 1992), but the behaviour of other catfishes such as *Ompok spp.*, *Mystus spp.* and *Wallago attu* is unclear. Elsewhere, catfishes of this type would typically show movements of the category (ii) type.

The anadromous hilsa shows large-scale movements from the estuary into the river during the monsoon season, typical of category (iii) migration. In the Hooghly River, a small peak in activity later in the winter has also been noted (Pillay and Rosa, 1963). There is also the suggestion of resident river populations in the Ganges (Pillay and Rosa, 1963) and Islam and Hossain (1983) have noted that small numbers are present near Rajshahi at all times of year.

The breeding season occurs here in July to November and January to March (Islam and Hossain, 1983).

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2.1 Critical Features of Migratory Behaviour; Fish Responses to Current

River discharges provide the essential directional cues to physiologically-prepared fishes to move upstream, whilst also offering increased resistance to progress. Work in the former USSR has demonstrated that fish tend to follow their migratory pathways against the resistance of the current in one of two ways (Pavlov, 1989).

Pelagic and some near-bottom dwelling species move near the surface of the water. Illumination and not the time of day is the principal criterion for movement, hence the fullness of the moon is important in determining the timing of migrations. Species which rely upon mainly tactile orientation, for example many of the catfishes, move against the current close to the bottom or near the banks at night. The moon or other sources of light can inhibit migratory movement of these species.

Fish normally migrate at an intermediate cruising speed and only rarely at maximum speed. If current velocity in the main river channel exceeds their swimming ability, the fish will move closer to the bank where velocities are generally slower. The presence of turbulence or whirlpools tends to disorientate the fish. The swimming speeds of bottom fish tend to be rather lower than those of pelagic species, of the order of 0.5-1.0 times the body length sec^{-1} compared to 3-4 times the body length sec^{-1} for pelagic species. Nevertheless, the rate of progress upstream is often similar, since the bottom fish are moving in slower currents (Pavlov, 1989).

During upstream spawning migrations, active swimming phases seem to alternate with shorter passive phases, due to fatigue or re-orientation in complex current systems. When spawning approaches, the basic response of the fish to the current changes and the more sustained active upstream movement of the fish gives way to a more active/passive swimming behaviour. At this time the overall swimming activity of the fish declines and they move into side channels and onto the floodplain. On the floodplain there is little directional current, as the flood advances rapidly but gently by the process of "creeping flow". Currents are generally below the threshold required to trigger the directional response and no doubt alter tactile, olfactory and visual senses that assist in the final orientation to the spawning or feeding grounds.

Distribution of fish on the floodplain seems much more random and less aggregated and directional. As the floods recede both adults and juveniles re-orientate to the current in their active/passive migration downstream back to the main channel.

Whilst this is the basic pattern, species differ in the extent of the various responses. All except those categorized as "black fishes" show the active upstream adult and passive downstream juvenile migrations (Figure 2.1). Distances of migration for both age-groups in category (i) can be very great. For example, *Pangasius spp*. is recorded as travelling over 1000 km in Cambodia. Those of category (ii) may travel tens of kilometres, whilst distances covered by category (iii) species are variable. For example hilsa is found up the Padma River as far as Rajshahi (Islam and Hossain, 1983), a distance of some 250 km from the sea.

Whilst most investigations on fish migratory responses have been carried out on European or North American species, the same groupings appear valid for warm-water species. For example, tagged specimens of the pelagic characins *Prochilodus spp.* and *Salminus spp.* follow the gradients of flow velocity in the main river and move during daylight hours, whilst the catfishes *Pseudoplatystoma spp.* and *Luciopimelodus spp.* follow the contours of the bottom and avoid the zones where current speeds are greatest (Poddubnyi *et al.*, 1981).

Current velocity is the main initial stimulus to upstream migration, and there are two indices which define the ability of the current to stimulate movement and the ability of the fish to respond. These are:

- **Threshold Current Velocity** (V_{thr}), the minimum current velocity which leads to an orientation reaction against the current (values range from 1-30 cm sec^{-1})
- **Critical velocity** (V_{cr}), the minimum current velocity at which fish begin to be carried away by the water flow.

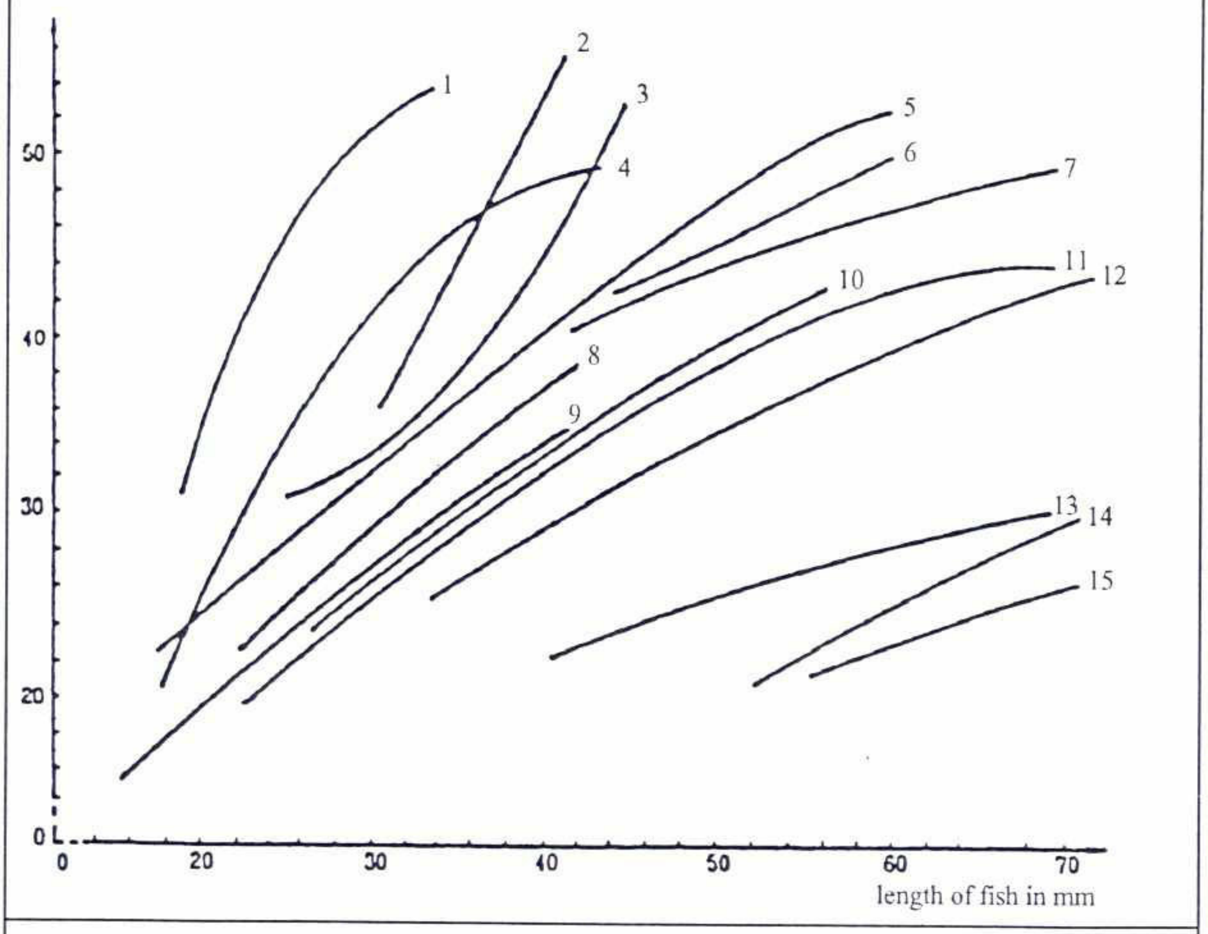
The V_{thr} needs to be exceeded to stimulate the fish to begin upstream movement, assuming that physiological factors, such as the hormone cycle of ripening fish, are at the appropriate stage.

The V_{thr} and V_{cr} vary with size of fish and also according to the species or category of fish (Figure 2.2). Typically, bottom-dwellers have critical velocities 2-3 times lower than those for species living in mid or upper levels of the water column. For these species there is a tendency for threshold velocities to be high and critical velocities to be low. The reverse is true for pelagic species.

Fish are also generally attracted to faster currents: attracting velocities are frequently 0.6-0.8 of the V_{cr}. For a wide selection of European species, the V_{cr} ranges from 0.7-0.9 m sec^{-1} (Malevanchik and Nikonorov, 1984).

One final factor which is known to affect the performance and response of migratory fishes to current velocity is temperature. Maximum swimming speed is affected both by temperature and length of fish. It is possible to predict their effects (Beach, 1984) using an empirical formula derived by Zoll (1982). The interaction of these two factors (Figure 2.2) shows that a 0.9 m fish has a predicted maximum swimming speed of only 4.3 m sec^{-1} at 10 °C, but this increases to 9.6 m sec^{-1} at 25 °C. Since maximum swimming speed must be closely related to V_{cr} , the critical current velocity, then temperature must be expected to have an effect on this value. This may be, however, a "within species" effect: there is no evidence that tropical species have a higher maximum swimming speed or critical velocity than do temperate species. In fact, the range of critical velocities found in tropical Brazil and temperate USSR appear to be similar.

Figure 2.2 Critical current velocities for different species and sizes of fish



1. Alburnus alburnus. 2. Leucaspis delineatus. 3. Ruitilus rutilus caspius. 4. Carassius carassius. 5. Abramis ballerus. 6. Perca fluviatilis. 7. Vimba vimba. 8. Nemachilus barbatulus. 9. Cottus gobio. 10. Rhodues sericeus. 11. Tinca tinca. 12. Cobitis taenia. 13. Acipenser guldenstadti. 14. Husa huso. 15. Acipenser stellatus.

2.2 Hatchling Movement

The early floods are extremely important for fish movement, not only for adult fish moving upstream and onto the floodplains for spawning, but also for transporting the developing hatchlings and fry to the rich feeding grounds of the floodplains.

The dispersal of carp hatchlings with the early floods has considerable significance in Bangladesh. A hatchling and fry fishery has been established along the banks of the Jamuna, Padma and smaller rivers such as the Old Brahmaputra, Dhaleswari and Baral rivers. This fishery, using fine mesh conical nets (savar nets), supplies "seed" for aquaculture. Some 70-75% of the total "seed" production of Rajshahi comes from 14 collection centres on the Padma River (Nabi and Hossain, 1983).

The early floods are not only important for transporting carp hatchlings, but they also carry a large number of other species. The development and drift of other species, such as *Chanda spp.* and *Glossogobius spp.* and species of prawn correspond to later peaks in river discharge in August and September (FAP 17 Interim Report, 1993).

The effects of regulators on the drift of hatchlings is unclear, although numbers caught inside and outside have differed. The hydrostatic pressure caused by head differences across regulators may sometimes be sufficient to kill hatchlings, but studies so far have not shown this in practice (see Interim Report, July 1993).

Further work is ongoing at a number of different regulators in the NE and NW regions of Bangladesh. Studies in the NC region are aimed at evaluating the natural drift of hatchlings along the Dhaleswari River, and vertical and horizontal movements down the Lohajang River. Both these rivers are free flooding at present, but plans are proposed for their regulation.

FAP 20 has already given some indications of the natural distribution of hatchlings in the water column. Initial findings showed little difference in the densities of hatchlings drifting in different levels of the water column, but when flow characteristics (theoretical) were considered, the largest numbers of hatchlings appeared to move with the surface layers. The numbers transported decreased exponentially down through the water column. FAP 17 results will elucidate the situation further.

It is clear that the annual monsoon rains and subsequent flooding in Bangladesh have considerable influence on the spawning and early development of many native fish species. The life cycles are intimately linked to the hydrologic cycle. Changes in the hydrology such as differing flow patterns of rivers and khals and the limiting of access to and from the floodplains brought about by flood control (embankments and regulators) must have an effect on the movements of fish and thence on the abundance of stocks.

The possibilities of maintaining adult migration and downstream drift of hatchlings through structural and operational modification to the engineering works are apparent from overseas experience. Work in South America and Russia shows that the use of fish passes at regulatory structures and artificial stocking are complementary strategies (Bonetto 1980; Poddabnyi *et al.*, 1984) and a combination of both approaches is now commonly employed in mitigation. For example, valuable sturgeon stocks are maintained in the Volga River by a combination of a massive rearing programme and the construction of fish passes on barriers in the lower reaches of the river (Pavlov and Vilenkin 1991; Pavlov 1989).

The following section discusses the options for use of fish passes and assesses the effects of regulators on the passage of fish. Modifications to the designs of regulators to improve their "fish- friendliness" are also suggested.

3 FISH PASSES AND "FISH-FRIENDLY REGULATORS"

A number of structures, which might collectively be called fish passes or fish ladders, have been devised to allow fish to bypass engineering structures used in water management. Normally these are found in association with structures that are essentially dams which cut across the main flow of the river. Where barrages may be planned that require a fish ladder for fish migrating upstream, the methodology for their design is already developed. If detailed knowledge of the biology of the fish concerned and the design parameters of the structure are available, a fish pass design can be tailored to the specific structure.

Dams and barrages are designed to maintain differences in heads of water far greater than the metre or so that may result from the flood control embankment engineering in Bangladesh. The concept of fish ladders to enable upstream migrant fish to surmount permanent large variations in water level may therefore not be generally applicable in Bangladesh, although the possibility of the construction of a barrage on the Ganges River may require use of this technology. The principles used in the design of fish ladders are essentially the same as for the design of structures that will allow the movement of fish onto the floodplain.

In order to accommodate the needs of migrating fishes in flood control schemes in Bangladesh, the characteristics of the migratory response must be considered.

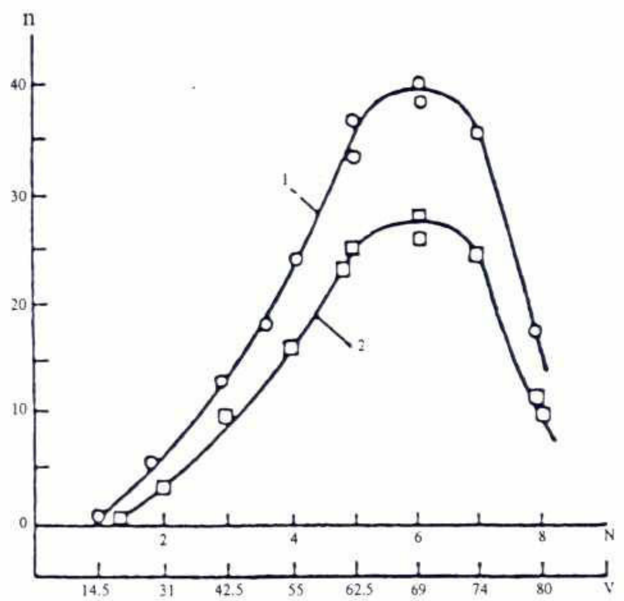
The V_{cr} should not be exceeded by the discharge of any regulatory device that the fish is expected to pass through against the current, or the fish will be forced downstream.

It is also vital that the stream of water coming through a fish pass or regulator must be higher than the V_{thr} in order to attract upstream migrators.

In Brazil, the flow of water though the Cachoeira de Emas fish ladder ranged between 0.5-2.5 m sec^{-1} (Godoy 1985). Below 0.5 m sec^{-1}, fish were not attracted to the pass, whilst above 2.3 m sec^{-1} the turbulence at the foot of the ladder discouraged entrance into the system. In the Salto Grande fish lock in Uruguay, the flow could be controlled to provide flows of 0.1 to 1.8 m sec^{-1} although optimum speed appeared to be around 0.9 m sec^{-1} (Delfino, Baigun and Quiros 1986). The fish using the pass were a mixture of pelagic charachids and bottom-dwelling catfish, but the range of current velocities appear similar to those reported from experience with other species in the ex-USSR.

There is a relationship between current velocity and numbers of fish attracted to the flow (Figure 3.1). The number of fishes moving upstream increases with flow rate until a peak is reached. The peak for the two species mentioned in Figure 3.1, around 70-80 cm sec^{-1}, is close to the V_{cr} range for the same species.

Figure 3.1 The relationship between quantity of fish entering a collection area and mean velocity of attractive flow



Data for a floating fish-pass. n = number of fish/2 hour period, N = number of pumps operating, V = velocity of attracting flow in CM Sec^{-1}. 1. Abramis brama 2. Stizostedion lucioperca (Pavlov 1989).

3.1 Fish Passes

There are basically two types of fish pass, the type in which fish actively swim upstream aided by the device and the type in which fish enter a strong compartment and are transferred over the obstacle without the expenditure of energy. The first category includes the pool and weir and pool and orifice type fish passes, whilst the second involves moving structures of the fish lift and fish lock type.

A major characteristic of a fish pass is the height at which it is operationally effective. The basic intention of a fish pass is to allow the fish to circumvent a barrier, usually between different water levels. Pool and weir type passes are most effective at heights of less than 10 m, whilst the pool and orifice variant may be used to negotiate heights of up to 40 m (Pavlov, 1989). The more elaborate fish lock can be effective up to 40 m, whilst mechanical fish lifts which store and transport fish vertically can be used to any height. In general, the greater the height to be circumvented the more costly the device. Those mechanisms which physically aid the fishes movement also tend to be more expensive.

In the FAP, structures to be circumvented are generally relatively low, and differences in water height are likely to be small when compared for example to hydroelectric dams. However, ideally there should be a difference in water height across the structure, since a flow of water is required to attract the migratory fishes.

The principle objectives of fish pass design should be to (McLeod and Nemenyi, 1940):

- maintain water velocity within the swimming capacity of the fish;
- avoid rapid change in flow pattern;
- provide resting areas as required;
- operate without manual control;
- discharge enough water to attract the fish;
- have a well-located fish entrance;
- be economical to construct and to maintain;
- operate without the interference of sediment and debris and
- require no more water than is available or can be allocated.

The selection of any fish pass structures for the FAP should be consistent with these criteria.

3.2 Pool and Weir Fish Passes

Sometimes referred to as the pool and traverse pass (Beach, 1984), this is the basis of the simplest fish ladder, in which a downward sloping channel is cut into a sequence of pools by a series of traverses or weirs (Figure 3.2). Each weir has a notch through which the migrating fish can swim in order to reach the next pool.

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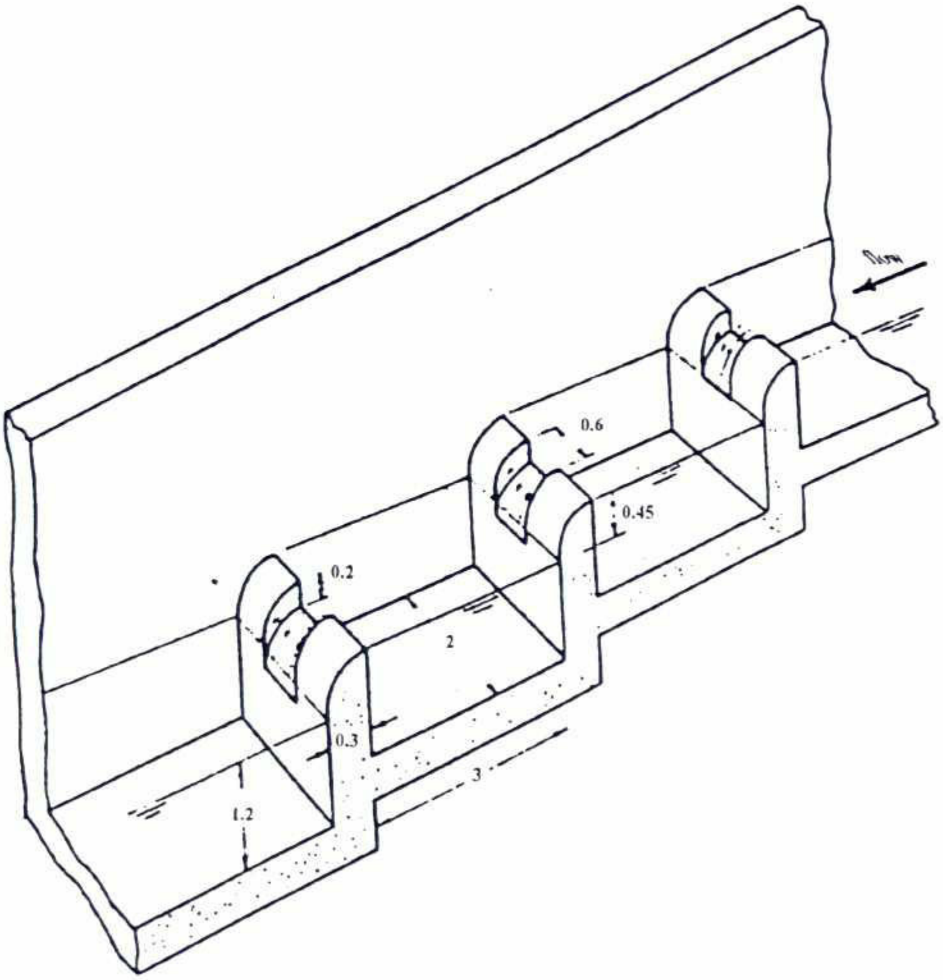
Figure 3.2 **A schematic diagram of a "pool and weir" fish pass with notched traverses. The dimensions shown are recommended as the absolute minima. The head difference between pools should not exceed 0.45m (after Beach, 1984)**



Recommendations on design requirements have been provided by Beach (1984) as part of UK regulatory requirements. These include:

- the change in water level across a traverse must not exceed 0.45 m;
- pools should have a minimum dimension of 3 m long x 2 m wide x 1.2 m deep;
- traverses should be 0.3 m thick with notches 0.6 m wide and at least 0.25 m deep;
- the downstream edge of both the notch and the traverse should be curved so as to reduce turbulence and prevent the formation of a free-spurting jet and
- the pass entrance should be located easily by fish at all flows.

The position of the entrance to the pass is of particular importance since it must be readily located by fish under all flow conditions. If sited too close to a weir or other outflow, the turbulence from these sources may disorientate the fish and prevent them from detecting the pass outflow. The pass outflow should also be downstream of any other in the vicinity, particularly those of "non-passable" discharges, since these might otherwise preferentially attract migrating fishes.

A particular advantage of the pool and weir type of fish pass is that it also facilitates the downstream drift of hatchlings and fry. For this reason, the upper "exit" should be placed in a position with regard to the upstream flow where it can be readily located by those young fish as well as by returning adults.

The pool and weir type of pass has been used extensively in Europe and North America although most commonly in connection with the passage of members of the family Salmonidae (salmon and trout), most of which are powerful swimmers. Quiros (1989) documents 29 fish passes which have been built as part of the impoundment and regulation of South American rivers. All but one of these are of the pool and weir type. The scale of many is rather larger than the dimensions given above, but those given by Beach (1984) can be considered as the minimum dimension. The fish for which these South American fish passes have been built have more in common with the Asian fish fauna of Bangladesh than the salmonid communities of the northern latitudes. They are used successfully by both the pelagic powerfully swimming characins, such as *Prochilodus spp.*, which may roughly equate to the major carps, and also by the bottom-moving types such as the catfishes (Quiros, 1989). The pool and weir type, therefore, seems to work with communities of tropical and sub-tropical fish as well as for those from temperate regions.

The versatility of this type of fish pass does mean that it can be employed on a larger scale. Whilst a cheap, simple design may be used to circumvent a weir of 1-2 m in height, they have been used for fish to overcome major barriers. In South America, passes of this type have been constructed to heights of up to 20 m (Quiros, 1989). For the most part, however, passes of this height are associated with dam construction for hydroelectric schemes, but they may be appropriate for barrages in Bangladesh.

The pool and orifice fish pass differs from the pool and weir pass in that passage between the two pools is through a hole in the weir wall rather than over a notch. This facilitates particularly the passage of bottom-moving species.

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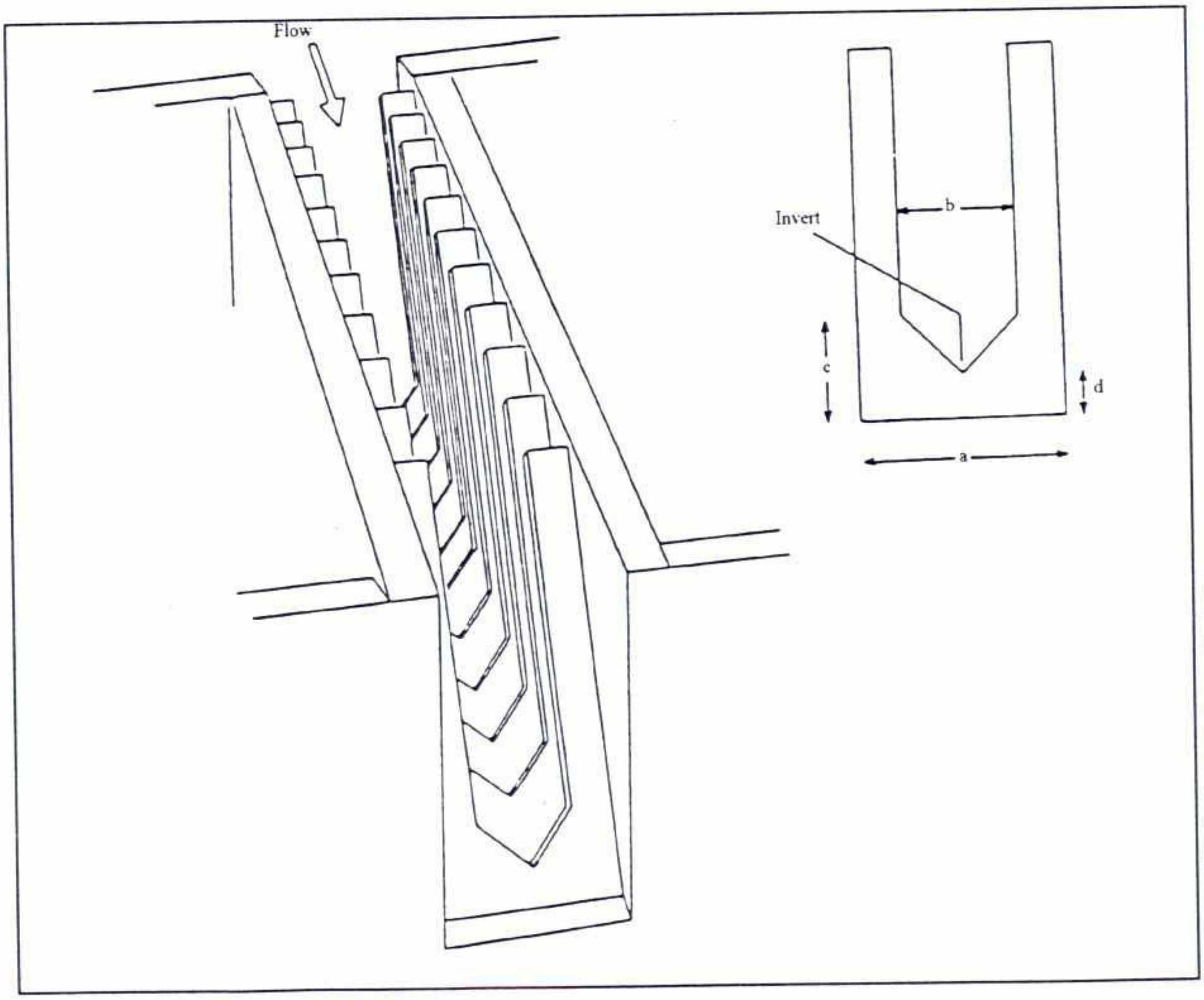
3.3 Denil Fish Pass

Similar to the pool and weir types, this relies upon the construction of a channel around or through the obstruction. In this case, the channel is traversed by a number of baffles which dissipate the energy of the current. The baffles are closely spaced and set at an angle to the axis of the channel. The notches in the baffles leave a relatively large portion of the channel available for the main flow through which the fish pass (Figure 3.3). The shape and position of spacing of the baffles play an important part in the effectiveness of this type of fish pass.

Figure 3.3 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 after Beach, 1984)



The hydraulics of passes of this type suggest however that the most economic design, with a readily located outflow and maximum space, is one with a gradient as steep as possible (Beach, 1984). This pattern has been used successfully for salmonids in Canada, UK and Denmark. A detailed example has been given by Beach (1984) for a Denil Pass constructed on the tidal reaches of a river in UK. At low tide the difference in water level to be ascended was 2.25 m whilst at high tide this was diminished and a proportion of the pass was submerged. This perhaps emulates the situation of a river in flood.

There are no records of the Denil Pass being used in the tropics and sub-tropics, but it may remain a possibility for by-passing the embankments of the FCD/I schemes. Effectiveness does not seem to be restricted to salmonids since there are records of catfish of 11 kg negotiating a Denil pass with a notch width in the baffles of only 2.25 m (McLeod and Nemenyi, 1940).

3.4 Fish Lifts

Fish lifts typically comprise a collection gallery, an operation chamber with a fish retention grid where fish may be counted and samples taken, and a moving and releasing device. They are associated mostly with dams in hydroelectric schemes and, in order to attract the fish, use the plume of water from both the turbines and the collection gallery. The migrating fishes swim up the plume and into the collection gallery which may be over 150 m long. Periodically, the inlet is closed by a crowding device which prevents the fish drifting back into the tailwater pond. The crowding device is then moved towards the dam, which shepherds the fish into the operation chamber of the lift itself from where they are raised to the outlet chute at the upper level of the dam (Figure 3.4). Such devices can be mechanically or hydraulically driven.

Fish lifts can be very effective when correctly sited and operated. The Volgogradsky hydraulic lift on the Volga River allows more than one million fish of all types to pass upstream each year (Pavlov, 1989). Fish are attracted into the collection gallery by water velocities of 0.8-1.8 m sec^{-1}.

Fish lifts are expensive and are only appropriate where a major device is being considered.

2a

Figure 3.4 The fish lock of the Volzhskaya hydroelectric dam on the Volga River. 1. outlet orifices, 2. operational gates, 3. crowding device, 4. hydroelectric unit (after Pavlov, 1989)

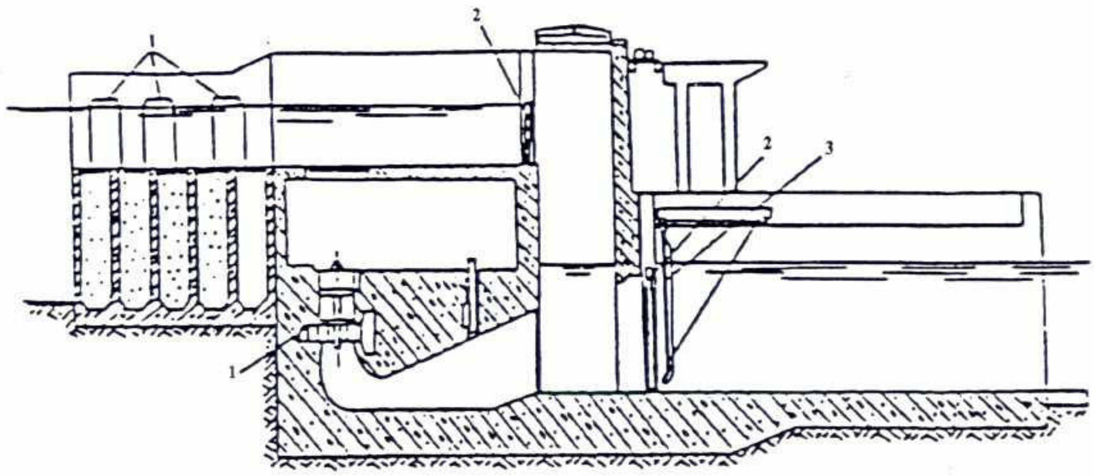
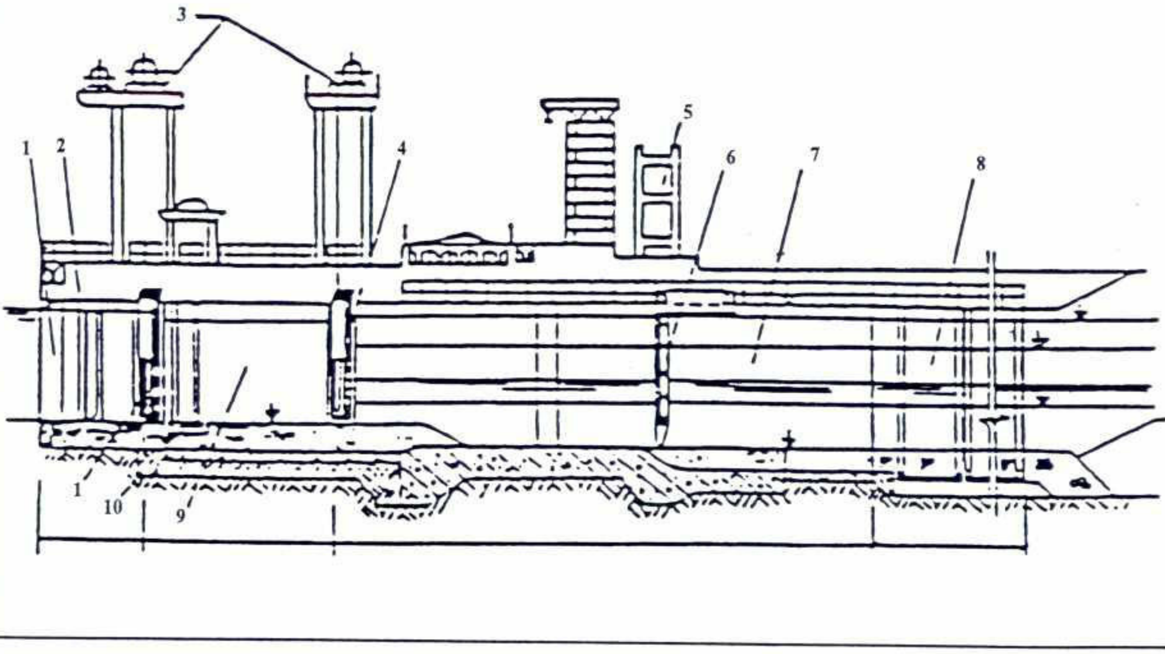


Figure 3.5 Longitudinal section through the sluice fish-pass at the Fedorovskiy hydraulic scheme on the Kuban River. 1. outlet chute, 2. litter-retaining screen, 3. gate control mechanism, 4. gates. 5. control structure, 6. crowding screen, 7. fish-collection gallery, 8. low approach chute, 9. working chamber, 10. fish-retention grid (after Pavlov, 1989)



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3.5 Sluice Fish Passes

These are variants of the fish lift design. They are operated rather like locks, by the raising and lowering of sluice gates alternately at the entrance and outlet parts (Figure 3.5). During the collecting period, the sluice gate controlling the entrance to the collecting chamber is raised. This is closed periodically and the fish are concentrated at the distal end of the pass by the crowding screen, by which time the water level in the operation chamber has filled to the level of the reservoir. The upper outlet gates are then raised to allow the fish to move out into the reservoir. Again, sluice fish passes have been used for a wide variety of fish in the former Soviet Union (Pavlov, 1989).

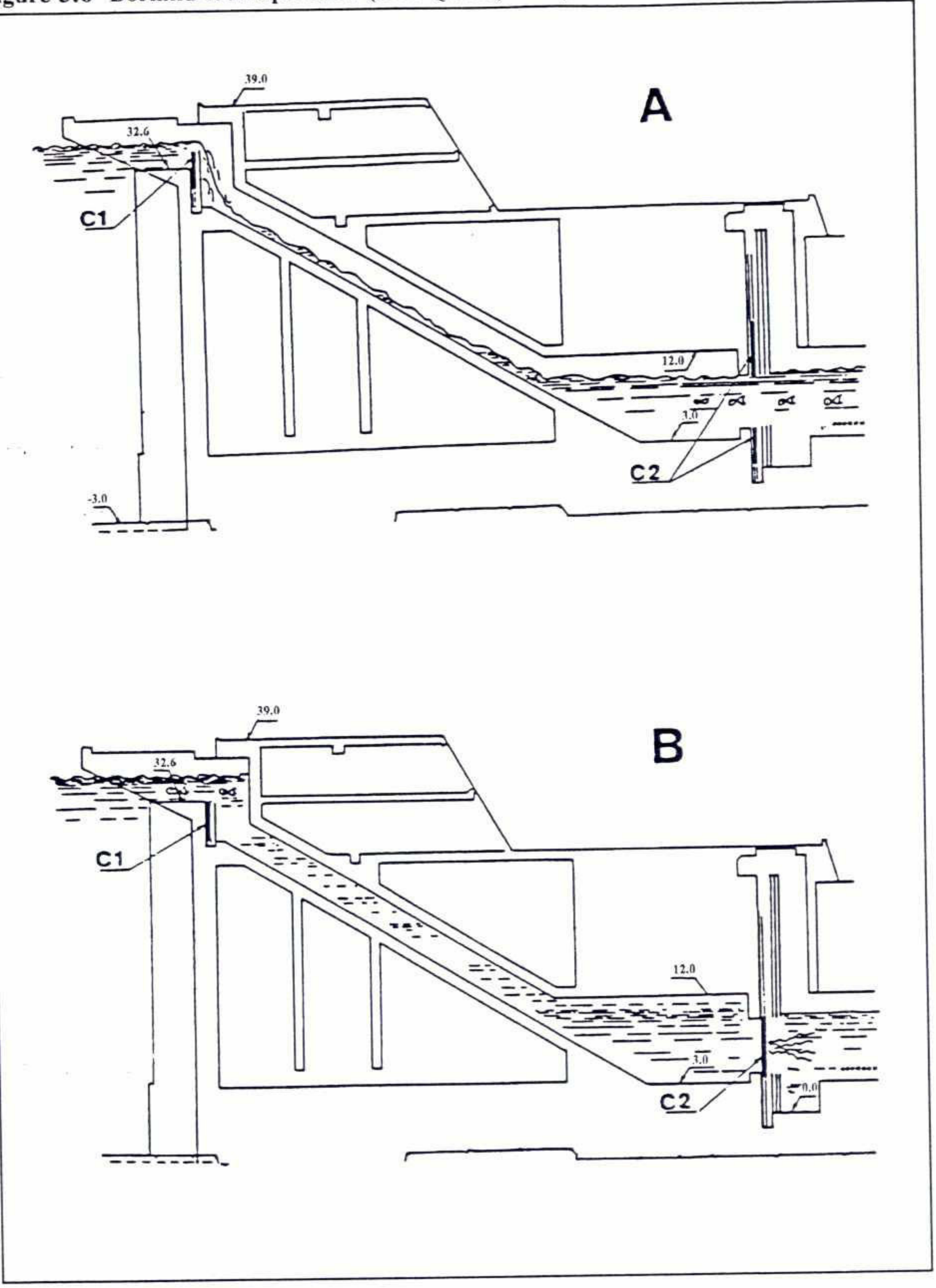
3.6 Fish Locks

The most commonly used pattern of fish lock is the Borland type (Clay 1961). This consists of a lower entrance chamber and an upper exit chamber, connected by a inclined shaft (Figure 3.6). The fish are attracted into the collection chamber by the flow allowed down the inclined shaft from the upper water level. The lower sluice gates can then be closed to allow the inclined shaft to fill with water. The velocity of the flow coming down the channel and out through the entrance is governed by the aperture of the upper sluices.

A substantial example of this type of fish pass was built against the Salto Grande dam on the middle reaches of the Uruguay River (Quiros 1989). It proved successful for the passage of both pelagic and bottom-dwelling species. However, it was noted that the pelagic species often shoaled outside the entrance for long periods, probably because inside there was no light and this initially inhibited their entry. It was also noticed that many fish did not enter, probably owing to the extensive areas of turbulence near the entrance to the pass. It was felt that more detailed planning of the fish lock should have been done before construction (Delfino *et al.*, 1986). This is not an uncommon experience, despite the fact that structures of this size are quite expensive. The two Borland locks at Salto Grande cost around US $1.2 million. The flow velocities for attracting the fish in this device ranged from 0.1 to 1.8 m sec^{-1}.

In the light of the cost of fish locks, they would probably be unsuitable for most flood control schemes in Bangladesh.

Figure 3.6 Borland lock operation (after Quiros, 1989)



A. Fish entering the lock
B. Fish leaving the lock
C1. Upper sluice-gate
C2. Lower sluice-gate

3.7 Mobile Devices

In the former Soviet Union, mobile barges have been developed for use on large rivers. Each barge contains a collection chamber around 60 m long, and submerged pumps create the current to attract the fishes into the chamber (Pavlov, 1989). On occasions, electrical guiding devices are also used. The barge has an associated transport vessel which can transport the fishes through navigation locks into the new area. This, however, is a very specialised form of fish pass.

3.8 "Fish-Friendly Regulators" in Bangladesh

Under the FAP compartmentalisation programme and within existing empoldered areas the common regulatory structures are sluice gates. These control both the inflow of water to an area and the outflow drainage from it. Sluices are normally situated across secondary rivers and drainage canals that traverse the area of the flood control scheme.

A regulator is basically a narrow gap that replaces the length of the floodplain edge as the route for flow onto the floodplain. Fish cannot bypass the regulator because of the embankments. The sill level and the width of the gap in relation to the area to be filled provide the regulation. Further regulation may be provided with gates.

Most often, the inflow of water is controlled by large undershot sluices (Figure 3.7), the gates of which can be opened between compartments and the rising river, to allow controlled volumes of water into the cultivated area. The drainage sluices can be the same type (undershot), but can take the form of a large steel gate which opens automatically as the pressure builds up behind it. Simpler overshot gates (Figure 3.8) can be used for the same purpose. The drainage sluices allow the evacuation of rain water flooding from the compartment during the rains and allow the water level in the compartment to be finely controlled in relation to the inflow channels, to facilitate rice cultivation.

The requirement in Bangladesh will not often be for the design of additions to regulatory structures for the benefit of fish, but rather for an assessment of the structural design of the regulator as a whole in respect of its "fish friendliness". This is inseparable from and secondary to the planned regulating function of each particular structure. The starting point is therefore a detailed specification of the function of the regulator.

Figure 3.7 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. (after Beach, 1984)

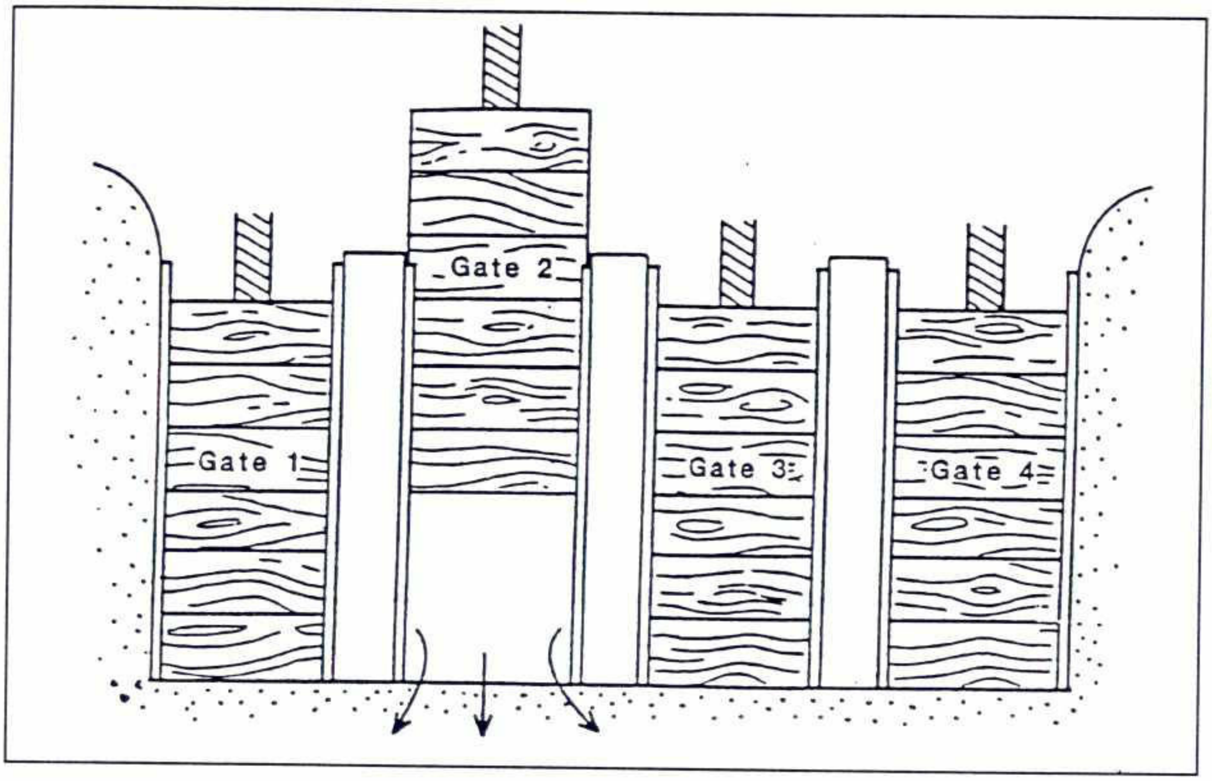
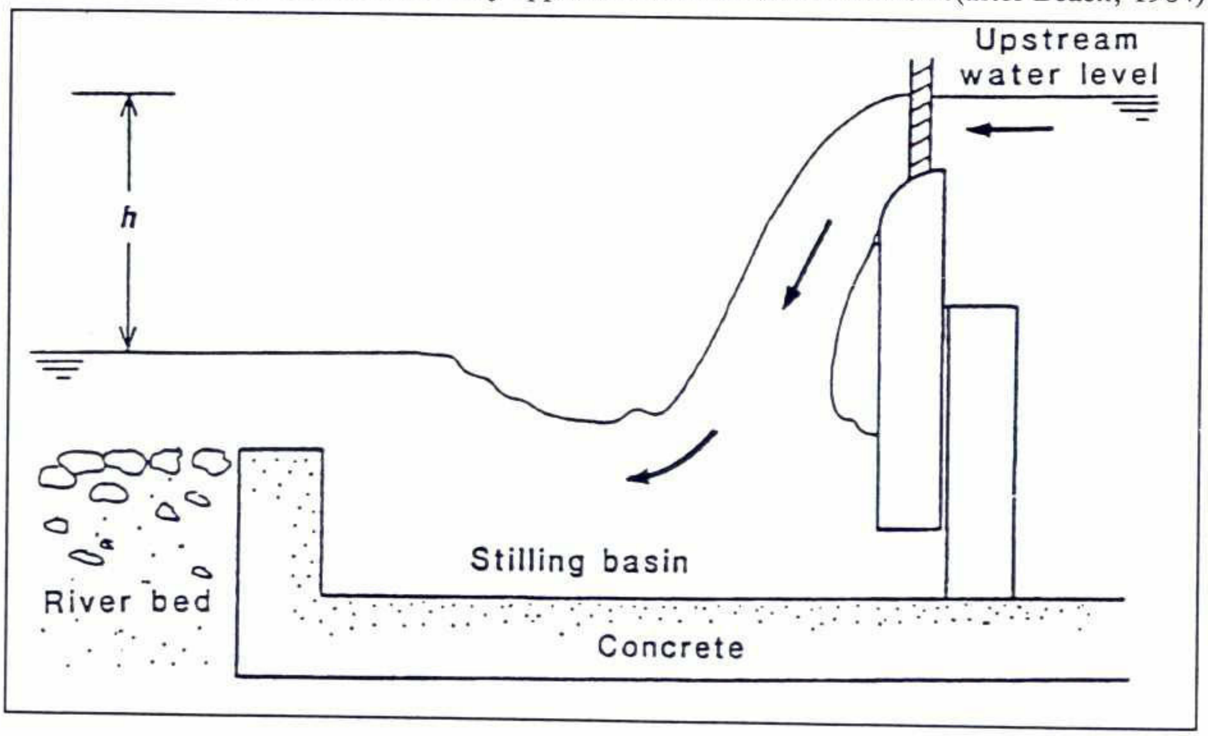


Figure 3.8 Overspill sluice with curved edge and stilling basin; this provides sufficient water depth for an easy approach and a smooth crest flow. (after Beach, 1984)



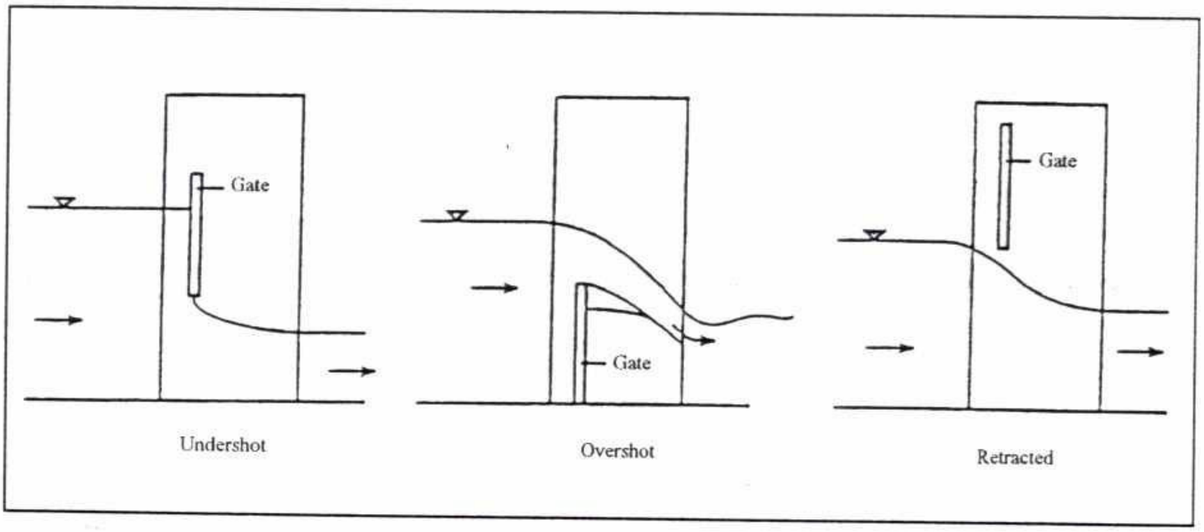
For example, a regulator is planned to hold water levels well below the natural level for the benefit of farmers and it is not necessary to open the gates for long to maintain the required level. On the other hand, fishing interests may require that the gates are at least partly open for a long period. Difficulties with energy dissipation due to lack of water depth downstream and the high head across the structure may rule this out. It is possible on the evidence available to give some initial guidelines for features of a "fish friendly" structure, and this has been addressed in the following sections. However, standard designs cannot be produced; each case must be considered individually.

3.9 Modes of Gate Operation

The only type of gate considered here is the vertical lift gate which has the advantages of economy, suitability for a wide range of heads and suitability for two way flow. Flow over or through other types of gate is not very different in hydraulic terms to the vertical lift gate in one of its modes of operation.

The gate can be operated in three modes, undershot, overshot and retracted, as shown in Figure 3.9. Overshot and retracted modes have similarities, but the flow characteristics of the latter are sufficiently different for it to be considered as a separate mode.

Figure 3.9 Modes of gate operation



On the assumption that there is a fixed flow area regardless of the upstream head (e.g. through a pipe of fixed diameter or an undershot gate on a regulator), then under free flow conditions the discharge rises in proportion to the root of the upstream head. In other words discharge rises slower than the upstream head. Under free flow conditions, if the discharge area is increasing as well as the head (e.g. under natural conditions), then the discharge rises in proportion to the upstream head raised to the power 1.5. The discharge therefore rises at a rate faster than the upstream head.

An undershot gate has a fixed flow area regardless of the upstream head and therefore discharge rises at a slower rate than the upstream head, whereas with an overshot or retracted gate, discharge rises at a faster rate than the upstream head. Head is measured above the crest of the gate and the "crest" of the retracted gate is the regulator sill.

Discharge of the overshot and undershot gate can be varied at a given upstream head by changing the level of the top or bottom of the gate respectively. Discharge for a retracted gate is fixed relative to the upstream head and overall discharge can only be changed independently, by varying the width of the opening. In practise this means varying the number of openings as in multi-gate structures.

These varying flow characteristics have implications for downstream level control and the downstream energy dissipation. Both these factors have to be considered when assessing the impact on the passage of fish.

3.10 Interaction of Regulator and Fish

The drainage sluices are most likely to attract actively migrating fishes. Drainage would commence as the rains build up and discharge the excess of water into the main channel at a time when the fish are moving upstream. If that discharge has the correct current velocity, and if the configuration and timing is also correct, then it is possible that migrating fishes may pass into the compartments through the drainage sluices[1]. If these conditions were not met then the sluices would act as a barrier. This would certainly be the case if pumped drainage is used.

Although the gates should be open as the river rises, inflows probably have little effect on attracting migratory adult and juvenile fish into the compartment, as the current may be

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[1] On the assumption that there is frictionless free flow downstream then the water velocity is a function of gravity (acceleration 9.81 m sec^{-2}) and water head difference (h): $V = 2(gh)^{0.5}$. Assuming a model length of an adult migratory species to be 25 cm then the critical velocity V_{cr} could range between 1.5-2.5 m sec^{-1}; equivalent to crossing a stream head of 10-30 cm. However, this does not take into account velocity loss due to frictional drag. Fish exploiting the velocity differences due to turbulence could no doubt ascend greater head heights than this theoretical calculation indicates.

flowing in the wrong direction to attract the fish. In the NE region of Bangladesh, where carp are migrating out of the *haors*, inward flows from the river would stimulate movement if the current speeds were above the V_{thr} for the species.

However, the inflow though the sluices may draw fish in with the current. In particular it would allow eggs and hatchlings to enter the compartments. The extent of passive larval drift into the compartments is currently being studied by FAP 17 and FAP 20. From the recent Third Fisheries Project Monitoring Programme is appears that wild major carp (type (ii) migratory spawners) are not abundant in enclosed *beels*, and it is possible that the inflow of young may be hindered or hatchlings even killed by the hydrostatic pressure caused by the regulation.

Evidence collected by FAP 17 so far suggests that the abundance of carp hatchlings is highest in the early stages of the cycle, but declines over a two month period. For other species peaks in drift are later, commonly in August and September, with some species occurring in enormous numbers in October and November (Interim Report, 1993). The monsoon rainfall in 1992 was low and so the pattern of hatchling drift measured in that year may not have been typical.

Regulators can have different effects on the movement of hatchlings and fry, depending upon the extent to which flooding is reduced and on the mode of operation of the sluices. Regulators affect fish in two distinct ways:

- by changing the timing and pattern of flow onto the floodplain and
- by causing actual impediment or harm to the fish.

3.11 Timing and Pattern of Flow Through a Regulator

The pattern of flow onto the floodplain may be changed merely by the presence of the regulator, by the gate mode used and by the gate operation programme. Possible effects on fish passage and distribution are examined below.

It is not known to what extent the imposition of regulators in the path of migrating adult fish actually influences their migration. The catching of hilsa at Charghat regulator shows that fish moving upstream along the Baral River towards its feeder river, the Padma encounter a barrier at the regulator. The behaviour of hilsa in response to the flows at the regulator has resulted in them grouping together whilst attempting to pass through against the flow. At this point they are easily caught by resident fishermen. Clearly the fish are unable to sustain the swimming speed necessary to pass through the sluices as fish are not caught upstream of the regulator. The effects of regulated flows on the migration of other fish species in Bangladesh are not clear, but such influences may be detrimental by creating flows too fast for fish to ascend or by diverting fish away from their proper spawning sites.

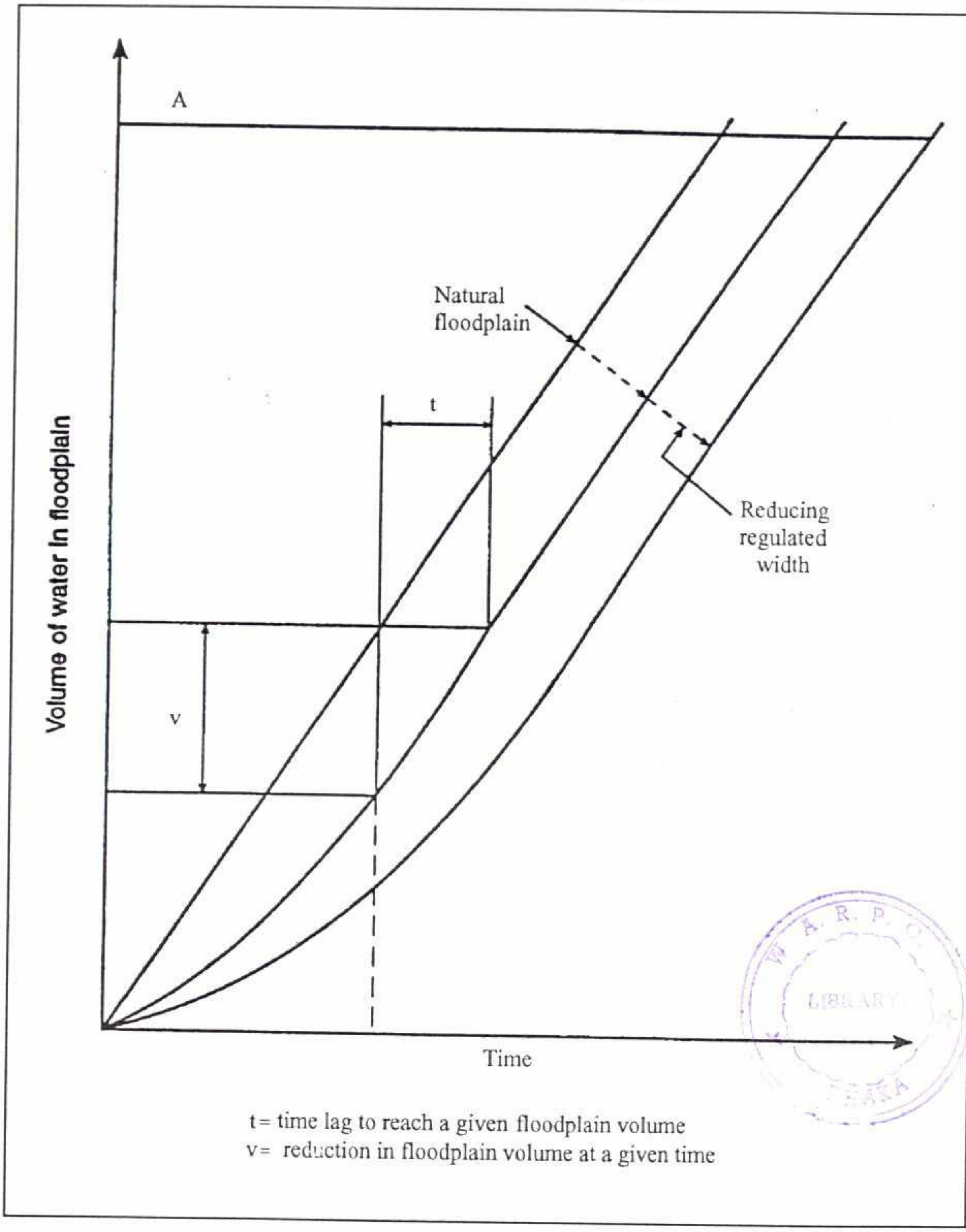
At the low pre-monsoon water levels when spawning migrations generally take place, the gates of drainage regulators should be fully open and the sill level should have been placed low enough to permit natural passage for fish. In some years there may be late spawning runs. This would generally be when rainfall is poor and the rivers are still slow enough for fish to swim upstream later in the monsoon season. Under these circumstances, regulators should not be generating heads and velocities high enough to stop the fish.

Regulators that control the inflow of water on to the floodplain should have sills set at a low enough level to allow flow from or to the floodplain at the earliest stage of the flood cycle. When flow enters, the driving head will be small and the discharge into the floodplain, relative to that entering the unrestricted floodplain, will be little more than the proportion of the regulator width to the open floodplain length. This low flow will cause the level in the floodplain to lag behind that in the river and the increased head across the regulator will increase the rate of flow. The width of the regulator will determine the maximum difference in head. The regulated volume in the floodplain therefore lags behind that entering the natural floodplain.

This is illustrated diagrammatically in Figure 3.10. For simplicity, the volume in the natural floodplain is shown as increasing linearly with time. The lag increases as the regulator width reduces. If line A represents an allowable volume, then the regulated floodplain will reach it later than the natural floodplain would, provided the river level continues to rise above or holds a peak for some time at the level represented by A. Otherwise the regulator will cause a shortfall in the volume of water on the floodplain.

Assuming that there is no shortfall in the volume of water on the floodplain, the total amount of fish passing through and dispersing relative to the natural floodplain will depend on whether the time lag inherent in the use of a regulator has an effect. If the slow build up in volume in the floodplain in the early stage of the cycle coincides with the greatest abundance of fish fry or adults then the regulated floodplain will not be as accessible to fry and adults as the natural floodplain.

Figure 3.10 Pattern of regulated flow onto the floodplain



In practise, the situation is more complex than outlined above, depending on the contouring of the floodplain and the length of the flow paths through the floodplain. Investigations with an advanced numerical model are therefore necessary to evaluate the full effect.

The effect of regulators on the passage and distribution of fish fry is dependent on the timing and duration fish fry movement. It is generally accepted that the peak density of fry occurs early in the monsoon cycle. This is supported by the initial survey results from FAP 17 hatchling studies. The peak of carp hatchling drift coincided with the rise in river levels at the end of June and early July in 1992. Carp species were still present in the later peak flows in August and September, although the drift at this time comprised mainly of other fish species, such as *Chanda* and *Glossogobius*, as well as prawn species.

The regulator at Charghat had an inconclusive effect on the densities of hatchlings drifting through it. On some days, there was a significant difference in the density of hatchlings caught downstream compared with the density sampled upstream of the regulator. Since the head differences created during the 1992 wet season may have been unusually low, the effects on hatchling survival may have been minimal. Continuation of the study during the 1993 monsoon at Charghat and at other regulators, such as Bauitara (Brahmaputra Right Embankment) and Talimnagar (Pabna Irrigation Project) will result in a greater understanding of the influence of regulators on hatchlings and fry.

3.12 The Influence of Gate Type on Inflow Pattern

The fully retracted gate gives the maximum discharge for a given upstream water level and the regulator should therefore be operating in this mode at the start of the flood cycle. If undershot gates are being used, discharge in relation to upstream water level slows down from the moment when the opening is submerged on the upstream side. For a regulator of a given width, therefore, undershot control will generate a larger head difference between river and floodplain than overshot and therefore a greater time lag in terms of entering water volume.

To maximise the volume of water in the floodplain while fish hatchling drift and fish movement is most prevalent, retracted gate operation should continue up to the point where the downstream level is at a height where gate regulation is required. Undershot gates should therefore have a top level at least this high.

3.13 The Influence of Gate Operation on Inflow Pattern

The prime requirement with regard to fish passage is that there is a flow through the regulator throughout the period when fish and fry move. This period coincides with rises in river discharge and it is not less than two months. Positive consideration should therefore be given to maintaining some flow over this period and particularly early in the monsoon, even though at times it may be more convenient, from a water level control point of view, to have the regulator closed during this period.

3.14 Sources of Impediment and Harm to Fish

Present evidence identifies four effects detrimental to fish:-

- impassability of structures to fish;
- damage to fish by rapid changes in pressure;
- physical damage to fish by contact with the structure and
- damage to fish by turbulence.

3.15 Impassable Structures

The undershot gate is the feature which usually comes to mind when impassable structures are discussed. The approach flow to an undershot gate is shown diagrammatically in Figure 3.11*(a)*. It can be seen that the gate draws flow from the full approach depth, but a pocket or pool forms against the gate. The size of the pocket varies, tending to extend further from the gate as the ratio of gate opening to upstream depth increases. The pocket is not still water; the drag of the high velocity stream underneath rotates the flow comparatively slowly in a reverse direction. There is a constant interchange of water between the main stream and the pocket and material of any type in the pocket will tend to be held for a time but eventually ejected.

Input to the pocket is mostly from the surface layer of the approach flow and floating bodies are certain to enter it. Material with a very high flotation only would resist the drawdown forces. Developing fish eggs are, in many cases, of neutral buoyancy and it is extremely unlikely that an undershot gate would do more than briefly delay eggs, hatchlings or fry in passage. It is not clear in the case of very young fish whether a delay is damaging or, if so, what degree of delay is significant. When ejected from the pocket, they could be subject to very high accelerations.

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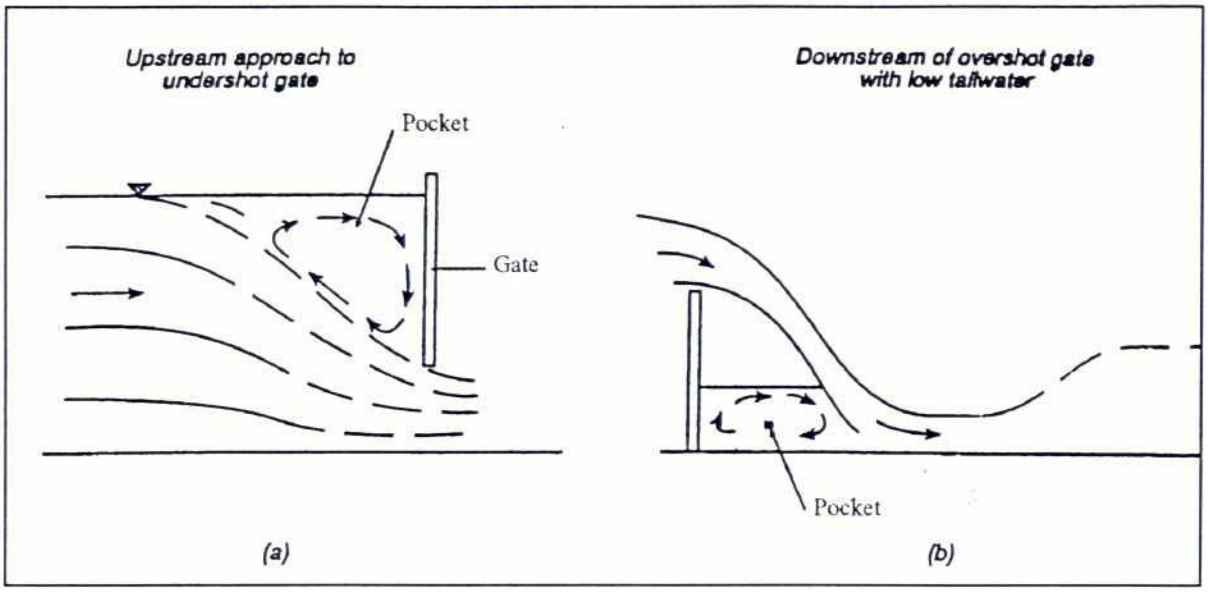
Figure 3.11 Occurrence of slow flow pockets



An overshot gate operating with a low tailwater level can develop a flow pattern on the downstream side in which a slow moving pocket of water is formed behind the nappe as shown in Figure 3.11*(b)*. The effect of this on the passage of fish is likely to be insignificant.

3.16 Changes in Pressure

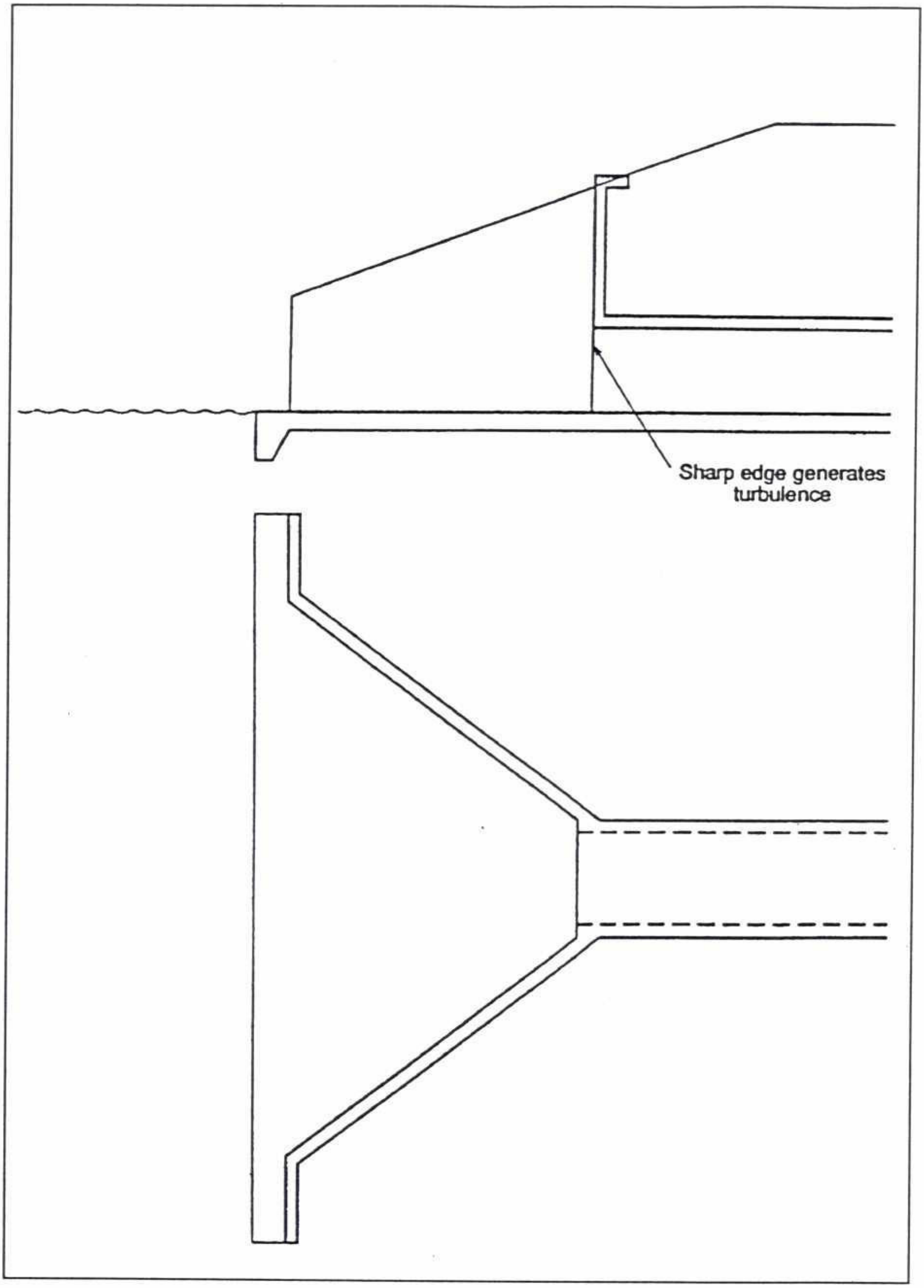
Fish adjust to changes in pressure with the aid of the swim bladder. The concern about water regulating structures is that they may impose changes in pressure on passing fish at such a rate that the fish are unable to adjust quickly enough to avoid damage to the swim bladder. It is usually assumed that very young fish will be at greatest risk.

The specific energy of the flow is the depth of flow (pressure) plus the kinetic energy (velocity). Therefore changes in velocity are echoed by changes in pressure. For a given discharge and upstream depth, the undershot gate will show the greatest pressure difference. The overshot gate will also subject passing fish to changes in pressure, but rather smaller and more slowly than the undershot gate. Flow through a retracted gate will generally give the least and slowest changes of pressure.

3.17 Contact with the Structure

Damage by physical contact with a gated regulator is likely to be limited in any mode of gate operation, because there is relatively little structure in the flow and the streamlines tend to guide fish round protruding parts such as pier noses.

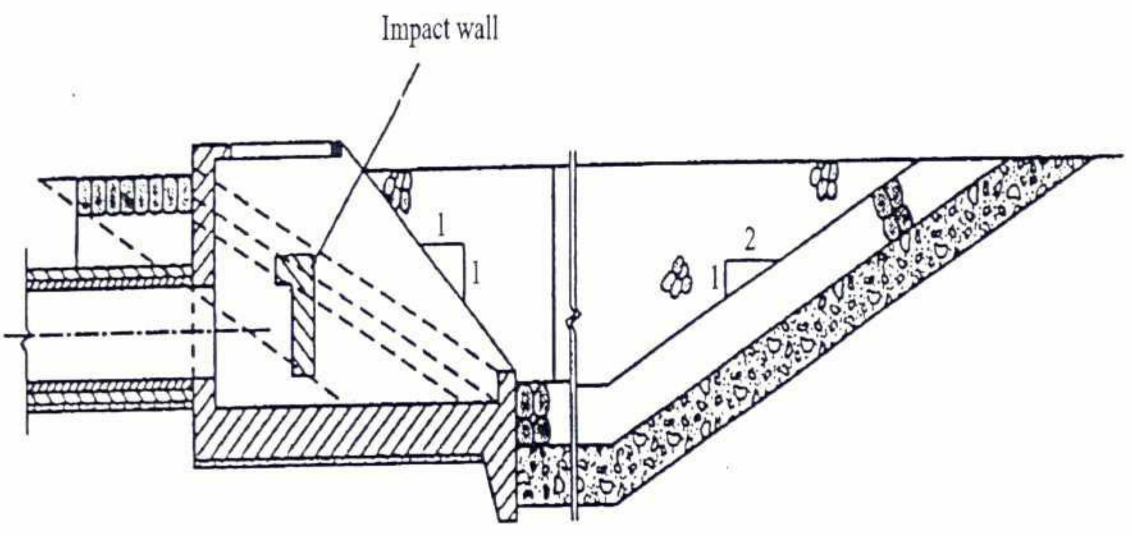
Figure 3.12 Sharp edged intake



A culvert or channel may, however, force the fish into close proximity to an extensive surface while travelling at high velocity. The danger of abrasive damage to fins and scales is therefore increased. A sharp edged entry creates turbulence just inside the entry which is not a problem hydraulically, but will increase the hazard for passing fish. Such designs are quite common and an example is shown in Figure 3.12. Where fish passage is expected a streamlined entry, including a streamlined soffit, would improve the design to some extent.

Under some circumstances, energy is dissipated by impact of the flow against a solid boundary, and this point of collision is clearly a hostile environment for fish. This situation can occur downstream of overshot gates when the ratio of tailwater depth to head over the weir is too low, as shown in Figure 3.11*(b)*.

Figure 3.13 Impact dissipator



Impact can also be used as a deliberate means of dissipating energy. Figure 3.13 shows an example of an impact energy dissipator, where the outflow from a culvert is directed against a vertical wall and then exits underneath the wall. In hydraulic terms this is a compact, highly efficient energy dissipator, and is particularly applicable to outlets where there is little or no tailwater to absorb the flow energy. Without the dissipator, erosion damage downstream could be severe. In every respect, this type of dissipator is damaging to fish, but equally it would be damaging for fish to pass into an area containing little or no water. It is probable that in situations where this type of outlet is used, passage of fish is not a major concern. If it is, it may be possible to double the outlet with another more friendly to fish, which can be brought into operation when there is sufficient downstream water depth for fish to pass.

3.18 Turbulence at Structures

Turbulence downstream of regulators has positive and negative aspects that require a compromise. A regulator is a deliberate restriction of the natural flow area. There will always be a head difference across the regulator at some time in the flood cycle, and usually most of the time. This head difference represents an energy that must be dissipated. Apart from systems used on high dams to dissipate energy as jets in the air, energy generally has to be dissipated by turbulence that eventually turns it to head. Turbulence is therefore necessary, but must be well controlled to avoid erosion damage downstream of the structure.

Fish in turbulent flows can be subjected to rapid fluctuations in pressure, high G-forces, disorienting eddies and impacts (of fast flow or slow flow). No quantitative evidence of these effects is available but it is clear that even if turbulence is necessary it should be minimised where possible in the interests of fish.

Any discussion of turbulent energy dissipation downstream of structures will include references to critical flow, supercritical flow, subcritical flow and hydraulic jump. These terms are briefly explained in Appendix I.

The flow conditions most commonly found downstream of an undershot gate are shown in Figure 3.14. In Figure 3.14*(a)*, the issuing jet is supercritical and the return to subcritical flow that will continue down the river occurs in the hydraulic jump, where turbulence will be considerable as energy is dissipated. The jump will be at its most intense when the gate opening is small and at this time turbulence most damaging to fish will be evident. In general, the wider the gate opening as a proportion of the upstream depth, the less intense will be the turbulence.

The hydraulic jump only forms at or close to a particular downstream depth. If the depth is too low, the high speed jet will continue over a long distance until it is gradually slowed by friction. In terms of fish passage this might be an improvement, but in hydraulic terms it would pose a threat of damage to the river channel downstream and to the security of the structure.

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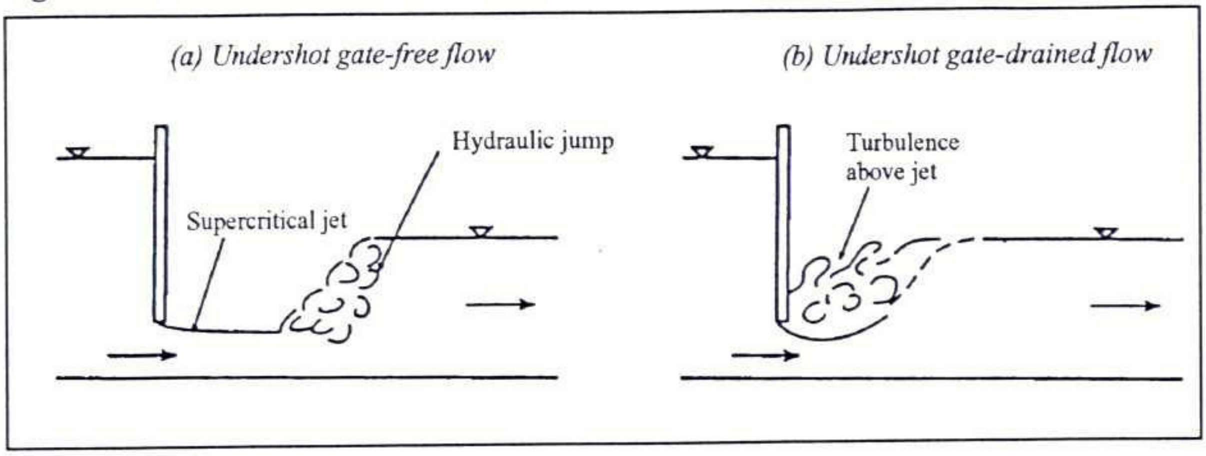
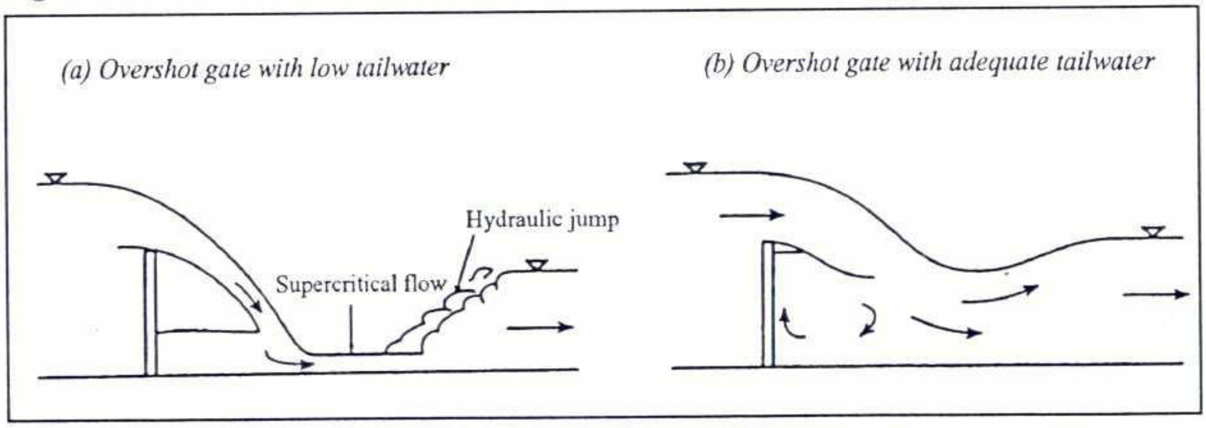
Figure 3.14 Flow downstream of undershot gate



If the tailwater depth is too high for a stable hydraulic jump, the tailwater will run over the jet as in Figure 3.14*(b)*. There will then be surging, turbulent water above the gate opening, as it is dragged away by the jet and falls back. However, most fish would be unlikely to pass through this area and the underlying flow would be relatively smooth.

Possible flow conditions downstream of an overshot gate are shown in Figure 3.15. Figure 3.15*(a)* shows the situation where the tailwater is low. The jet pushes the water away and, as with the undershot gate, forms a hydraulic jump further downstream or in extreme circumstances continues as a high speed jet. If the tailwater is high enough, the downstream conditions will appear as in Figure 3.15*(b)* with, in most cases, a comparatively smooth dissipation of energy.

Figure 3.15 Flow downstream from an overshot gate



Flow through a fully retracted gate over a broad sill is the smoothest form of passage through an overshot gate, and therefore generally the most fish friendly mode in term of turbulence.

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It is not possible to say that one mode of gate operation is best, because the turbulence downstream of a regulator is determined principally by the head difference across the regulator (the energy head) and the depth of tailwater available downstream to absorb it. The latter is determined by the regulation programme. The choice of gate operation therefore may be limited by these two factors.

3.19 Information from Site Visit to Charghat Regulator

The regulator on the Baral River at Charghat controls inflow to the Baral from the Padma River. Water passing through the regulator outfalls through the Hurasagar River into the Jamuna. The regulator has three undershot gates, separated by piers and estimated to be 12 ft wide. During the 1992 monsoon, rainfall had been unusually low and conditions may not have been typical. An inspection of the regulator was made on 24 August 1992, when each gate was opened to approximately 8 ft. Gauge boards upstream and downstream of the regulator showed the head difference to be 0.4 m. At this head and depth of water, the gates were drowned and flow was as shown in Figure 3.14*(b)* and described above. Water between the piers above the gate outlets was heaving, with frequent surges creating surface waves. Although the effect was noisy, a short distance downstream the flow was comparatively smooth.

Hilsa were being caught downstream of the regulator with scoop nets on poles around 24 ft long. The nets were being hauled with ropes in the downstream direction implying that the fish were moving upstream. If this were so, the fish would tend to rest and congregate in numbers, before attempting a run through the regulator. There was no fishing taking place upstream, suggesting that the fish were not aggregating upstream or that very few were getting through.

The fish being caught were mostly about 220 mm long with an occasional one up to 500 mm. The mean velocity through the regulator was estimated to be 2.8 m sec^{-1}. Detailed information on burst (or darting) speeds for fish species in Bangladesh is not at present available. However, for an "average" fish with a length of 220 mm, a burst speed above this may be possible if the water temperature was above 20 °C, but the endurance would be very short (Zhou, 1982).

With all gates open, the fish would not be able to start a run from close to the gates. It would therefore be difficult for the small fish to pass the regulator, although the larger ones would be unlikely to have much difficulty. The significance of the movement of hilsa of this size up this river at this time of the year is not known. However, it emphasises the point that when regulators are known to be in the path of migrating adult fish care should be taken to ensure that the regulator does not develop a high head at the time the fish are passing. This is a danger when water levels are low and regulation requirements alone allow a regulator much narrower than the natural channel.

3.20 Lohajang Regulator Designs

Consultation with FAP 20 engineers enabled FAP 17 to assess the needs for water regulation at a number of regulators in the CPP in conjunction with what is known about fish movement in that area. The main focus of attention was on the planned regulator for the Lohajang River.

With the cooperation of FAP 20, a number of runs were made with the Mike 11 numerical model, which showed the effect of gate operation on regulation for the proposed regulator on the Lohajang River[2].

Since fully retracted gates appeared on initial assessment to offer the most benefits to fish passage, the first runs were made using regulation based only on changing the number of fully open vents. Problems were noted in the regulation:

a) the open area could be changed only in relatively coarse steps so that fine regulation was difficult;

b) when a change was made, the characteristic that discharge rises at a faster rate than upstream water level and vice versa caused fairly rapid change in the controlled level, which in practise would have called for frequent gate changes to maintain a reasonably steady level, and

c) combination of the two features above could cause a hunting effect that would make smooth regulation particularly difficult.

2 Discussion concerning the structures for the compartmentalisation of the Tangail area (FAP 20) and model runs explaining the effects of varying the regulators are available from FAP 17.

An overshot gate has the same characteristics as a retracted gate and some of the same difficulties could arise. A regulator that relies entirely on overshot gate control does not therefore appear to be a feasible proposition. On the other hand the undershot gate, characteristic of a discharge that rises and falls more slowly than the upstream level, looks more suited to fine, stable regulation.

Additional runs were made on the FAP 20 numerical model with regulation by undershot gate and it was found that regulation could be smoothly achieved. The requirements of regulation for the Lohajang River and the requirements of fish passage are not mutually compatible and some compromise will have to be devised for a practical regulator. There must be some compromises to enable water to be controlled efficiently for agricultural production whilst allowing the maximum number of migrating fish and fry to make use of the floodplain.

4 RECOMMENDATIONS OF OTHER PROJECTS

Most regional FAP projects had provision for only short duration fisheries studies, which could not consider all aspects of the effects of flood control on fisheries. Sufficient emphasis was given to the replacement of "lost fisheries" with artificial stocking and aquaculture development, but there is little consideration of structural or operational mitigation against the deleterious effects on riverine and floodplain fish.

Consultation with the FAP projects has highlighted the need for guidance on the best designs and operation of regulators for future projects to allow passage of fish. This section offers a brief summary of the recommendations concerning regulators and fish movement that have been proposed by the main FAP projects.

FAP 1

The plans for river training of the Brahmaputra, under the auspices of FAP 1, have not considered the effects on adult fish migration or on the drift of hatchlings. These aspects should be considered if continued river training and strengthening of the BRE are necessary.

FAP 2

No recommendations for fish passes are necessary under the concept of the "Green River", allowing open access to the Atrai river system and boundary floodplains for migratory species. FAP 2 recommends that the results of the FAP 17 investigation into "fish-friendly regulators" should be considered and in the meantime "it is recommended that gates be left fully open, especially during the early flood and for as long as it is safe to do so, to allow the maximum opportunity for fish to pass."

FAP 3

Proposals for the inclusion of fish passes or "fish-friendly regulators" are not given in the final supporting fisheries document of FAP 3. However, recommendations for proposed research into the most appropriate designs of water control structures, such as sluice gates and regulators, to facilitate the free passage of fish (adults, juveniles and fry) were proposed and hence this has been addressed in the work carried out by FAP 17 and FAP 20. In addition, investigations aimed at acquiring a greater understanding of natural annual migrations between floodplains and rivers were recommended.

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FAP 3.1

Mitigation approaches to fisheries losses are proposed by the Jamalpur Priority Project Study, indicating that the design of regulators can be improved to allow recruitment from the Jamuna and Old Brahmaputra rivers. A draft design is presented, with overshot gates for passage of hatchling drift for two months before maximum flood levels and to minimise the disturbance of water that would damage fish. The operation of the regulator will also allow surviving fish to move back to the river. There is little chance for bottom-dwelling species to move through the structure with the rising flood water, so the possible inclusion of an additional undershot pass should be considered.

FAP 4

The water resources management plan of the SW region recommends an off-take for the Gorai River to overcome siltation problems and this may only be considered in the context of a barrage across the Ganges River. The implications for riverine fisheries of this type of major structure are considerable. The effects may be likened to those of Farraka Barrage, which is thought to have devastated the hilsa fishery by obstructing their migration. There is, however, a proposal for a full environmental impact assessment at pre-feasibility level if such a scheme is to be considered by the government. At that stage, the effects on fish movement must be fully assessed.

FAP 5

Reports of fish behaviour at regulators were mentioned by FAP 5 (Gumti Phase II and Noakhali North Projects - Feasibility Reports) at the Third FAP Conference. Specific research on fish movement with respect to regulators has not been reported by projects apart from FAP 17, which is intensively monitoring the movement of hatchlings through regulators of different types in the NE, NC and NW regions of Bangladesh.

FAP 5 has considered the redesign of a regulator at Kamakhali *Khal*, the drainage channel from the Noakhali North FCD Project, and proposed a passageway for fish. This entails a separate opening to allow fish through the regulator into the scheme and presupposes (from anecdotal evidence) their direction and intention of movement. Also, as with many other FCD scheme proposals, the FAP 5 design presumes there would be sufficient flooding on the inside of the scheme to enable fish to survive. This is contradictory to the aims of the FCD schemes which are targeted at agriculture to provide flood protection of crops, with flooding typically less than 70 cm. In the SE region head differences are unlikely to be sufficient to warrant a need for structures designed for fish passage over considerable heights. Hence there is a conflict between allowing water and fish in and keeping water out for the benefit of crops. The design details of the regulator at Kamakhali *Khal* have not been assessed.

FAP 6

At a recent seminar in July 1993, FAP 6 detailed fisheries management policies for the North East region. A major part of this was the emphasis on fish passes. Detailed designs of passes were discussed and the most appropriate vertical lift design was proposed for implementation in a pilot project at Marala.

In FAP 6's opinion, there was no doubt that fish passes were necessary. The need for fish passes was evident from the head differences that may be created by establishing embankments along rivers of considerable discharge. Over time the level of the river rises, and there may be as much as a 10 m difference in the level of water in the *haor* and river. Fish migrating from the *haor* to the river at the beginning of the rains may, if they encounter an open passage (an open regulator or breach in the embankment), have a considerable inclination to traverse. FAP 6 noted that most regulators were closed at that time of year, since the boro rice crop may not have been harvested and so protection against flooding from the rising rivers is the aim. If fish passes are to be installed in major regulators, their operation could affect the benefits of flood control for agriculture.

The biological information on fish movement is still sparse and the most appropriate designs for salmonids may not be appropriate for Indian major carps and catfishes. Anecdotal evidence on the migration and spawning of carp from fishermen formed the basis of the FAP 6 conclusions. No observational evidence was recorded. No observations have been reported of carp or catfishes leaping during their spawning runs in the same way as salmonids will do to scale a waterfall.

The proposal to install a fish pass at Marala in Shanir *Haor* Project will have to be followed by intensive monitoring of fish movement through the pass and fish behaviour at the regulator. Although the downstream movement of fishes was mentioned and a "fish-friendly" sluiceway will be provided in addition to the vertical slot fish pass, FAP 6 was unable to provide information on what species would be aided by this. Downstream drifting hatchlings, which are extremely important in the NE region, will be flushed through the fish pass with the force of the water. No guidelines to enable velocities to be adjusted to ensure survival of hatchlings and fry were given at this stage. It is important that not only is adult migration considered in the pilot phase, but also the survival of their young. No work on hatchling movement in the NE region has been reported by FAP 6. FAP 17 will provide such information for April to August 1993 and results will be available by the end of the year.

FAP 20

FAP 20 has recently proposed mitigation measures for fisheries in the Tangail Compartmentalisation Pilot Project (CPP) (CPP Working Paper CPPWP - 93/01, 1993). These are:

- to enhance fisheries production with floodplain stocking programmes;
- aquaculture development projects;
- to renovate the hatchery at Askekpur to provide stocking material for pond aquaculture and floodplain stocking;
- to guarantee adequate water levels in *beels* to enable *beel* fishes to reproduce and
- to strengthen local fisheries institutions with training and support from CPP staff.

There is no recommendation for the installation of fish passes, as the head differences were considered insufficient to warrant these and the proposed regulators were "comparatively fish-friendly". However this may not be the case in all circumstances. The provision for "fish-friendly regulators" appears to consider only the downstream drift of hatchlings and not the possible upstream active migration of adult fish, in particular bottom dwelling catfishes.

5 CONCLUSIONS

It is clear that the effects of flood control schemes on the migration of fishes has been overlooked in the past. Although this is now recognised as an important consideration, the lack of information on timing and pathways of migration of different fish species in Bangladesh limits the scope of recommendations possible in this report.

The degree to which modifications to regulators is necessary is dependent upon the difference in the level of water upstream and downstream, or inside and outside FCD/I schemes. Where head differences are three metres or more, such as in the NE region of Bangladesh, and flood control schemes are likely to interfere with migration routes, the installation of a fish pass is necessary. For head differences less than a metre, regulators in common use in Bangladesh can simply be modified and operations adjusted to cause the least damage to fishes and to allow passage of fish at the time of upstream, downstream or river to floodplain movements.

Assessment of the main characteristics of a "fish friendly" structure are summarised below, along with the practical limitations.

The regulator should allow some flow throughout the period of the early monsoon to maximise fish passage. If the regulated level inside the flood control scheme is kept low, the head across the regulator could be very high during this period and might create difficulties with fine control of the regulator.

At the time of peak fry abundance, the discharge through the regulator should be equivalent to that onto the natural floodplain i.e. the downstream level should be rising as fast as the upstream level. If this requirement cannot be met, a wider regulator is required.

No type of gate is considered to be totally impassable to fish. If stoppage or delay does occur it would be at undershot gates. From the point of view of limitation of rapid changes in pressure, contact with the structure and turbulence, overshot or retracted gates are preferable to undershot gates.

However, retracted gate operation may lead to problems of energy dissipation due to unsymmetrical flow downstream. Therefore for smooth water level regulation, undershot gates have definite advantages over overshot or retracted gates.
Free surface flow through regulator gates (overshot flow) is preferable to undershot flow to

facilitate fish passage through a regulating structure. In this context, a narrow regulator that requires little or no gate operation to control the downstream level appears advantageous, but complete control of water cannot be achieved. In terms of overall "fish friendliness", the former conclusion takes precedence because a narrow structure lacks operational flexibility and increases energy dissipation problems downstream.

A practical compromise between efficient regulation and "fish-friendliness" will probably require a combination of undershot and overshot gate operation.

Where a regulator is designed to control downstream water levels well below the natural levels, the threat to the security of the structure from downstream erosion will be the primary concern. Conditions for fish passage may not be worse and could actually be better due to a more gradual dissipation of energy.

A regulator cannot completely reproduce the pattern of flow on an unregulated floodplain. Even when a regulator is intended only to exclude catastrophic floods and not otherwise change the natural sequence of flooding, there will tend to be negative effects on floodplain fisheries.

The delay in the movement of adults and hatchlings as a result of the restricted entry to the floodplain, and reduction of time of rapid growth for the fish at the beginning of the monsoon, is detrimental to all floodplain dependent species. This assumes that fish movement and fry abundance reaches a distinct peak early in the monsoon cycle. Although quantitative data on adult movement is lacking, if as assumed movement occurs with the early flooding, then a regulator wide enough to minimise flow restriction during this period (ie low head loss across the structure) is necessary.

The knowledge about carp movements in Bangladesh is somewhat contradictory to that already established from work in India and evidence of carp spawning within the borders is anecdotal. There is a need for specific studies to investigate migration of native fishes more thoroughly. FAP 17 is trying to address this issue. The threshold and critical velocities applying to different species need to be determined if designs for fish passes and the operation of regulators are to be successful in allowing fish movement.

The composition and timing of hatchling movements, and the effects of regulators on these, are being studied by FAP 17. As results from 1993 studies become available, they will be discussed and disseminated amongst interested parties.

6 RECOMMENDATIONS

High rise fish passes to allow fish migrating against the current to pass permanent barrages are not a pressing requirement in Bangladesh (with the exception of the NE region), but there are occasions where structures may impede migration of adult fish. The methodology for designing this type of fish pass is available, but further investigation of the swimming performance of the major fish species involved is required to allow it to be applied. The proposals of FAP 6 to construct a fish pass in a pilot project should be supported. Findings may only be appropriate for the NE region, but there may be a future requirement to accommodate migrating fish at sites where larger structures are planned, e.g. the Ganges Barrage. The pilot project for a fish pass at Marala will establish the usefulness of the structure in aiding the passage of local fish species.

Although undershot regulator gates give easily manageable control of downstream level, which is the primary purpose of the structures, they can be damaging to fish. Undershot gates can be the principal form of control, but outer vents should be arranged for overshot or retracted operation to facilitate fish passage. These should be sized so that in normal circumstances they can be left in use continuously for the first four months of the monsoon without seriously interfering with the control function.

More quantitative evidence is required on the damage caused to fish by increases in pressure from turbulence and high current velocities, to establish whether more extensive and/or expensive modifications to regulator designs are justified.

Regulators have the potential to cause catastrophic damage downstream. In view of the possible complexity of the downstream conditions relating to energy dissipation, it is essential that the design of all but the smallest structures is verified with hydraulic physical model tests.

There is a requirement for clear guidelines on the need for fish passes or specifically designed "fish-friendly regulators" for use by planners. It is apparent from the diverse opinions voiced by members of the FAP projects that a consensus view on this has not yet been reached. The regional differences must be considered. The NE region may need special consideration due to the assumed nature of the carp breeding behaviour. Schemes in the SW region may necessitate the inclusion of regulators designed to open and close with rising and falling water levels due to the tidal influence. The final guidelines may be sufficiently broad to cover most schemes or they may be so complicated that all schemes have to be considered individually and prior research undertaken to ascertain movements of fishes through the river systems concerned.

The work undertaken by FAP 17 on the movement of hatchlings in free flowing and regulated waterways, and on the assessment of breeding seasons and locations may clarify the movement of the common species through particular river systems and be sufficiently reproducible to be assumed the usual behavioural pattern. However the hydrological cycle has considerable influence on the behaviour of fishes and if this is unusual, as experienced in the 1992 wet season, patterns of behaviour may be less discernable.

7 FUTURE WORK

There is a need to collect further information relating to :

a) the pathways and timing of migration of adults of native fish species in Bangladesh.

b) the range of discharge and flow characteristics through existing regulators in flood control schemes.

c) swimming speeds, including the threshold and critical velocities relating to native species.

d) intensive monitoring of the usefulness of a fish pass, including: control of throughput to attract and aid fish through the pass; fish species targeted and species making use of the pass (both upstream and downstream movements); any detrimental effects caused by high or low velocities though the pass; the proportion of the standing stock using the route through the pass, compared with other possible routes and the passage of hatchlings through the pass.

e) further investigations of the effects of different regulators and their operation on fish physiology, including any damage to the swim bladder by changes in pressure.

The existing work of FAP 17 attempts to address **a)**. In addition provision of background information on the natural drift and the effect of regulators on the drift of hatchlings through different river systems in Bangladesh will be provided by the end of 1993.

FAP 6 is proposing to evaluate **d)**, but it is unclear whether this work will be completed in time for this to be useful for the FAP.

Proposals for a second phase of FAP 17, which aims to evaluate pilot projects for the mitigation of the effects of flood control on capture fisheries, will be formulated by the end of 1993. These proposals may include some of the topics listed above.

APPENDIX 1

Explanation of some hydraulic terms

Critical flow has a number of properties but the most important physical feature is that the velocity of critical flow is equal to the velocity of a wave of low amplitude in that depth of water. Such a wave would therefore appear to be standing still. If the flow velocity was higher than critical (supercritical flow) the wave would be swept downstream but when the flow velocity was lower than critical (subcritical) the wave would travel upstream.

In practical terms, this means that if the flow from a regulator gate is supercritical, the flow is not influenced by any feature downstream. Moreover, the change from supercritical flow to the subcritical flow in the river downstream will be abrupt, creating a 'hydraulic jump' that is accompanied by considerable turbulence and energy loss. The stilling basin of a regulator can be designed to induce the 'hydraulic jump' to deliberately dissipate energy in a short distance and thereby protect the channel bed and banks further downstream. It is the energy dissipation downstream of a regulator that is considered to be one of the more damaging features of a regulator in relation to the passage of fish.

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