THE UNIVERSITY OF ALBERTA

BIOLOGICAL AND HYDRAULIC CONSIDERATIONS OF FISH PASSAGE THROUGH CULVERTS

by

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A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF MASTER OF SCIENCE

IN

WATER RESOURCES

DEPARTMENT OF CIVIL ENGINEERING

EDMONTON, ALBERTA

SPRING, 1987

ISBN 0-315-37740-2

THE UNIVERSITY OF ALBERTA

RELEASE FORM

NAME OF AUTHOR MARGARET A. FAIRBAIRN

TITLE OF THESIS BIOLOGICAL AND HYDRAULIC CONSIDERATIONS OF FISH PASSAGE THROUGH CULVERTS

DEGREE FOR WHICH THESIS WAS PRESENTED MASTER OF SCIENCE

YEAR THIS DEGREE GRANTED SPRING, 1987

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Date 13 March '87

ABSTRACT

This thesis presents the results of an experimental study on the hydraulics of two types of culvert fishways. Four designs of the fish-weirs and three designs of the fish-baffles were studied. Based on velocity, depth and visualization measurements, the designs were tested to see if they were able to provide upstream fish movement. The fish-weirs caused low depths of flow at low discharges on the weir and immediately downstream (along the centerline) as well as high velocities which could be an obstacle to the fish. An important question to be asked is how relevant are the low discharges in prototype conditions and are they below the minimum fish passage discharge for natural river conditions? The fish-baffles also caused low depths at the lower discharges and some high velocities which the fish may or may not have to contend with depending upon the fishes path as the fish-baffles do not span the entire width of the culvert as do the fish-weirs.

ACKNOWLEDGEMENTS

The author would like to thank a number of people for their help in this project. First of all, Dr. N. Rajaratnam for his valuable guidance and supervision during the study. Financial support was provided by Alberta Transportation, Alberta Fish and Wildlife and Dr. N. Rajaratnam and is greatly appreciated. The author is also grateful to: Mr. C. Katopodis for his helpful direction and criticism; Mr. S. Lovell and Mrs. L. Flint-Petersen for their help in the building and maintenance of the scale models in the T. Blench Hydraulics Laboratory and especially my husband, Neil for his reassurance and patience during the past three and half years.

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LIST OF SYMBOLS

A_o – average area

B – baffle

d_o – hydraulic depth

D – diameter

F_o – Froude number

g – acceleration due to gravity

L – model spacing for the fish-weirs and fish-baffles

$L*$ – twice the model spacing for the fish-baffles

L_r – ratio of prototype to model lengths

m – to denote maximum values

M – suffix for model

n – Manning's roughness coefficient

P – suffix for prototype

P_w – wetted perimeter

R_h – hydraulic radius

Q – model discharge

Q_M – model discharge

Q_P – prototype discharge

Q_r – ratio of prototype to model discharge

S_o – slope

T – top width

u – model velocity in the X direction

u_m – maximum value of u

u_M – model velocity

u_P – prototype velocity

V_o – average velocity in the X direction

V_r - ratio of prototype to model velocities

W - weir

y - depth in the Y direction (vertical) in the models

y_M - model depth

y_o - central depth in the plain culverts

y_p - prototype depth

x - longitudinal distance

z - coordinate distance in the Z (transverse) direction

1. INTRODUCTION

Culverts are commonly used for road-stream crossings and are generally adequate for preservation of the fish resource in small and medium-sized streams provided they are properly designed and installed. Road construction in or near the aquatic environment can affect the fish resource in several ways. Major concerns are the possibilities of blocking fish movement, removal or siltation of spawning gravels and other vital habitats, and erosion resulting from construction activities.

The effects of construction on fish populations can be minimized by route selection, construction scheduling and techniques, and stream crossing design provided data are available on fish migration routes and times, spawning and nursery areas, and general life histories. The problem of fish passage through culverts has been the topic of extensive research, especially dealing with upstream migration of Pacific salmon in western North America.

This thesis will bring together pertinent information on the problems culverts impose on the fishery resource from a literature review. Types and timing of migrations, swimming capabilities, fish passage requirements and design methods to meet them are reviewed in Chapter 2.

A major focus of this paper is to present a model study on two types of culvert fishways (fish-weirs and fish-baffles). The hydraulic performance of these fishways was tested through velocity, depth and flow pattern measurements. The experimental model study of the two culvert fishways was undertaken at the T. Blench Hydraulics Laboratory, University of Alberta. The experimental procedure, data analysis and conclusions and recommendations will be covered in Chapters 3 to 6.

2. LITERATURE REVIEW

2.1 General introduction

This chapter will review the biological, hydrological and hydraulic considerations pertaining to culvert installation, as well as, review the various fishway designs for culverts.

2.2 Biological considerations

Insurmountable barriers to upstream fish movement can occur as a result of high water velocities through poorly designed culverts. To assist in the preparation of efficient design guidelines which would minimize environmental damage from this cause, certain biological aspects must be understood and studied.

This section of chapter 2 will explain and discuss these biological considerations such as the types of fish movement (runs), fish swimming speeds and performance and the biological and environmental factors which can affect the performance.

2.2.1 Fish movement

There are three types of fish movement (runs); 1. spawning run 2. feeding or rearing run 3. temporary migration. All of the three types of fish movement which greatly depend on the fish swimming speed and performance will also depend on the biological and environmental parameters (fish length, temperature, etc.).

2.2.1.1 Spawning run

This is the most important and well-studied of the three and timing is very important. Spawning is triggered by a combination of degree days and water temperature and must occur at a particular time (Watts, 1974). Spawning times differ among species (Table 2.1); so it is important to know the species of fish for the particular stream or river in question so as to enable the designer to produce velocities in the culvert during the spawing period which are suitable for that particular species. Also, fish must not be delayed for lengthy periods especially when nearing the spawning beds.

Gebhards and Fisher (1972) suggested that a delay of six consecutive days for salmon and trout is the maximum that could be tolerated without damaging the spawning capability of fish when they are ripe and ready to spawn; and Dryden and Stein (1975) suggested that fish indigeneous to the Northwest Territories could tolerate a delay of only three days without serious biological consequences. The period of time beyond which delay becomes harmful has been termed the "Critical Migration Delay Period".

The relationship between the timing of the spawning migration and the culvert design discharge may be elucidated by defining the "Fish Migration Discharge" or "Critical Migration Discharge", as the maximum discharge during which fish are able to migrate through the culvert.

2.2.1.2 Feeding or rearing run

This run occurs when fish are swept downstream during high flows until they reach an area where the velocities allow them to maintain that position in the stream. These fish (all size ranges) will move back upstream to their feeding or rearing areas and this will occur during the lower flows. This run can also occur daily if the culvert was placed between the feeding or rearing areas and the resting areas so that there might be a need for continual movement through the culvert.

2.2.1.3 Temporary migration to larger streams

Streams which freeze solid force fish to move to larger rivers downstream. At breakup, these fish will want to move upstream to spawn, feed and will include all age classes.

2.2.2 Fish speed and performance

The movement of fish through water can be classified into three major categories based on speed and time: sustained, prolonged and burst swimming speeds. These activity levels in fish are commonly defined on the basis of the time for which a given speed can be maintained. These levels of activity can also be defined on the basis of a velocity-time (endurance) curve. Endurance curves for sockeye salmon (*Oncorhynchus nerka nerka*) and rainbow trout (*Salmo gairdneri*) are shown in Figure 2.1. In both cases the endurance curve can be divided into three straight lines corresponding to the main activity levels.

These swimming speeds vary among the fish species and some examples of the limits associated with the three performance levels for some fish as suggested by Bell (1973) are outlined in Table 2.2. Each reflects not only the constraints imposed by time, but also on the biochemical processes which supply the fuel for their application.

2.2.2.1 **Sustained speed**

This speed can be maintained for long periods (greater than 200 minutes) without resulting in muscular fatigue (Brett, 1967). The metabolism for this activity level is basically aerobic. This speed has been divided into three subcategories: routine activity, schooling and cruising.

Routine activity involves the daily movements of fish for foraging, station holding and territorial behavior. Quantitative field measurements of routine activity have proven to be difficult (Beamish, 1978). In the laboratory, routine activity is generally equated to the locomotion displayed by fish whose only movements are spontaneous.

Schooling includes many characteristics of the routine activity except that the activity involves organized groups of fish (ie., Clupeids and tunas). The organized spatial distribution of fish within a school may, in fact, reduce the hydrodynamic resistance of individuals, thus providing for increased swimming efficiency (Beamish, 1978).

Cruising activity is identified by higher swimming speeds such as in migrations and by negatively buoyant fish to maintain hydrostatic equilibrium. This description embodies the unstated definition of sustained activity in the literature where such levels are based on experimental techniques when fish are forced to adopt a specified relatively high activity level sustained for fairly long periods. Table 2.3 lists some examples of sustained cruising speeds for various fish species.

2.2.2.2 Prolonged speed

This speed is defined in relation to sustained and burst as those speeds that can be maintained for between 15 seconds and 200 minutes and ends in fatigue. Energy is supplied through aerobic and/or anaerobic pathways. In field studies, it has been difficult to distinguish accurately between sustained and prolonged speeds. Many laboratory based observations have been made on prolonged swimming activity in fish (Brett, 1964,67; Brett and Glass, 1973; Jones et al., 1974).

Brett (1964) introduced the concept of "critical swimming speed" to accurately quantify prolonged activity in fish. It is the maximum velocity fish could maintain for a precise time period until they develop fatigue or exhaustion. The formula described by Brett (1964) is as follows:

$$U_{crit}\text{(critical swimming speed)} = u_i + (t_i/t_{ii} * u_{ii})$$

where u_i is the highest velocity maitained for the prescribed period (cm sec^{-1}); u_{ii} is the water velocity increment (cm sec^{-1}); t_i (min) is the length of time the fish swam at the "fatigued" velocity; t_{ii} (min) is the prescribed period of swimming (Table 2.4).

2.2.2.3 Burst speed

Burst speed is maintained for a relatively short duration (less than 15 seconds). It is characterized by an initial acceleration phase of unsteady swimming followed by a steady phase (sprint) (Beamish, 1978). The metabolism is basically anaerobic as it is a short-term high swimming performance activity. This speed is essential for survival - capture of prey, avoidance of predators and negotiation of rapid currents. Table 2.5 gives some examples of burst speeds for various species.

Bainbridge (1958a) concluded that on average, fish up to one meter in length should be able to swim up to ten times their own body length, but only for a brief period of 1 second or so, beyond which velocity would decrease exponentially. Weihs (1974) offered the intriguing suggestion that by alternating periods of fast swimming and motionless glide, fish can reduce the expenditure of energy required to cover a given distance by over 50 percent.

2.2.3 Biological constraints on performance

The three swimming speeds are affected to varying degrees by the following biological contraints: size (length, weight, condition), sex and maturity, disease and injury.

2.2.3.1 Size

Of the biological constraints on performance capacity, size is among the most important (Beamish, 1978). Size is usually related to either length, weight or condition of the fish.

Length of fish has been studied the most in relation to fish swimming performance. Thompson (1917, cited in Beamish, 1978) found that sustained and prolonged speeds should be proportional to the length of fish raised to the power of 0.5 based on the assumption that the volume of the body and hence the proportionate amount of muscle increases as the cube of the length, while the surface area increases as the square of the length. Also, burst or maximum speeds were independant of length. Bainbridge (1958a) concluded that speed at any frequency of tail beat is shown to be directly related to the length of the specimen, measured from the tip of the snout to the most posterior extremity of the tail. Figures 2.2, 2.3 and 2.4 show relationships between the length of the fish and the three activity levels.

Swimming performance is most often expressed on the basis of length but has been described also for weight. Fry and Cox (1970) found the prolonged speed of rainbow trout (*Salmo gairdneri*) to increase with weight raised to the power of 0.13.

A condition factor or index relating weight to length (W/L^3) has frequently been used to provide a relative measure of well-being of fish (Carlander, 1950). Green

(1964) noted after rearing wild and domestic brook trout (*Salvelinus fontinalis*) stocks under similar hatchery conditions that the wild stocks out performed the domestic stocks. This follows the finding made by Vincent (1960) that wild stocks have less fat content than domestic stocks.

2.2.3.2 Sex and maturity

Little information is available on the influence of sex or stage of maturity on swimming capacity. Blaxter (1969 cited in Webb, 1975) stated that fish approaching sexual maturity tend to be less excitable and have reduced performance. Idler and Clemens (1959, cited in Brett, 1965b) reported that during maturation the gonad of the female has from two to five times the relative weight of that of the male which could cause reduction in swimming performance.

A study by Huston (1964 cited in Dane, 1978a) on the spawning population of cutthroat trout (*Salmo clarki*) above and below a culvert in a small stream in Montana, revealed the female/male ratio above the structure was less than found downstream. The difference in size between the male and female was not considered sufficient to fully explain the population shift, and it is likely that the swimming ability of a mature female is reduced somewhat by the heavy presence of her spawn. Brett (1965b) indicated that critical speed was slightly greater for males than the females of the sockeye salmon (*Oncorhynchus nerka nerka*).

2.2.3.3 Disease and injury

The swimming performance of fish can be substantially impaired by a deterioration of their physical condition.

2.2.4 Environmental constraints on speed and performance

Swimming speeds are affected by numerous environmental factors. The environmental constraints which are of greatest importance are temperature; oxygen and carbon dioxide; and pollutants.

2.2.4.1 Temperature

This is probably of greatest importance. Much research has been done on the effect temperature has on swimming performance of a variety of species (Fry, 1947; Fry and Hart, 1948; Brett, Hollands and Alderdice, 1958; Griffiths and Alderdice, 1972; Lauman, 1976).

Fry and Hart (1948) studied cruising speed in relation to water temperature where cruising speed was taken as that speed at which the fish could swim steadily for some considerable period of time, although presumably after hours fatigue would set in. They noted a difference in the cruising speed of goldfish (*Carassius auratus*) which were thermally adapted to the temperature of which measurements were made and those acclimated to ~~the~~ temperature levels of 5, 15, 25, 35°C and measured over the biokinetic range appropriate to each level of acclimation (Figure 2.5). Brett, Hollands and Alderdice (1958) studied the effect of temperature on the cruising speed of young sockeye

(*Oncorhynchus nerka nerka*) and coho salmon (*Oncorhynchus kisutch*). They defined cruising speed as the swimming speed which a fish can maintain consistently for a minimum period of one hour under a strong stimulus without gross variation in performance. There findings noted that temperature has a profound effect on cruising speed (Figure 2.6).

Although it apparently has little effect on sprint (burst) performance (Blaxter, 1969), temperature markedly affects sustained and prolonged swimming. Highest sustained speed is best at temperatures above 15°C (59°F). Bell (1973) stated that temperatures on either side of the optimum range of any species adversely affect swimming performance. Reduction of swimming effort of 50 percent may occur as a result of temperature (Bell, 1973). Lauman (1976) in his paper on salmonid passage at stream-road crossings noted swimming stamina is reduced as water temperature decreases; being highest at 18-24°C (65-75°F) and lowest at 0-4°C (32-40°F). Optimum temperature for swimming ability for juveniles is 20°C (68°F). Atlantic salmon (*Coregonus canadensis*) and rainbow trout (*Salmo gairdneri*) experience reduced movements and jumping activity when water temperatures are less than 6°C (42°F).

2.2.4.2 Oxygen and carbon dioxide

Oxygen levels above air saturation can increase performance (Brett, 1964) (Figure 2.7). At high temperatures, the oxygen content of water is reduced, and this reduces the swimming performance, overriding positive temperature effects on swimming performance that would be expected to increase this performance (Brett, 1964).

Brett (1965b) studied the relation of size to rate of oxygen consumption and sustained swimming speed of sockeye salmon (*Oncorhynchus nerka nerka*). He noted that at the highest sustained level of performance the muscular demand for oxygen is met by the maximum rate of oxygen uptake. For fish acclimated to lower levels of oxygen, oxygen levels of 60 percent saturation are required before performance is affected (Dahlberg et al., 1968).

Webb (1971b) measured the increased oxygen consumption used for swimming with increased swimming speed (Figure 2.8). Bell (1973) stated that swimming speeds are affected by available oxygen and swimming speed may be reduced by 60 percent at oxygen levels of 1/3 saturation. Reduction of oxygen levels to between 90 and 60 percent air saturation reduces swimming performance in salmonids (Webb, 1975). Lauman (1976) studied salmonid passage at stream-road crossings and noted that changes in dissolved oxygen concentrations from 7 mg/L to 3 mg/L can reduce sustained swimming speeds by 500 percent.

High levels of carbon dioxide apparently have little effect on performance (Dahlberg et al., 1968).

2.2.4.3 Environmental pollutants

The influence of those pollutants introduced into the environment either directly or indirectly by man or through his activities has received attention only in the recent years with most of the effort expended in the determination of their lethal concentrations. Of particular concern to the swimming capacity of fish are those pollutants which influence the exchange of respiratory gases or the metabolic pathways involved in the mobilization of energy. Such pollutants as pulpwood fiber, copper and fenitrothion (insecticide) have been studied and shown to decrease the swimming performance (Beamish, 1978).

Sewage and other organic waste places a demand on the dissolved oxygen in a stream which decreases the oxygen supply required by migrating fish (Metsker, 1970).

Fish are also deleteriously affected by siltation in streams. Sediment transported in the water column can abrade delicate membranes in the fish's gills, reducing their ability to function and increasing their vulnerability to disease which could further reduce gill function. In severe situations, silt can clog the fish's gills and cause suffocation (Dane, 1978a).

2.3 Hydraulic and Hydrological considerations

The dominant aspect of culvert conflict is obstruction to upstream fish migration which, in turn, is generally controlled by the hydraulic and hydrologic conditions at the site.

To ensure that upstream fish migration is not adversely affected by the presence of a culvert, certain hydraulic and hydrologic conditions must be met at the site and maintained through the period of fish migration. The water velocity and depth of flow within the culvert and adjacent to the culvert are the primary criteria for successful fish passage. In addition slope of the culvert, culvert invert, culvert length and design discharge will also affect fish passage.

2.3.1 Water velocity

Water velocity within the culvert largely determines the success or failure of fish passage at the site. Because of the uniformity of the culvert, fish are faced with an almost constant velocity profile throughout the structure and the lack of resting areas in particular, maximizes the effort required by the fish to swim through a culvert.

Water velocities in culverts depend upon a number of factors including culvert size (diameter), length, slope, roughness and tailwater conditions, all of which can be manipulated to produce various results. It is through control of these variables that velocities and fish passage can be controlled at the culvert site.

The relationship between water velocity through a culvert and culvert length is critical to fish passage. Fisheries and Marine Service (1958 cited in Dane, 1978a) recommended the following water velocity-culvert length criteria for pink salmon (*Oncorhynchus gorbuscha*) and chum salmon (*Oncorhynchus keta*):

1. velocities in the culvert should not exceed 1.2 m/s (3.9 ft/s) for culverts under 24.4 meters (80 feet) in

length.

2. velocities in the culvert should not exceed 0.9 m/s (3.0 ft/s) for culverts over 24.4 meters (80 feet) in length.
3. culverts in excess of 61 meters (200 feet) in length are not recommended and special consideration will be required on a site specific basis if such culverts are necessary.

Table 2.6 (Lauman, 1976) lists maximum water velocities for a variety of culvert lengths for certain adult fish species. Figure 2.9 (Lauman, 1976) gives recommended maximum velocities for juvenile salmonids.

As mentioned earlier, roughness factor, size (diameter) of the structure and slope are also causes of excessive water velocities. Roughness factors vary for culverts and natural stream bottoms (Table 2.7). The impact of this factor is generally unimportant except when smooth concrete or steel pipe and concrete aprons are utilized. Velocity is not affected by culvert diameter except when the structure is considerably undersized and a head is developed (pooling at upstream end). In that case, the head causes higher velocities. Head should not be designed into projects where fish passage is desired. Slope is an important factor determining velocities in culverts. Slopes steeper than 1/2 percent generally create excessive velocities for fish passage.

Water velocities block fish movement simply by exceeding the swimming speed ability of the fish. Swimming ability, as mentioned earlier varies with species, size and age of fish and water quality. The average cross-section velocity of flow through which fish must pass should be less than the sustained swimming speed of the smallest sized fish that must pass through the structure (Evans and Johnston, 1976). Evans and Johnston (1976) recommended that maximum allowable velocities should be around 4 ft/s (1.2 m/s) for trout and 6.0 ft/s (1.8 m/s) for salmon and steelhead (*Salmo gairdneri*). Brett's (1965a) laboratory tests of salmon swimming speed effeciencies, based on energy output, showed optimum efficiency at water velocities around 2 ft/s (0.61 m/s).

2.3.2 Water depth

Water in the culvert must be of sufficient depth to permit the fish to generate maximum power when migrating through the structure. The depth required is directly related to fish size with larger fish requiring deeper water. When insufficient depths are encountered, fish are unable to produce full propulsion. The two most frequently encountered reasons for insufficient water depth are steep slopes and/or wide, flat channel bottom.

Dane (1978a) stated that the depth recommended by the Fisheries and Marine Service in the 1958 specifications for culvert installations is 0.23 meters (9.1 inches). LGL

Limited (1983) recommended that the culvert should be placed such that a minimum depth of 15 to 20 centimeters (6 - 8 inches) of water is maintained throughout the length during periods of minimum stream discharge. These depth requirements are not species specific but studies have recommended minimum depths for specific fish species.

Metsker (1970) recommends a minimum water depth for Pacific salmons (*Oncorhynchus* spp.) and steelhead (*Salmo gairdneri*) of 20.3 to 25.4 cm (8 to 10 inches). Gebhards and Fisher (1972) also agreed with Metsker's recommendations. Evans and Johnston (1976) recommend a minimum water depth of 15.2 cm (6 inches) for resident trout and 30.5 cm (12 inches) for salmon and steelhead (*Salmo gairdneri*). Lauman (1976) recommended minimum depth criteria for a variety of species:

1. 24.4 cm (9.6 inches) for chinook salmon (*Oncorhynchus tshawytscha*).
2. 18.3 cm (7.2 inches) for other salmon, steelhead (*Salmo gairdneri*), sea-run cutthroat (*Salmo* spp.) and other trout over 50.8 cm (20 inches).
3. 12.2 cm (4.8 inches) for trout under 50.8 cm (20 inches) and kokanee (*Oncorhynchus nerka kennerlyi*).

Where more than one species is present, criteria should be selected that will accomodate all species. Minimum depths required for instream movement of juveniles will vary with species and size of fish present. Generally, 6.1 cm (2.4

inches) is sufficient for passage of juveniles.

2.3.3 Slope

Culvert gradients should be kept as flat as possible to assure fish passage. Maximum culvert gradient allowable for fish passage must be computed on the basis of swimming capability of the fish species, depth of water in the culvert during the period of fish passage and length of the culvert.

Generally a gradient of 1/2 percent will adequately pass fish (trout) in culverts 36 inches or smaller in diameter (Gebhards and Fisher, 1972). Dryden and Stein (1975) also stressed that the culvert gradient should be kept as close to zero percent as foundations and stream conditions permit, with the condition that upstream and downstream velocity barriers are not formed as a result. Lauman (1976) stated that slope is the most important factor determining velocity in culverts. Slopes steeper than 0.5 percent (1/2 foot drop in 100 feet) generally create excessive velocities for fish passage.

2.3.4 Excessive entrance jump

The two basic causes for a jump at the downstream end of a structure are bed scour and slope of the structure placement. Bed scour occurs most frequently in steep gradient streams with erodible bottom material. Placement of a flat sloped structure on steep sloped stream builds in a jump.

Fish have difficulty in jumping when an adequate pool is not available for them to gain the required swimming speed and vertical thrust. Although fish are capable of jumping a considerable distance, any passage condition which requires them to leave the water is undesirable (Gebhards and Fisher, 1972). Under no circumstances should the over-pour from the culvert into the pool exceed 1 foot (0.3 meters) in head (Gebhards and Fisher, 1972). The lower the jump, under water conditions that occur when migration takes place, the less difficulty the fish will have in passing the obstacle. Lauman (1976) states approximate dimensions that should be used to design a jump pool when a jump cannot be avoided:

1. pool length should equal 3 times the maximum width of the culvert or a minimum of 10 feet (3.1 meters).
2. pool width should equal 2 times the maximum width of the culvert or a minimum of 8 feet (2.4 meters).
3. depth should equal 1-1/2 to 2 times the height of the jump required with a minimum depth of 2 feet (0.6 meters) and a maximum depth of 10 feet (3.1 meters).

2.3.5 Design discharge

The culvert should have sufficient capacity to pass the design flood (generally a 1 in 50 year flood and sometimes a 1 in 100 year flood) with no backwatering or ponding at the upstream end of the culvert. There should also be freeboard allowance for passage of debris.

An important factor of fish passage design is determining a reasonable hydrograph for the crossing site so that the appropriate discharges during periods of fish migration can be determined. Factors which influence streamflow and consequently the shape of the hydrograph include the geographic location of the drainage basin, the general slope, land cover, type and depth of the soils.

It is during fish migration that the discharge should not be greater than the Critical Migration Discharge as defined earlier. A major fish passage objective of culvert design is, therefore, to ensure that the Critical Migration Discharge is not exceeded more often than is considered "safe" for the fish as defined by the Critical Migration Delay period (Dane, 1978a).

Examining historic stream flow data is a useful means of selecting a design discharge; however, in many instances, such records are not available or are not of sufficient detail to allow this type of analysis. Other methods which are used include empirical formulae such as the Rational method, unit hydrograph techniques, computer models and analysis of existing gauged data.

A design migration discharge equivalent to approximately 30 percent of the average annual flood (the average annual flood being defined as that discharge having a recurrence interval of 2.33 years) has been suggested for use as a guide in British Columbia (Dane, 1978a). In

Alberta, when fish passage is required, acceptable fish passage water velocities for up to the 1:10 year design discharge must be accomodated (Alberta Fish and Wildlife, 1985).

2.4 Culvert fishways

In the event that the above culvert hydraulic and hydrological criteria cannot meet the required swimming speeds during migration periods then alternative provisions for fish passage must be employed. Constructing a fish passage device through a culvert essentially opposes the entire basic idea of the culvert. The culvert is made to pass water downstream at the highest possible rate, whereas the fish passage facility built into it must afford a relatively easy upstream path for the migrating fish. Optimum fish passage requires that the culvert be placed at a gradient approaching zero, or that velocities be slowed by some type of energy dissipation device.

Baffles, consisting of blocks or plates attached to the barrel floor in regular patterns have been recommended for simulating natural channel conditions. Baffles act as energy dissipators, lengthen the flow path and increase roughness, thereby generating reduced water velocities and increased depths. Baffles change the flow pattern in their immediate vicinity and create a sequence of slow and fast water zones.

A variety of baffle types have been studied such as the pool and weir fishway (low barrier culvert baffles and alternate low barrier culvert baffles), paired baffles, alternate baffles, offset baffles, slot-orifice fishway and spoiler baffles.

2.4.1 Pool and weir fishway

Early efforts to solve the fish barrier problem centered around the use of the pool and weir fishway. Vertical low barrier culvert baffles (Figure 2.10) spaced at regular intervals were placed on the culvert floor perpendicular to the centerline forming a series of pools and overfall weirs. Two distinct types of flow (Figure 2.10) can occur in this type of fishway, "plunging" or "streaming". When plunging flow occurs the water drops from pool to pool in a step fashion. The kinetic energy is dissipated in each pool, thus affording the fish a relatively quiescent resting area prior to each ascent of a weir. For higher discharges streaming flow exists. During streaming flow, water skims over the weir tops at a high velocity with little energy dissipation, a type of flow which is unsatisfactory for fish passage. This fish passage device is not successful due to it shallow depth and tendancy for the water to go to a streaming flow at a relatively low discharge.

Another type is an alternate barrier designed to swing the flow back and forth across the culvert bottom (Figure 2.11). The purpose of this device is to increase the length and decrease the slope of the water's path, thereby decreasing the velocity. This fishway is also unsuccessful because it makes a tortuous path for the fish to swim at low flows and soon drowns out when the flow increases slightly.

2.4.2 Paired baffles

This fishway was modelled and tested by McKinley and Webb (1956) (Figure 2.12) with little success. It was unsatisfactory at low flows and ineffectively dissipated energy at high flows.

2.4.3 Alternate baffles

Again, this fishway device was modelled and tested by McKinley and Webb (1956) (Figure 2.12) and was unsuccessful. It created depths in successive pools that were below minimum at low flows and created completely unstable flow patterns at high flows.

2.4.4 Offset baffles

The offset baffle configuration consists of "paired" baffles attached to the sides and bottom of the box culvert and extending out into the flow of water (Figure 2.13). One of the baffles entends out from one side of the culvert, ending short of the mid-point or center the culvert and is positioned perpendicular (90 degrees) to the flow of water. The opposing baffle extends out from the other culvert wall at an oblique (30 degrees) angle to the flow of the water and also terminates before the center of the culvert at a position slightly upstream from its paired member. The offset baffles were developed for box culverts through extensive model testing for slopes up to five percent by McKinley and Webb (1956).

The offset baffles act as isolated roughness elements. As the depth of water rises appreciably over the tops of the sills (baffles), the flow passing over them creates wakes on the "leeward" side. Under these conditions, the resting pools in the longitudinal spaces between the baffles are to a large extent drowned out and the sills themselves become the primary elements. Therefore, in order to obtain a resting place, the fish would have to seek out the low velocity zone immediately behind the sill.

One unfortunate aspect of this baffle system is that they have a considerable effect on the efficiency of the culvert to pass flows. Tests conducted by McKinley and Webb (1956) on a 10-foot (3.1 meter) wide box culvert on a 3.5 percent slope, at a high flow, showed that the efficiency of the baffled culvert was 69 percent for sills 12 inches (0.3 meters) high and 57 percent when the sills were 16 inches (0.41 meters) high. A vertical wall three times the baffle height was placed along the centerline of the culvert floor. One half was baffled and other side left open to free flow. This arrangement with baffles 12 inches (0.3 meters) high resulted in an efficiency of 80.5 percent.

Testing of the offset baffles (McKinley and Webb, 1956) indicated good cleaning characteristics. Although this may be so for small sizes of bed material, the strength of the circulation required to sweep out material several inches in diameter would surely result in an unsuitable resting area. Several of these installations in Oregon and Washington have filled with bed material and are no longer completely effective.

Engel (1974) modelled offset baffles in circular culverts. For circular culverts, an effective width is used which is defined as the distance perpendicular to the length of the culvert between the points where the horizontal crests of a pair of baffles meet the curved boundary of the culvert (Figure 2.14).

Katopodis et al. (1978) studied the hydraulics of the offsets in model and prototype. They provide details of these studies and a method of judging baffle adequacy; they recommend a minimum baffle height of 300 millimeters and a limiting slope of 5 percent. They reported only minor problems with ice and debris. Although these baffles have been used successfully in passing salmonids, experience with other fish species is lacking. The effectiveness of the offsets is inversely proportional to the culvert slope and may allow fish passage for slopes up to 5 percent.

2.4.5 Slot orifice fishway

A slot orifice fishway is a rectangular shaped channel with a series of full depth vertical slot orifices arranged in a systematic pattern (Figure 2.15).

The slot orifice fishway is a proven fishway with many advantages (Dass, 1970). It provides stable low velocity flow conditions for a wide range of headwater and tailwater depths, is self-cleaning, and is simple and economical to construct. For a box culvert installation, the fishway exit (at the upstream end of the culvert) can be constructed outside the culvert barrel, as shown in Figure 2.15. At some distance downstream from the entrance (about two to three times the depth of the box culvert) the fishway may be constructed within the culvert barrel adjacent to the wall. The effect of this is to constrict the flow and raise the water surface in the lower reach of the culvert. However, since the fishway occupies a reach downstream from the contracted entrance section and in the supercritical flow zone, the headwater level upstream from the culvert is not affected by the fishway and the entrance conditions for the culvert still controls the upstream flow depth.

Watts (1974) suggested an appurtenance orifice fish passage structure which can be attached within a cmp (corrugated metal pipe) or pipe arch structure (Figure 2.16) but has not been tested.

2.4.6 Spoiler baffles

Spoilers are individual blocks usually constructed from concrete and were modelled by Engel (1974) (Figure 2.17). Morris (1959 cited in Engel, 1974) stated that if the blocks are far enough apart longitudinally so that each block is not within the wake zone of the one preceeding it, then they act as isolated roughness elements.

The length of the wake behind the blocks is decided by the height of the blocks. A height of one foot (0.3 meters) would provide a wake zone of approximately 5 to 6 feet (1.5-1.8 meters). This height would also provide adequate coverage for the fish. Therefore, the minimum height for the prototype blocks was taken to be one foot (0.3 meters).

The lateral spacing between adjacent blocks behave like contractions. As the flow emerges at the the leeward end of the blocks, there is a horizontal expansion which cuts into the wake zone, as defined by the horizontal vertical profile, thus shortening the effective low velocity region behind the blocks. In order to minimize this, the width of the blocks was taken as 1.33 times the height.

The profile of each block was defined by a circular arc which met the top tangentially. This was expected to give considerable reduction in drag and thus would be less retardant to the flow (Hoerner, 1958 cited in Engel, 1974). The cross-section of the block perpendicular to the flow was maintained rectangular since it was felt that no significant advantage would be gained by providing a three-dimensional curved surface.

The lateral spacing would be equal to the width of the blocks. This would provide adequate space for the fish whereas a wider spacing would reduce the "block cover" unnecessarily.

The hydraulics of the spoiler baffles have been studied in model and prototype and can be predicted (Katopodis et al., 1978). Katopodis et al. (1978) concluded that the effectiveness of the spoilers was similar to the offsets which is inversely proportional to the culvert slope and may allow for fish passage for slopes up to 5 percent. Also, they proved to be less prone to damage by ice and debris than the offsets.

2.5 Summary

This chapter presented a limited review of the biological, hydraulic and hydrological considerations associated with culvert installations. Since the optimization of the hydraulic efficiency of a culvert and the creation of optimum fish passage conditions within the culvert are mutually exclusive objectives, a compromise must be affected.

Table 2.1 Spawning times for various fish species in the Athabasca River System, Alberta. (adapted from Alberta Fish and Wildlife, 1986)

SPECIES		SPAWNING TIMES
Arctic Grayling	Thymallus arcticus	April 23 - June 10
Lake Whitefish	Coregonus clupeaformis	Oct 1 - Jan 30
Mountain Whitefish	Prosopium williamsoni	Sept 15 - Oct 23
Lake Trout	Salvelinus namaycush	Sept 15 - Oct 15
Dolly Varden	Salvelinus confluentus	Sept 1 - Oct 1
Brook Trout	Salvelinus fontinalis	Oct 1 - Nov 15
Rainbow Trout	Salmo gairdneri	May 15 - June 15
Northern Pike	Esox lucius	April 15 - June 10
Goldeye	Hiodon alosoides	May 15 - July 15
Yellow Perch	Perca flavescens	April 15 - June 1
Walleye	Stizostedion vitreum	April 15 - June 1

Table 2.2 Relative swimming speeds (m/s) of average size adult fish. (adapted from Bell, 1973)

SPECIE	CRUISING SPEED	SUSTAINED SPEED	BURST SPEED
Brown Trout	0 - 0.7	0.7 - 1.9	1.9 - 3.9
Carp	0 - 0.4	0.4 - 1.2	1.2 - 2.6
Chinook	0 - 2.7	2.7 - 3.3	3.3 - 6.8
Coho	0 - 2.7	2.7 - 3.2	3.2 - 6.6
Grayling	0 - 0.8	0.8 - 2.1	2.1 - 4.3
Lamprey	0 - 0.3	0.3 - 0.9	0.9 - 1.9
Shad	0 - 0.7	0.7 - 2.2	2.2 - 4.5
Sockeye	0 - 1.0	1.0 - 3.1	3.1 - 6.3
Steelhead	0 - 1.4	1.4 - 4.2	4.2 - 8.1
Suckers	0 - 0.4	0.4 - 1.6	1.6 - 3.1
Trout	0 - 0.6	0.6 - 2.0	2.0 - 4.1
Whitefish	0 - 0.4	0.4 - 1.3	1.3 - 2.7

Table 2.3 Sustained cruising speeds for various fish species. (adapted from Beamish, 1978)

SPECIES		a	b	c
Pink salmon	*Oncorhynchus gorbuscha*	64	11	23-78
Coho salmon	*Oncorhynchus kisutch*	55	228	30-162
Sockeye salmon	*Oncorhynchus nerka*	56	834	40-158
Sockeye salmon	*Oncorhynchus nerka*	65	18	33-99
Chinook Salmon	*Oncorhynchus tshawytscha*	84	37	4-176
Cutthroat trout	*Salmo clarki*	34.5	7	0-44.7
Steelhead trout	*Salmo gairdneri*	72	2	9-44
Steelhead trout	*Salmo gairdneri*	42-59	/	0.2-26
Atlantic salmon	*Salmo salar*	50-70	/	12-25
Atlantic salmon	*Salmo salar*	53-87	15	0-17

where column a = length of fish (cm)
column b = number of fish
column c = range of sustained cruising speed (cm/sec)

Table 2.4 Critical swimming speeds for various fish species. (adapted from Beamish, 1978)

SPECIES		a	b	c	d	e
Goldeye	*Hiodon alosoides*	2	22.5	10	10	60
Lake whitefish	*Coregonus clupeaformis*	159	6-51	10	10	34.1-72.1
Sockeye salmon	*Oncorhynchus nerka*	5	17.2	10	60	33.5
Sockeye salmon	*Oncorhynchus nerka*	5	18.4	10	60	21.9
Steelhead trout	*Salmo gairdneri*	6	30.6	10	10	66.6
Arctic char	*Salvelinus alpinus*	11	35.5	10	10	100.2
Arctic grayling	*Thymallus articus*	94	7-34	10	10	52-72
Northern pike	*Esox lucius*	192	12-62	10	10	19-47
Longnose sucker	*Catostomus catostomus*	169	4-53	10	10	23-91
White sucker	*Catostomus commersoni*	20	17-37	10	10	48-73
Walleye	*Stizostedion vitreum*	54	8-38	10	10	38-84

where column a = number of fish
column b = length of fish (cm)
column c = velocity increments (cm/sec)
column d = time between increments (min)
column e = critical velocity (cm/sec)

Table 2.5 Burst swimming speeds for various fish species.

(adapted from Beamish, 1978)

SPECIES		a	b	c	d
Coho salmon	<u>Oncorhynchus kisutch</u>	9	44-67	161-216	10-15
Coho salmon	<u>Oncorhynchus kisutch</u>	5	51-76	220-372	0.1
Coho salmon	<u>Oncorhynchus kisutch</u>	4	36-61	287-533	1.5
Sockeye salmon	<u>Oncorhynchus nerka</u>	15	55-69	155-203	10-15
Chinook salmon	<u>Oncorhynchus tshawytscha</u>	6	51-97	543-668	1.5
Steelhead salmon	<u>Salmo gairdneri</u>	10	58-67	186-226	10-15
Steelhead salmon	<u>Salmo gairdneri</u>	6	61-81	536-817	1.5
Brown trout	<u>Salmo trutta</u>	19	13-37	137-305	2-5
Brook trout	<u>Salvelinus fontinalis</u>	1	11.2	93	10
Western sucker	<u>Catostomus occidentalis</u>	10	37-43	305	1.5-2.5

where column a = number of fish
column b = length of fish (cm)
column c = burst velocity (cm/sec)
column d = time (sec)

Table 2.6 Recommended maximum water velocities in culverts for adult fish passage. (adapted from Lauman, 1976)

Culvert length (ft.)	Recommended maximum water velocity (fps)		
	Salmon & Steelhead	Trout	Kokanee
Under 100 and all baffled culverts	8	4	3
100 to 200	4	2	1.5
200 to 300	3	1.5	1.1
300 to 400	2	1	0.75
400 to 500	1.8	0.9	0.66

Table 2.7 Roughness factors for various type channels. (adapted from Lauman, 1976)

Bottom type	Roughness factor
Concrete pipe (smooth)	0.012
Concrete apron (smooth)	0.012
Steel pipe (smooth)	0.012
Corrugated stack	0.024
Natural bottom (gravel bar)	0.025
Natural bottom (boulders)	0.035 to 0.06

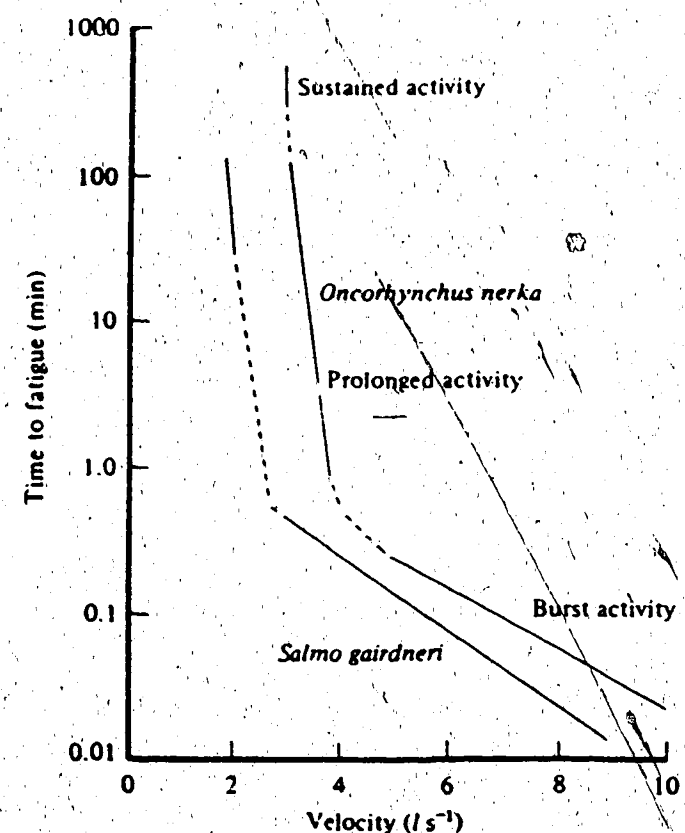


Figure 2.1 Endurance curves for sockeye salmon (*Oncorhynchus nerka*) and rainbow trout (*Salmo gairdneri*). (adapted from Blake, 1983)

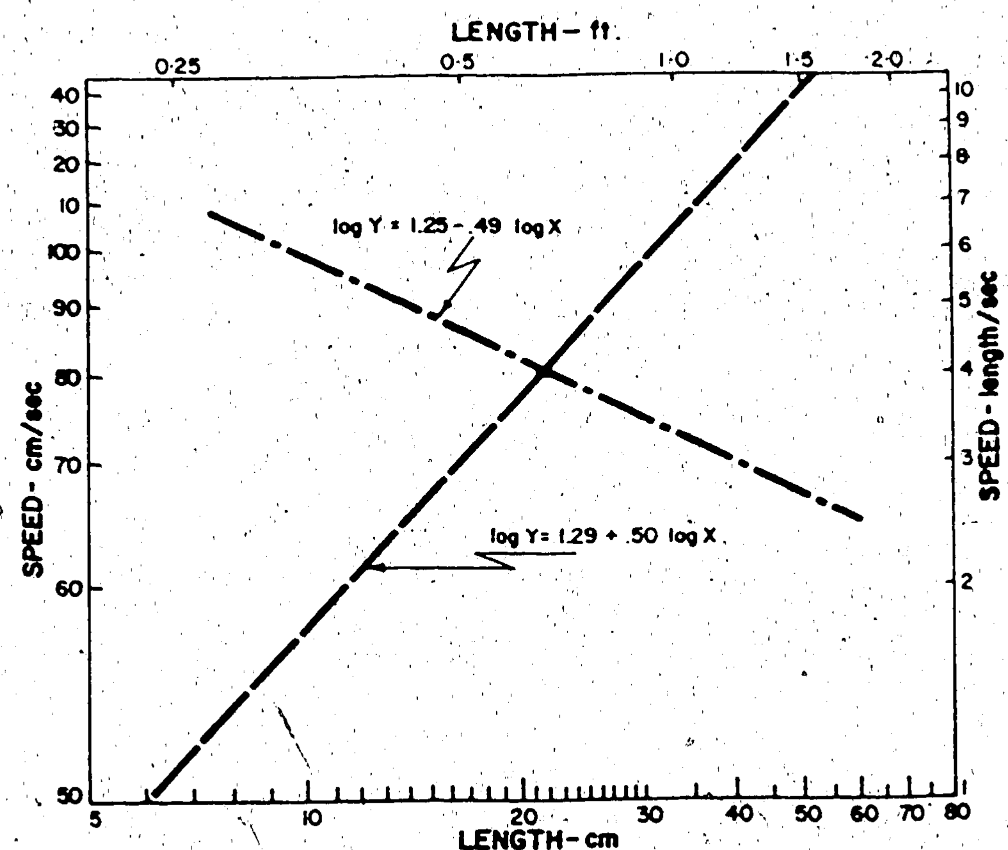


Figure 2.2 Relationship between 60 min maximum sustained swimming speed and total length of young sockeye salmon. (adapted from Brett, 1965b)

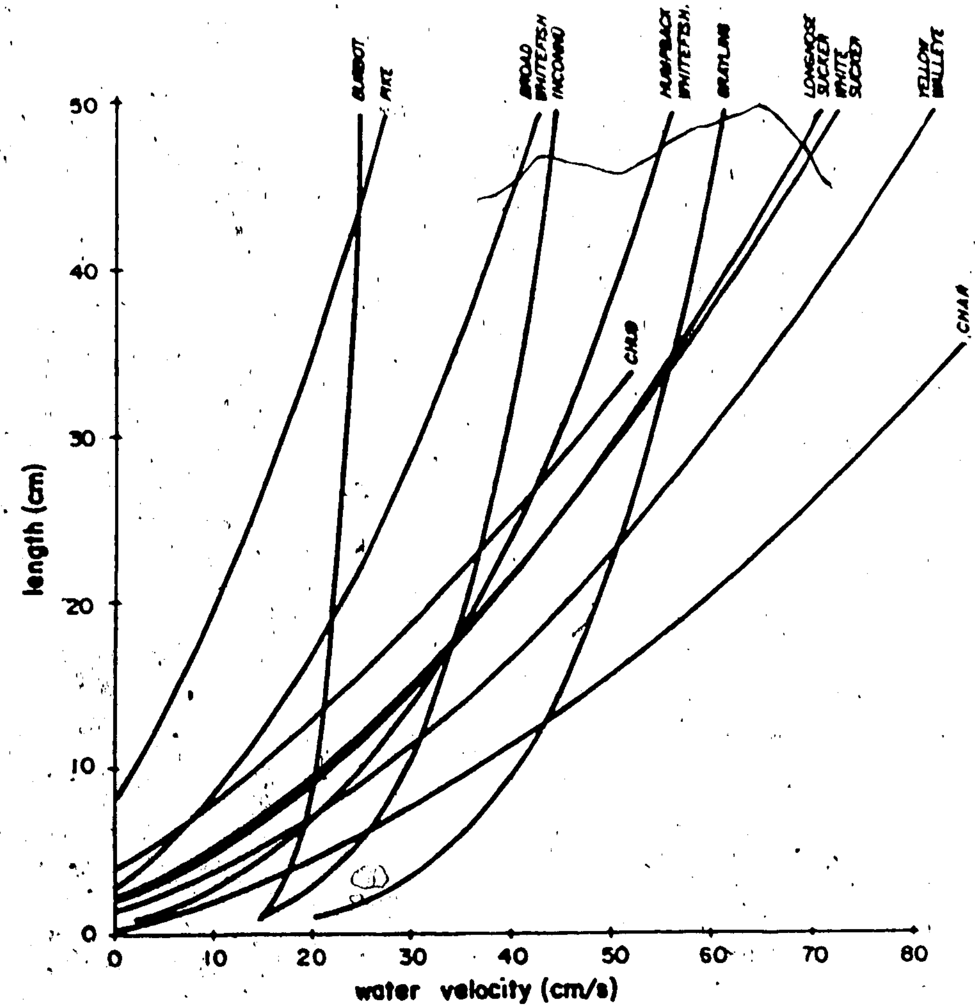


Figure 2.3 Relationship between fork length and ability to move 100 meters in 10 min in water velocities up to 80 cm/s for fish from the Mackenzie River. adapted from Jones, Kiceniuk, and Bamford, 1974)

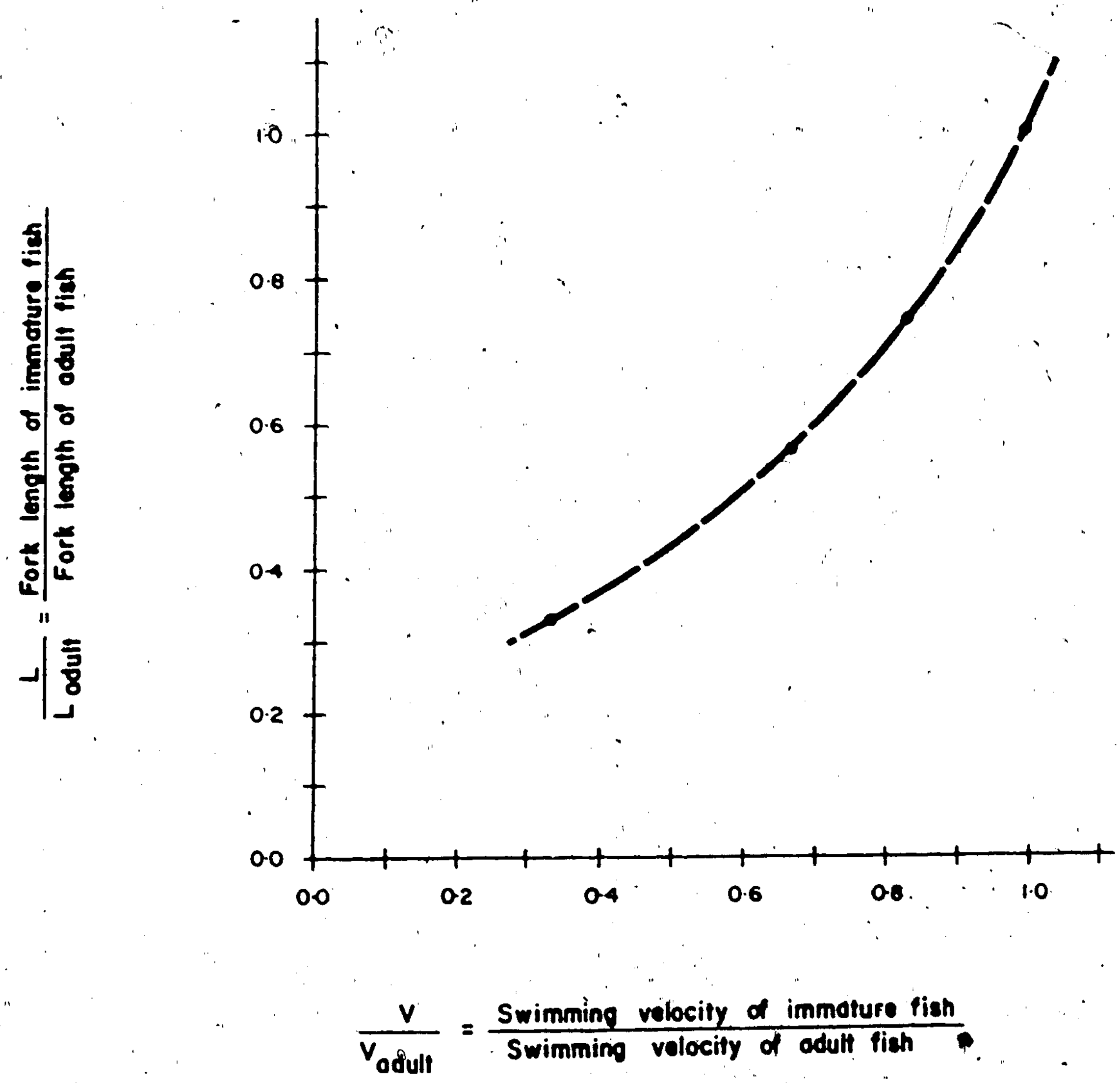


Figure 2.4 Relative swimming velocity versus relative length - length of fish based on Arctic grayling data. (adapted from Dane, 1978a)

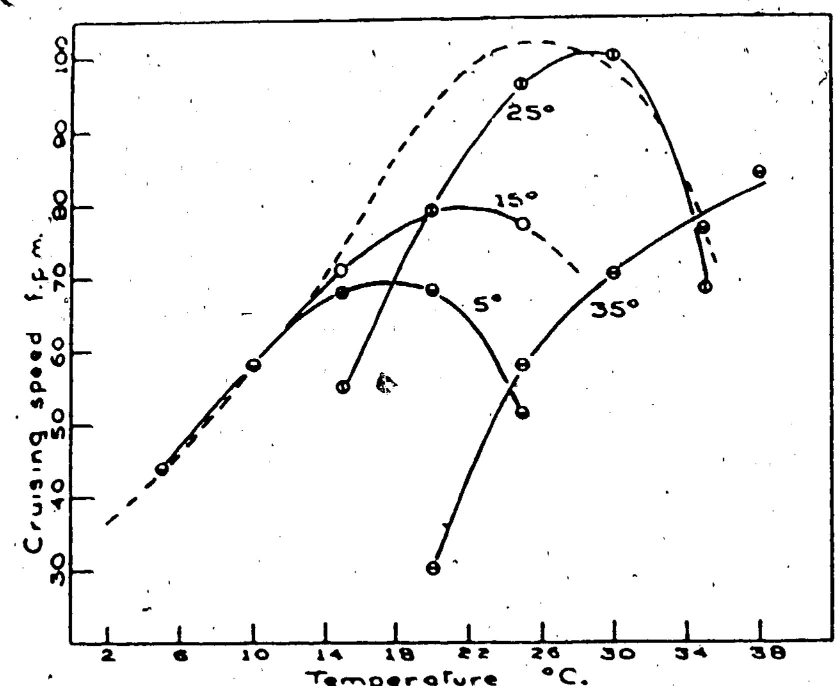


Figure 2.5 The relationship between temperature and sustained swimming rate in goldfish acclimated to various levels of temperature and tested at various other temperatures. (adapted from Fry and Hart, 1948)

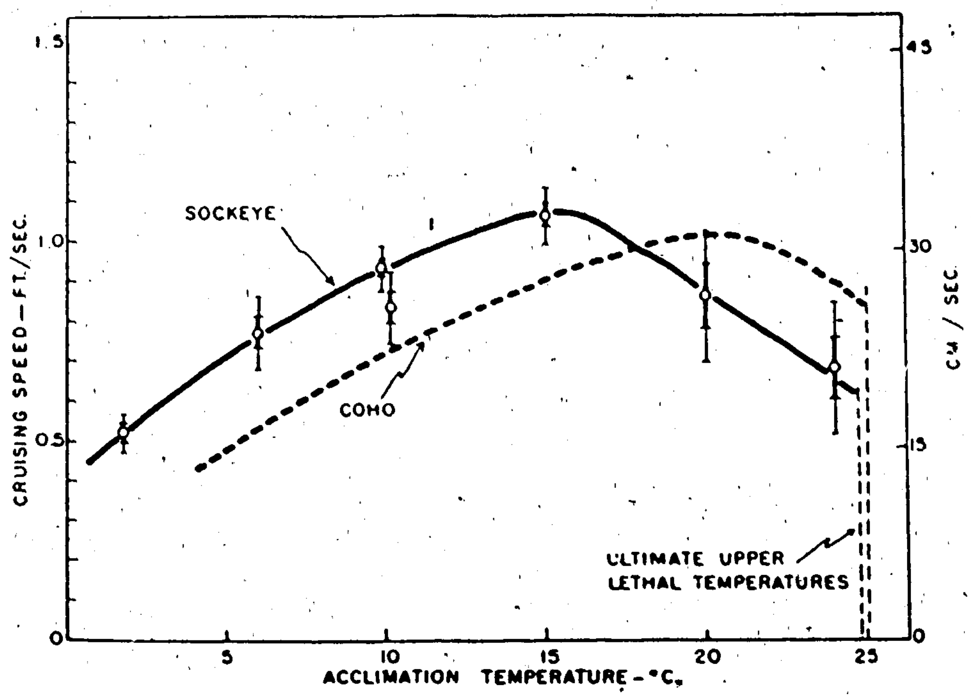


Figure 2.6 Variation in cruising speed for temperature acclimated underyearling sockeye and coho salmon. (adapted from Brett, Hollands and Alderdice, 1958)

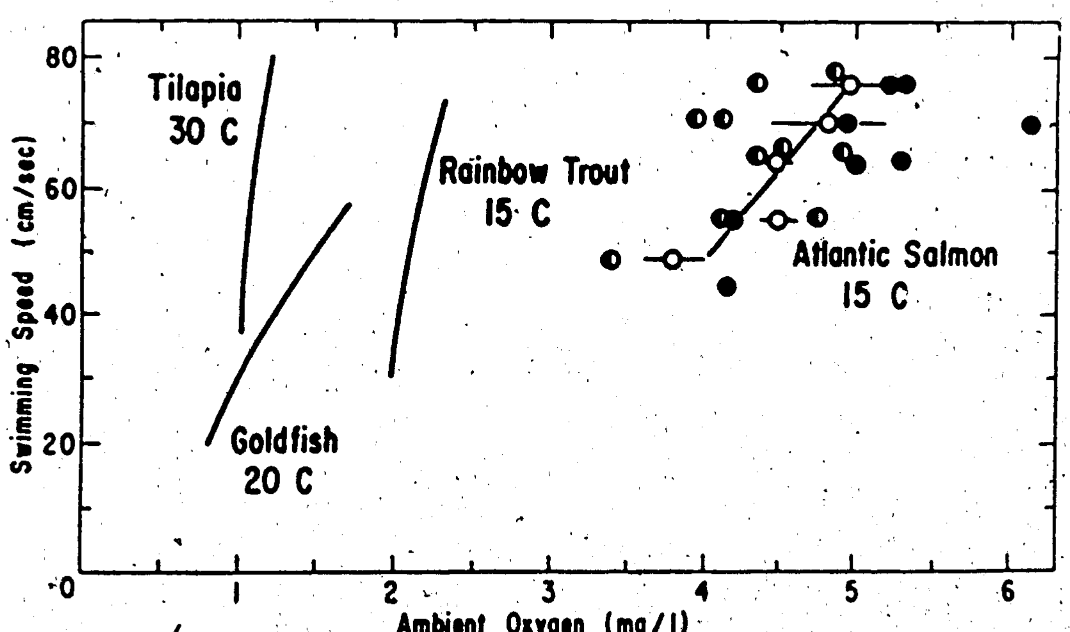


Figure 2.7 Sustained swimming performance in relation to ambient oxygen concentrations. (adapted from Kutty and Saunders, 1973)

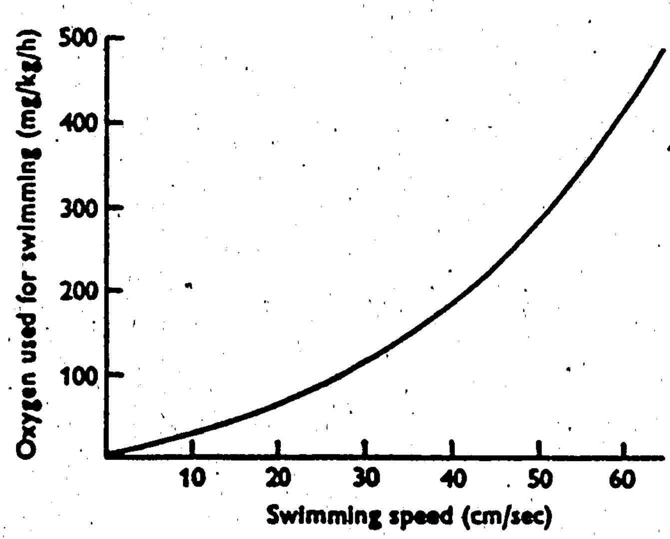


Figure 2.8 Oxygen consumption in relation to swimming speed. (adapted from Webb, 1971b)

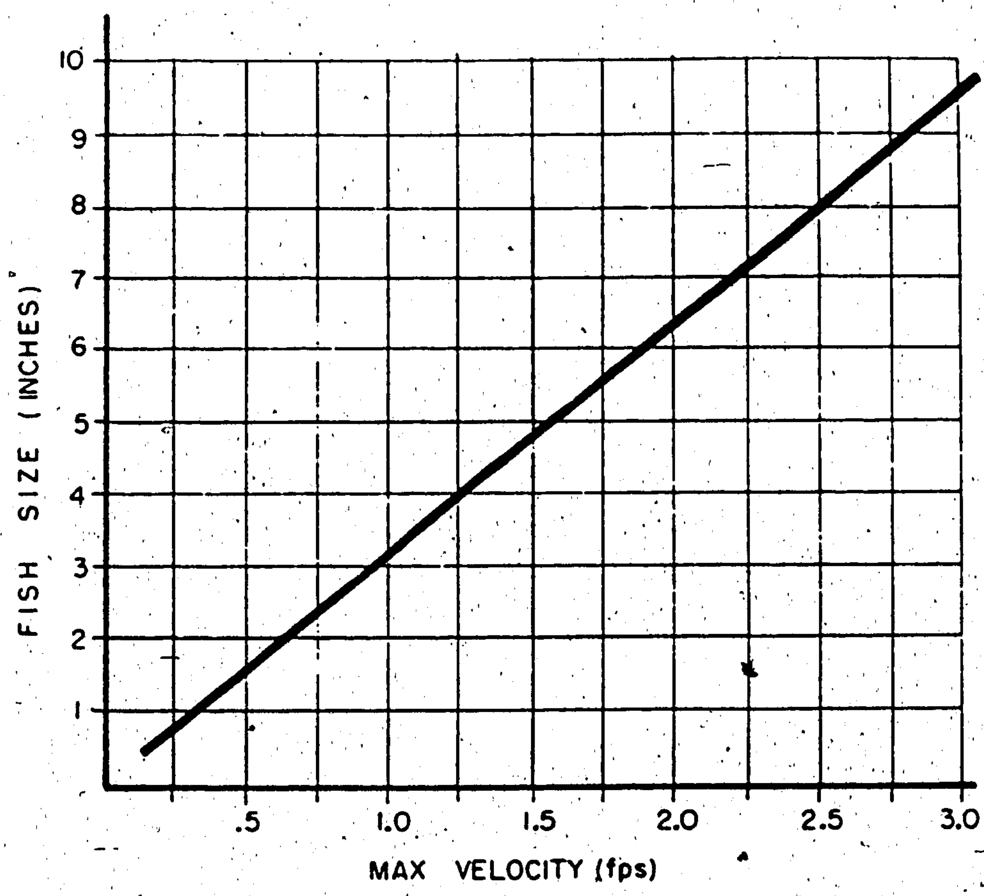


Figure 2.9 Recommended maximum velocities for upstream passage of juvenile salmonids. (adapted from Lauman, 1976)

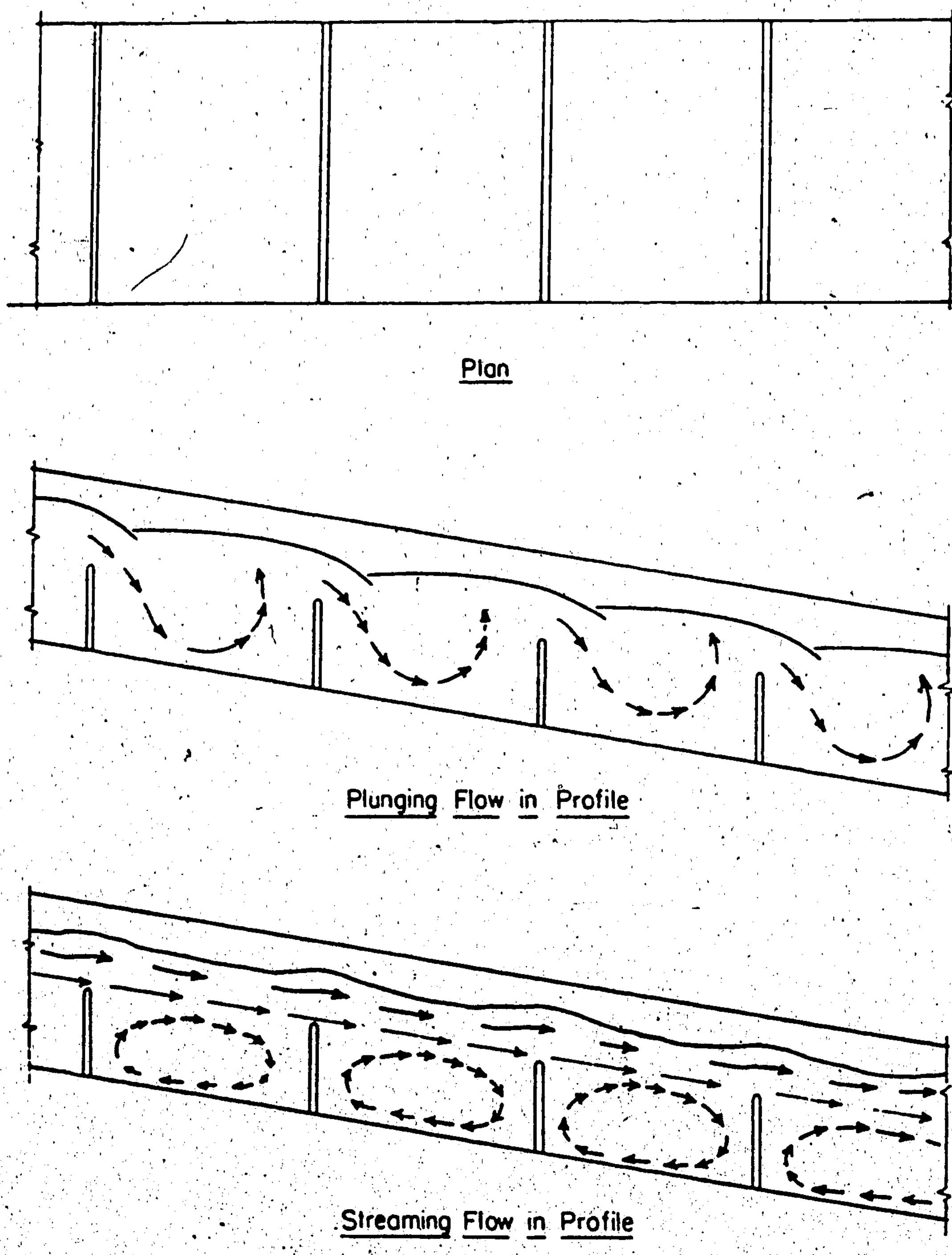


Figure 2.10 Vertical low barrier culvert baffles showing 'plunging' and 'streaming' flows. (adapted from Watts, 1974)

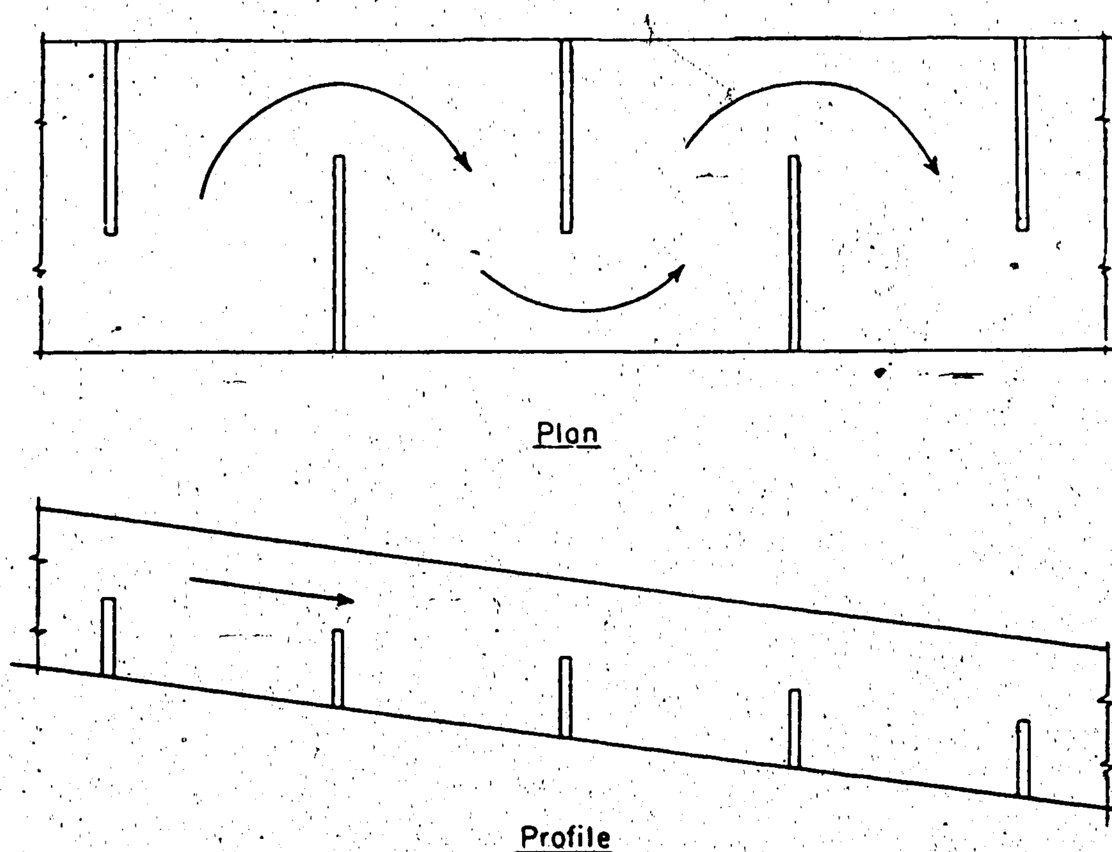


Figure 2.11 Alternate low barrier culvert baffles. (adapted from Watts, 1974)

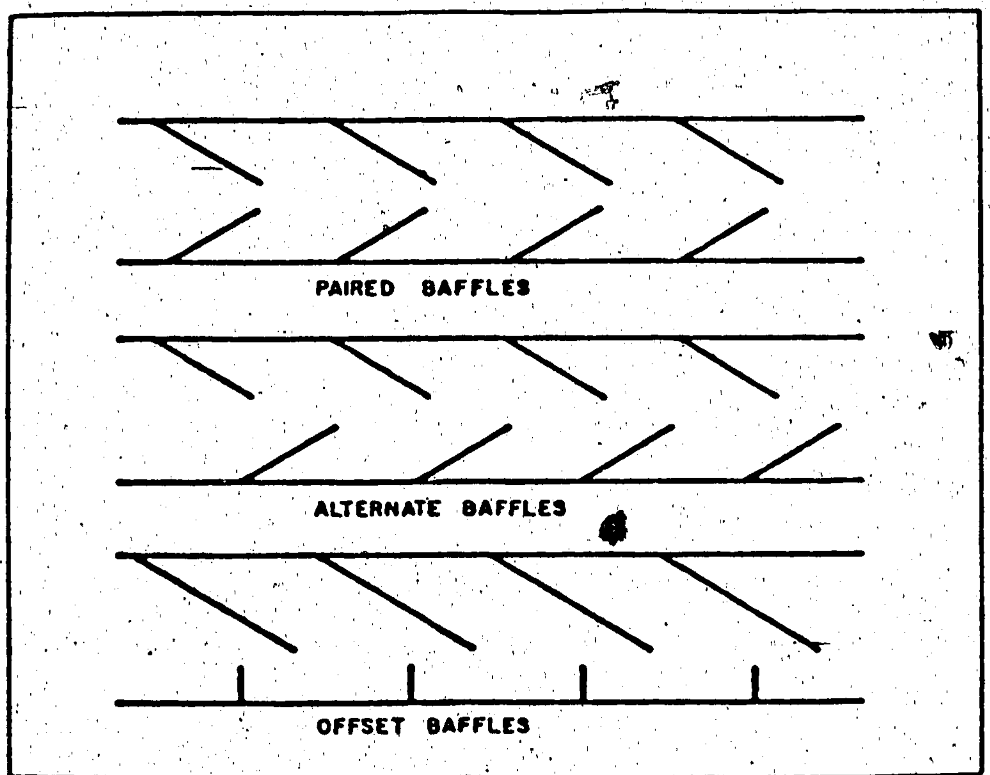


Figure 2.12 Paired and Alternate baffles (adapted from McKinley and Webb, 1956)

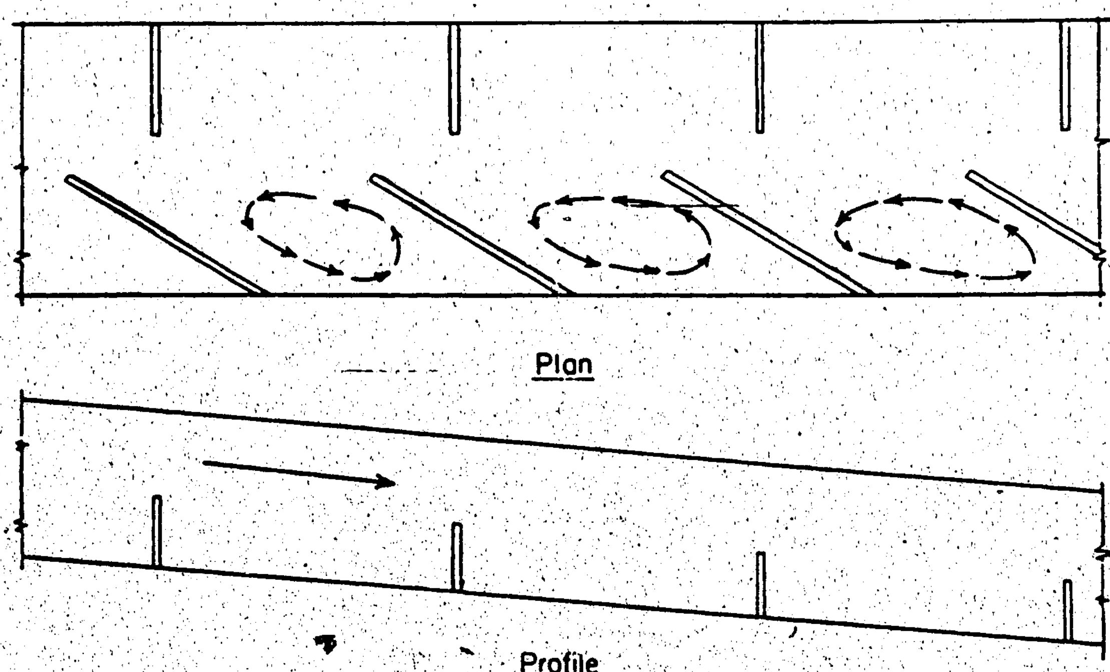


Figure 2.13 Offset baffles (adapted from Watts, 1974)

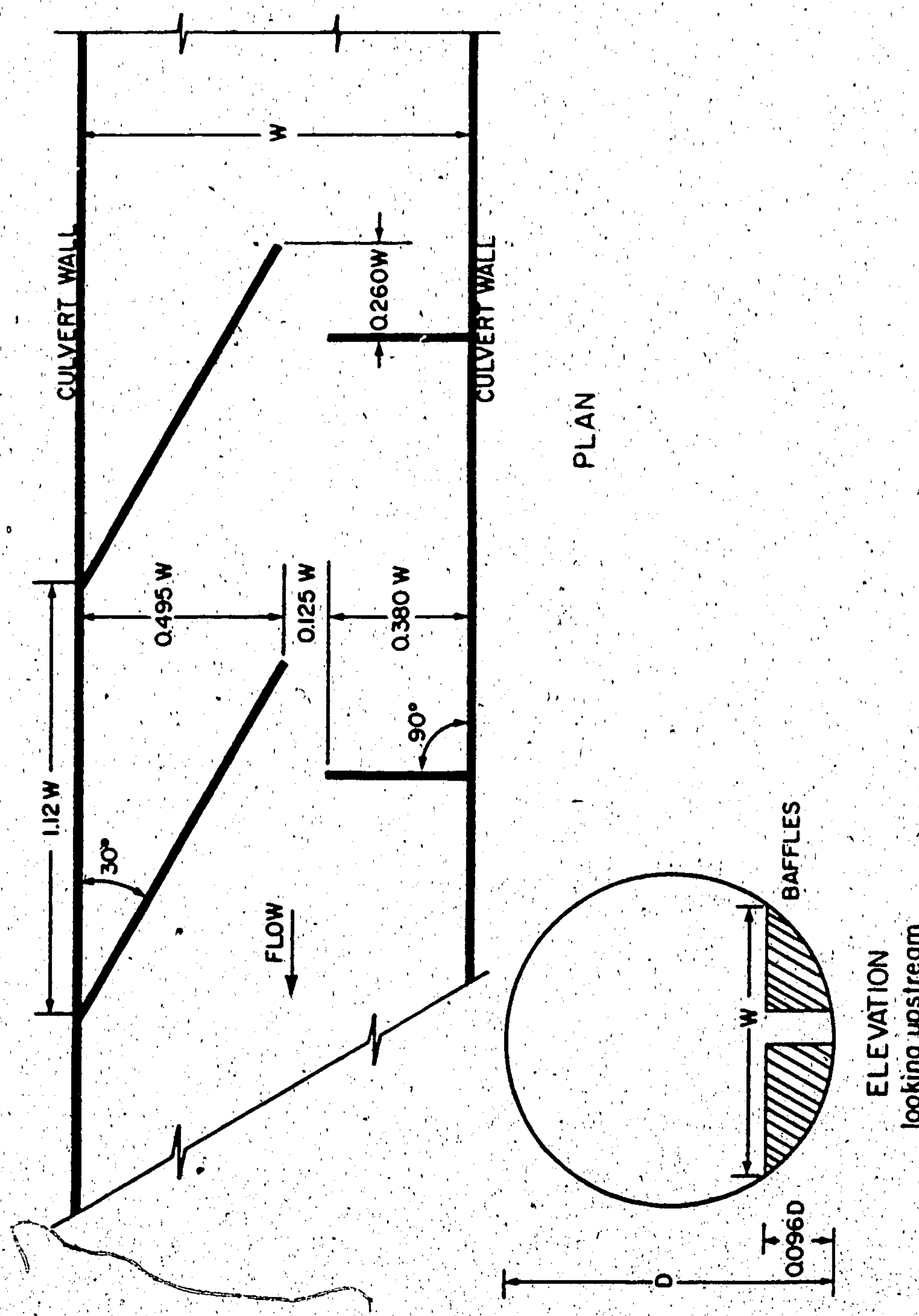


Figure 2.14 Offset baffles design dimensions (adapted from Katopodis, Robinson and Sutherland, 1978)

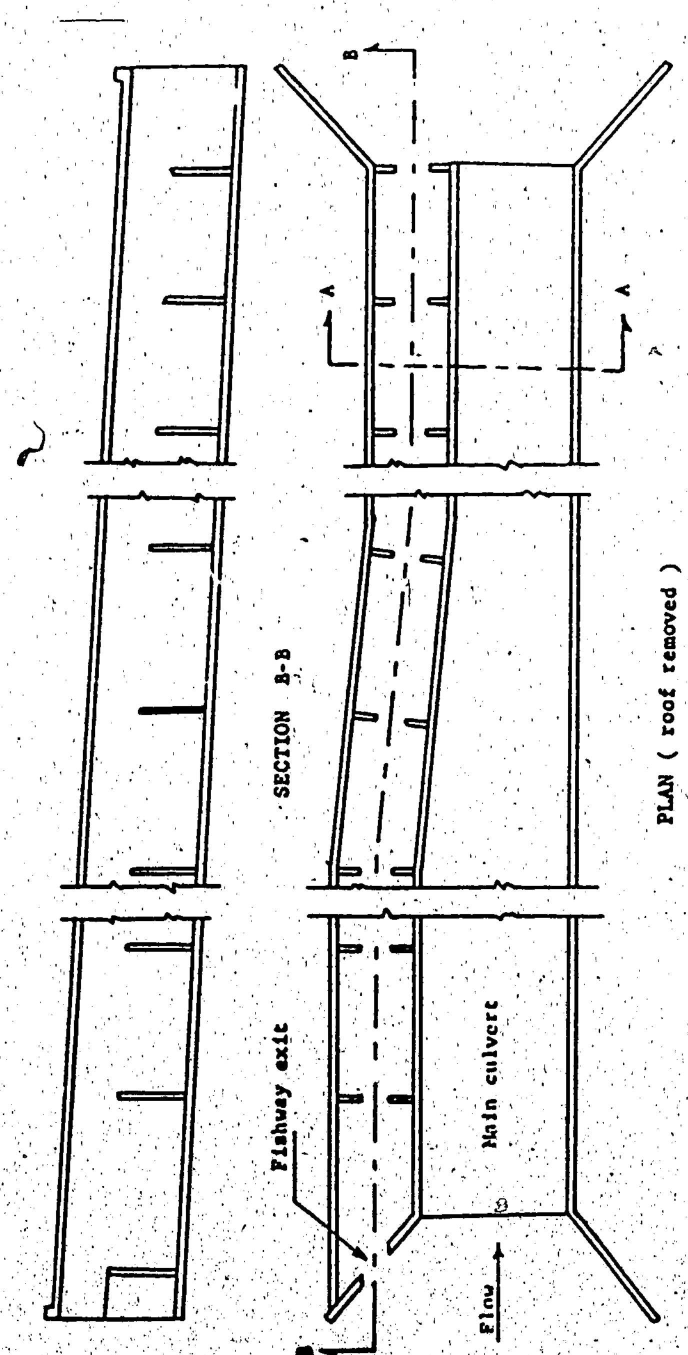


Figure 2.15 Slot Orifice Fishway. (adapted from Dass, 1970)

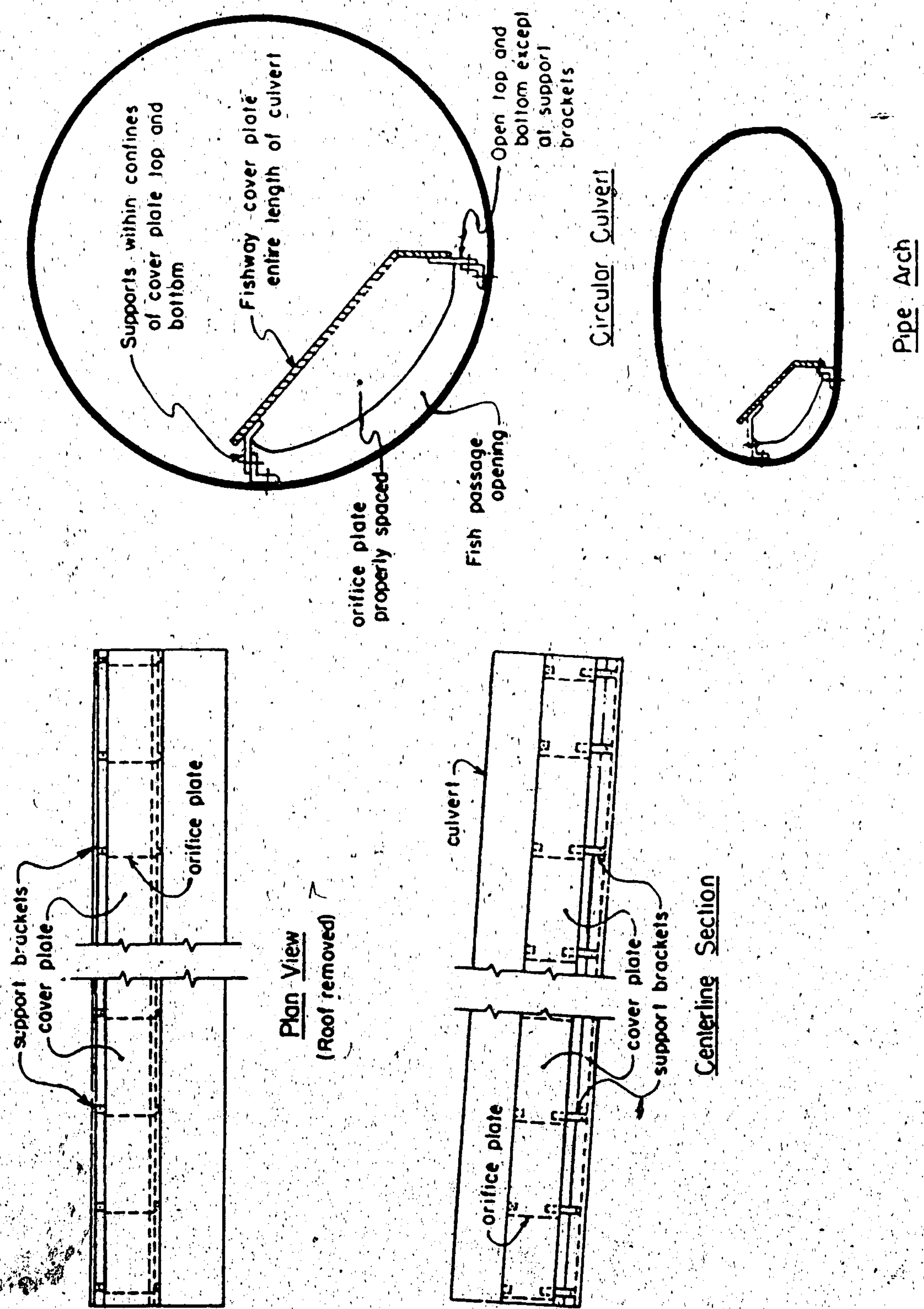


Figure 2.16 Proposed Orifice fishway for culverts or pipe arch. (adapted from Watts, 1974)

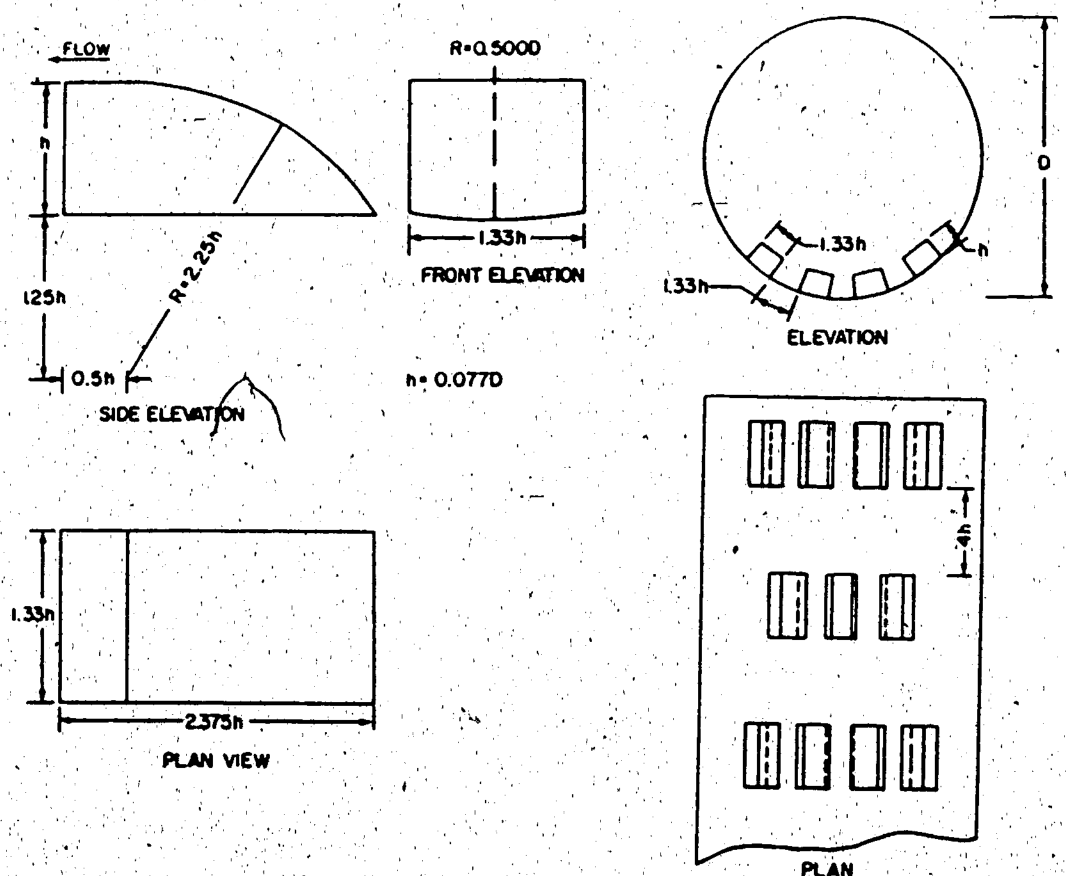


Figure 2.17 Spoiler baffles design dimensions. (adapted from Engel, 1974)

3. EXPERIMENTAL ARRANGEMENTS

3.1 Apparatus

Two culvert fishway designs were studied at the T. Blench Hydraulics Laboratory of the University of Alberta. To study the hydraulics of the fish-weirs, a 410 mm (16 inch) diameter culvert with a length of 6 m (approximately 20 feet) and helical corrugations with an amplitude of 13 mm and wave length of 65 mm and helix angle of 30^{o} was used. (It would have been more reasonable to use a pipe with corrugations running perpendicular to the length of the pipe but unfortunately we could not procure one in the present time frame of the project.) For studying the hydraulics of the (smaller) fish-baffles, this culvert had to be treated in a special way. This procedure is described in Chapter 4.

This culvert (pipe) was installed in a flume 0.5 m wide, 0.5 m deep and 8 m long. Water was supplied to the horizontal flume from an underground sump located at the downstream end of the flume by means of a pipe located in the pipeline leading from the sump to the head-tank located at the upstream end of the flume. Figure 3.1 shows a plan view of the flume with the culvert in place (Plate 3.1). At the downstream end of this flume, an adjustable tailgate was in place but was left in the down position as the experiments were to have no tailwater control. At the upstream end, the culvert projected into the head-tank which was provided with a horizontal piece of wood with holes cut out to keep the the water level in the head-tank stable and not surging. The slope of the flume was adjustable using a mobile hydraulic lift.

3.2 Hydrometric techniques

The water discharge through the culvert was measured by a magnetic flow meter located in the supply line. The depth of flow in the fishway models was measured with a point gauge of least count of 0.3 mm (0.001 feet). The velocity profiles were measured with a 3 mm external diameter Prandtl-type pitot-static tube which was connected to a manometer board where pressure head differences were measured.

The circulation patterns were obtained by using a dye-filled syringe and releasing the dye as a passive plume. Photographic records were made of most of the experiments.

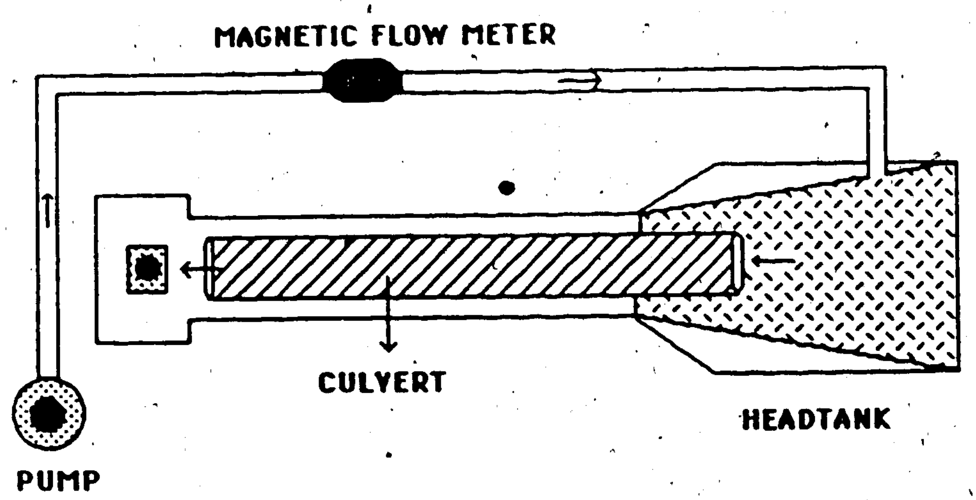


Figure 3.1 Plan-view of the Experimental Set-up.

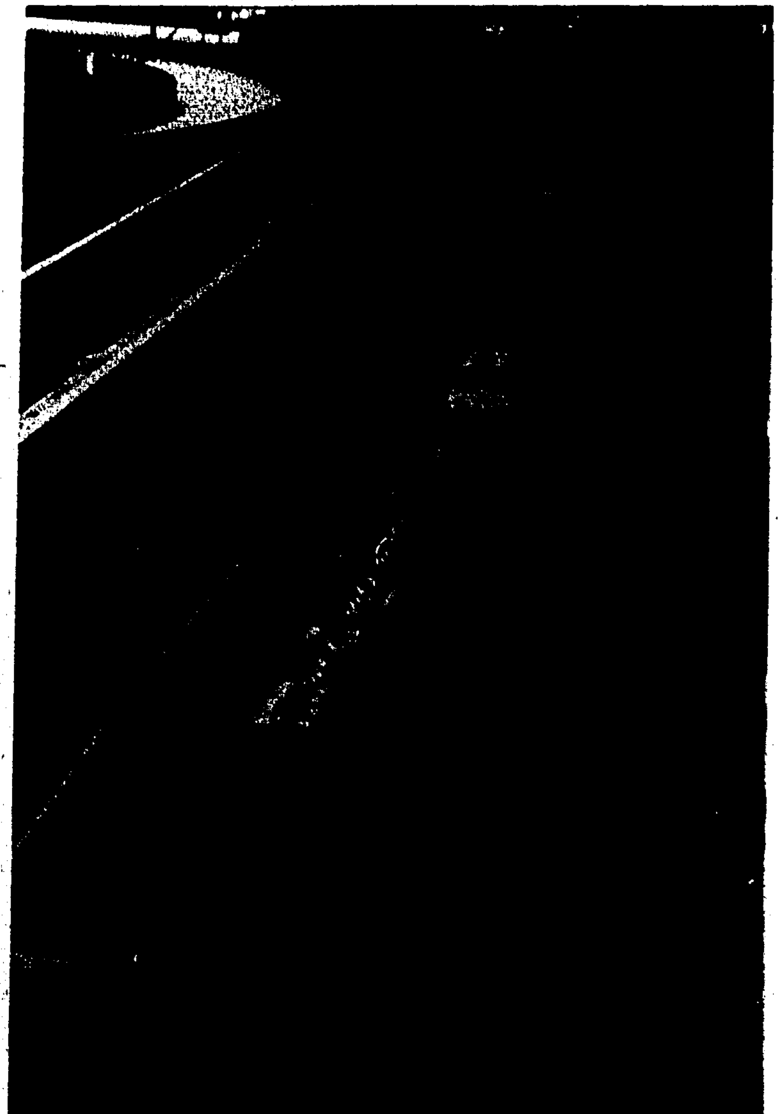


Plate 3.1 A View of the Experimental Arrangement.

4. EXPERIMENTS AND EXPERIMENTAL RESULTS

Tables 4.1 to 4.4 provide a summary of all experiments performed on the plain culverts and the two culvert fishway designs. A code system was designed to easily identify the different experiments performed. The first digit of the code describes the type of culvert (1 represents Culvert #1, 2 represents Culvert #2). The second digit of the code (0, 1, 2, 3, 4, 5, 6, 7) describes the type of culvert fishway design tested (0 represents plain culverts, 1, 2, 3, and 4 represent the fish-weir and 5, 6, and 7 represent the fish-baffles). For each of the seven designs tested, the model scale was fixed at 6.75. The third and forth digits denote the slope of the culvert (10, 30, 50 correspond to 1.0%, 3.0% and 5.0% respectively). The last three digits of the code represent the model discharge (350, 100, 025, 005 correspond to 35.0, 10.0, 2.5, and 0.5 L/s). The last letter denotes a qualitative description and was optional (p, u, v correspond to depth profile, velocity profile and visualization tests).

Since flow over the fish-weirs and fish-baffles will be predominantly a gravity-inertia type of flow, the main model criterion will be the Froude number:

$$F_o = V_o/\sqrt{gd_o} \qquad (1)$$

where V_o is the average velocity in the X direction in the plain culverts, g is the acceleration due to gravity, d_o is the hydraulic depth, equal to A_o/T, where A_o is the average area and T is the top width. Using the Froude similarity criterion, if L_r is the scale factor (i.e. the ratio of any prototype length to the corresponding model length), then the velocity ratio will be equal to

$$V_r = \sqrt{L_r} \tag{2}$$

and the discharge ratio will be equal to

$$Q_r = (L_r)^{2.5} \tag{3}$$

For this study the scale factor was 6.75 which was determined by dividing the prototype culvert diameter (108 inches) by the model culvert diameter (16 inches). Therefore, to calculate the prototype velocity, discharge and depth the following equations can be used in conjunction with equations 2 and 3:

$$u_P = u_M * \sqrt{L_r} \tag{4}$$

$$Q_P = Q_M * (L_r)^{2.5} \tag{5}$$

$$y_P = y_M * L_r \tag{6}$$

For example, given Q_M=0.5 L/s, u_M=0.40 m/s and y_M=1.9 cm: Calculate the prototype dicharge, velocity and depth using equations (4) to (6) when L_r=6.75:

$$Q_P = 0.5 * (6.75)^{2.5}$$
$$= 0.5 * 118.4$$
$$= 59.2 \text{ L/s}$$

$$u_P = 0.40 * \sqrt{6.75}$$
$$= 0.40 * 2.60$$
$$= 1.04 \text{ m/s}$$

$$y_P = 1.9 * (6.75)$$
$$= 12.8 \text{ cm}$$

All data refer to the models or unless otherwise indicated but can be converted to prototype using the above Froudian similitude criterion.

4.1 Plain culvert #1

Tests on a plain 410 mm (16 in) diameter culvert with helical corrugations were performed. A total of 23 tests were performed with culvert slopes of 5, 3, 2, 1, and 0.5 percent and model discharges ranging from 17 to 68 L/s. The model Manning 'n' was calculated based on Manning's equation

$$n = \frac{A_o R_h^{2/3} S_o^{1/2}}{Q} \tag{7}$$

where A_o is the area of flow, R_h is the hydraulic radius, equal to A_o/P_w, where P_w is the wetted perimeter, S_o is the slope and Q is the model discharge. The model Manning 'n' was found to vary with the slope ranging from 0.014 to 0.024 and this variation is shown in Figure 4.1.

If y_o is the (centerline) depth of uniform flow and if V_o is the mean velocity of uniform flow, the variation of y_o and V_o with the (model) flow rate Q (in L/s) for different slopes are shown respectively in Figures 4.2 and 4.3. These figures also contain some calculated values, especially for very small flow rates. The uniform flow depth y_o and mean velocity V_o are used respectively as depth and velocity scales (later) in assessing the hydraulic performance of the fish-weirs. Table 4.1 presents the experimental results on the plain culvert in detail.

In Table 4.1, A_o is the area of flow, T is the water surface width, d_o is the hydraulic depth, equal to A_o/T and F_o is the Froude number. It can be seen that for slopes of 3% and 5%, for all the runs, the flow was supercritical whereas for the runs with 1% slope, F_o varied from about 0.77 to 0.96.

4.2 Fish-weirs: designs 1-4

An end-view of the fish-weir used in designs 1-4 is shown in Figure 4.4 and Plate 4.1. It has a thickness (in the flow direction) of 65 mm. The longitudinal spacing L (from center to center) of the fish-weirs was respectively 980, 490, 245 and 735 mm for the designs 1 to 4. These four designs were tested for slopes of 1, 3, and 5% and for model discharges ranging from 0.5 to 35.0 L/s. The four discharges studied (Q=35.0, 10.0, 2.5, and 0.5 L/s) were chosen after qualitiative visualization of the flows in the fish-weir model for the first design and were continued for all designs for comparison purposes:

1. Q=35.0 L/s - the fish-weirs were completely submerged and was chosen to represent flooding conditions.
2. Q=10.0 L/s - the depth of flow over the fish-weirs averaged around 6 centimeters.
3. Q=2.5 L/s - the flow was concentrated through the central portion of the fish-weir but the depth of flow did reach the high sections of the fish-weirs.

4. Q=0.5 L/s - the flow was concentrated through the central portion of the fish-weirs.

For each of these experiments, a reach near the center-part of the culvert was identified as a region of fully-developed flow and this reach was free from the inlet and exit effects. In this region, a length roughly equal to the spacing L, located symmetrically on either side of a fish-weir (located in this region) was chosen for detailed measurement (Figure 4.5) and is referred to as a cell.

In this cell, the water surface profile along the centerline was measured. In addition, at a number of stations (indicated in Figure 4.5) the u(y) velocity profile (wherein u is the time-averaged turbulent axial velocity at a normal distance of y above the datum (located between the crest and trough of the corrugations)) was measured using a Prandtl-type pitot-static tube of external diameter of 3 millimeters. Detailed plots and the data for the depth and velocity profiles are available in the report by Rajaratnam, Fairbairn and Katopodis (1986). Table 4.2 presents the summarized experimental results for the fish-weirs in detail.

4.3 Plain culvert #2

The corrugated pipe which housed the fish-weir designs presented a problem in that the height of the corrugations (13 mm) was comparable to the (model) height of the fish-baffles (28 mm). Hence, it was decided to fill the corrugations in the bottom part of the test pipe (up to the bottom level of the baffles) with cement mortar (see Plates 4.2 and 4.3). This made it necessary to run some tests to find the modified Manning 'n' of this altered pipe. The results for 'n' are shown in Figure 4.6 and great variation can be seen due to the effects of the mortar.

The variation of y_o and V_o with the flow rate Q were calculated for the three slopes of 1, 3, and 5% and are shown in Figures 4.7 and 4.8 respectively. These figures also show some calculated values, especially for very small discharges. The uniform flow depth y_o and mean velocity V_o are used respectively as depth and velocity scales (later) in assessing the hydraulic performance of the fish-baffles. Table 4.3 presents the experimental results for Culvert #2.

4.4 Fish-baffles: designs 5-7

The fish-baffles that were tested are shown in Figure 4.9. These were arranged in a special staggered pattern as indicated in Figure 4.10, L is only half the wave-length or spacing and L* = 2L is the correct wave-length. The fish-baffles were studied for the three spacings of L* = 1.176, 588 and 388 mm.

Experiments were performed with fish-baffle designs 5 to 7 in which the water surface profile along the centerline of the culvert was measured for approximately a full cell (-0.5 - x/L* - +0.5). Profiles of u(y) were measured at a number of verticals along the centerline as well as at a couple of stations in the slot between the baffles (indicated in Figure 4.10) {denoted by a z value in the data tables}. Detailed water surface and velocity profiles and data are available in the report by Rajaratnam, Fairbairn and Katopodis (1986).

Table 4.1 Experimental Results from Culvert #1.

CODE	S_o (%)	Q (m^3/s)	y_o (cm)	A_o (m^2)	T (m)	V_o (m/s)	d_o (cm)	n	F_o
1010350	1	0.035	13.3	0.037	0.381	0.94	9.7	0.019	0.964
1010100	1	0.010	7.2	0.015	0.310	0.65	4.8	0.019	0.944
1010025	1	0.0025	3.7	0.0058	0.234	0.43	2.5	0.019	0.872
1010005	1	0.0005	1.7	0.0019	0.163	0.26	1.2	0.019	0.768
1030350	3	0.035	11.0	0.027	0.361	1.3	7.5	0.021	1.518
1030100	3	0.010	5.7	0.011	0.282	0.90	3.9	0.021	1.456
1030025	3	0.0025	3.0	0.0042	0.213	0.59	2.0	0.021	1.340
1030005	3	0.0005	1.4	0.0014	0.148	0.36	0.94	0.021	1.183
1050350	5	0.035	9.9	0.025	0.349	1.42	7.2	0.024	1.694
1050100	5	0.010	5.4	0.0103	0.276	0.97	3.7	0.024	1.603
1050025	5	0.0025	2.8	0.0039	0.206	0.64	1.9	0.024	1.485
1050005	5	0.0005	1.3	0.0013	0.143	0.39	0.91	0.024	1.306

Table 4.2 Experimental Results for Culvert Fish-weir Designs: #1, #2, #3 and #4.

CODE	So (%)	Q (m3/s)	Fo	L (cm)	x/L	y (cm)	y/yo	um (m/s)	um/Vo
1110350	1	0.035	0.964	98.5	-0.46	15.7	1.2	0.82	0.9
					-0.38	16.2	1.2	0.82	0.9
					-0.30	15.8	1.2	0.78	0.8
					-0.09	15.9	1.2	0.77	0.8
					-0.05	15.9	1.2	0.85	0.9
					0.00	15.7	1.2	1.00	1.1
					0.05	14.6	1.1	1.00	1.1
					0.08	14.2	1.1	1.01	1.1
					0.12	14.0	1.1	0.99	1.1
					0.16	13.1	1.0	1.01	1.1
					0.24	13.8	1.0	0.98	1.0
					0.31	15.9	1.2	0.91	1.0
1110350	1	0.035	0.964	98.5	0.39	15.8	1.2	0.86	0.9
1210350	1	0.035	0.964	49.3	-0.22	17.2	1.3	0.81	0.8
					-0.18	17.2	1.3	0.79	0.8
					-0.14	17.0	1.3	0.82	0.9
					-0.10	16.8	1.3	0.88	0.9
					-0.06	16.6	1.3	0.90	1.0
					0.00	16.1	1.2	0.90	1.0
					0.10	15.8	1.2	0.94	1.0
					0.13	15.5	1.2	0.94	1.0
					0.16	15.3	1.2	0.96	1.0
					0.24	15.2	1.1	0.93	1.0
					0.32	14.8	1.1	0.93	1.0
1210350	1	0.035	0.964	49.3	0.40	15.1	1.1	0.92	1.0
1310350	1	0.035	0.964	24.6	-0.44	16.6	1.2	0.88	0.9
					-0.37	16.7	1.3	0.88	0.9
					-0.28	16.7	1.3	0.88	0.9
					-0.21	16.6	1.2	0.88	0.9
					-0.13	16.8	1.3	0.89	0.9
					0.00	16.8	1.3	0.90	1.0
					0.19	16.4	1.2	0.89	0.9
					0.26	16.6	1.2	0.89	0.9
					0.33	16.4	1.2	0.89	0.9
					0.44	16.3	1.2	0.89	0.9
1310350	1	0.035	0.964	24.5	0.48	16.5	1.2	0.88	0.9
1410350	1	0.035	0.964	73.9	-0.45	15.8	1.2	0.81	0.9
					-0.33	16.4	1.2	0.80	0.9
					-0.15	16.0	1.2	0.79	0.8
					-0.09	15.7	1.2	0.82	0.9
					-0.04	15.6	1.2	0.90	1.0
					0.00	15.8	1.2	0.94	1.0
					0.09	14.9	1.1	0.91	1.0
					0.16	14.8	1.1	0.91	1.0
					0.21	14.2	1.1	0.92	1.0
					0.32	14.9	1.1	0.85	0.9
1410350	1	0.035	0.964	73.9	0.42	16.2	1.2	0.81	0.9

CODE	So (%)	Q (m3/s)	Fo	L (cm)	x/L	y (cm)	y/yo	um (m/s)	um/Vo
1110100	1	0.010	0.944	98.5	-0.46	9.4	1.3	0.50	0.8
					-0.38	9.8	1.4	0.48	0.7
					-0.30	9.8	1.4	0.46	0.7
					-0.09	10.2	1.4	0.44	0.7
					-0.05	10.0	1.4	0.52	0.8
					0.00	9.4	1.3	0.71	1.1
					0.05	8.2	1.1	0.75	1.2
					0.08	7.4	1.0	0.79	1.2
					0.12	7.3	1.0	0.78	1.2
					0.16	8.1	1.1	0.67	1.0
					0.24	9.0	1.3	0.57	0.9
					0.31	9.3	1.3	0.55	0.8
1110100	1	0.010	0.944	98.5	0.39	9.3	1.3	0.50	0.8
1210100	1	0.010	0.944	49.3	-0.22	10.7	1.5	0.53	0.8
					-0.18	10.5	1.5	0.51	0.8
					-0.14	10.5	1.5	0.54	0.8
					-0.10	10.5	1.5	0.58	0.9
					-0.06	10.4	1.5	0.63	1.0
					0.00	9.7	1.4	0.65	1.0
					0.10	9.6	1.3	0.68	1.1
					0.13	9.5	1.3	0.68	1.1
					0.16	9.5	1.3	0.67	1.0
					0.24	9.8	1.4	0.61	0.9
					0.32	10.3	1.4	0.56	0.9
1210100	1	0.010	0.944	49.3	0.40	10.4	1.5	0.55	0.9
1310100	1	0.010	0.944	24.6	-0.44	10.2	1.4	0.62	1.0
					-0.37	10.7	1.5	0.62	1.0
					-0.28	10.9	1.5	0.60	0.9
					-0.21	10.8	1.5	0.61	0.9
					-0.13	10.5	1.5	0.63	1.0
					0.00	9.9	1.4	0.71	1.1
					0.19	9.1	1.3	0.75	1.2
					0.26	9.1	1.3	0.76	1.2
					0.33	9.1	1.3	0.71	1.1
					0.44	9.2	1.3	0.69	1.1
1310100	1	0.010	0.944	24.6	0.48	9.8	1.4	0.63	1.0
1410100	1	0.010	0.944	73.9	-0.45	9.8	1.4	0.57	0.9
					-0.33	9.9	1.4	0.53	0.8
					-0.15	10.2	1.4	0.52	0.8
					-0.09	10.2	1.4	0.53	0.8
					-0.04	10.1	1.4	0.67	1.0
					0.00	9.5	1.3	0.70	1.1
					0.09	8.4	1.2	0.79	1.2
					0.16	8.6	1.2	0.77	1.2
					0.21	9.4	1.3	0.63	1.0
					0.32	9.3	1.3	0.64	1.0
1410100	1	0.010	0.944	73.9	0.42	9.9	1.4	0.59	0.9

Table 4.2 Continued...

CODE	So (%)	Q (m3/s)	Fo	L (cm)	x/L	y (cm)	y/yo	um (m/s)	um/Vo
1110025	1	0.0025	0.872	98.5	-0.46	6.0	1.6	0.22	0.5
					-0.35	6.5	1.8	0.21	0.5
					-0.30	6.6	1.8	0.21	0.5
					-0.09	6.8	1.8	0.17	0.4
					-0.05	6.8	1.8	0.26	0.6
					0.00	6.1	1.6	0.52	1.2
					0.05	4.9	1.3	0.63	1.5
					0.08	4.5	1.2	0.65	1.5
					0.12	5.6	1.5	0.57	1.3
					0.16	5.3	1.4	0.49	1.1
					0.24	5.6	1.5	0.41	1.0
					0.31	6.0	1.6	0.34	0.8
1110025	1	0.0025	0.872	98.5	0.39	6.0	1.6	0.31	0.7
1210025	1	0.0025	0.872	49.3	-0.22	7.3	2.0	0.28	0.7
					-0.18	7.2	[illegible]	0.28	0.7
					-0.14	7.1	[illegible]	0.29	0.7
					-0.10	7.1	1.9	0.33	0.8
					-0.06	7.0	1.9	0.44	1.0
					0.00	6.3	1.7	0.46	1.1
					0.10	6.4	1.7	0.42	1.0
					0.13	6.6	1.8	0.40	0.9
					0.16	6.9	1.9	0.40	0.9
					0.24	6.6	1.8	0.41	1.0
					0.32	6.7	1.8	0.37	0.9
1210025	1	0.0025	0.872	49.3	0.40	6.9	1.9	0.33	0.8
1310025	1	0.0025	0.872	24.6	-0.44	6.7	1.8	0.41	1.0
					-0.37	6.8	1.8	0.41	1.0
					-0.28	6.8	1.8	0.39	0.9
					-0.21	6.9	1.9	0.41	1.0
					-0.13	6.8	1.8	0.43	1.0
					0.00	6.4	1.7	0.46	1.1
					0.19	6.8	1.8	0.39	0.9
					0.26	6.8	1.8	0.39	0.9
					0.33	6.8	1.8	0.40	0.9
					-0.44	6.7	1.8	0.39	0.9
1310025	1	0.0025	0.872	24.6	0.48	7.0	1.9	0.37	0.9
1410025	1	0.0025	0.872	73.9	-0.45	6.2	1.7	0.28	0.7
					-0.33	6.3	1.7	0.27	0.6
					-0.15	6.6	1.8	0.2[illegible]	0.6
					-0.08	6.6	1.8	0.29	0.7
					-0.04	6.4	1.7	0.45	1.0
					0.00	5.7	1.5	0.55	1.3
					0.08	5.1	1.4	0.52	1.2
					0.16	6.0	1.6	0.52	1.1
					0.21	5.2	1.4	0.47	1.1
					0.32	5.7	1.5	0.46	1.1
1410025	1	0.0025	0.872	73.9	0.42	6.2	1.7	0.37	0.9

CODE	So (%)	Q (m3/s)	Fo	L (cm)	x/L	y (cm)	y/yo	um (m/s)	um/Vo
1110005	1	0.0005	0.768	98.5	-0.46	4.1	2.4	0.06	0.2
					-0.38	4.5	2.6	0.05	0.2
					-0.30	4.5	2.6	0.05	0.2
					-0.09	4.8	2.8	0.05	0.2
					-0.05	4.8	2.8	0.03	0.1
					0.00	3.8	2.2	0.27	1.0
					0.08	3.2	1.9	0.35	1.4
					0.12	3.6	2.1	0.24	0.9
					0.16	3.3	1.9	0.21	0.8
					0.24	3.6	2.1	0.20	0.8
					0.31	4.0	2.3	0.17	0.7
1110005	1	0.0005	0.768	98.5	0.39	4.1	2.4	0.15	0.6
1210005	1	0.0005	0.768	49.3	-0.22	4.1	2.4	0.25	1.0
					-0.18	4.0	2.3	0.26	1.0
					-0.14	4.1	2.4	0.27	1.0
					-0.10	4.1	2.4	0.28	1.1
					-0.06	4.0	2.3	0.32	1.2
					0.00	3.7	2.2	0.34	1.3
					0.10	3.7	2.2	0.34	1.3
					0.13	3.7	2.2	0.33	1.3
					0.16	3.7	2.2	0.33	1.3
					0.24	3.9	2.3	0.32	1.2
					0.32	3.7	2.2	0.28	1.1
1210005	1	0.0005	0.768	49.3	0.40	4.0	2.3	0.26	1.0
1310005	1	0.0005	0.768	24.6	-0.44	3.7	2.2	0.29	1.1
					-0.37	3.7	2.2	0.27	1.0
					0.19	3.7	2.2	0.24	0.9
					0.26	3.6	2.1	0.24	0.9
					0.33	3.7	2.2	0.24	0.9
					0.44	3.6	2.1	0.26	1.0
1310005	1	0.0005	0.768	24.6	0.48	3.8	2.2	0.26	1.0
1410005	1	0.0005	0.768	73.9	-0.45	2.9	1.7	0.22	0.8
					-0.33	3.0	1.7	0.22	0.8
					-0.15	3.3	1.9	0.23	0.9
					-0.10	3.3	1.9	0.23	0.9
					0.09	2.5	1.5	0.22	0.9
					0.16	2.8	1.6	0.22	0.8
					0.21	2.4	1.4	0.22	0.8
					0.32	2.7	1.6	0.21	0.8
1410005	1	0.0005	0.768	73.9	0.42	3.1	1.8	0.21	0.8

Table 4.2 Continued...

CODE	So (%)	Q (m3/s)	Fo	L (cm)	x/L	y (cm)	y/yo	um (m/s)	um/Vo
1130350	3	0.035	1.518	98.5	-0.46	12.0	1.1	1.27	1.0
					-0.38	12.4	1.1	1.22	0.9
					-0.30	12.5	1.1	1.16	0.9
					-0.08	14.8	1.3	0.87	0.7
					-0.05	14.7	1.3	1.14	0.9
					0.00	14.0	1.3	1.29	1.0
					0.05	13.5	1.0	1.27	1.0
					0.08	13.0	1.2	1.30	1.0
					0.12	12.4	1.1	1.28	1.0
					0.16	11.3	1.0	1.25	1.0
					0.24	11.3	1.0	1.28	1.0
					0.31	11.8	1.1	1.28	1.0
1130350	3	0.035	1.518	98.5	0.39	12.0	1.1	1.35	1.0
1230350	3	0.035	1.518	49.3	-0.22	15.1	1.4	1.07	0.8
					-0.18	15.0	1.4	1.02	0.8
					-0.14	15.2	1.4	1.02	0.8
					-0.10	15.2	1.4	1.02	0.8
					-0.06	15.1	1.4	1.13	0.9
					0.00	14.6	1.3	1.12	0.9
					0.10	14.0	1.3	1.08	0.8
					0.13	13.3	1.2	1.11	0.9
					0.16	12.8	1.2	1.10	0.9
					0.24	12.3	1.1	1.14	0.9
					0.32	11.3	1.0	1.18	0.9
1230350	3	0.035	1.518	49.3	0.40	11.4	1.0	1.22	0.9
1330350	3	0.035	1.518	24.6	-0.44	13.6	1.2	1.20	0.9
					-0.37	13.5	1.2	1.21	0.9
					-0.28	13.7	1.2	1.22	0.9
					-0.21	13.7	1.2	1.25	1.0
					-0.13	13.7	1.2	1.21	0.9
					0.00	13.9	1.3	1.21	0.9
					0.19	13.9	1.3	1.21	0.9
					0.26	13.8	1.3	1.21	0.9
					0.33	14.0	1.3	1.23	0.9
					0.44	13.8	1.3	1.23	0.9
1330350	3	0.035	1.518	24.6	0.48	14.0	1.3	1.17	0.9
1430350	3	0.035	1.518	73.9	-0.45	11.6	1.1	1.19	0.9
					-0.33	12.8	1.2	1.13	0.9
					-0.15	13.7	1.2	1.03	0.8
					-0.09	14.1	1.3	1.10	0.8
					-0.04	13.7	1.2	1.27	1.0
					0.00	13.6	1.2	1.26	1.0
					0.09	12.3	1.1	1.25	1.0
					0.16	11.4	1.0	1.27	1.0
					0.21	10.4	0.9	1.26	1.0
					0.32	10.3	0.9	1.19	0.9
1430350	3	0.035	1.518	73.9	0.42	11.3	1.0	1.17	0.9

CODE	So (%)	Q (m3/s)	Fo	L (cm)	x/L	y (cm)	y/yo	um (m/s)	um/Vo
1130100	3	0.010	1.456	98.5	-0.46	8.2	1.4	0.68	0.8
					-0.38	9.0	1.6	0.58	0.6
					-0.30	9.2	1.6	0.59	0.7
					-0.09	9.8	1.7	0.43	0.5
					-0.05	10.0	1.8	0.57	0.6
					0.00	8.7	1.5	0.77	0.9
					0.05	7.9	1.4	0.85	0.9
					0.08	6.8	1.2	0.95	1.1
					0.12	5.8	1.0	1.04	1.2
					0.16	4.9	0.9	1.09	1.2
					0.24	5.9	1.0	1.05	1.2
					0.31	7.2	1.3	0.89	1.0
1130100	3	0.010	1.456	98.5	0.39	6.9	1.2	0.92	1.0
1230100	3	0.010	1.456	49.3	-0.22	9.8	1.7	0.52	0.6
					-0.18	9.7	1.7	0.51	0.6
					-0.14	9.7	1.7	0.54	0.6
					-0.10	9.8	1.7	0.63	0.7
					-0.06	9.8	1.7	0.79	0.8
					0.00	9.2	1.6	0.78	0.9
					0.10	7.9	1.4	[illegible]	0.9
					0.13	7.4	1.3	[illegible]	1.0
					0.16	7.4	1.3	[illegible]	1.0
					0.24	6.9	1.2	0.90	1.0
					0.32	7.2	1.3	0.81	0.9
1230100	3	0.010	1.456	49.3	0.40	8.9	1.6	0.72	0.8
1330100	3	0.010	1.456	24.6	-0.44	8.1	1.4	0.78	0.9
					-0.37	9.1	1.6	0.74	0.8
					-0.28	10.2	1.8	0.68	0.8
					-0.21	10.4	1.8	0.70	0.8
					-0.13	10.1	1.8	0.70	0.8
					0.00	9.4	1.6	0.77	0.9
					0.19	8.4	1.5	0.86	1.0
					0.26	8.2	1.4	0.88	1.0
					0.33	8.0	1.4	0.86	1.0
					0.44	8.0	1.4	0.86	1.0
1330100	3	0.010	1.456	24.6	0.48	8.4	1.5	0.77	0.9
1430100	3	0.010	1.456	73.9	-0.45	7.4	1.3	0.85	0.9
					-0.33	8.4	1.5	0.66	0.7
					-0.15	9.2	1.6	0.57	0.6
					-0.09	9.4	1.6	0.55	0.6
					-0.04	9.4	1.6	0.75	0.8
					0.00	8.9	1.6	0.78	0.9
					0.09	7.0	1.2	0.92	1.0
					0.16	5.5	1.0	1.05	1.2
					0.21	4.8	0.8	1.03	1.1
					0.32	7.3	1.3	0.69	0.8
1430100	3	0.010	1.456	73.9	0.42	8.4	1.5	0.65	0.7

Table 4.2 Continued...

CODE	So (%)	Q (m3/s)	Fo	L (cm)	x/L	y (cm)	y/yo	um (m/s)	um/Vo
1130025	3	0.0025	1.340	98.5	-0.46	5.5	1.8	0.32	0.5
					-0.38	6.2	2.1	0.27	0.5
					-0.30	6.4	2.1	0.27	0.5
					-0.08	7.0	2.3	0.34	0.6
					-0.05	7.1	2.4	0.31	0.5
					0.00	6.0	2.0	0.60	1.0
					0.05	4.8	1.6	0.88	1.5
					0.08	2.8	0.9	0.87	1.5
					0.16	3.8	1.3	0.78	1.3
					0.24	4.2	1.4	0.59	1.0
					0.31	4.8	1.6	0.55	0.9
1130025	3	0.0025	1.340	98.5	0.39	5.1	1.7	0.52	0.9
1230025	3	0.0025	1.340	49.3	-0.22	6.6	2.2	0.32	0.5
					-0.18	6.8	2.3	0.32	0.5
					-0.14	6.9	2.3	0.34	0.6
					-0.10	6.8	2.3	0.38	0.6
					-0.06	6.7	2.2	0.48	0.8
					0.00	6.0	2.0	0.57	1.0
					0.10	5.0	1.7	0.71	1.2
					0.13	4.6	1.5	0.73	1.2
					0.16	4.3	1.4	0.70	1.2
					0.24	5.2	1.7	0.62	1.1
					0.32	5.6	1.9	0.58	1.0
1230025	3	0.0025	1.340	49.3	0.40	5.8	1.9	0.57	1.0
1330025	3	0.0025	1.340	24.6	-0.44	6.1	2.0	0.53	0.9
					-0.37	6.1	2.0	0.54	0.9
					-0.28	6.1	2.0	0.53	0.9
					-0.21	6.1	2.0	0.55	0.9
					-0.13	6.1	2.0	0.56	0.9
					0.00	5.7	1.9	0.61	1.0
					0.19	5.5	1.8	0.66	1.1
					0.26	5.5	1.8	0.63	1.1
					0.33	5.7	1.9	0.59	1.0
					0.44	5.9	2.0	0.54	1.0
1330025	3	0.0025	1.340	24.6	0.48	6.4	2.1	0.54	1.0
1430025	3	0.0025	1.340	73.9	-0.45	5.6	1.9	0.32	0.5
					-0.33	5.9	2.0	0.29	0.5
					-0.15	6.5	2.2	0.30	0.5
					-0.08	6.6	2.2	0.32	0.5
					-0.04	6.4	2.1	0.51	0.9
					0.00	5.5	1.8	0.58	1.0
					0.08	3.6	1.2	0.72	1.2
					0.16	4.0	1.3	0.63	1.1
					0.21	4.3	1.4	0.52	0.9
					0.32	4.9	1.6	0.44	0.7
1430025	3	0.0025	1.340	73.9	0.42	5.4	1.8	0.37	0.6

CODE	So (%)	Q (m3/s)	Fo	L (cm)	x/L	y (cm)	y/yo	um (m/s)	um/Vo
1130005	3	0.0005	1.183	98.5	-0.46	3.3	2.4	0.22	0.6
					-0.38	3.8	2.7	0.15	0.4
					-0.30	4.0	2.9	0.15	0.4
					-0.09	4.6	3.3	0.05	0.1
					-0.05	4.7	3.4	0.07	0.2
					0.00	3.8	2.7	0.43	1.2
					0.24	2.0	1.4	0.29	0.8
					0.31	2.6	1.9	0.26	0.7
1130005	3	0.0005	1.183	98.5	0.39	2.8	2.0	0.24	0.7
1230005	3	0.0005	1.183	49.3	-0.22	4.1	2.9	0.25	0.7
					-0.18	4.2	[illegible]	0.26	0.7
					-0.14	4.3	3.1	0.28	0.8
					-0.10	4.3	3.1	0.29	0.8
					-0.06	4.2	3.0	0.38	1.1
					0.00	3.7	2.6	0.44	1.2
					0.13	3.0	2.1	0.47	1.3
					0.16	3.0	2.1	0.32	0.9
					0.24	3.4	2.4	0.24	0.7
					0.32	3.3	2.4	0.27	0.8
1230005	3	0.0005	1.183	49.3	0.40	3.7	2.6	0.27	0.8
1330005	3	0.0005	1.183	24.6	-0.44	3.5	2.5	0.25	0.7
					-0.37	3.5	2.5	0.26	0.7
					0.19	[illegible]	2.1	0.21	0.6
					0.26	3.3	2.4	0.23	0.6
					0.33	3.4	2.4	0.26	0.7
					0.44	3.3	2.4	0.28	0.8
1330005	3	0.0005	1.183	24.6	0.48	3.6	2.6	0.27	0.8
1430005	3	0.0005	1.183	73.9	-0.45	2.4	1.7	0.21	0.6
					-0.33	2.7	1.4	0.21	0.6
					-0.15	3.2	2.3	0.23	0.6
					-0.10	3.4	[illegible]	0.22	0.6
					0.09	1.3	0.9	0.23	0.6
					0.16	1.6	1.1	0.22	0.6
					0.21	1.4	1.0	0.23	0.6
					0.32	1.8	1.3	0.22	0.6
1430005	3	0.0005	1.183	73.9	0.42	2.3	1.6	0.22	0.6

Table 4.2 Continued...

CODE	So (%)	Q (m3/s)	Fo	L (cm)	x/L	y (cm)	y/yo	um (m/s)	um/Vo
1150350	5	0.035	1.694	98.5	-0.46	10.8	1.1	1.50	1.1
					-0.38	11.1	1.1	1.47	1.0
					-0.30	11.2	1.1	1.50	1.1
					-0.08	12.7	1.3	1.28	0.9
					-0.05	13.4	1.4	1.52	1.1
					0.00	12.9	1.3	1.59	1.1
					0.05	12.3	1.2	1.54	1.1
					0.08	11.6	1.2	1.55	1.1
					0.12	10.9	1.1	1.53	1.1
					0.16	9.8	1.0	1.49	1.0
					0.24	8.3	0.9	1.43	1.0
					0.31	8.9	1.0	1.39	1.0
1150350	5	0.035	1.694	98.5	0.39	10.7	1.1	1.53	1.1
1250350	5	0.035	1.694	49.3	-0.22	11.6	1.2	1.26	0.9
					-0.18	12.2	1.2	1.25	0.9
					-0.14	13.1	1.3	1.20	0.9
					-0.10	14.2	1.4	1.25	0.9
					-0.06	14.3	1.4	1.37	1.0
					0.00	14.7	1.5	1.34	0.9
					0.10	14.2	1.4	1.26	0.9
					0.13	13.7	1.4	1.25	0.9
					0.16	13.3	1.3	1.20	0.9
					0.24	12.3	1.2	1.27	0.9
					0.32	11.0	1.1	1.36	1.0
1250350	5	0.035	1.694	49.3	0.40	10.5	1.1	1.43	1.0
1350350	5	0.035	1.694	24.6	-0.44	13.1	1.3	1.37	1.0
					-0.37	13.0	1.3	1.38	1.0
					-0.28	13.0	1.3	1.40	1.0
					-0.21	12.7	1.3	1.35	1.0
					-0.13	12.9	1.3	1.38	1.0
					0.00	12.8	1.3	1.37	1.0
					0.19	13.0	1.3	1.32	0.9
					0.28	12.8	1.3	1.34	0.9
					0.33	12.9	1.3	1.34	0.9
					0.40	12.8	1.3	1.35	1.0
1350350	5	0.035	1.694	24.6	0.48	13.1	1.3	1.35	1.0
1450350	5	0.035	1.694	73.9	-0.45	10.1	1.0	1.30	0.9
					-0.33	11.3	1.1	1.29	0.9
					-0.15	13.1	1.3	1.15	0.8
					-0.09	13.1	1.3	1.18	0.8
					-0.04	13.0	1.3	1.47	1.0
					0.00	12.9	1.3	1.40	1.0
					0.08	11.4	1.2	1.43	1.0
					0.16	10.0	1.0	1.42	1.0
					0.21	9.1	0.9	1.43	1.0
					0.32	8.8	0.9	1.36	1.0
1450350	5	0.035	1.694	73.9	0.42	9.4	0.9	1.31	0.9

CODE	So (%)	Q (m3/s)	Fo	L (cm)	x/L	y (cm)	y/yo	um (m/s)	um/Vo
1150100	5	0.010	1.603	98.5	-0.46	5.3	1.0	1.06	1.1
					-0.38	6.3	1.2	0.86	0.9
					-0.30	8.4	1.6	0.78	0.8
					-0.08	9.5	1.8	0.50	0.5
					-0.05	9.7	1.8	0.70	0.7
					0.00	8.7	1.6	0.8[illegible]	0.9
					0.05	7.6	1.4	0.98	1.0
					0.08	6.3	1.2	1.05	1.1
					0.12	5.6	1.0	1.11	1.1
					0.16	4.4	0.8	1.16	1.2
					0.24	5.3	1.0	1.06	1.1
					0.31	6.5	1.2	1.00	1.0
1150100	5	0.010	1.603	98.5	0.39	6.1	1.1	1.09	1.1
1250100	5	0.010	1.603	49.3	-0.22	9.2	1.7	0.68	0.7
					-0.18	9.3	1.7	0.66	0.7
					-0.14	9.6	1.8	0.66	0.7
					-0.10	9.8	1.8	0.77	0.8
					-0.06	9.9	1.8	0.90	0.9
					0.00	8.8	1.6	0.86	0.9
					0.10	8.0	1.5	0.96	1.0
					0.13	7.3	1.4	0.96	1.0
					0.16	6.8	1.3	0.98	1.0
					0.24	5.9	1.1	1.03	1.1
					0.32	5.7	1.1	0.98	1.0
1250100	5	0.010	1.603	49.3	0.40	7.8	1.4	0.79	0.8
1350100	5	0.010	1.603	24.6	-0.44	7.1	1.3	0.87	0.9
					-0.37	7.6	1.4	0.82	0.8
					-0.28	9.4	1.7	0.76	0.8
					-0.21	9.5	1.8	0.75	0.8
					-0.13	9.2	1.7	0.77	0.8
					0.00	8.9	1.6	0.78	0.8
					0.19	8.0	1.5	0.82	0.8
					0.26	7.6	1.4	0.85	0.9
					0.33	7.6	1.4	0.87	0.9
					0.40	7.4	1.4	0.84	0.9
1350100	5	0.010	1.603	24.6	0.48	7.7	1.4	0.78	0.8
1450100	5	0.010	1.603	73.9	-0.45	6.6	1.2	0.92	0.9
					-0.33	6.9	1.3	0.82	0.8
					-0.15	8.7	1.6	0.62	0.6
					-0.09	8.7	1.6	0.55	0.6
					-0.04	8.8	1.6	0.90	0.9
					0.00	8.5	1.6	0.90	0.9
					0.09	6.2	1.1	1.04	1.1
					0.16	4.4	0.8	1.16	1.2
					0.21	3.5	0.6	1.14	1.2
					0.32	4.6	0.9	1.02	1.1
1450100	5	0:010	1.603	73.9	0.42	6.5	1.2	0.83	0.9

Table 4.2 Continued...

CODE	So (%)	Q (m3/s)	Fo	L (cm)	x/L	y (cm)	y/yo	um (m/s)	um/Vo
1150025	5	0.0025	1.485	98.5	-0.46	4.6	1.6	0.49	0.8
					-0.38	5.4	1.9	0.35	0.6
					-0.30	6.0	2.1	0.28	0.5
					-0.23	6.5	2.3	0.22	0.3
					-0.08	7.1	2.5	0.16	0.3
					-0.05	7.3	2.6	0.32	0.5
					0.00	5.4	1.9	0.59	0.9
					0.05	4.7	1.7	0.90	1.4
					0.08	2.9	1.0	0.91	1.4
					0.12	1.9	0.7	1.01	1.6
					0.16	2.5	0.9	0.92	1.4
					0.24	3.4	1.2	0.86	1.3
					0.31	3.0	1.1	0.86	1.3
1150025	5	0.0025	1.485	98.5	0.39	3.7	1.3	0.70	1.1
1250025	5	0.0025	1.485	49.3	-0.22	6.7	2.4	0.39	0.6
					-0.18	6.7	2.4	0.37	0.6
					-0.14	6.9	2.5	0.37	0.6
					-0.10	6.9	2.5	0.42	0.7
					-0.06	6.9	2.5	0.52	0.8
					0.00	5.8	2.1	0.62	1.0
					0.10	4.9	1.8	0.78	1.2
					0.13	4.3	1.5	0.77	1.2
					0.16	3.9	1.4	0.78	1.2
					0.24	4.8	[illegible]	0.63	1.0
					0.32	5.2	[illegible]	0.52	0.8
1250025	5	0.0025	1.485	49.3	0.40	5.7	[illegible]	0.42	0.7
1350025	5	0.0025	1.485	24.6	-0.44	5.6	2.0	0.65	1.0
					-0.37	5.9	2.1	0.64	1.0
					-0.28	6.2	2.2	0.63	1.0
					-0.21	6.0	2.1	0.65	1.0
					-0.13	6.0	2.1	0.67	1.0
					0.00	5.5	2.0	0.69	1.1
					0.19	5.1	1.8	0.79	1.2
					0.26	5.0	1.8	0.77	1.2
					0.33	5.0	1.8	0.78	1.2
					0.40	4.8	1.7	0.72	1.1
1350025	5	0.0025	1.485	24.6	0.48	5.3	1.9	0.70	1.1
1450025	5	0.0025	1.485	73.9	-0.45	4.7	1.7	0.44	0.7
					-0.33	5.4	1.9	0.40	0.7
					-0.19	6.2	2.2	0.35	0.5
					-0.08	6.5	2.3	0.37	0.6
					-0.04	6.3	2.3	0.55	0.9
					0.00	5.4	1.9	0.62	1.0
					0.08	3.1	1.1	0.79	1.2
					0.21	3.2	1.1	0.77	1.2
					0.32	3.7	1.3	0.56	0.9
1450025	5	0.0025	1.485	73.9	0.42	4.5	1.6	0.46	0.7

CODE	So (%)	Q (m3/s)	Fo	L (cm)	x/L	y (cm)	y/yo	um (m/s)	um/Vo
1150005	5	0.0005	1.306	98.5	-0.46	2.8	2.1	0.23	0.6
					-0.38	3.5	2.7	0.17	0.4
					-0.30	3.7	2.8	0.11	0.3
					-0.11	4.7	3.6	0.07	0.2
					0.00	4.1	3.1	0.35	0.9
					0.14	2.2	1.7	0.35	0.9
					0.31	1.9	1.4	0.40	1.0
					0.35	2.0	1.5	0.30	0.8
					0.39	1.9	1.4	0.37	1.0
1150005	5	0.0005	1.306	98.5	0.43	2.2	1.7	0.22	0.6
1250005	5	0.0005	1.306	49.3	-0.22	4.1	3.1	0.18	0.5
					-0.18	4.2	3.2	0.19	0.5
					-0.14	4.4	3.3	0.21	0.5
					-0.10	4.4	3.3	0.24	0.6
					-0.06	4.4	3.3	0.32	0.8
					0.00	3.7	2.8	0.40	1.0
					0.13	2.2	1.7	0.27	0.7
					0.16	2.3	1.7	0.12	0.3
					0.24	2.9	2.2	0.15	0.4
					0.32	2.8	2.1	0.15	0.4
1250005	5	0.0005	1.306	49.3	0.40	3.2	2.4	0.15	0.4
1350005	5	0.0005	1.306	24.6	-0.44	3.4	2.6	0.20	0.5
					-0.37	3.4	2.6	0.20	0.5
					0.19	2.8	2.1	0.13	0.3
					0.26	3.0	2.3	0.10	0.3
					0.33	3.1	2.3	0.13	0.3
					0.40	3.2	2.4	0.13	0.3
1350005	5	0.0005	1.306	24.6	0.48	3.5	2.7	0.13	0.3
1450005	5	0.0005	1.306	73.9	-0.45	1.9	1.4	0.16	0.4
					-0.33	2.3	1.7	0.14	0.4
					-0.15	3.0	2.3	0.31	0.8
					-0.10	3.2	2.4	0.30	0.8
1450005	5	0.0005	1.306	73.9	0.42	1.6	1.2	0.23	0.6

Table 4.3 Experimental Results from Culvert #2.

CODE	S_o (%)	Q (m^3/s)	y_o (cm)	A_o (m^2)	T (m)	V_o (m/s)	d_o (cm)	n	F_o
2010350	1	0.035	10.9	0.027	0.352	1.30	7.7	0.012	1.496
2010100	1	0.010	4.6	0.008	0.253	1.25	3.2	0.008	2.231
2010025	1	0.0025	1.9	0.002	0.169	1.25	1.2	0.004	3.644
2010005	1	0.0005	0.85	0.0007	0.114	0.77	0.6	0.004	3.174
2030350	3	0.035	8.3	0.019	0.321	1.84	5.9	0.013	2.415
2030100	3	0.010	3.8	0.006	0.232	1.67	2.6	0.009	3.319
2030025	3	0.0025	1.6	0.002	0.155	1.25	1.3	0.007	3.519
2030005	3	0.0005	0.86	0.0007	0.155	0.76	0.6	0.007	3.111
2050350	5	0.035	7.8	0.017	0.314	2.06	5.4	0.014	2.826
2050100	5	0.010	3.6	0.006	0.227	1.67	2.6	0.011	3.279
2050025	5	0.0025	1.5	0.002	0.151	1.25	1.3	0.008	3.456
2050005	5	0.0005	0.80	0.0006	0.111	0.83	0.5	0.008	3.606

Table 4.4 Experimental Results for Culvert Fish-baffle Designs #5, #6 and #7.

CODE	So (%)	Q (m3/s)	Fo	L (cm)	L* (cm)		x/L*	y (cm)	y/yo	um (m/s)	um/Vo
2510350	1	0.035	1.496	58.8	117.6		-0.45	12.1	1.1	1.08	0.8
							-0.38	12.7	1.2	1.08	0.8
							-0.31	13.1	1.2	0.99	0.8
							-0.25	13.0	1.2	1.03	0.8
							-0.10	12.6	1.2	1.08	0.8
							-0.01	12.1	1.1	1.07	0.8
							0.09	12.4	1.1	1.02	0.8
							0.19	13.2	1.2	0.95	0.7
							0.24	13.2	1.2	1.01	0.8
							0.32	13.1	1.2	4.03	0.8
							0.48	12.6	1.2	1.01	0.8
						(z=-3.6cm)	-0.22	13.6	1.2	1.02	0.8
						(z=-3.6cm)	-0.19	13.8	1.3	1.14	0.9
						(z=+2.7cm)	0.28	13.7	1.3	0.93	0.7
						(z=+2.7cm)	0.30	13.5	1.2	0.76	0.6
2510350	1	0.035	1.496	58.8	117.6		-	-	-	-	-
2610350	1	0.035	1.496	29.4	58.8		-0.40	14.5	1.3	0.92	0.7
							-0.33	14.4	1.3	0.93	0.7
							-0.25	14.0	1.3	0.93	0.7
							-0.17	14.1	1.3	0.93	0.7
							-0.08	13.8	1.3	0.94	0.7
							0.02	13.9	1.3	0.94	0.7
							0.15	14.1	1.3	0.95	0.7
							0.25	13.6	1.2	0.96	0.7
							0.35	13.9	1.3	0.93	0.7
							0.47	13.9	1.3	0.93	0.7
						(z=+2.7cm)	-0.18	13.9	1.3	0.79	0.6
						(z=+2.7cm)	-0.15	13.9	1.3	0.83	0.6
						(z=-3.6cm)	0.31	14.2	1.3	0.86	0.7
						(z=-3.6cm)	0.35	14.1	1.3	1.03	0.8
						(z=-7.6cm)	-0.25	13.2	1.2	1.00	0.8
2610350	3	0.035	1.496	29.4	58.8		-	-	-	-	-

CODE	So (%)	Q (m3/s)	Fo	L (cm)	L* (cm)		x/L*	y (cm)	y/yo	um (m/s)	um/Vo
2710350	3	0.035	1.496	19.4	38.8		-0.45	14.5	1.3	0.93	0.7
							-0.38	14.5	1.3	0.92	0.7
							-0.24	14.4	1.3	0.92	0.7
							-0.15	14.5	1.3	0.93	0.7
							-0.10	14.5	1.3	0.93	0.7
							0.00	14.4	1.3	0.93	0.7
							0.10	14.3	1.3	0.94	0.7
							0.24	13.7	1.3	0.97	0.7
							0.39	14.1	1.3	0.95	0.7
							0.49	14.5	1.3	0.94	0.7
						(z=-3.6cm)	-0.14	14.4	1.3	0.90	0.7
						(z=-3.6cm)	-0.10	14.5	1.3	0.97	0.7
						(z=+2.7cm)	0.35	14.1	1.3	0.85	0.7
						(z=+2.7cm)	0.40	14.1	1.3	0.84	0.6
						(z=-7.6cm)	0.24	13.0	1.2	0.98	0.8
2710350	1	0.010	1.496	19.4	38.8		-	-	-	-	-
2510100	1	0.010	2.231	58.8	117.6		-0.45	5.7	1.2	0.95	0.8
							-0.38	6.5	1.4	0.91	0.7
							-0.31	7.0	1.5	0.87	0.7
							-0.25	6.4	1.4	1.06	0.8
							-0.10	5.7	1.2	1.05	0.8
							-0.01	5.7	1.2	1.05	0.8
							0.09	5.7	1.2	1.03	0.8
							0.19	6.3	1.4	0.95	0.8
							0.24	6.9	1.5	1.05	0.8
							0.32	6.7	1.5	1.02	0.8
							0.48	5.4	1.2	0.95	0.8
						(z=-3.6cm)	-0.22	6.3	1.4	0.85	0.7
						(z=-3.6cm)	-0.19	6.6	1.4	1.06	0.8
						(z=+2.7cm)	0.28	6.7	1.5	0.57	0.5
						(z=+2.7cm)	0.30	6.5	1.4	0.60	0.5
2510100	1	0.010	2.231	58.8	117.6		-	-	-	-	-

Table 4.4 Continued...

CODE	So (%)	Q (m3/s)	Fo	L (cm)	L* (cm)		x/L*	y (cm)	y/yo	um (m/s)	um/Vo
2610100	1	0.010	2.231	29.4	58.8		-0.40	7.3	1.6	0.73	0.6
							-0.33	8.4	1.8	0.70	0.6
							-0.25	8.3	1.8	0.72	0.6
							-0.17	7.8	1.7	0.76	0.6
							-0.08	6.3	1.4	0.90	0.7
							0.02	5.8	1.3	0.91	0.7
							0.15	8.1	1.8	0.72	0.6
							0.25	8.7	1.9	0.76	0.6
							0.35	7.3	1.6	0.80	0.6
							0.47	5.7	1.2	0.88	0.7
						(z=+2.7cm)	-0.18	7.7	1.7	0.64	0.5
						(z=+2.7cm)	-0.15	7.3	1.6	0.81	0.6
						(z=-3.6cm)	0.31	7.9	1.7	0.74	0.6
						(z=-3.6cm)	0.35	7.4	1.6	0.96	0.8
						(z=-7.6cm)	-0.25	7.1	1.5	0.59	0.5
2610100	1	0.010	2.231	29.4	58.8		-	-	-	-	-
2710100	1	0.010	2.231	19.4	38.8		-0.45	8.0	1.7	0.70	0.6
							-0.38	7.4	1.6	0.69	0.6
							-0.24	7.4	1.6	0.73	0.6
							-0.15	7.7	1.7	0.69	0.6
							-0.10	7.9	1.7	0.70	0.6
							0.00	7.5	1.6	0.70	0.6
							0.10	7.4	1.6	0.71	0.6
							0.24	7.1	1.5	0.75	0.6
							0.39	7.3	1.6	0.70	0.6
							0.49	7.7	1.7	0.69	0.6
						(z=-3.6cm)	-0.14	7.9	1.7	0.67	0.5
						(z=-3.6cm)	-0.10	7.9	1.7	0.72	0.6
						(z=+2.7cm)	0.35	7.9	1.7	0.66	0.5
						(z=+2.7cm)	0.40	7.7	1.7	0.89	0.7
						(z=-7.6cm)	0.24	6.3	1.4	0.61	0.5
2710100	1	0.010	2.231	19.4	38.8		-	-	-	-	-

CODE	So (%)	Q (m3/s)	Fo	L (cm)	L* (cm)		x/L*	y (cm)	y/yo	um (m/s)	um/Vo
2510025	1	0.0025	3.644	58.8	117.6		-0.45	3.7	1.9	0.55	0.4
							-0.38	4.1	2.2	0.50	0.4
							-0.31	4.5	2.4	0.44	0.4
							-0.25	4.1	2.2	0.48	0.4
							-0.10	[illegible]	1.9	0.59	0.5
							-0.01	[illegible]	1.9	0.57	0.5
							0.09	3.7	1.9	0.54	0.4
							0.19	4.5	2.4	0.44	0.4
							0.24	4.2	2.2	0.54	0.4
							0.32	3.7	1.9	0.56	0.4
							0.48	3.7	1.9	0.33	0.3
						(z=-3.6cm)	-0.22	3.6	1.9	0.48	0.4
						(z=-3.6cm)	-0.19	4.5	2.4	0.63	0.5
						(z=+2.7cm)	0.28	3.4	1.8	0.27	0.2
						(z=+2.7cm)	0.30	4.4	2.3	0.38	0.3
2510025	1	0.0025	3.644	58.8	117.6		-	-	-	-	-
2610025	1	0.0025	3.644	29.4	58.8		-0.40	4.8	2.5	0.47	0.4
							-0.33	5.1	2.7	0.42	0.3
							-0.25	4.6	2.4	0.51	0.4
							-0.17	4.1	2.2	0.47	0.4
							-0.08	4.1	2.2	0.55	0.4
							0.02	4.3	2.3	0.54	0.4
							0.15	4.8	2.5	0.42	0.3
							0.25	4.4	2.3	0.53	0.4
							0.35	4.2	2.2	0.41	0.3
							0.47	4.0	2.1	0.52	0.4
						(z=+2.7cm)	-0.18	4.5	2.4	0.44	0.4
						(z=+2.7cm)	-0.15	4.5	2.4	0.55	0.4
						(z=-3.6cm)	0.31	4.6	2.4	0.44	0.4
						(z=-3.6cm)	0.35	4.8	2.5	0.60	0.5
						(z=-7.6cm)	-0.25	3.6	1.9	0.41	0.3
2610025	1	0.0025	3.644	29.4	58.8		-	-	-	-	-

Table 4.4 Continued...

CODE	So (%)	Q (m3/s)	Fo	L (cm)	L* (cm)		x/L*	y (cm)	y/yo	um (m/s)	um/Vo
2710025	1	0.0025	3.644	19.4	38.8		-0.45	4.9	2.6	0.43	0.3
							-0.38	5.1	2.7	0.42	0.3
							-0.24	4.5	2.4	0.52	0.4
							-0.15	4.3	2.3	0.52	0.4
							-0.10	5.1	2.7	0.43	0.3
							0.00	4.7	2.5	0.44	0.4
							0.10	5.3	2.8	0.40	0.3
							0.24	4.5	2.4	0.50	0.4
							0.38	5.0	2.6	0.45	0.4
							0.48	4.8	2.5	0.45	0.4
						(z=-3.6cm)	-0.14	4.6	2.4	0.45	0.4
						(z=-3.6cm)	-0.10	4.7	2.5	0.48	0.4
						(z=+2.7cm)	0.35	4.5	2.4	0.37	0.3
						(z=+2.7cm)	0.40	4.6	2.4	0.54	0.4
						(z=-6.1cm)	0.24	4.0	2.1	0.38	0.3
2710025	1	0.0025	3.644	19.4	38.8		-	-	-	-	-
2510005	1	0.0005	3.174	58.8	117.6		-0.45	1.6	1.9	0.36	0.5
							-0.38	2.0	2.4	0.32	0.4
							-0.31	2.2	2.6	0.29	0.4
							-0.10	1.6	1.9	0.45	0.6
							-0.01	1.8	2.1	0.38	0.5
							0.08	1.8	2.1	0.35	0.5
							0.18	2.3	2.7	0.31	0.4
							0.32	1.6	1.9	0.43	0.6
							0.48	1.8	2.1	0.20	0.3
						(z=-3.6cm)	-0.22	1.5	1.8	0.44	0.6
						(z=-3.6cm)	-0.18	2.3	2.7	0.56	0.7
						(z=+2.7cm)	0.28	1.4	1.6	0.40	0.5
						(z=+2.7cm)	0.30	1.8	2.1	0.30	0.4
2510005	1	0.0005	3.174	58.8	117.6		-	-	-	-	-
2610005	1	0.0005	3.174	29.4	58.8		-0.40	2.5	2.9	0.29	0.4
							-0.33	2.6	3.1	0.26	0.3
							-0.17	2.1	2.5	0.23	0.3
							-0.08	2.1	2.5	0.41	0.5
							0.02	2.1	2.5	0.28	0.4
							0.18	2.5	2.9	0.24	0.3
							0.35	1.9	2.2	0.19	0.2
							0.47	2.2	2.6	0.33	0.4
						(z=+2.7cm)	-0.18	1.7	2.0	0.39	0.5
						(z=+2.7cm)	-0.15	1.8	2.1	0.44	0.6
						(z=-3.6cm)	0.31	2.0	2.4	0.36	0.5
						(z=-3.6cm)	0.35	2.0	2.4	0.46	0.6
						(z=-6.1cm)	-0.25	1.5	1.8	0.35	0.5
2610005	1	0.0005	3.174	29.4	58.8		-	-	-	-	-

CODE	So (%)	Q (m3/s)	Fo	L (cm)	L* (cm)		x/L*	y (cm)	y/yo	um (m/s)	um/Vo
2710005	1	0.0005	3.174	19.4	38.8		-0.45	2.7	3.2	0.27	0.4
							-0.38	2.7	3.2	0.26	0.3
							-0.15	2.4	2.8	0.20	0.3
							-0.10	2.2	2.6	0.19	0.2
							0.00	2.4	2.8	0.30	0.4
							0.10	2.6	3.1	0.28	0.4
							0.39	2.0	2.4	0.17	0.2
							0.49	2.4	2.8	0.29	0.4
						(z=-3.6cm)	-0.14	2.3	2.7	0.29	0.4
						(z=-3.6cm)	-0.10	2.5	2.9	0.40	0.5
						(z=+2.7cm)	0.35	2.3	2.7	0.33	0.4
						(z=+2.7cm)	0.40	2.3	2.7	0.37	0.5
						(z=-6.1cm)	0.24	1.9	2.2	0.29	0.4
2710005	1	0.0005	3.174	19.4	38.8		-	-	-	-	-
2530350	3	0.035	2.415	58.8	117.6		-0.45	9.8	1.2	1.51	0.8
							-0.38	10.3	1.2	1.46	0.8
							-0.31	10.5	1.3	1.46	0.8
							-0.25	10.4	1.3	1.53	0.8
							-0.10	9.5	1.1	1.51	0.8
							-0.01	9.4	1.1	1.55	0.8
							0.09	9.9	1.2	1.51	0.8
							0.19	11.0	1.3	1.46	0.8
							0.24	10.7	1.3	1.54	0.8
							0.32	10.5	1.3	1.51	0.8
							0.48	9.2	1.1	1.57	0.9
						(z=-3.6cm)	-0.22	10.8	1.3	1.45	0.8
						(z=-3.6cm)	-0.19	11.0	1.3	1.72	0.9
						(z=+2.7cm)	0.28	10.6	1.3	1.29	0.7
						(z=+2.7cm)	0.30	10.6	1.3	1.35	0.7
2530350	3	0.035	2.415	58.8	117.6		-	-	-	-	-
2630350	3	0.035	2.415	29.4	58.8		-0.40	11.4	1.4	1.36	0.7
							-0.33	11.4	1.4	1.35	0.7
							-0.25	11.1	1.3	1.37	0.7
							-0.17	11.1	1.3	1.36	0.7
							-0.08	11.2	1.3	1.36	0.7
							0.02	11.0	1.3	1.35	0.7
							0.15	11.0	1.3	1.36	0.7
							0.25	10.7	1.3	1.41	0.8
							0.35	11.1	1.3	1.36	0.7
							0.47	11.4	1.4	1.35	0.7
						(z=+2.7cm)	-0.18	11.2	1.3	1.10	0.6
						(z=+2.7cm)	-0.15	11.0	1.3	1.13	0.6
						(z=-3.6cm)	0.31	11.5	1.4	1.54	0.8
						(z=-3.6cm)	0.35	11.4	1.4	1.54	0.8
						(z=-7.6cm)	-0.25	9.5	1.1	1.37	0.7
2630350	3	0.035	2.415	29.4	58.8		-	-	-	-	-

Table 4.4 Continued...

CODE	So (%)	Q (m3/s)	Fo	L (cm)	L* (cm)		x/L*	y (cm)	y/yo	um (m/s)	um/Vo
2730350	3	0.035	2.415	19.4	38.8		-0.45	11.6	1.4	1.35	0.7
							-0.38	11.6	1.4	1.35	0.7
							-0.24	11.3	1.4	1.36	0.7
							-0.15	11.6	1.4	1.37	0.7
							-0.10	11.6	1.4	1.36	0.7
							0.00	11.7	1.4	1.36	0.7
							0.10	11.8	1.4	1.36	0.7
							0.24	11.3	1.4	1.38	0.8
							0.39	11.3	1.4	1.35	0.7
							0.49	11.6	1.4	1.36	0.7
						(z=-3.6cm)	-0.14	11.5	1.4	1.18	0.6
						(z=-3.6cm)	-0.10	11.6	1.4	1.63	0.9
						(z=+2.7cm)	0.35	11.5	1.4	0.88	0.5
						(z=+2.7cm)	0.40	11.6	1.4	1.14	0.6
						(z=-7.6cm)	0.24	10.5	1.3	1.28	0.7
2730350	3	0.035	2.415	19.4	38.8		-	-	-	-	-
2530100	3	0.010	3.319	58.8	117.6		-0.45	4.6	1.2	1.12	0.7
							-0.38	4.8	1.3	1.16	0.7
							-0.31	5.0	1.3	1.11	0.7
							-0.25	5.9	1.6	1.22	0.7
							-0.10	4.6	1.2	1.17	0.7
							-0.01	5.0	1.3	1.12	0.7
							0.09	5.0	1.3	1.15	0.7
							0.19	5.1	1.3	1.12	0.7
							0.24	5.6	1.5	1.26	0.8
							0.32	4.8	1.2	1.08	0.6
							0.48	4.8	1.3	1.20	0.7
						(z=-3.6cm)	-0.22	5.9	1.6	1.06	0.6
						(z=-3.6cm)	-0.19	5.8	1.5	1.23	0.7
						(z=+2.7cm)	0.28	5.2	1.4	1.05	0.6
						(z=+2.7cm)	0.30	5.1	1.3	1.22	0.7
2530100	3	0.010	3.319	58.8	117.6		-	-	-	-	-
2630100	3	0.010	3.319	29.4	58.8		-0.40	4.9	1.3	1.10	0.7
							-0.33	5.2	1.4	1.06	0.6
							-0.25	6.0	1.6	1.12	0.7
							-0.17	6.6	1.7	1.06	0.6
							-0.08	6.1	1.6	1.08	0.6
							0.02	5.1	1.3	1.13	0.7
							0.15	4.9	1.3	1.11	0.7
							0.25	5.7	1.5	1.18	0.7
							0.35	6.4	1.7	1.08	0.6
							0.47	5.6	1.5	1.11	0.7
						(z=+2.7cm)	-0.18	6.4	1.7	0.86	0.5
						(z=+2.7cm)	-0.15	6.3	1.7	0.89	0.6
						(z=-3.6cm)	0.31	6.3	1.7	0.93	0.6
						(z=-3.6cm)	0.35	6.3	1.7	1.11	0.7
						(z=-7.6cm)	-0.25	5.0	1.3	0.87	0.5
2630100	3	0.010	3.319	29.4	58.8		-	-	-	-	-

CODE	So (%)	Q (m3/s)	Fo	L (cm)	L* (cm)		x/L*	y (cm)	y/yo	um (m/s)	um/Vo
2730100	3	0.010	3.319	19.4	38.8		-0.45	6.2	1.6	0.97	0.6
							-0.38	6.1	1.6	0.96	0.6
							-0.24	6.3	1.7	1.07	0.6
							-0.15	6.5	1.7	1.02	0.6
							-0.10	6.4	1.7	0.99	0.6
							0.00	6.1	1.6	0.97	0.6
							0.10	6.3	1.7	0.93	0.6
							0.24	6.3	1.7	1.02	0.6
							0.39	6.3	1.7	0.99	0.6
							0.49	6.1	1.6	0.99	0.6
						(z=-3.6cm)	-0.14	6.1	1.6	0.76	0.5
						(z=-3.6cm)	-0.10	6.2	1.6	0.86	0.5
						(z=+2.7cm)	0.35	6.6	1.7	0.77	0.5
						(z=+2.7cm)	0.40	6.6	1.7	1.02	0.6
						(z=-7.6cm)	0.24	4.5	1.2	0.86	0.5
2730100	3	0.010	3.319	19.4	38.8		-	-	-	-	-
2530025	3	0.0025	3.519	58.8	117.6		-0.45	2.1	1.3	0.82	0.7
							-0.38	2.7	1.7	0.78	0.6
							-0.31	3.6	2.3	0.66	0.5
							-0.25	4.0	2.5	0.71	0.6
							-0.10	2.3	1.4	0.74	0.6
							-0.01	2.1	1.3	0.82	0.7
							0.09	2.6	1.6	0.80	0.6
							0.19	3.4	2.1	0.71	0.6
							0.24	4.3	2.7	0.66	0.5
							0.32	2.3	1.4	0.82	0.7
							0.48	2.0	1.3	0.80	0.6
						(z=-3.6cm)	-0.22	2.0	1.3	0.56	0.4
						(z=-3.6cm)	-0.19	3.2	2.0	0.91	0.7
						(z=+2.7cm)	0.28	2.3	1.4	0.64	0.5
						(z=+2.7cm)	0.30	3.4	2.1	0.90	0.7
2530025	3	0.0025	3.519	58.8	117.6		-	-	-	-	-
2630025	3	0.0025	3.519	29.4	58.8		-0.40	4.3	2.7	0.54	0.5
							-0.33	4.6	2.9	0.46	0.4
							-0.25	4.2	2.6	0.61	0.5
							-0.17	2.7	1.7	0.55	0.5
							-0.08	2.9	1.8	0.72	0.6
							0.02	3.1	1.9	0.67	0.5
							0.15	4.2	2.6	0.49	0.4
							0.25	4.1	2.6	0.57	0.5
							0.35	3.0	1.9	0.40	0.3
							0.47	2.9	1.8	0.65	0.5
						(z=+2.7cm)	-0.18	3.7	2.3	0.53	0.4
						(z=+2.7cm)	-0.15	4.0	2.5	0.65	0.5
						(z=-3.6cm)	0.31	3.3	2.1	0.57	0.5
						(z=-3.6cm)	0.35	3.8	2.4	0.75	0.6
						(z=-7.6cm)	-0.25	3.0	1.9	0.43	0.3
2630025	3	0.0025	3.519	29.4	58.8		-	-	-	-	-

Table 4.4 Continued...

CODE	So (%)	Q (m3/s)	Fo	L (cm)	L* (cm)		x/L*	y (cm)	y/yo	um (m/s)	um/Vo
2730025	3	0.0025	3.519	19.4	38.8		-0.48	4.1	2.6	0.62	0.5
							-0.38	4.2	2.6	0.59	0.5
							-0.24	4.2	2.6	0.60	0.5
							-0.10	4.2	2.6	0.41	0.3
							0.00	4.1	2.6	0.42	0.3
							0.10	4.1	2.6	0.48	0.4
							0.24	4.2	2.6	0.67	0.5
							0.39	4.0	2.5	0.55	0.4
							0.49	4.0	2.5	0.55	0.4
						(z=-3.6cm)	-0.14	3.8	2.2	0.43	0.3
						(z=-3.6cm)	-0.10	4.4	2.8	0.56	0.4
						(z=+2.7cm)	0.35	3.4	2.1	0.48	0.4
						(z=+2.7cm)	0.40	4.3	2.7	0.67	0.5
						(z=-6.1cm)	0.24	3.4	2.1	0.47	0.4
2730025	3	0.0025	3.519	19.4	38.8		-	-	-	-	-
2530005	3	0.0005	3.111	58.8	117.6		-0.45	0.9	1.0	0.54	0.7
							-0.38	1.5	1.7	0.47	0.6
							-0.31	1.7	2.0	0.44	0.6
							-0.10	0.9	1.0	0.66	0.9
							-0.01	0.8	0.9	0.62	0.8
							0.09	1.2	1.4	0.54	0.7
							0.19	1.9	2.2	0.36	0.5
							0.32	1.2	1.4	0.46	0.5
							0.48	0.8	0.9	0.62	0.8
						(z=-3.6cm)	-0.22	0.5	0.6	0.56	0.7
						(z=-3.6cm)	-0.19	1.0	1.2	0.37	0.5
						(z=+2.7cm)	0.28	0.6	0.7	0.56	0.7
						(z=+2.7cm)	0.30	1.2	1.4	0.41	0.5
2530005	3	0.0005	3.111	58.8	117.6		-	-	-	-	-
2630005	3	0.0005	3.111	29.8	58.8		-0.40	2.1	2.4	0.38	0.5
							-0.33	2.5	2.9	0.31	0.4
							-0.17	1.4	1.6	0.23	0.3
							-0.08	1.0	1.2	0.49	0.6
							0.02	1.5	1.7	0.38	0.5
							0.15	2.0	2.3	0.24	0.3
							0.35	1.3	1.5	0.17	0.2
							0.47	1.6	1.9	0.35	0.5
						(z=+2.7cm)	-0.18	1.1	1.3	0.41	0.5
						(z=+2.7cm)	-0.10	1.4	1.6	0.48	0.6
						(z=-3.6cm)	0.31	1.0	1.2	0.48	0.6
						(z=-3.6cm)	0.35	1.6	1.9	0.55	0.7
						(z=-6.1cm)	-0.25	1.0	1.2	0.44	0.6
2630005	3	0.0005	3.111	29.4	58.8		-	-	-	-	-
2730005	3	0.0005	3.111	19.4	38.8		-0.45	2.1	2.4	0.32	0.4
							-0.38	2.1	2.4	0.27	0.4
							-0.15	1.5	1.7	0.23	0.3
							-0.10	1.6	1.9	0.18	0.2
							0.00	1.6	1.9	0.43	0.6
							0.10	2.1	2.4	0.37	0.5
							0.39	1.4	1.6	0.25	0.3
							0.49	1.6	1.9	0.44	0.6
						(z=-3.6cm)	-0.14	1.3	1.5	0.38	0.5
						(z=-3.6cm)	-0.10	1.7	2.2	0.62	0.8
						(z=+2.7cm)	0.35	1.2	1.4	0.34	0.4
						(z=+2.7cm)	0.40	1.6	1.9	0.55	0.7
						(z=-6.1cm)	0.24	1.1	1.3	0.34	0.4
2730005	3	0.0005	3.111	19.4	38.8		-	-	-	-	-
2550350	3	0.035	2.826	58.8	117.6		-0.45	8.3	1.1	1.81	0.9
							-0.38	8.2	1.1	1.80	0.9
							-0.31	9.2	1.2	1.77	0.9
							-0.25	9.6	1.2	1.99	1.0
							-0.10	9.8	1.3	1.80	0.9
							-0.01	9.8	1.3	1.81	0.9
							0.09	8.2	1.1	1.85	0.9
							0.19	9.1	1.2	1.82	0.9
							0.24	9.4	1.2	2.02	1.0
							0.32	10.1	1.3	1.85	0.9
							0.48	8.9	1.1	1.88	0.9
						(z=-3.6cm)	-0.22	9.0	1.2	1.77	0.9
						(z=-3.6cm)	-0.19	9.4	1.2	2.12	1.0
						(z=+2.7cm)	0.28	9.5	1.2	1.67	0.8
						(z=+2.7cm)	0.30	9.5	1.2	1.66	0.8
2550350	5	0.035	2.826	58.8	117.6		-	-	-	-	-
2650350	5	0.035	2.826	29.4	58.8		-0.40	9.6	1.2	1.66	0.8
							-0.33	9.7	1.2	1.64	0.8
							-0.25	9.9	1.3	1.64	0.8
							-0.17	10.1	1.3	1.61	0.8
							-0.08	10.3	1.3	1.58	0.8
							0.02	10.3	1.3	1.56	0.8
							0.15	10.4	1.3	1.56	0.8
							0.25	9.9	1.3	1.66	0.8
							0.35	9.9	1.3	1.63	0.8
							0.47	9.5	1.2	1.65	0.8
						(z=+2.7cm)	-0.18	10.0	1.3	1.28	0.6
						(z=+2.7cm)	-0.15	9.9	1.3	1.38	0.7
						(z=-3.6cm)	0.31	10.1	1.3	1.66	0.8
						(z=-3.6cm)	0.35	10.0	1.3	1.95	0.9
						(z=-7.6cm)	-0.25	8.5	1.1	1.59	0.8
2650350	5	0.035	2.826	29.4	58.8		-	-	-	-	-

Table 4.4 Continued...

CODE	So (%)	Q (m3/s)	Fo	L (cm)	L* (cm)		x/L*	y (cm)	y/yo	um (m/s)	um/Vo
2750350	5	0.035	2.826	19.4	38.8		-0.45	10.7	1.4	1.56	0.8
							-0.38	10.6	1.4	1.57	0.8
							-0.24	10.5	1.3	1.59	0.8
							-0.15	10.7	1.4	1.61	0.8
							-0.10	10.8	1.4	1.56	0.8
							0.00	10.6	1.4	1.56	0.8
							0.10	10.8	1.4	1.57	0.8
							0.24	10.2	1.3	1.63	0.8
							0.39	10.3	1.3	1.64	0.8
							0.49	10.4	1.3	1.64	0.8
						(z=-3.6cm)	-0.14	10.4	1.3	1.49	0.7
						(z=-3.6cm)	-0.10	10.5	1.3	1.84	0.9
						(z=+2.7cm)	0.35	10.3	1.3	1.36	0.7
						(z=+2.7cm)	0.40	10.2	1.3	1.50	0.7
						(z=-7.6cm)	0.24	9.3	1.2	1.44	0.7
2750350	5	0.035	2.826	19.4	38.8		-	-	-	-	-
2750100	5	0.035	3.279	58.8	117.6		-0.45	5.3	1.5	1.21	0.7
							-0.38	5.2	1.4	1.23	0.7
							-0.31	4.9	1.4	1.20	0.7
							-0.10	3.9	1.1	1.28	0.8
							-0.01	5.0	1.4	1.26	0.8
							0.09	5.1	1.4	1.26	0.8
							0.19	5.2	1.4	1.22	0.7
							0.32	4.1	1.1	1.31	0.8
							0.48	4.7	1.3	1.26	0.8
						(z=-3.6cm)	-0.22	5.2	1.4	1.26	0.8
						(z=-3.6cm)	-0.19	5.5	1.5	1.46	0.9
						(z=+2.7cm)	0.28	4.9	1.4	1.19	0.7
						(z=+2.7cm)	0.30	4.9	1.4	1.36	0.8
2550100	5	0.010	3.279	58.8	117.6		-	-	-	-	-
2650100	5	0.010	3.279	29.4	58.8		-0.40	4.9	1.4	1.24	0.7
							-0.33	5.2	1.4	1.21	0.7
							-0.25	5.9	1.6	1.26	0.8
							-0.17	6.2	1.7	1.16	0.7
							-0.08	5.8	1.6	1.16	0.7
							-0.02	5.0	1.4	1.21	0.7
							0.15	4.8	1.3	1.19	0.7
							0.25	5.5	1.5	1.30	0.8
							0.35	5.9	1.6	1.21	0.7
							0.47	5.0	1.4	1.23	0.7
						(z=+2.7cm)	-0.18	6.6	1.8	0.96	0.6
						(z=+2.7cm)	-0.15	6.2	1.7	1.04	0.6
						(z=-3.6cm)	0.31	6.0	1.7	0.98	0.6
						(z=-3.6cm)	0.35	6.0	1.7	1.23	0.7
						(z=-7.6cm)	-0.25	4.2	1.2	1.05	0.6
2650100	5	0.010	3.279	29.4	58.8		-	-	-	-	-

CODE	So (%)	Q (m3/s)	Fo	L (cm)	L* (cm)		x/L*	y (cm)	y/yo	um (m/s)	um/Vo
2750100	5	0.010	3.279	19.4	38.8		-0.45	5.9	1.6	1.05	0.6
							-0.38	5.8	1.6	1.00	0.6
							-0.24	6.0	1.7	1.20	0.7
							-0.15	6.1	1.7	1.08	0.6
							-0.10	5.6	1.6	1.09	0.7
							0.00	5.4	1.5	1.04	0.6
							0.10	5.9	1.6	1.03	0.6
							0.24	5.9	1.6	1.22	0.7
							0.39	5.7	1.6	1.08	0.6
							0.49	5.5	1.5	1.08	0.6
						(z=-3.6cm)	-0.14	5.6	1.6	0.83	0.5
						(z=-3.6cm)	-0.10	5.8	1.6	1.08	0.6
						(z=+2.7cm)	0.35	5.7	1.6	0.81	0.5
						(z=+2.7cm)	0.40	5.9	1.6	1.04	0.6
						(z=-7.6cm)	0.24	4.0	1.1	0.93	0.6
2750100	5	0.010	3.279	19.4	38.8		-	-	-	-	-
2550025	5	0.0025	3.465	58.8	117.6		-0.45	1.7	1.1	1.00	0.8
							-0.38	2.0	1.3	1.01	0.8
							-0.31	2.3	1.5	0.97	0.8
							-0.10	1.7	1.4	0.95	0.8
							-0.01	1.9	1.3	0.95	0.8
							0.09	2.0	1.3	0.99	0.8
							0.19	3.0	2.0	0.87	0.7
							0.32	2.1	1.4	0.78	0.6
							0.48	1.9	1.3	0.94	0.8
						(z=-3.6cm)	-0.22	2.5	1.7	0.69	0.6
						(z=-3.6cm)	-0.19	3.4	2.3	0.85	0.7
						(z=+2.7cm)	0.28	2.5	1.7	0.69	0.6
						(z=+2.7cm)	0.30	3.2	2.1	0.79	0.6
2550025	5	0.0025	3.465	58.8	117.6		-	-	-	-	-
2650025	5	0.0025	3.465	29.4	58.8		-0.40	3.8	2.5	0.65	0.5
							-0.33	4.4	2.9	0.55	0.4
							-0.25	4.2	2.8	0.67	0.5
							-0.17	2.6	1.7	0.63	0.5
							-0.08	2.6	1.7	0.82	0.7
							0.02	2.3	1.5	0.80	0.6
							0.15	4.2	2.8	0.57	0.5
							0.25	3.9	2.6	0.66	0.5
							0.35	2.7	1.8	0.54	0.4
							0.47	2.2	1.5	0.83	0.7
						(z=+2.7cm)	-0.18	3.2	2.1	0.68	0.5
						(z=+2.7cm)	-0.15	3.9	2.6	0.68	0.5
						(z=-3.6cm)	0.31	3.1	2.1	0.63	0.5
						(z=-3.6cm)	0.35	3.7	2.5	0.85	0.7
						(z=-7.6cm)	-0.25	2.6	1.7	0.42	0.3
2650025	5	0.0025	3.465	29.4	58.8		-	-	-	-	-

Table 4.4 Continued...

CODE	So (%)	Q (m3/s)	Fo	L (cm)	L* (cm)		x/L*	y (cm)	y/yo	um (m/s)	um/yo
2750025	5	0.0025	3.465	19.4	38.8		-0.48	3.4	2.3	0.69	0.6
							-0.38	3.8	2.5	0.63	0.5
							-0.24	3.9	2.6	0.62	0.5
							-0.10	3.4	2.3	0.34	0.3
							0.00	3.6	2.4	0.48	0.4
							0.10	3.6	2.4	0.52	0.4
							0.24	4.1	2.7	0.62	0.5
							0.39	3.4	2.3	0.44	0.4
							0.49	3.2	2.1	0.64	0.5
						(z=-3.6cm)	-0.14	2.8	1.9	0.51	0.4
						(z=-3.6cm)	-0.10	3.6	2.4	0.70	0.6
						(z=+2.7cm)	0.35	2.9	1.9	0.57	0.5
						(z=+2.7cm)	0.40	4.0	2.7	0.76	0.6
						(z=-6.1cm)	0.24	3.0	2.0	0.47	0.4
2750025	5	0.0025	3.465	19.4	38.8		-	-	-	-	-
2550005	5	0.0005	3.606	58.8	117.6		-0.45	0.8	1.0	0.71	0.9
							-0.38	1.2	1.5	0.66	0.8
							-0.31	1.9	2.4	0.65	0.8
							-0.10	0.7	0.9	0.61	0.7
							-0.01	0.6	0.8	0.73	0.9
							0.08	1.0	1.3	0.67	0.8
							0.19	1.9	2.4	0.55	0.7
							0.32	1.1	1.4	0.51	0.6
							0.48	0.6	0.8	0.73	0.9
						(z=-3.6cm)	-0.22	0.5	0.6	0.55	0.7
						(z=-3.6cm)	-0.19	1.6	2.0	0.69	0.8
						(z=+2.7cm)	0.28	0.8	1.0	0.52	0.6
						(z=+2.7cm)	0.30	1.4	1.8	0.69	0.8
2550005	5	0.0005	3.606	58.8	117.6		-	-	-	-	-
2650005	5	0.0005	3.606	29.4	58.8		-0.40	1.6	2.0	0.44	0.5
							-0.33	2.0	2.5	0.34	0.5
							-0.17	1.4	1.8	0.17	0.2
							-0.08	0.5	0.6	0.70	0.8
							0.02	1.4	1.8	0.50	0.6
							0.15	1.6	2.0	0.31	0.4
							0.35	1.0	1.3	0.19	0.2
							0.47	0.9	1.1	0.60	0.7
						(z=+2.7cm)	-0.18	1.0	1.3	0.51	0.6
						(z=+2.7cm)	-0.15	1.2	1.5	0.36	0.4
						(z=-3.6cm)	0.31	0.7	0.9	0.52	0.6
						(z=-3.6cm)	-0.35	1.4	1.8	0.63	0.8
						(z=-6.1cm)	-0.25	0.8	1.1	0.41	0.5
2650005	5	0.0005	3.606	29.4	58.8		-	-	-	-	-

CODE	So (%)	Q (m3/s)	Fo	L (cm)	L* (cm)		x/L*	y (cm)	y/yo	um (m/s)	um/yo
2750005	5	0.0005	3.606	19.4	38.8		[illegible]	2.0	2.5	0.35	0.4
							[illegible]	2.1	2.6	0.27	0.3
							-0.15	1.2	1.5	0.22	0.3
							-0.10	1.2	1.5	0.16	0.2
							0.00	1.3	1.6	0.44	0.5
							0.10	1.9	2.4	0.36	0.4
							0.39	1.0	1.3	0.27	0.3
							0.49	1.3	1.6	0.51	0.6
						(z=-3.6cm)	-0.14	0.8	1.0	0.47	0.6
						(z=-3.6cm)	-0.10	1.7	2.1	0.71	0.9
						(z=+2.7cm)	0.35	0.8	1.0	0.73	0.9
						(z=+2.7cm)	0.40	1.7	2.1	0.51	0.6
						(z=-6.1cm)	0.24	0.9	1.1	0.33	0.4
2750005	5	0.0005	3.606	19.4	38.8		-	-	-	-	-

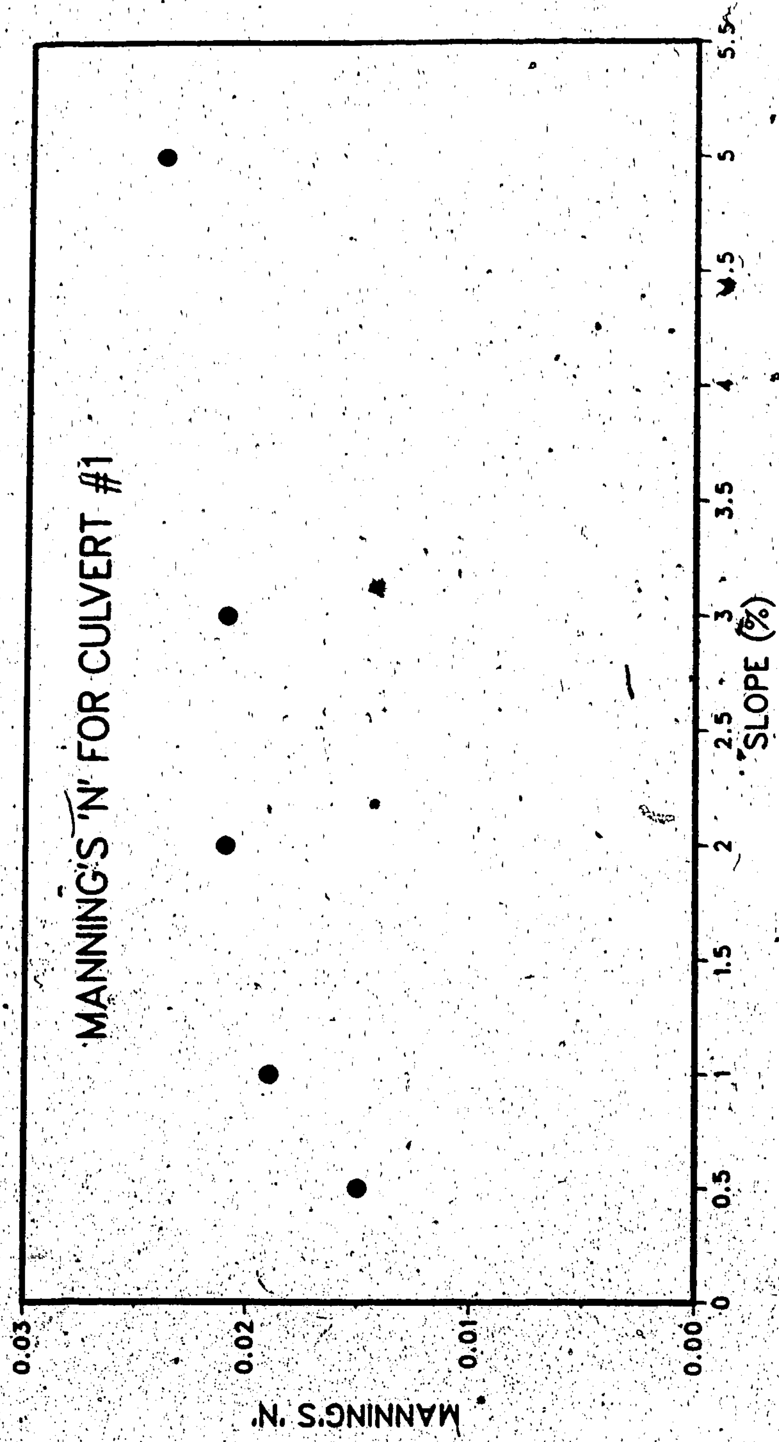


Figure 4.1 Manning's 'n' for Culvert #1.

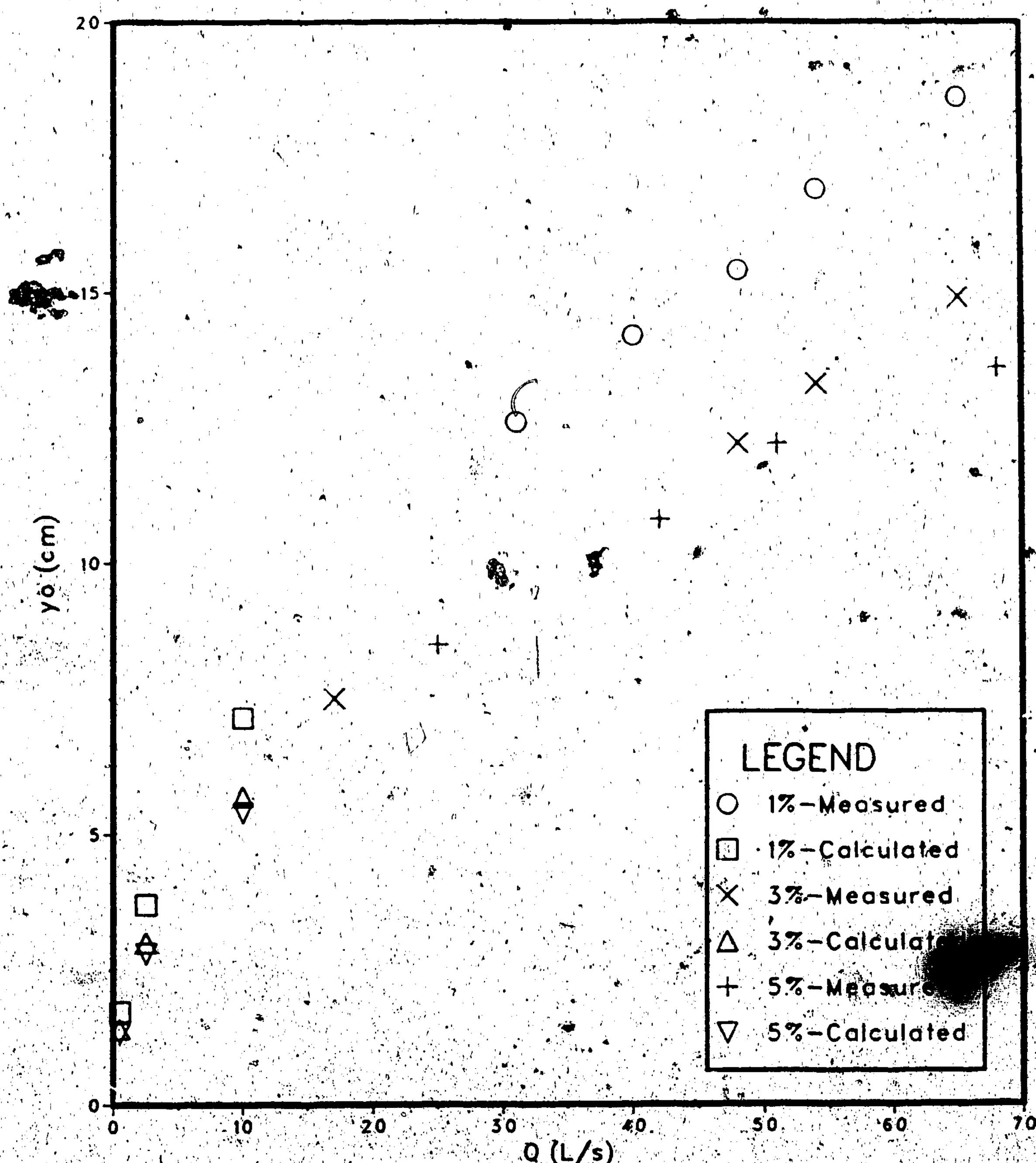


Figure 4.2 Average Depth (y_o) versus Model Discharge (Q) for Culvert #1.

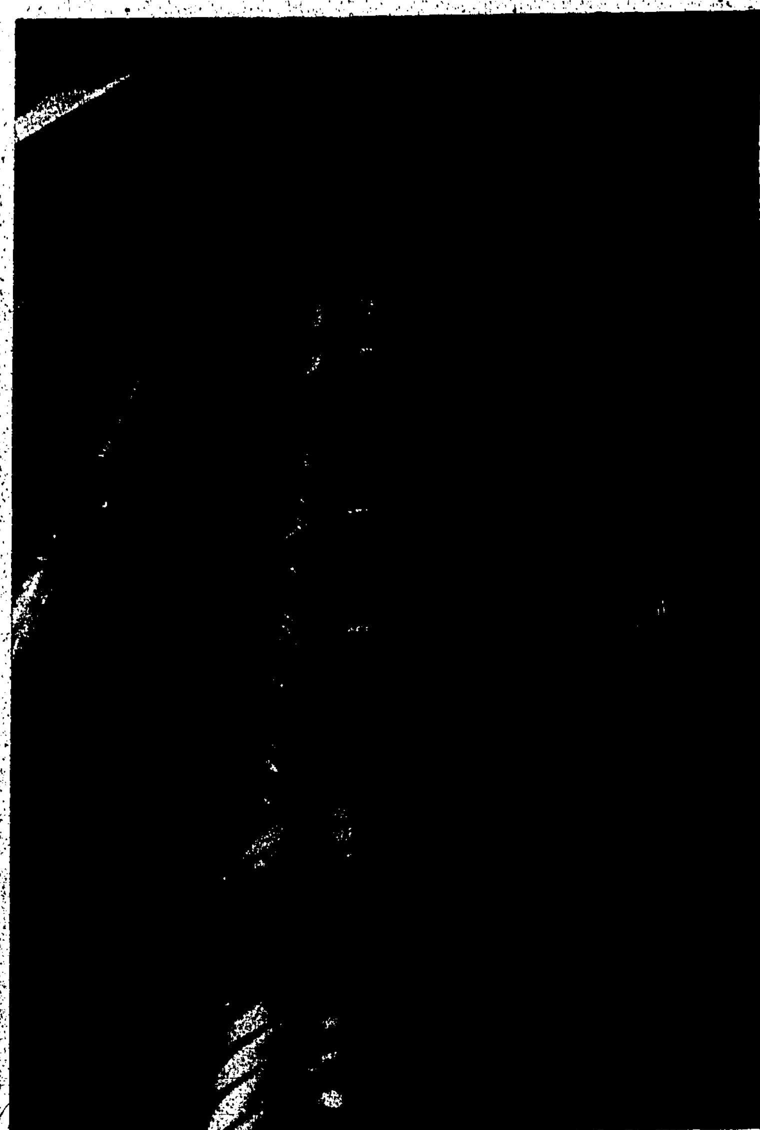


Plate 4.2 Overview of Culvert #2 with Fish-baffles

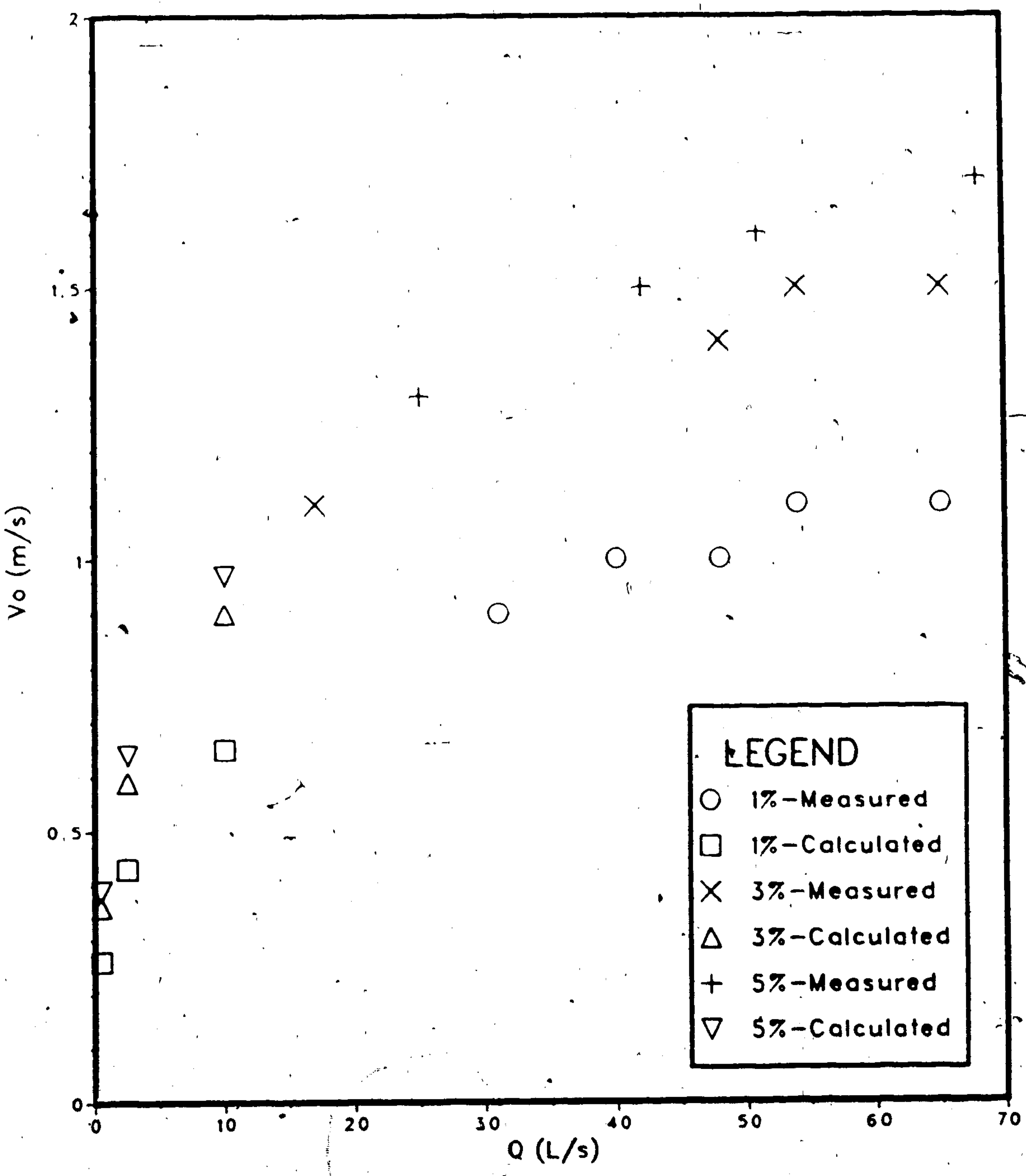
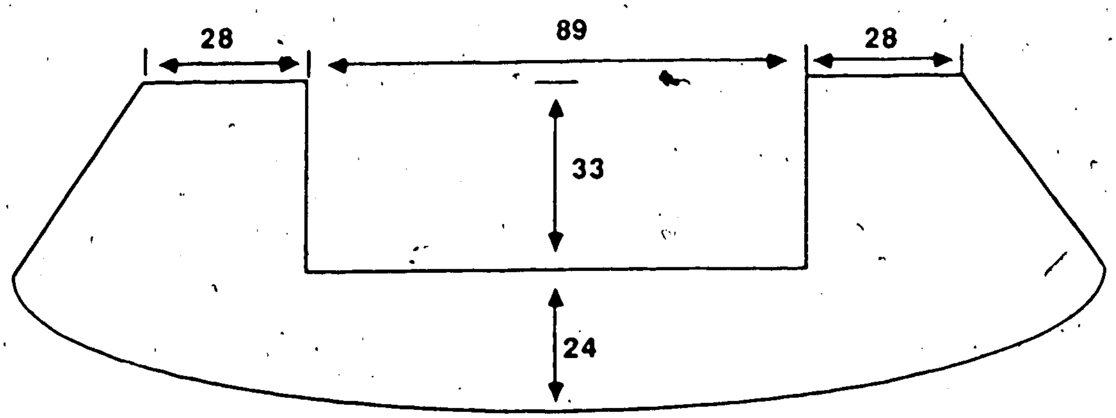


Figure 4.3 Average Velocity (V_o) versus Model Discharge (Q) for Culvert #1.



WEIR THICKNESS = 65

NOTE: all measurements are in millimeters

Figure 4.4 Fish-weir Geometry.

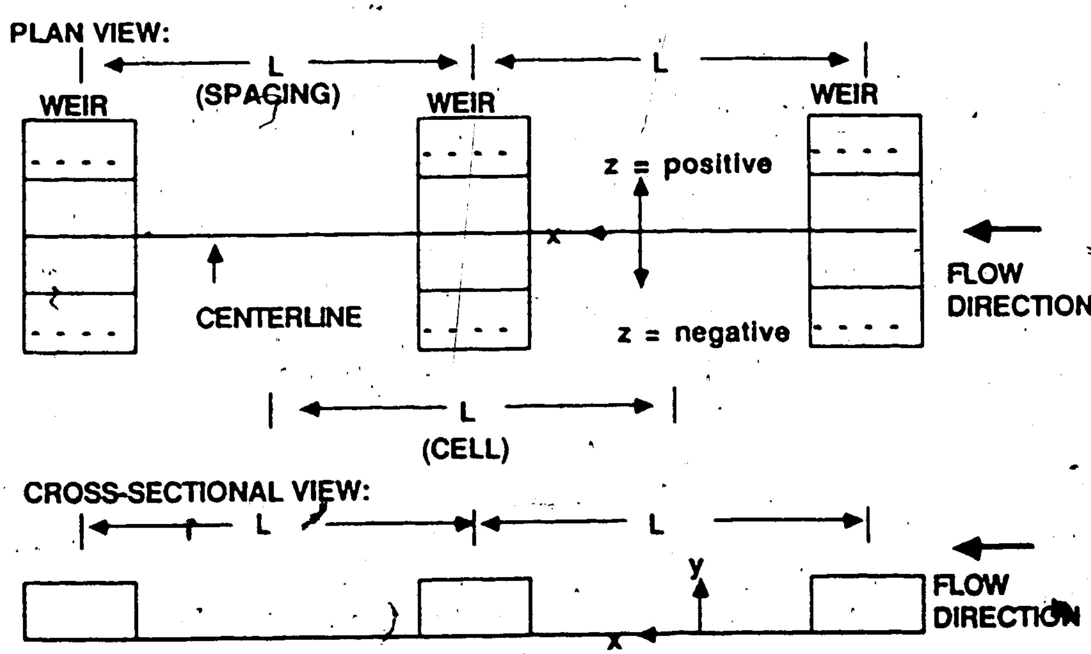


Figure 4.5 Arrangement of Fish-weirs.

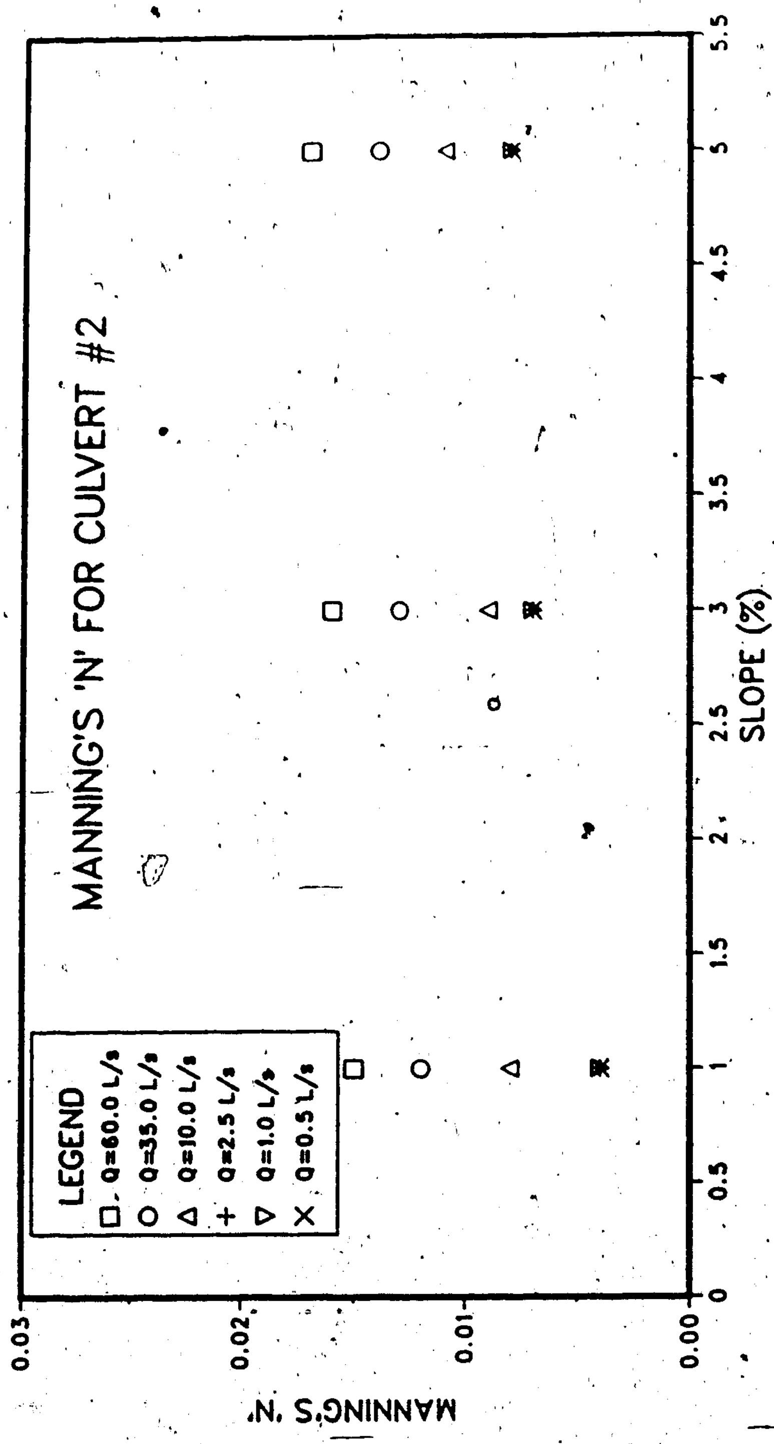


Figure 4.6 Manning's 'n' for Culvert #2.

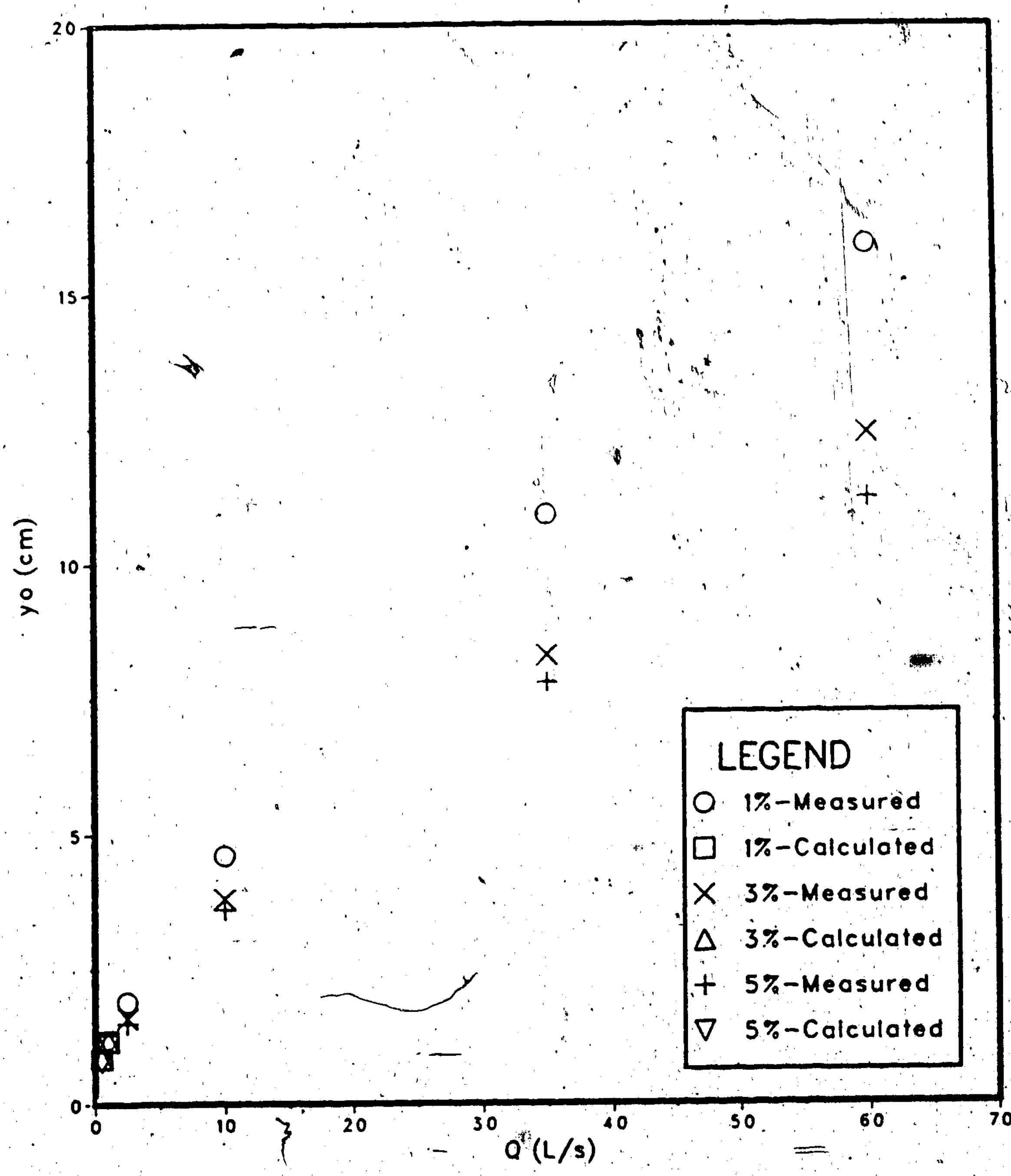


Figure 4.7 Average Depth (y_o) versus Model Discharge (Q) for Culvert #2.

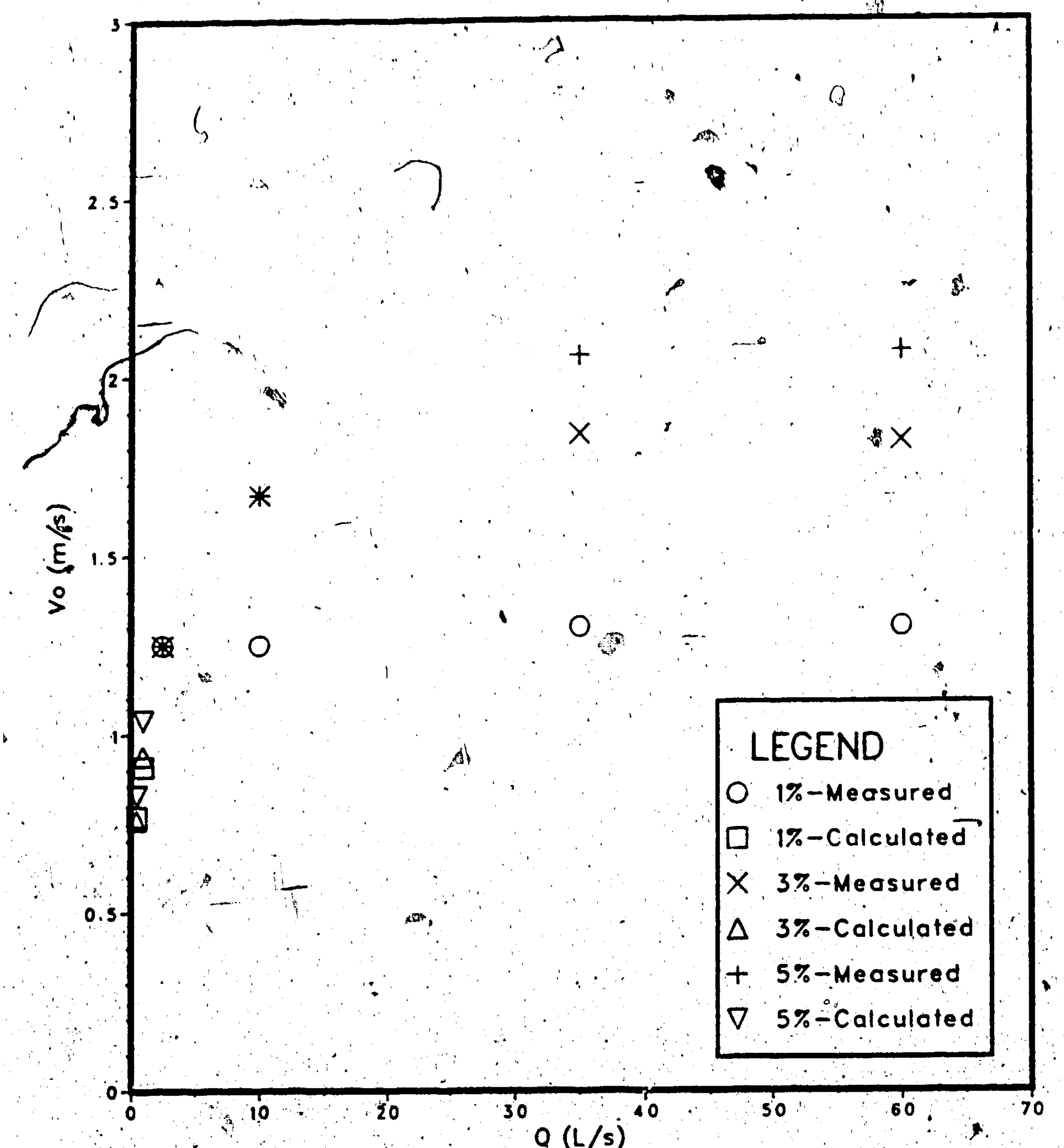


Figure 4.8 Average Velocity (V_o) versus Model Discharge (Q) for Culvert #2.

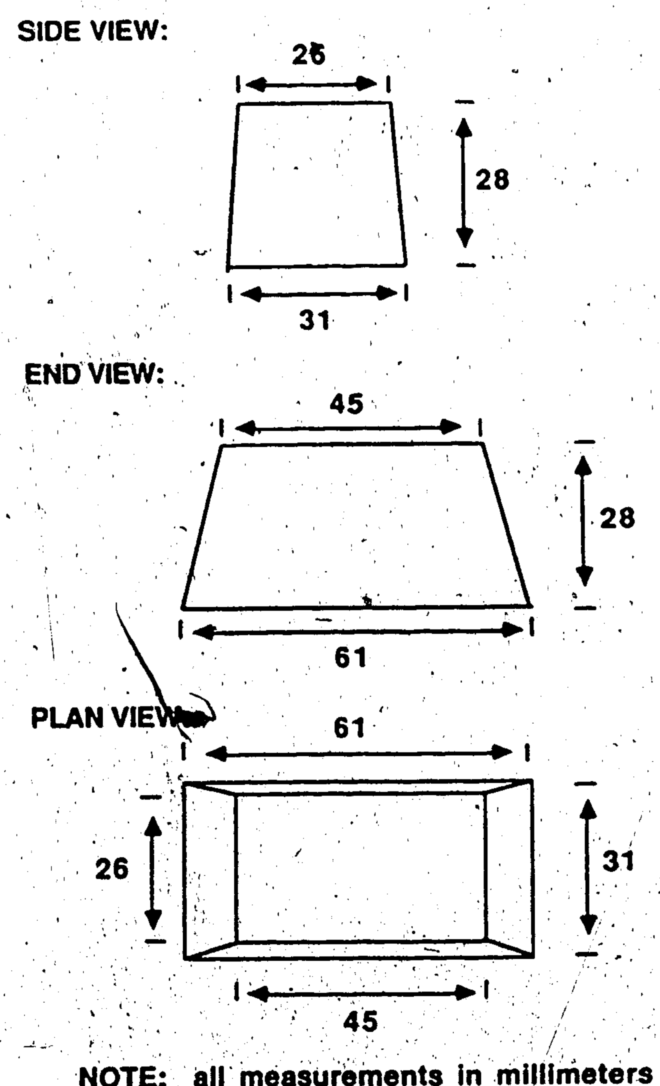


Figure 4.9 Fish-baffle Geometry.

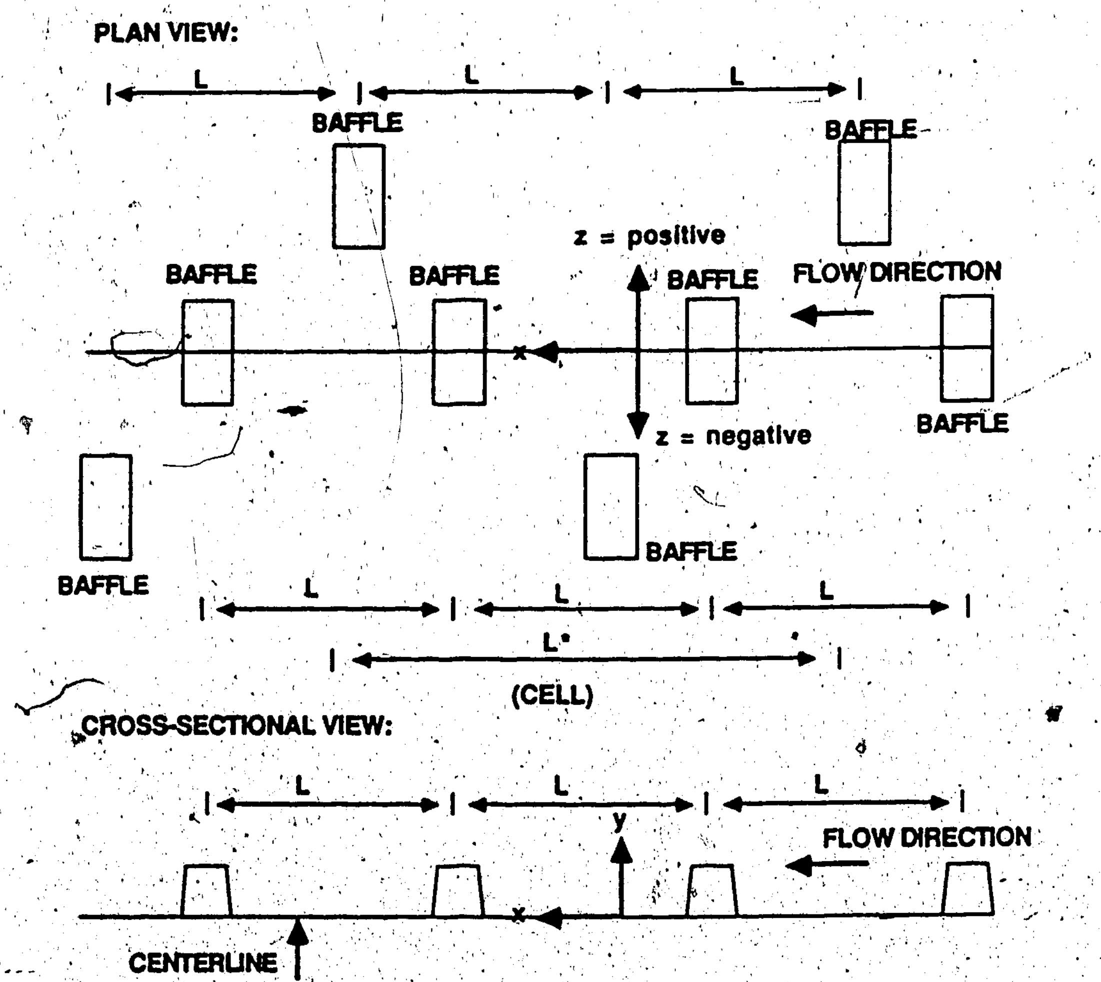


Figure 4.10 Arrangement of Fish-baffles.

Plate 4.1 Fish-weir Model

Plate 4.3 Close-up of Culvert #2 with Fish-baffles

5. ANALYSIS

5.1 Fish-weirs: designs 1-4

5.1.1 Depth Profiles

A study of the depth profiles (Figure 5.1) indicates that in general, as the flow approaches the fish-weir, the depth increases due to the flow obstruction and the water surface falls as the water passes over the weir and continues to accelerate until it faces the backed up water caused by the downstream weir (Plate 5.1). The nature of the variation of the water depth changes from one design to another due to the spacing length between the fish-weirs as well as with the slope and the discharge (Plates 5.2, 5.3, 5.4 and 5.5).

A non-dimensionlized depth (y/y_o) where y is the water depth in the models and y_o is the average depth in culvert #1 was calculated for each specific design for the three slopes of 1, 3, and 5% and the model discharges varying from 0.5 to 35.0 L/s. These variation of y/y_o with x/L for a full cell and for the designs are shown in Figure 5.2 {(a-c for Design 1, (g-i) for Design 2, (m-o) for Design 3 and (s-u) for Design 4}. A study of these figures illustrate the effect of baffle spacing on the increase of depth as well as the effect of the slope of the culvert and the flow rate.

This increase of depth is noticeable at the two lowest discharges where the fish-weirs have an effect on the flow regime (ie., where y/y_o is much greater than 1.0). At the two highest discharges the fish-weirs have less of an effect (ie., where y/y_o is close to 1.0)(Table 5.1).

From the model study, the fish-weirs could be an obstacle to upstream fish movement at the lowest discharge (Q_M=0.5 L/s - Q_P=2.1 ft^3/s) as the depths over the central portion of the fish-weir and immediately downstream are very low for all four designs at all three slopes (depth range: y_M=0.2-4.8 centimeters and y_P=1.4-32.4 centimeters or 0.5-12.8 inches). The recommended minimum depth for the trout species is 6 inches (15 centimeters) which inhabit most of Alberta's mountain streams. Table 5.2 summarizes the depth and velocity values (model and prototype) for the center portion of the fish-weirs for the two lowest discharges. An important question to be asked is how significant is the lowest discharge (Q_M=0.5 L/s, Q_P=2.1 ft^3/s) for fish passage in natural stream conditions? There is a chance that this discharge could produce very low depths in natural stream conditions and fish passage may not be possible. It is essential that the prototype discharges are studied for the natural stream conditions so as to know what is the minimum fish passage discharge.

5.1.2 Velocity profiles

A study of the numerous centerline velocity profiles (Figure 5.3) shows that at most of these sections, the velocity distribution is (approximately) uniform either through most of the depth or at least in the upper half of the flow. For each section a characteristic velocity u_m was chosen which is equal to the maximum velocity at that section. In most of the sections, it is a measure (perhaps conservative) of the velocity which the fish will have to contend with while passing upstream through the culvert.

The velocities for all four designs at all three slopes at the lowest discharge (Q_M=0.5 L/s - Q_P=2.1 ft^3/s) ranged between u_M= 0.03-0.47 m/s (u_P= 0.08-1.22 m/s or 0.26-4.01 ft/s). At the second lowest discharge (Q_M=2.5 L/s - Q_P=10.4 ft^3/s), the velocities ranged between u_M= 0.16-1.01 m/s (u_P= 0.42-2.62 m/s or 1.36-8.61 ft/s). The majority of the velocities were at the lower end of the range. These velocities are less than the recommended velocities for fish passage outlined in Chapter 2. Evans and Johnston (1976) recommended that the maximum allowable velocities for trout is 4 ft/sec (1.2 m/s). An important aspect in the measuring of the water velocities is the length of the maximum velocities between fish-weirs as all fish have a maximum swimming distance for a particular water velocity before it must rest. Therefore, it is essential that the length of the maximum velocities is calculated and related to the particular fish species in question so as to mimimize this length.

A non-dimensionalized velocity (u_m/V_o) where u_m is the maximum velocity and V_o is the uniform velocity was calculated for designs 1 to 4 for the three slopes of 1, 3, 5% and model discharges varying from 0.5 to 35.0 L/s. The variation of u_m/V_o with x/L for the full cell for designs 1-4 is shown in the remaining figures of Figure 5.2. A study of these plots indicates that the maximum value of u_m/V_o for each design occurs immediately downstream of the fish-weirs.

For design 1, for the slope of 1%, $(u_m/V_o)_m$ = 1.5 where $(u_m/V_o)_m$ denotes the maximum value of (u_m/V_o). For slopes of 3% and 5%, the corresponding maximum value of (u_m/V_o) is also about 1.5. For design 2, this maximum value is about 1.3. For designs 3 and 4, the maximum value is about 1.2. Table 5.2 summarizes the maximum values for the dimensionless depth and characteristic velocity variations for the fish-weirs.

A step-wise multiple regression was applied to the following model variables: S_o, Q, L, y_{min}, u_{mm}, y_o and $Q/D^{5/2}$ to determine the relationship between the model minimum depth (y_{min}) and the following variables $Q/D^{5/2}$, S_o, y_o and L. Also, to determine a relationship between the maximum value of the maximum velocity (u_{mm}) and the same four independent variables ($Q/D^{5/2}$, S_o, y_o and L). The results for this regression are presented in Appendix A.

5.2 Fish-baffles: designs 5-7

5.2.1 Depth profiles

A study of these water surface profiles (Figure 5.4) indicates that the fish-baffles do not function like the fish-weirs but simply appear to act like large roughness elements increasing the resistance to flow thereby producing larger depths of flow and reducing the maximum velocities. The effects of the three spacings on the flow patterns are shown in Plates 5.6 to 5.8.

The depth profile data for all three fish-baffle designs at the lowest discharge (Q_M=0.5 L/s - Q_P=2.1 ft^3/s) indicate a depth range (y_M) of 0.5-2.7 centimeters (y_P= 3.4-18.2 centimeters or 1.3-7.2 inches). For the second lowest discharge (Q_M=2.5 L/s - Q_P=10.4 ft^3/s), the depth range (y_M) is 1.7-5.3 centimeters (y_P= 11.5-35.8 centimeters or 4.5-14.1 inches). The depths for the lowest discharge are below the recommended depths for fish passage outlined in Chapter 2. Again, the minimum recommended depths for the trout species is 15 centimeters (6 inches) (Evans and Johnston, 1976). Since the fish-baffles are designed to have the greatest effect at the lower flow rates, the depths measured with the fish-baffles in place for all the designs are still quite low. This could indicate that the lowest discharge may produce low depths in natural stream conditions resulting in no possible fish passage. Again, it is important that the minimum fish passage discharge be known.

The variation of y/y_o with x/L* for the designs 5 to 7 is shown in Figure 5.5 {(a-c) for design 5, (g-i) for design 6 and (m-o) for design 7}. For design 5, $(y/y_o)_m$ (i.e. the maximum value of y/y_o) for 1% slope is about 1.4 for larger flow rates whereas for the smaller flow rates, it is as large as 2.6. This indicates that the fish-baffles are effective at the lower flow rates (ie., y/y_o is much greater than 1.0). For the same design, for the 5% slope, the corresponding maximum values are about 1.4 and 2.3 respectively. Table 5.3 lists the maximum values for the dimensionless depth and characteristic velocities variations for designs 5 to 7 for the three slopes and the four model discharges.

5.2.2 Velocity profiles

Considering the characteristic velocity ratio (u_m/V_o), the variation of this ratio with x/L* is shown in Figure 5.5 {(d-f) for design 5, (j-l) for design 6 and (p-r) for design 7}. For design 5, the maximum value of (u_m/V_o) (ie., $(u_m/V_o)_m$) varies from about 0.5 to 1.0 depending mainly upon the flow rate (Table 5.3). For design 6 and design 7 the corresponding limits are 0.4 to 0.9. From these figures, one can also note that the velocities in the slot area between the staggered baffles lie within these limits. These figures indicate that the fish-baffles do reduce the maximum velocities since u_m/V_o is less than 1.0.

The fish-baffles do not span the entire width of the culvert so the fish swimming upstream can choose its own desirable path and may not have to contend with the maximum velocities at all times. Table 5.4 lists the minimum and maximum velocities and depths for the two lowest discharges and gives both model and prototype values for a scale ratio (L_r = 6.75). The velocity range (u_M) for the lowest discharge (Q_M=0.5 L/s - Q_P=2.1 ft^3/s) for all three fish-baffle designs and at the three slopes is 0.16-0.73 m/s (u_P= 0.42-1.90 m/s or 1.36-6.22 ft/s). At the second lowest discharge, the velocity range (u_M) is 0.27-1.01 m/s (u_P= 0.70-2.62 m/s or 2.30-8.60 ft/s. A majority of these measured velocities for the two lowest discharges are below the recommended maximum allowable velocity of 4 ft/sec (1.21 m/s).

From the flow visualization experiments, the fish-baffles caused large eddies between the pairs of baffles (Plates 5.6 to 5.8) for the two smallest discharges thus giving the fish many resting areas while moving upstream through the culvert.

Again, a step-wise multiple regression was applied to the same model variables as in the fish-weirs and the results are available in Appendix A.

Table 5.1 Maximum values for the Dimensionless Depth and Characteristic Velocity variations for the Fish-weirs.

CODE	$(y/y_0)_m$	$(u_m/V_o)_m$	CODE	$(y/y_0)_m$	$(u_m/V_o)_m$
1110350	1.2	1.1	1110100	1.4	1.2
1210350	1.3	1.0	1210100	1.5	1.1
1310350	1.3	1.0	1310100	1.5	1.2
1410350	1.2	1.0	1410100	1.4	1.2
1110025	1.8	1.5	1110005	2.8	1.4
1210025	2.0	1.1	1210005	2.4	1.3
1310025	1.9	1.1	1310005	2.2	1.1
1410025	1.8	1.3	1410005	1.9	0.9
1130350	1.3	1.0	1130100	1.8	1.2
1230350	1.4	0.9	1230100	1.7	1.0
1330350	1.3	1.0	1330100	1.8	1.0
1430350	1.3	1.0	1430100	1.6	1.2
1130025	2.4	1.5	1130005	3.4	1.2
1230025	2.3	1.2	1230005	3.1	1.3
1330025	2.1	1.1	1330005	2.6	0.8
1430025	2.2	1.2	1430005	2.4	0.6
1150350	1.4	1.1	1150100	1.8	1.2
1250350	1.5	1.0	1250100	1.8	1.1
1350350	1.3	1.0	1350100	1.8	0.9
1450350	1.3	1.0	1450100	1.6	1.2
1150025	2.6	1.6	1150005	3.6	1.0
1250025	2.5	1.2	1250005	3.3	1.0
1350025	2.2	1.2	1350005	2.7	0.5
1450025	2.3	1.2	1450005	2.4	0.8

Table 5.2 Model(16 inch diameter) and Prototype(108 inch diameter) (L_r=6.75) Depth and Velocity measurements for the Fish-weirs.

Design	S_0	Q_M	Q_P		y_M	y_P		u_M	u_P	
	(%)	(m^3/s)	(m^3/s)	(ft^3/s)	(cm)	(cm)	(in)	(m/s)	(m/s)	(ft/s)
1	1	.0025	0.290	10.4	3.1	20.9	8.2	0.52	1.35	4.4
1	1	.0005	0.059	2.1	0.8	5.4	2.1	0.27	0.70	2.3
1	3	.0025	0.290	10.4	3.0	20.2	8.0	0.60	1.56	5.1
1	3	.0005	0.059	2.1	0.8	5.4	2.1	0.43	1.12	3.7
1	5	.0025	0.290	10.4	2.4	16.2	6.4	0.59	1.53	5.0
1	5	.0005	0.059	2.1	1.1	7.4	2.9	0.35	0.91	3.0
2	1	.0025	0.290	10.4	3.3	22.3	8.8	0.46	1.20	3.9
2	1	.0005	0.059	2.1	0.7	4.7	1.8	0.34	0.88	2.9
2	3	.0025	0.290	10.4	3.0	20.2	8.0	0.57	1.48	4.8
2	3	.0005	0.059	2.1	0.7	4.7	1.8	0.44	1.14	3.7
2	5	.0025	0.290	10.4	2.8	18.9	7.4	0.62	1.61	5.3
2	5	.0005	0.059	2.1	0.7	4.7	1.8	0.40	1.04	3.4
3	1	.0025	0.290	10.4	3.4	23.0	9.0	0.46	1.20	3.9
3	1	.0005	0.059	2.1	0.4	2.7	1.1	-	-	-
3	3	.0025	0.290	10.4	2.7	18.2	7.2	0.61	1.58	5.2
3	3	.0005	0.059	2.1	0.2	1.4	0.6	-	-	-
3	5	.0025	0.290	10.4	2.5	16.9	6.6	0.69	1.79	5.9
3	5	.0005	0.059	2.1	0.2	1.4	0.6	-	-	-
4	1	.0025	0.290	10.4	2.7	18.2	7.2	0.55	1.43	4.7
4	1	.0005	0.059	2.1	0.3	2.0	0.8	-	-	-
4	3	.0025	0.290	10.4	2.5	16.9	6.6	0.58	1.51	5.0
4	3	.0005	0.059	2.1	0.4	2.7	1.1	-	-	-
4	5	.0025	0.290	10.4	2.4	16.2	6.4	0.62	1.61	5.3
4	5	.0005	0.0.59	2.1	0.3	2.0	0.8	-	-	-

Table 5.3 Maximum values for the Dimensionless Depth and Characteristic Velocity Variations for the Fish-baffles.

CODE	$(y/y_o)_m$	$(u_m/V_o)_m$	CODE	$(y/y_o)_m$	$(u_m/V_o)_m$
2510350	1.3	0.9	2510100	1.5	0.8
2610350	1.3	0.8	2610100	1.9	0.8
2710350	1.3	0.8	2710100	1.7	0.7
2510025	2.4	0.5	2510005	2.7	0.7
2610025	[illegible].7	0.5	2610005	3.1	0.6
2710025	2.8	0.4	2710005	3.2	0.5
2530350	1.3	0.9	2530100	1.6	0.8
2630350	1.4	0.8	2630100	1.7	0.7
2730350	1.4	0.9	2730100	1.7	0.6
2530025	2.7	0.7	2530005	2.2	0.9
2630025	2.9	0.6	2630005	2.9	0.7
2730025	2.8	0.5	2730005	2.4	0.8
2550350	1.3	1.0	2550100	1.5	0.9
2650350	1.3	0.9	2650100	1.8	0.8
2750350	1.4	0.9	2750100	1.7	0.7
2550025	2.3	0.8	2550005	2.4	0.9
2650025	2.9	0.7	2650005	2.5	0.8
2750025	2.7	0.6	2750005	2.6	0.9

Table 5.4 Model(16 inch diameter) and Prototype(108 inch diameter) (L_r=6.75) Depth and Velocity measurements for the Fish-baffles.

Design	S_o	Q_M	Q_P		y_M	y_P		u_M	u_P	
	(%)	(m^3/s)	(m^3/s)	(ft^3/s)	(cm)	(cm)	(in)	(m/s)	(m/s)	(ft/s)
5	1	.0025	.290	10.4	3.4*	23.0	9.0	0.27*	0.70	2.30
5	1	.0025	.290	10.4	4.6**	31.0	12.2	0.44	1.14	3.75
5	1	.0025	.290	10.4	4.5	30.4	12.0	0.63**	1.64	5.37
5	1	.0005	.059	2.1	1.4*	9.4	3.7	0.40	1.04	3.41
5	1	.0005	.059	2.1	2.3**	15.5	6.1	0.56**	1.45	4.77
5	1	.0005	.059	2.1	1.8	12.2	4.8	0.20*	0.52	1.70
6	1	.0025	.290	10.4	3.6*	24.3	9.6	0.41*	1.06	3.49
6	1	.0025	.290	10.4	4.2	28.4	11.2	0.41*	1.06	3.49
6	1	.0025	.290	10.4	5.1**	34.4	13.6	0.42	1.09	3.58
6	1	.0025	.290	10.4	4.5	30.4	12.0	0.55**	1.43	4.69
6	1	.0005	.059	2.1	1.5*	10.1	4.0	0.35	0.91	2.98
6	1	.0005	.059	2.1	2.6**	17.6	6.9	0.26	0.68	2.22
6	1	.0005	.059	2.1	1.9	12.8	5.0	0.19*	0.49	1.62
6	1	.0005	.059	2.1	2.0	13.5	5.3	0.46**	1.20	3.92
7	1	.0025	.290	10.4	4.0*	27.0	10.6	0.39	1.01	3.32
7	1	.0025	.290	10.4	5.3**	35.8	14.1	0.40	1.04	3.41
7	1	.0025	.290	10.4	4.5	30.4	12.0	0.37*	0.96	3.15
7	1	.0025	.290	10.4	4.6	31.0	12.2	0.54**	1.40	4.60
7	1	.0005	.059	2.1	1.9*	12.8	5.0	0.29	0.75	2.47
7	1	.0005	.059	2.1	2.7**	18.2	7.2	0.26	0.68	2.22
7	1	.0005	.059	2.1	2.0	13.5	5.3	0.17*	0.44	1.45
7	1	.0005	.059	2.1	2.5	16.9	6.6	0.40**	1.04	3.41
5	3	.0025	.290	10.4	2.0*	13.5	5.3	0.81	2.08	6.82
5	3	.0025	.290	10.4	3.6**	24.3	9.6	0.66	1.71	5.62
5	3	.0025	.290	10.4	2.0	13.5	5.3	0.56*	1.45	4.77
5	3	.0025	.290	10.4	3.2	21.6	8.5	0.91**	2.36	7.76
5	3	.0005	.059	2.1	0.5*	3.4	1.3	0.56	1.45	4.77
5	3	.0005	.059	2.1	1.9**	12.8	5.0	0.36*	0.94	3.07
5	3	.0005	.059	2.1	0.9	6.1	2.4	0.66**	1.71	5.62
6	3	.0025	.290	10.4	2.7*	18.2	7.2	0.55	1.43	4.69
6	3	.0025	.290	10.4	4.6**	31.0	12.2	0.46	1.20	3.92
6	3	.0025	.290	10.4	3.0	20.2	8.0	0.40*	1.04	3.41
6	3	.0025	.290	10.4	3.8	25.6	10.1	0.75**	1.95	6.39
6	3	.0005	.059	2.1	1.0*	6.8	2.6	0.44	1.14	3.75
6	3	.0005	.059	2.1	1.0*	6.8	2.6	0.48	1.25	4.09
6	3	.0005	.059	2.1	1.0*	6.8	2.6	0.49	1.27	4.18
6	3	.0005	.059	2.1	2.5**	16.9	6.6	0.31	0.80	2.64
6	3	.0005	.059	2.1	1.3	8.8	3.4	0.17*	0.44	1.45
6	3	.0005	.059	2.1	1.6	10.8	4.2	0.55**	1.43	4.69

Table 5.4 Continued...

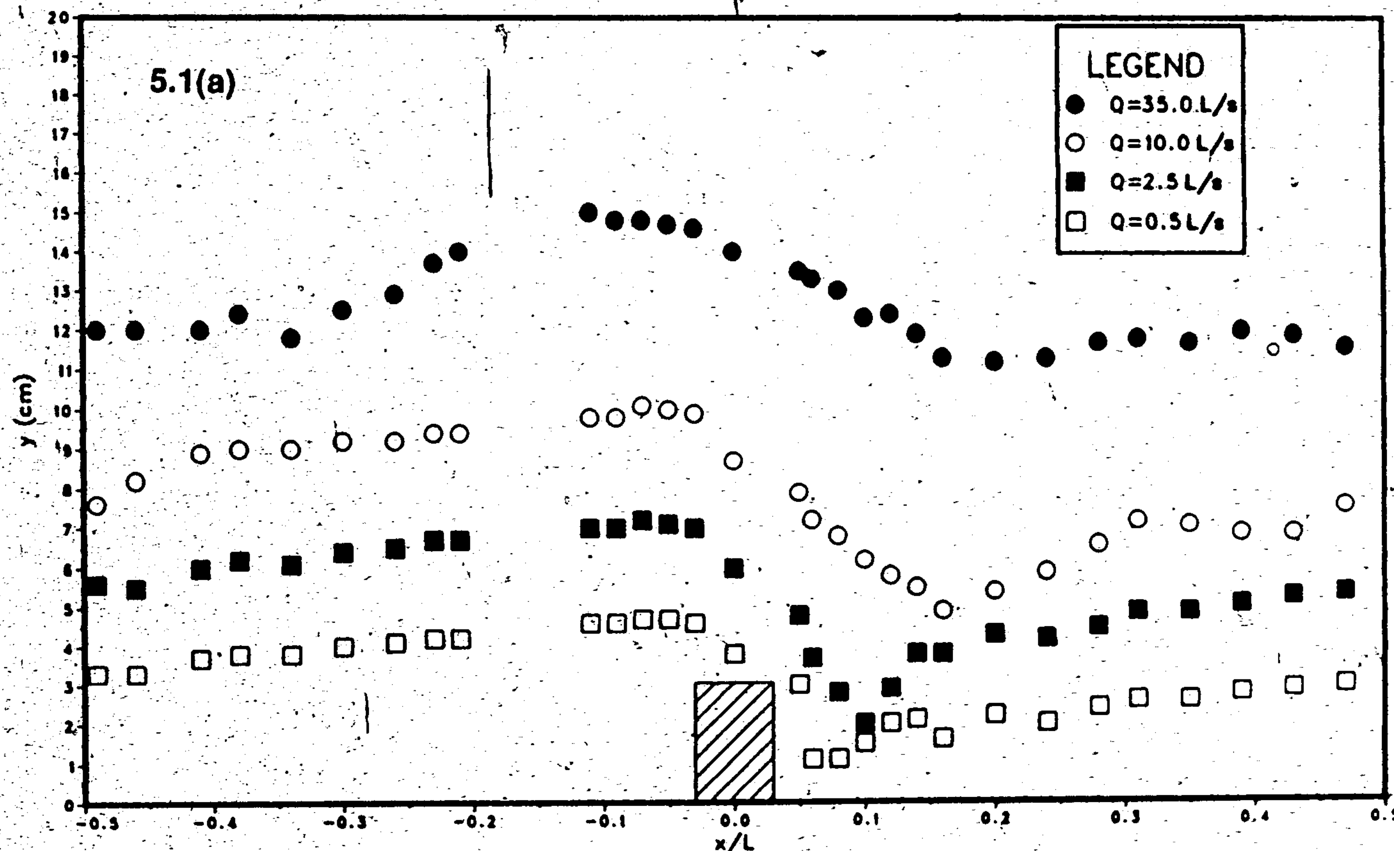
Design	S_o	Q_M	Q_P		y_M	y_P		$\bar{u}_M$	$\bar{u}_P$	
	(%)	(m^3/s)	(m^3/s)	(ft^3/s)	(cm)	(cm)	(in)	(m/s)	(m/s)	(ft/s)
7	3	.0025	.290	10.4	3.4*	23.0	9.0	0.47	1.22	4.01
7	3	.0025	.290	10.4	3.4*	23.0	9.0	0.48	1.25	4.09
7	3	.0025	.290	10.4	4.4**	29.7	11.7	0.56	1.45	4.77
7	3	.0025	.290	10.4	4.2	28.4	11.2	0.41*	1.06	3.49
7	3	.0025	.290	10.4	4.3	29.0	11.4	0.67**	1.74	5.71
7	3	.0005	.059	2.1	1.1*	7.4	2.9	0.34	0.88	2.90
7	3	.0005	.059	2.1	2.1**	14.2	5.6	0.27	0.70	2.30
7	3	.0005	.059	2.1	2.1**	14.2	5.6	0.32	0.83	2.73
7	3	.0005	.059	2.1	2.1**	14.2	5.6	0.37	0.96	3.15
7	3	.0005	.059	2.1	1.6	10.8	4.2	0.18*	0.47	1.53
7	3	.0005	.059	2.1	1.7	11.5	4.5	0.62**	1.61	5.28
5	5	.0025	.290	10.4	1.7*	11.5	4.5	0.95	2.47	8.10
5	5	.0025	.290	10.4	1.7*	11.5	4.5	1.00	2.60	8.52
5	5	.0025	.290	10.4	3.4**	23.0	9.0	0.85	2.21	7.24
5	5	.0025	.290	10.4	2.5	16.9	6.6	0.69*	1.79	5.88
5	5	.0025	.290	10.4	2.0	13.5	5.3	1.01**	2.62	8.61
5	5	.0005	.059	2.1	0.5*	3.4	1.3	0.55	1.43	4.69
5	5	.0005	.059	2.1	1.9**	12.8	5.0	0.55	1.43	4.69
5	5	.0005	.059	2.1	1.9**	12.8	5.0	0.65	1.69	5.54
5	5	.0005	.059	2.1	1.1	7.4	2.9	0.51*	1.32	4.35
5	5	.0005	.059	2.1	0.6	4.0	1.6	0.73**	1.90	6.22
6	5	.0025	.290	10.4	2.2*	14.8	5.8	0.83	2.16	7.07
6	5	.0025	.290	10.4	4.4**	29.7	11.7	0.55	1.43	4.69
6	5	.0025	.290	10.4	2.6	17.6	6.9	0.42*	1.09	3.58
6	5	.0025	.290	10.4	3.7	25.0	9.8	0.85**	2.21	7.24
6	5	.0005	.059	2.1	0.5*	3.4	1.3	0.70**	1.82	5.97
6	5	.0005	.059	2.1	2.0**	13.5	5.3	0.34	0.88	2.90
6	5	.0005	.059	2.1	1.4	9.4	3.7	0.17*	0.44	1.45
7	5	.0025	.290	10.4	2.9*	19.6	7.7	0.51	1.32	4.35
7	5	.0025	.290	10.4	2.9*	19.6	7.7	0.57	1.48	4.86
7	5	.0025	.290	10.4	4.0**	27.0	10.6	0.76**	1.97	6.48
7	5	.0025	.290	10.4	3.4	23.0	9.0	0.34*	0.88	2.90
7	5	.0005	.059	2.1	0.8*	5.4	2.1	0.47	1.22	4.01
7	5	.0005	.059	2.1	0.8*	5.4	2.1	0.73**	1.90	6.22
7	5	.0005	.059	2.1	2.1**	14.2	5.6	0.27	0.70	2.30
7	5	.0005	.059	2.1	1.2	8.1	3.2	0.16*	0.42	1.36

* denotes the minimum value

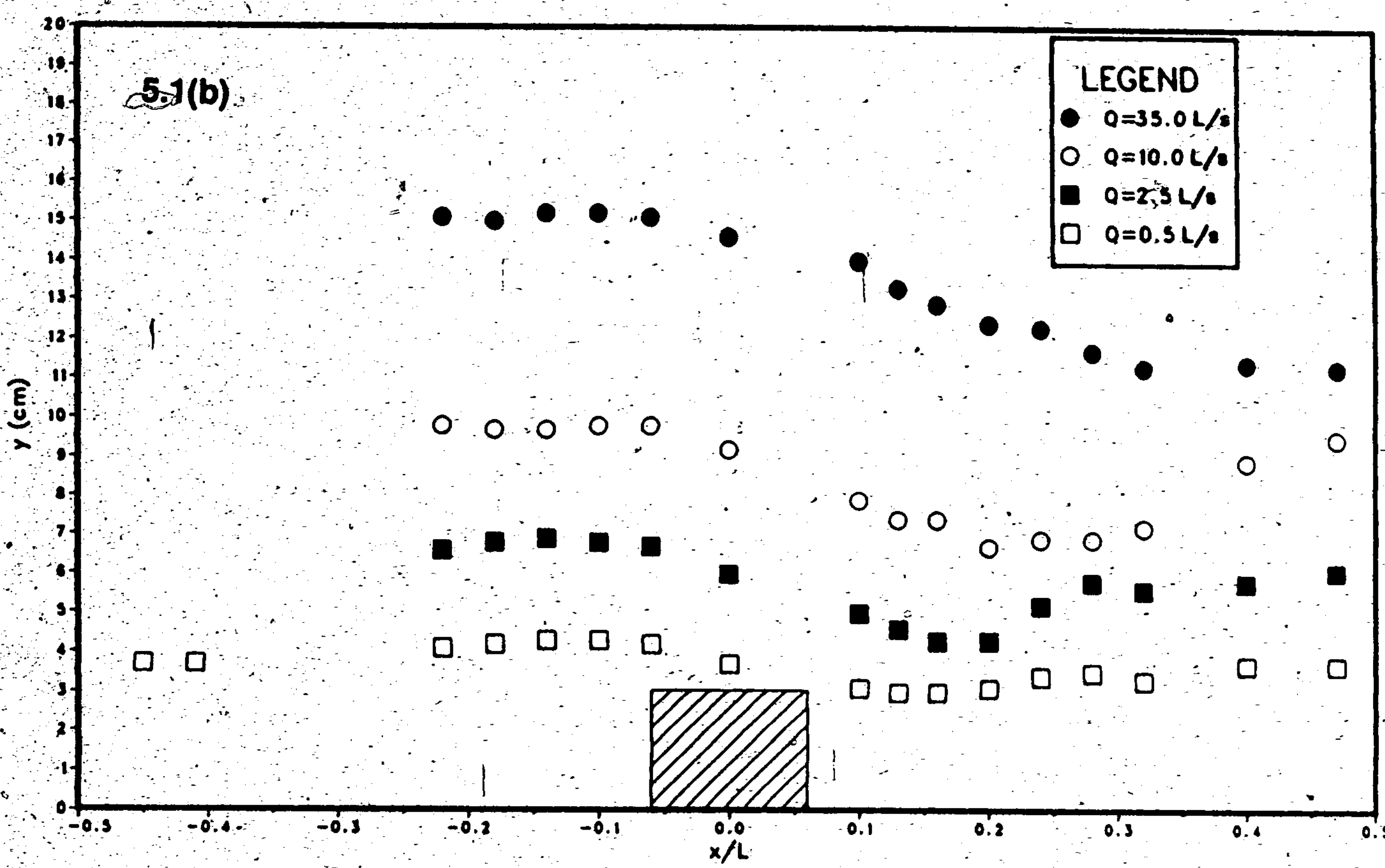
** denotes the maximum value

Figure 5.1 Depth Profiles for Fish-weir Design's #1 to #4 at the 3% Slope.

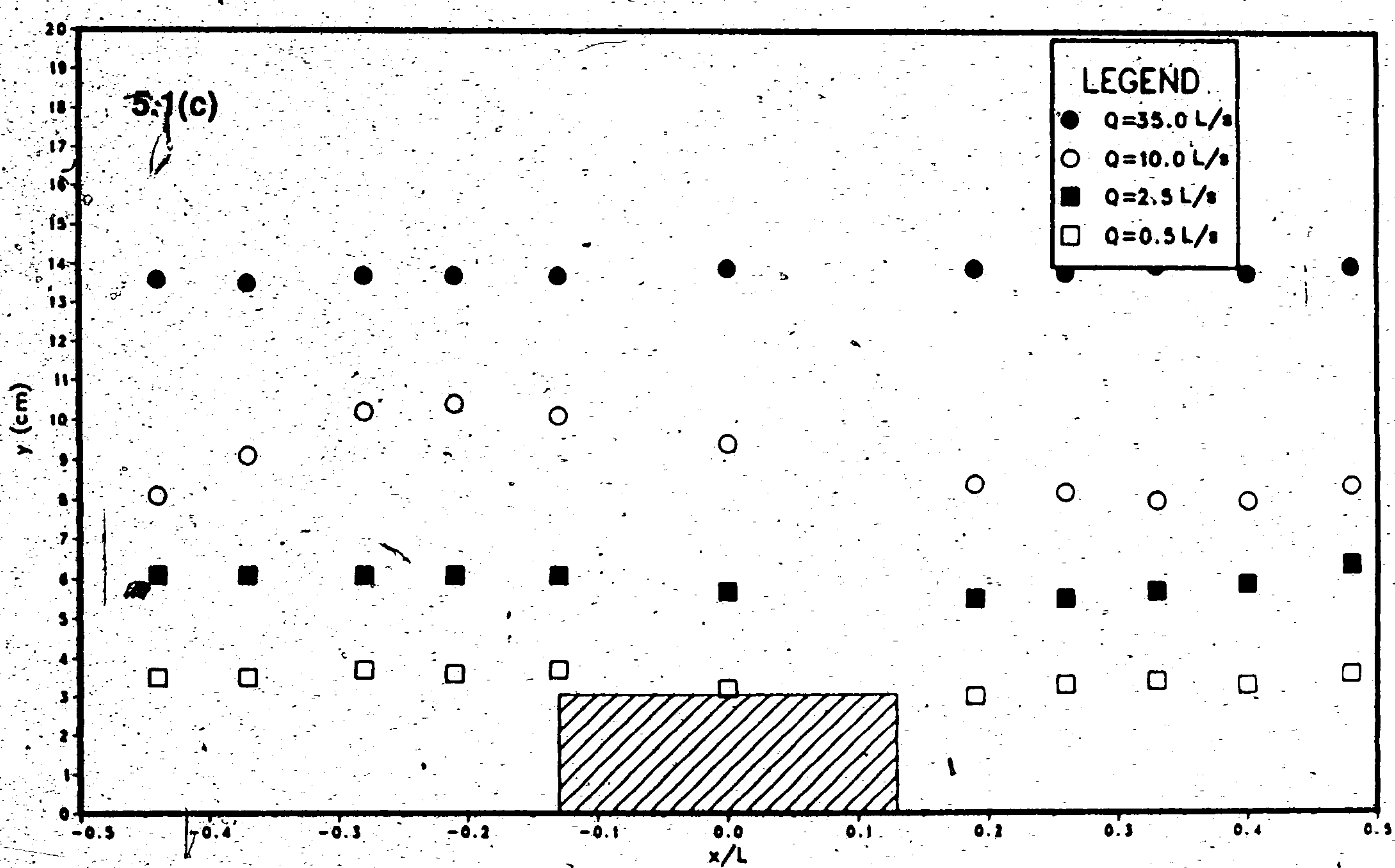
DEPTH PROFILES FOR DESIGN #1 – So=3%



DEPTH PROFILES FOR DESIGN #2 – So=3%



DEPTH PROFILES FOR DESIGN #3 – So=3%



DEPTH PROFILES FOR DESIGN #4 — So=3%

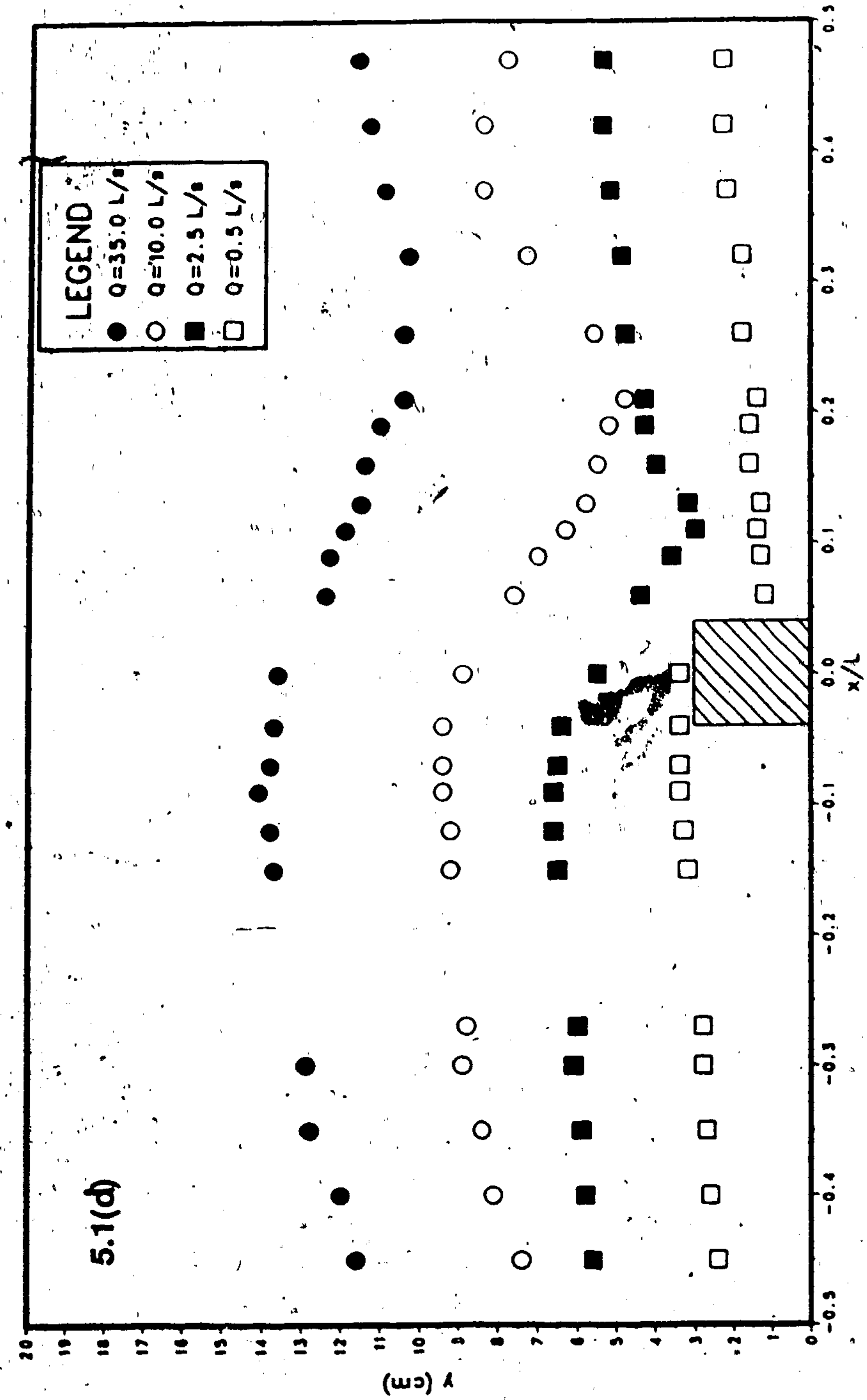
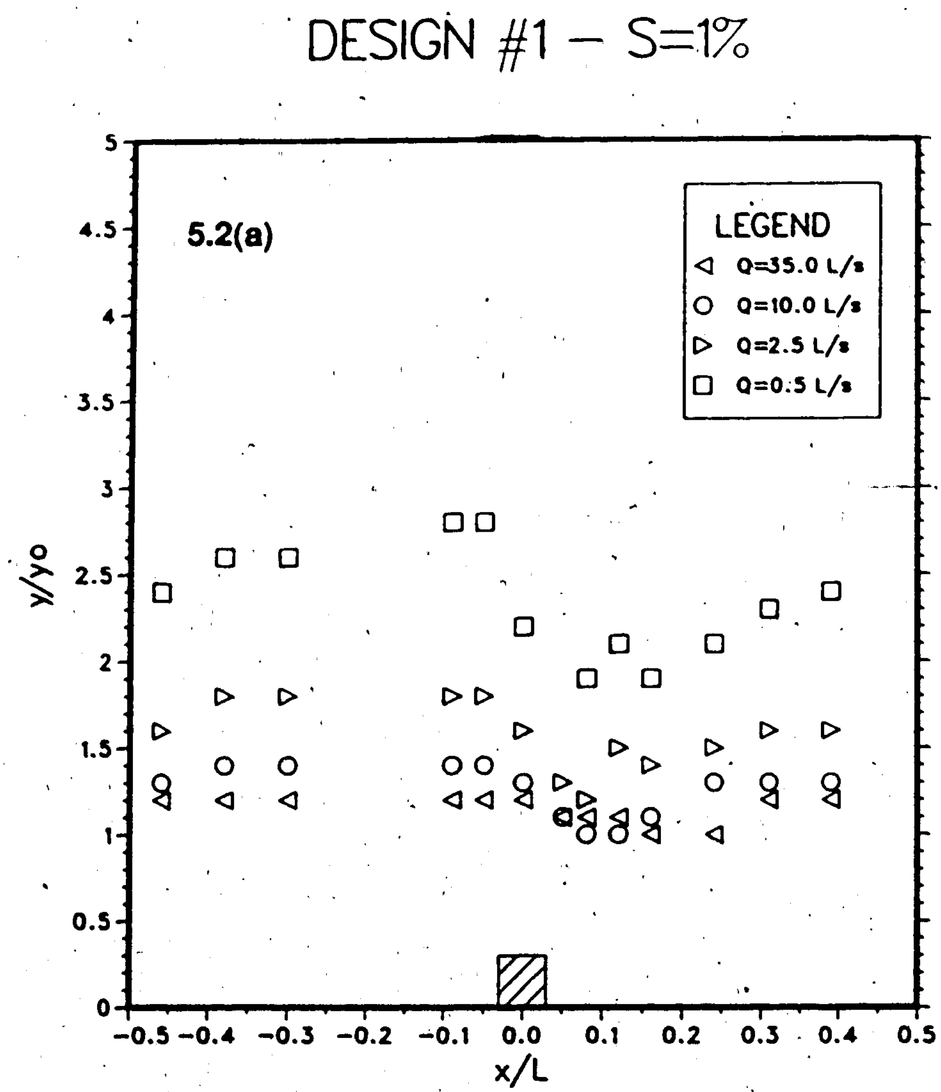
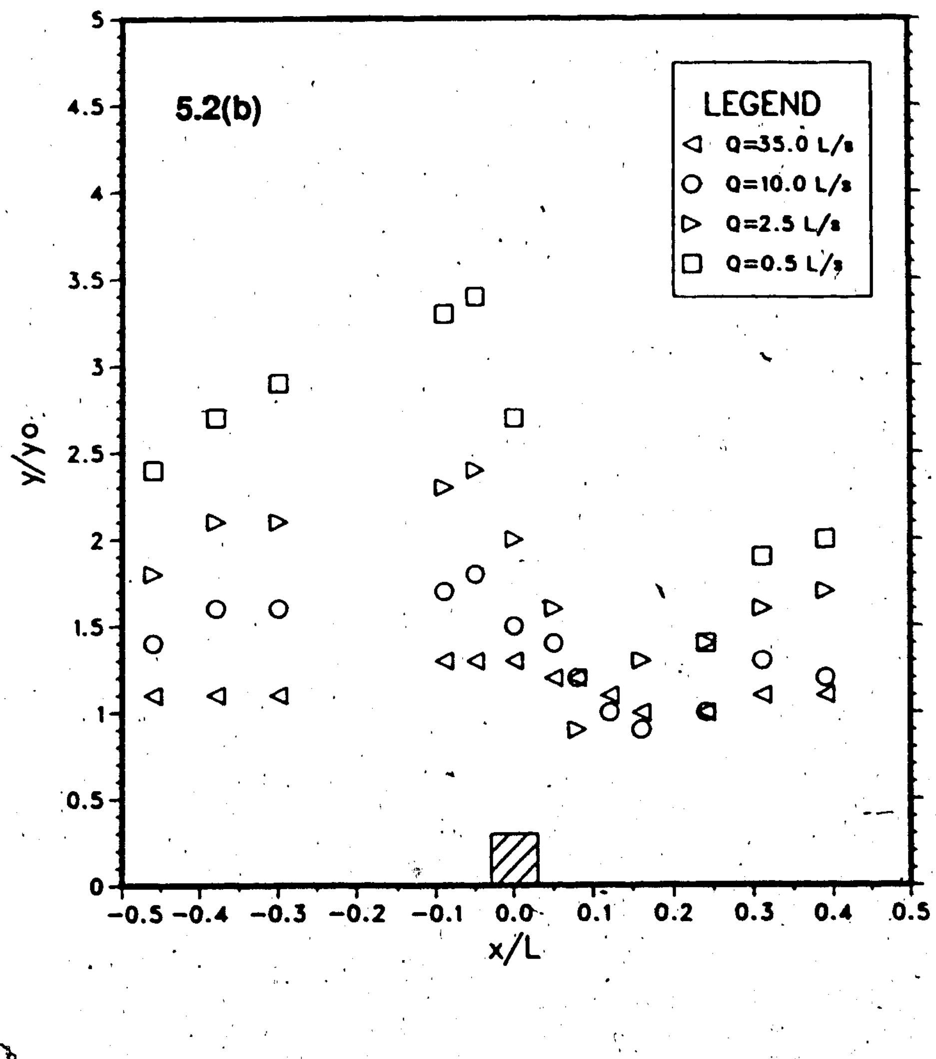


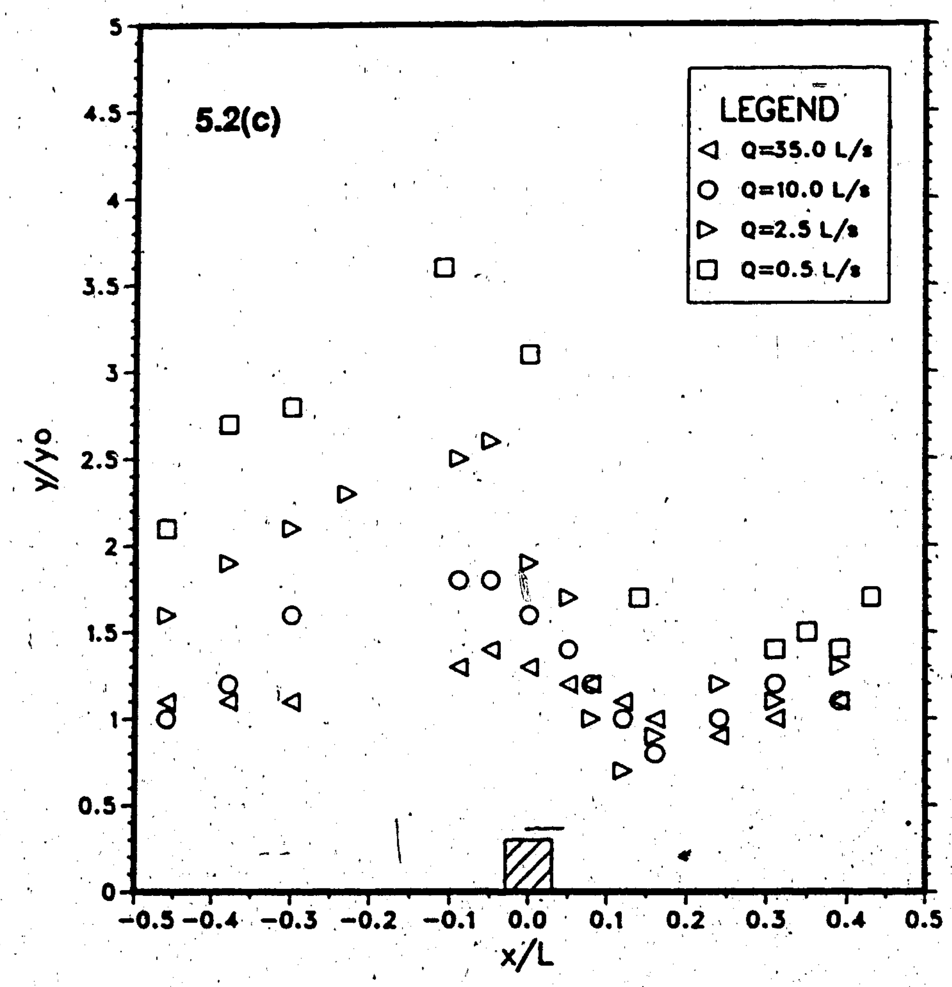
Figure 5.2 Dimensionless Depth and Characteristic Velocity Variations for Fish-weir Designs #1 to #4.


DESIGN #1 – S=1%
5.2(a)
LEGEND
Q=35.0 L/s
Q=10.0 L/s
Q=2.5 L/s
Q=0.5 L/s
y/yo
x/L
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5 -0.4 -0.3 -0.2 -0.1 0.0 0.0 0.1 0.2 0.3 0.4 0.5

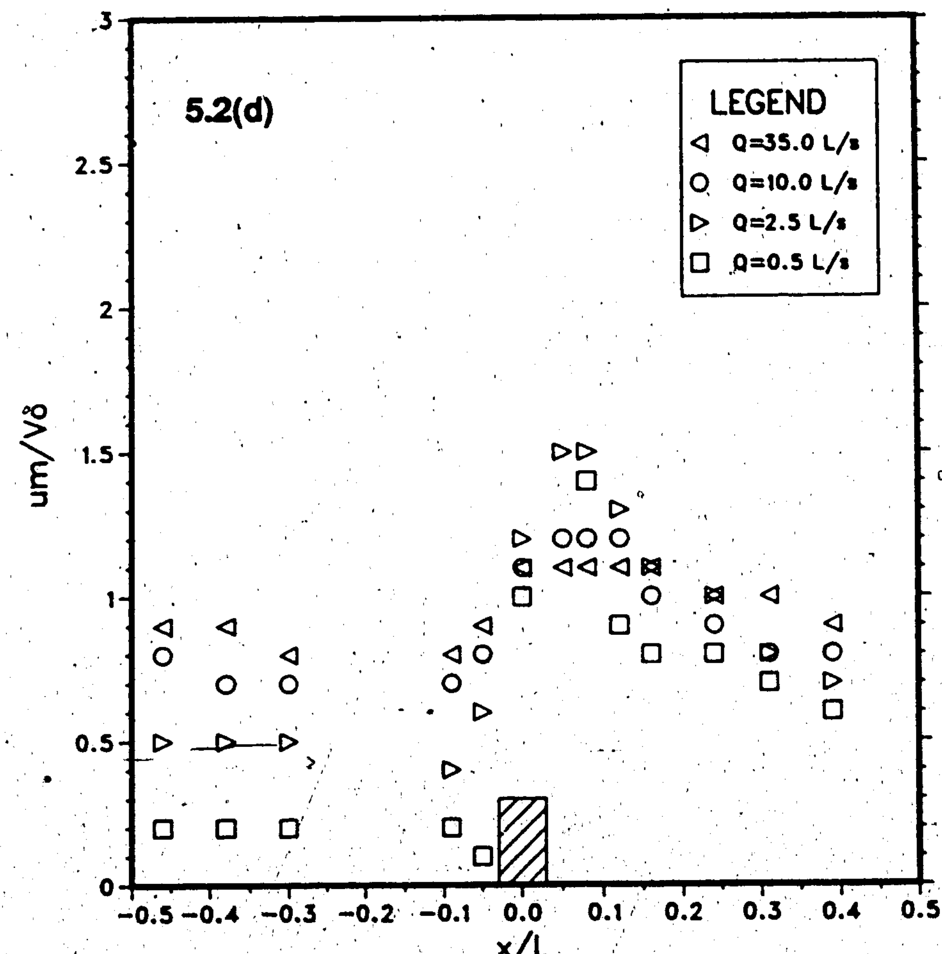
DESIGN #1 – S=3%


5.2(b)
LEGEND
Q=35.0 L/s
Q=10.0 L/s
Q=2.5 L/s
Q=0.5 L/s
y/yo
x/L
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
−0.5
−0.4
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3
0.4
0.5

DESIGN #1 – S=5%

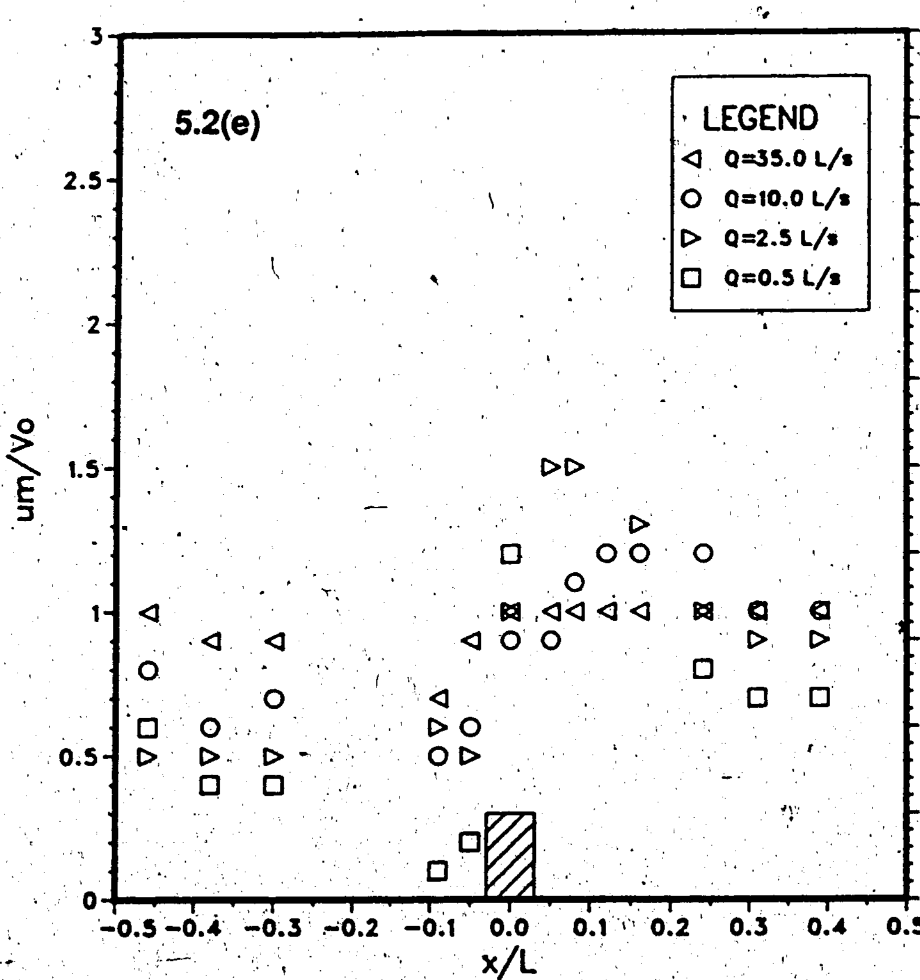

5.2(c)
LEGEND
Q=35.0 L/s
Q=10.0 L/s
Q=2.5 L/s
Q=0.5 L/s
y/yo
x/L
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
−0.5
−0.4
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3
0.4
0.5

DESIGN #1 – S=1%

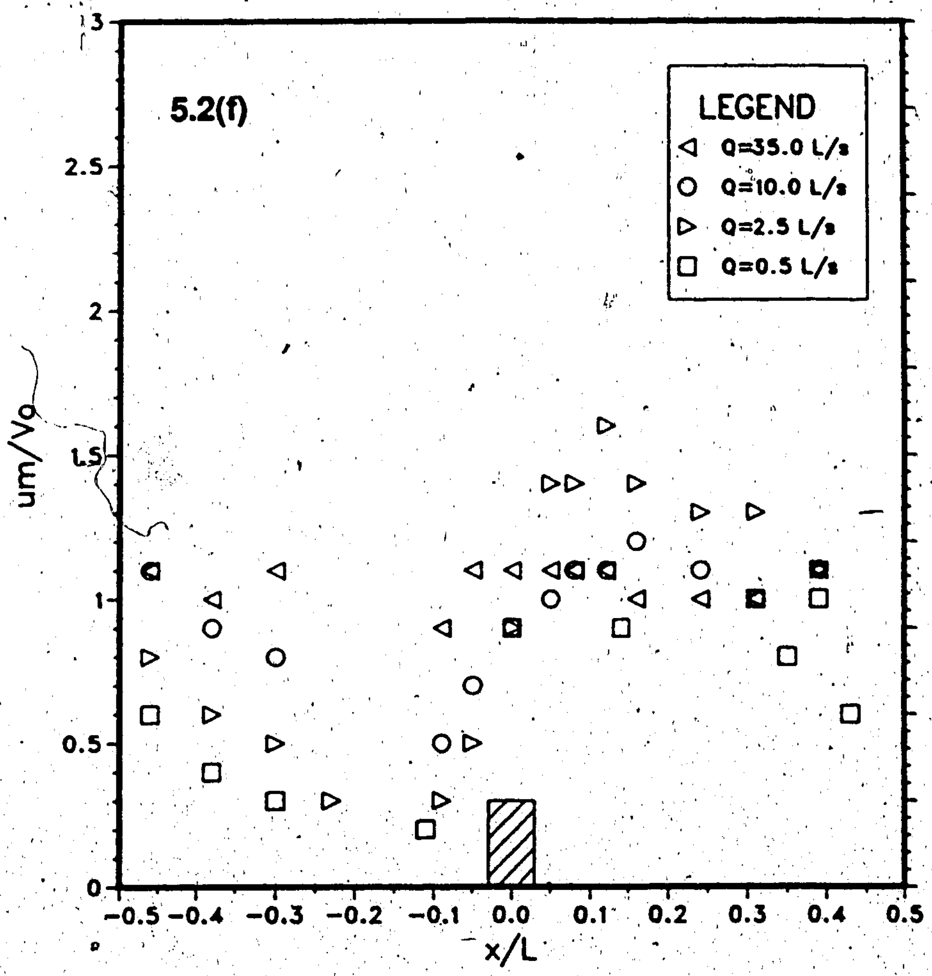


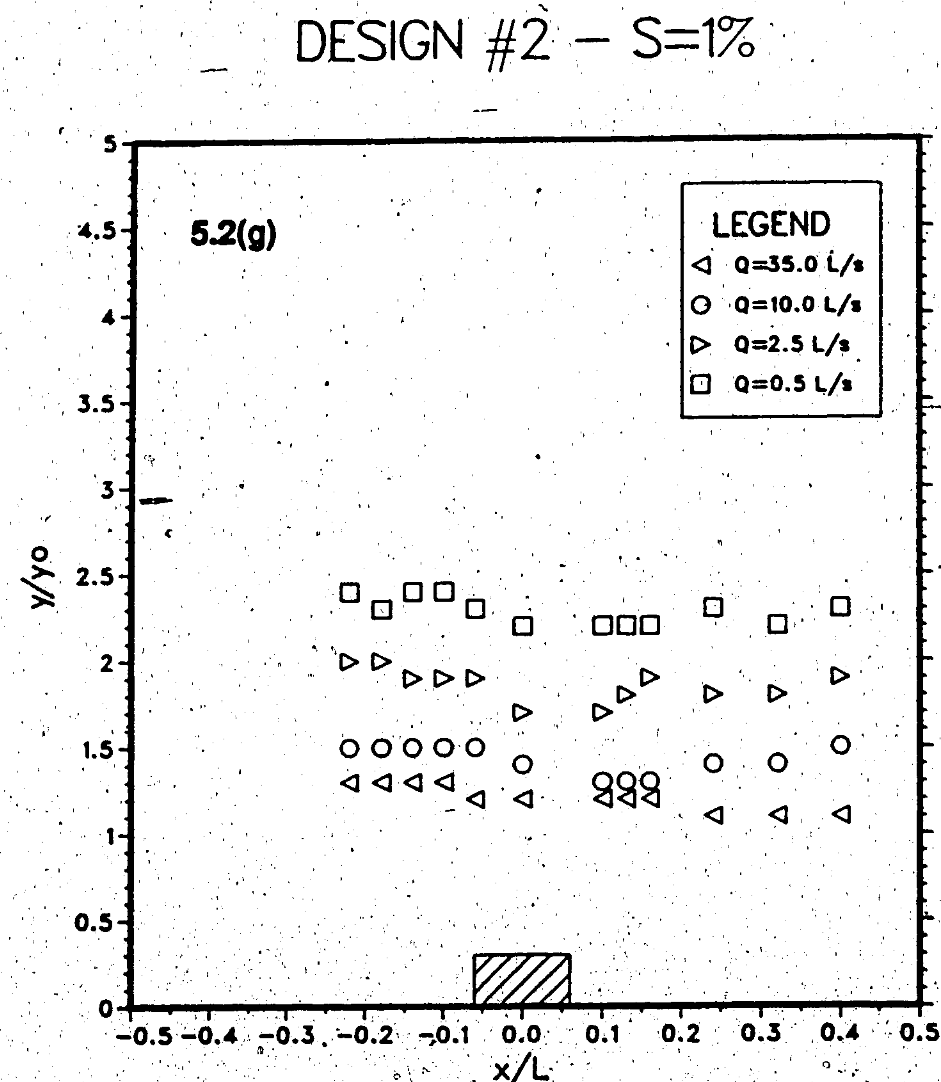
5.2(d)
LEGEND
Q=35.0 L/s
Q=10.0 L/s
Q=2.5 L/s
Q=0.5 L/s
um/Vδ
x/L
3
2.5
2
1.5
1
0.5
0
-0.5 -0.4 -0.3 -0.2 -0.1 0.0 0.1 0.2 0.3 0.4 0.5

DESIGN #1 – S=3%

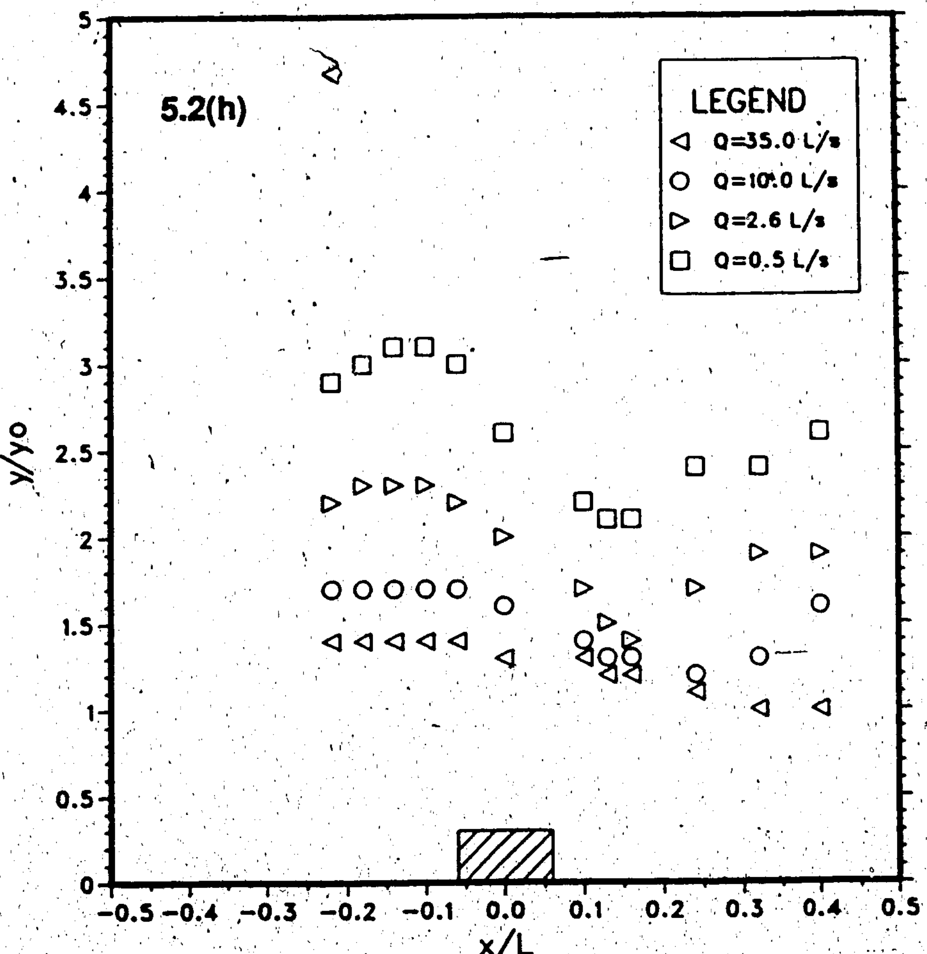

5.2(e)
LEGEND
Q=35.0 L/s
Q=10.0 L/s
Q=2.5 L/s
Q=0.5 L/s
um/Vo
x/L
0
0.5
1
1.5
2
2.5
3
-0.5
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
0.5

DESIGN #1 – S=5%


5.2(f)
LEGEND
Q=35.0 L/s
Q=10.0 L/s
Q=2.5 L/s
Q=0.5 L/s
um/Vo
x/L
0
0.5
1
1.5
2
2.5
3
−0.5
−0.4
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3
0.4
0.5

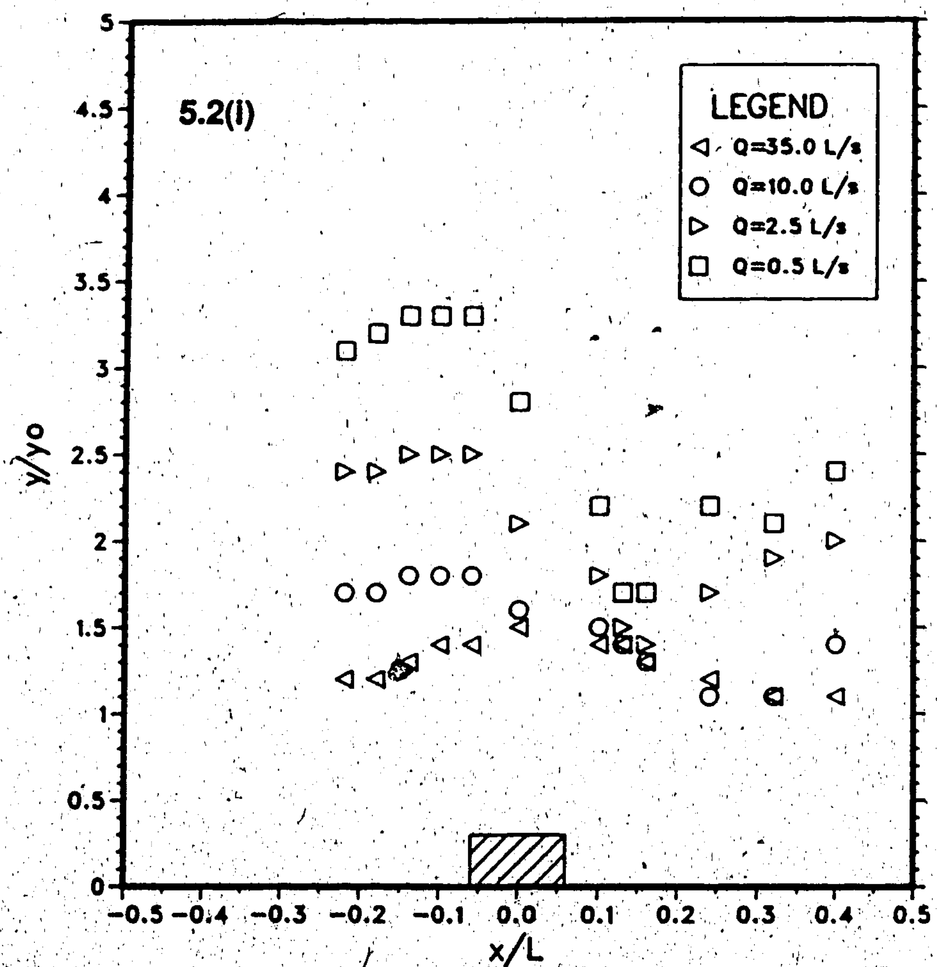

DESIGN #2 – S=1%
5.2(g)
LEGEND
Q=35.0 L/s
Q=10.0 L/s
Q=2.5 L/s
Q=0.5 L/s
y/yo
x/L
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
−0.5
−0.4
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3
0.4
0.5

DESIGN #2 – S=3%

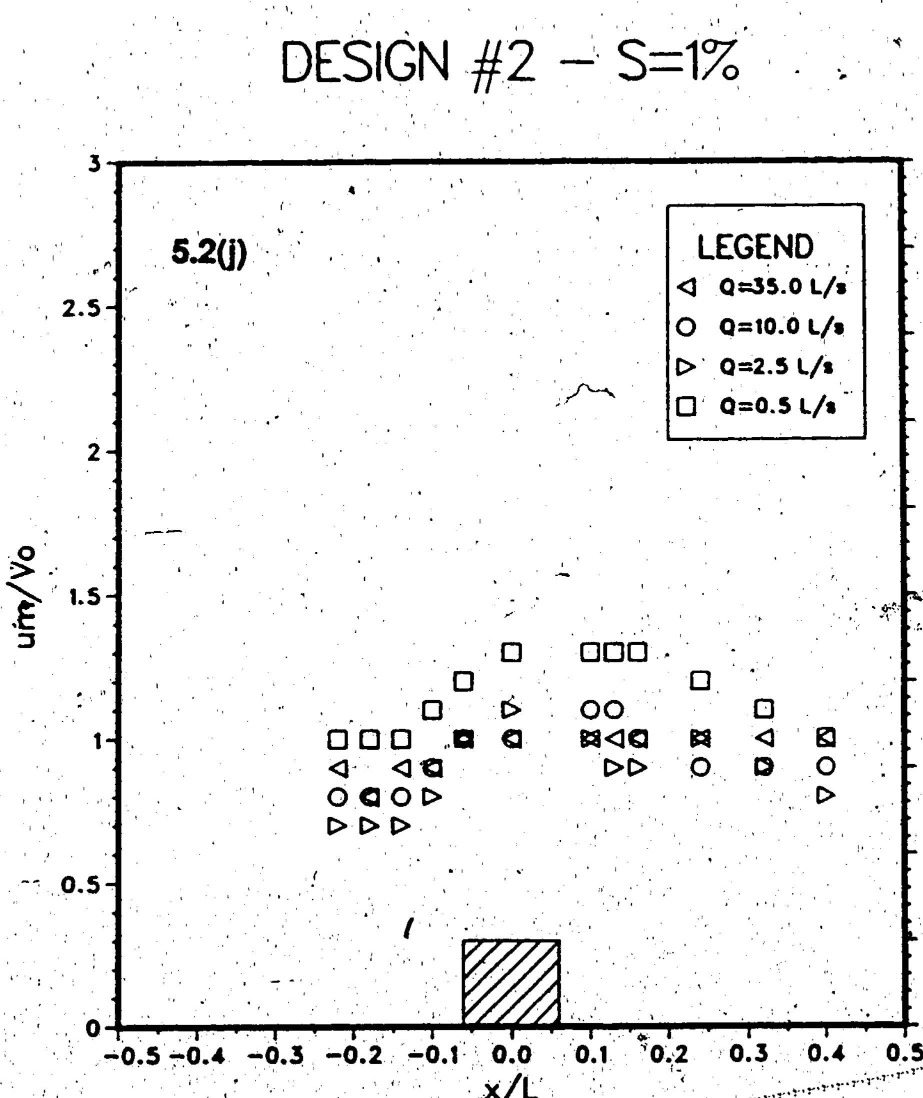


5.2(h)
LEGEND
Q=35.0 L/s
Q=10.0 L/s
Q=2.6 L/s
Q=0.5 L/s
y/yo
x/L
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
-0.5
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
0.5

DESIGN #2 – S=5%

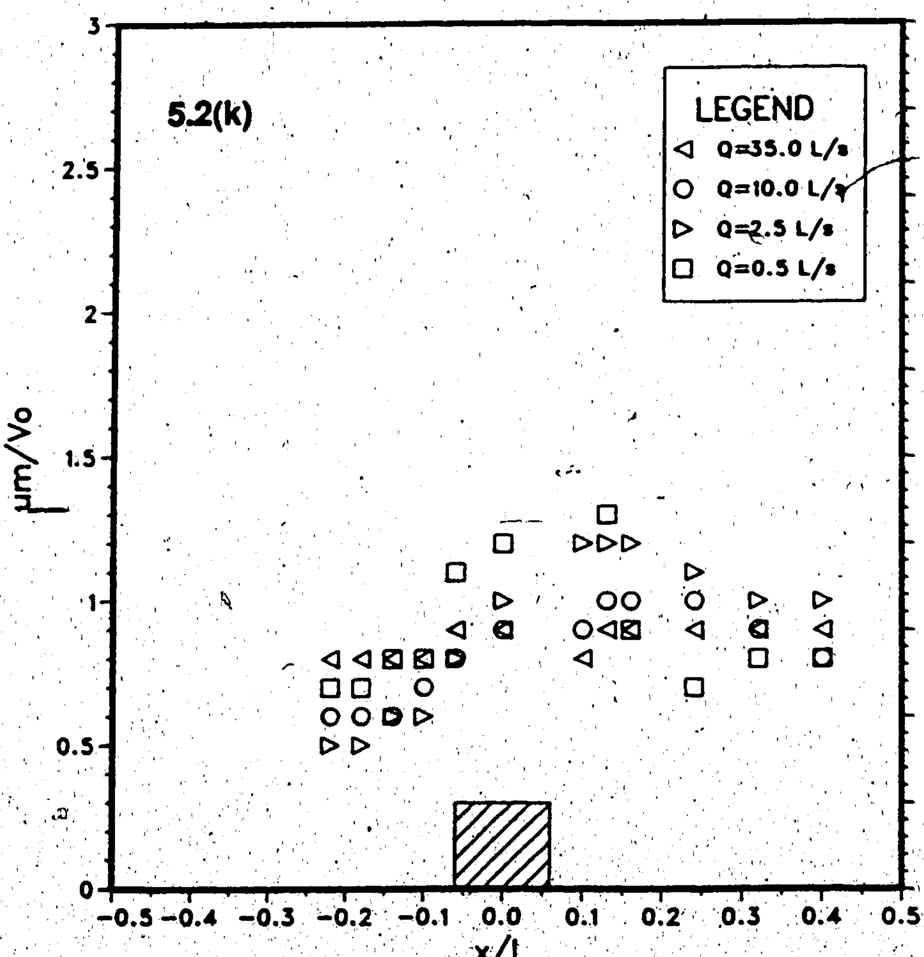


5.2(i)
LEGEND
Q=35.0 L/s
Q=10.0 L/s
Q=2.5 L/s
Q=0.5 L/s
y/yo
x/L
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
−0.5
−0.4
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3
0.4
0.5



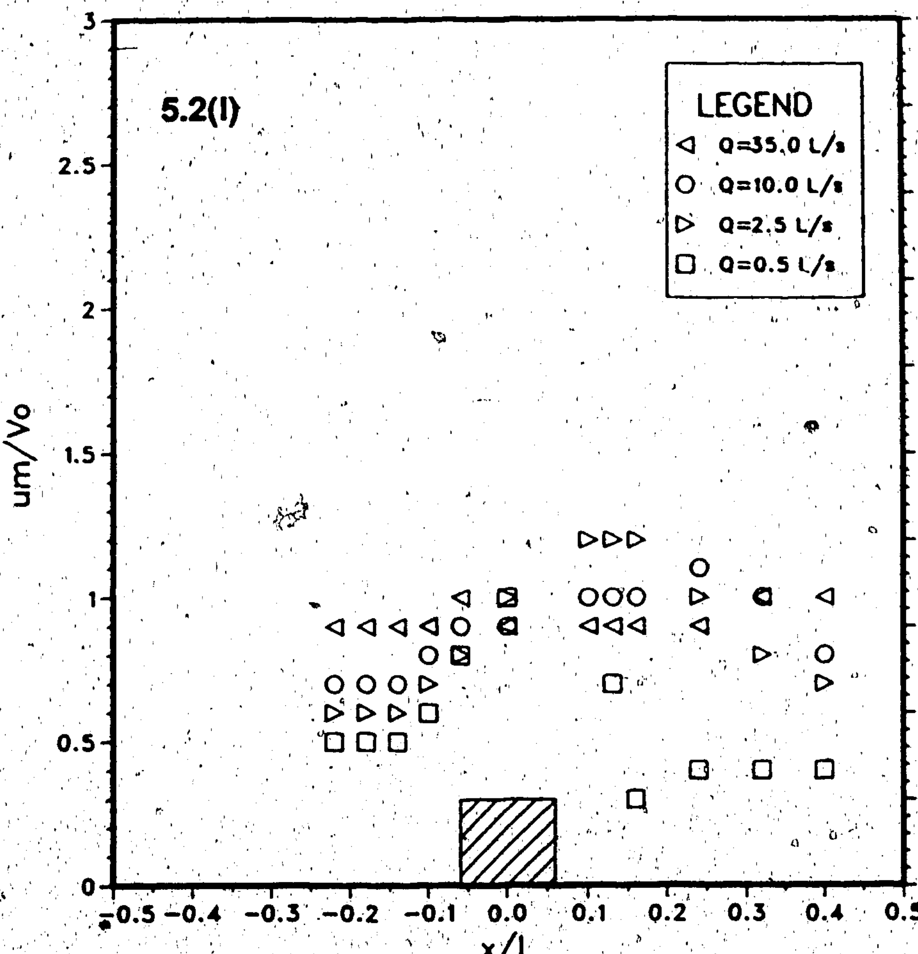
DESIGN #2 - S=1%
5.2(j)
LEGEND
Q=35.0 L/s
Q=10.0 L/s
Q=2.5 L/s
Q=0.5 L/s
um/Vo
x/L

DESIGN #2 - S=3%

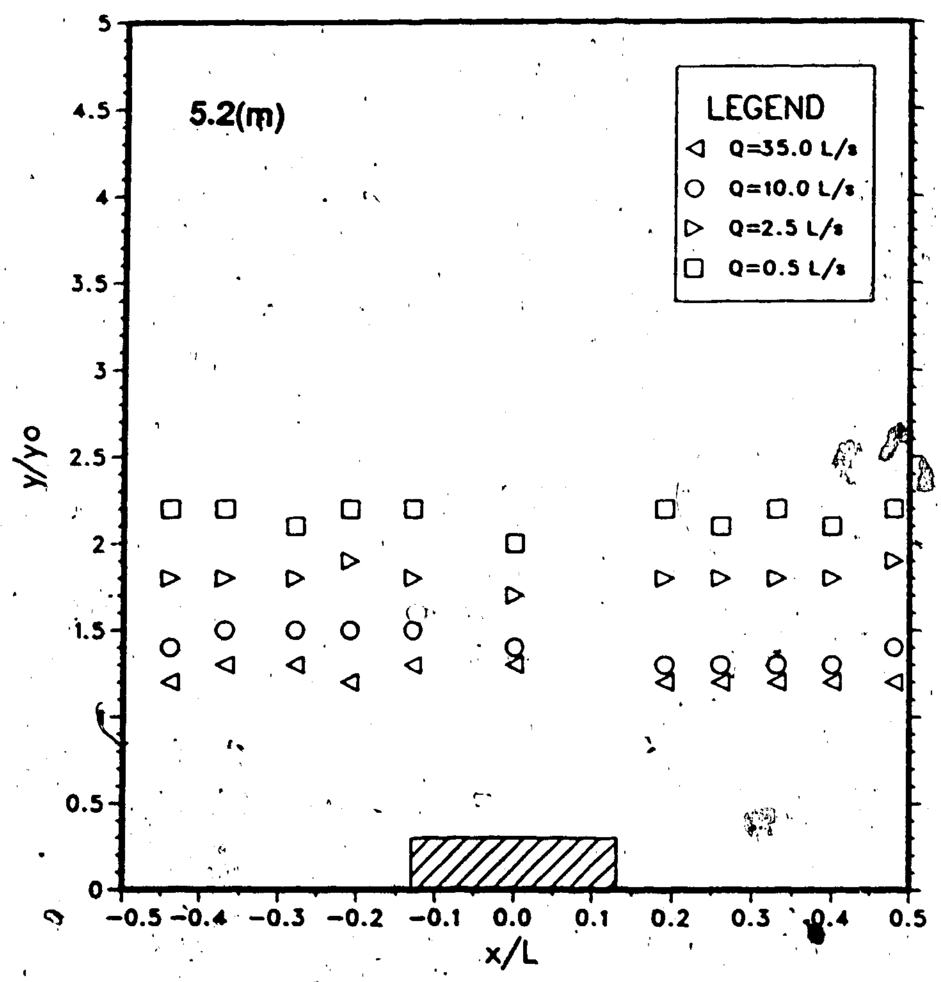


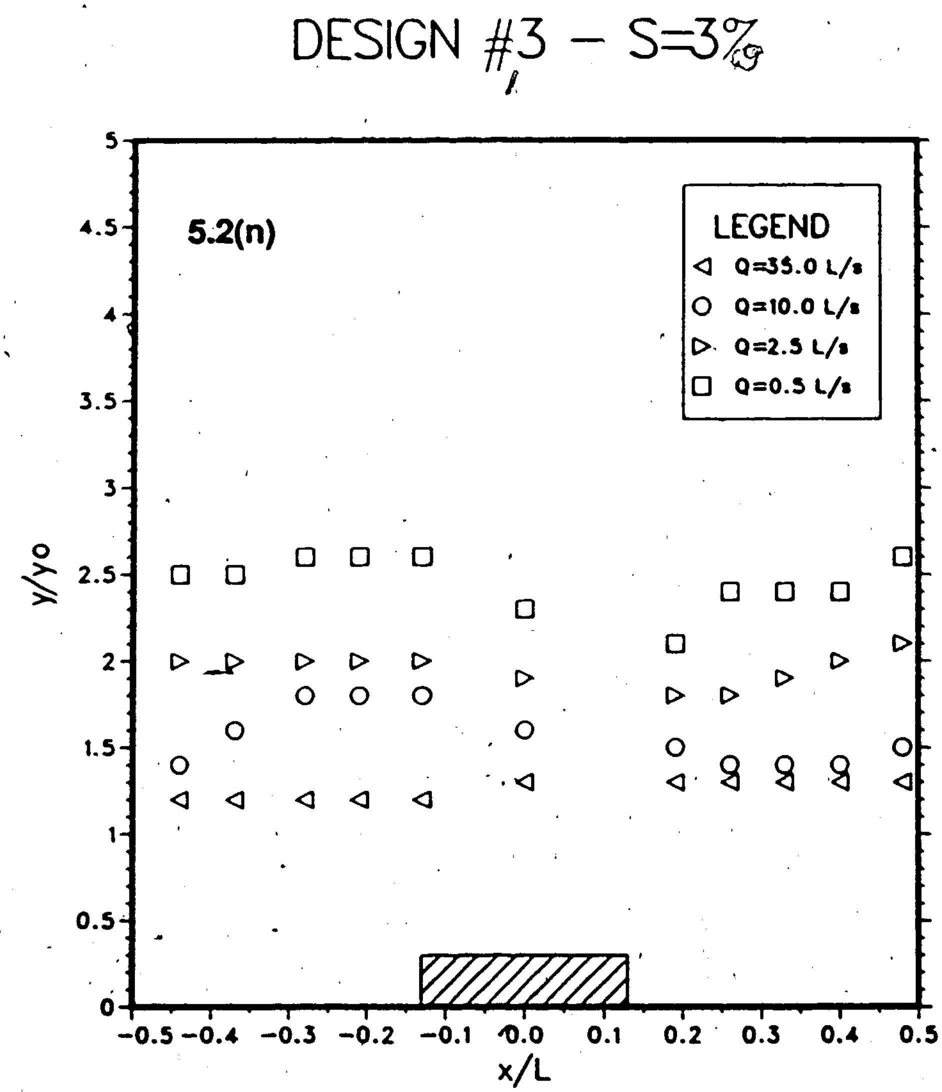
5.2(k)
LEGEND
Q=35.0 L/s
Q=10.0 L/s
Q=2.5 L/s
Q=0.5 L/s
um/Vo
x/L
0
0.5
1
1.5
2
2.5
3
-0.5
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
0.5

DESIGN #2 – S=5%

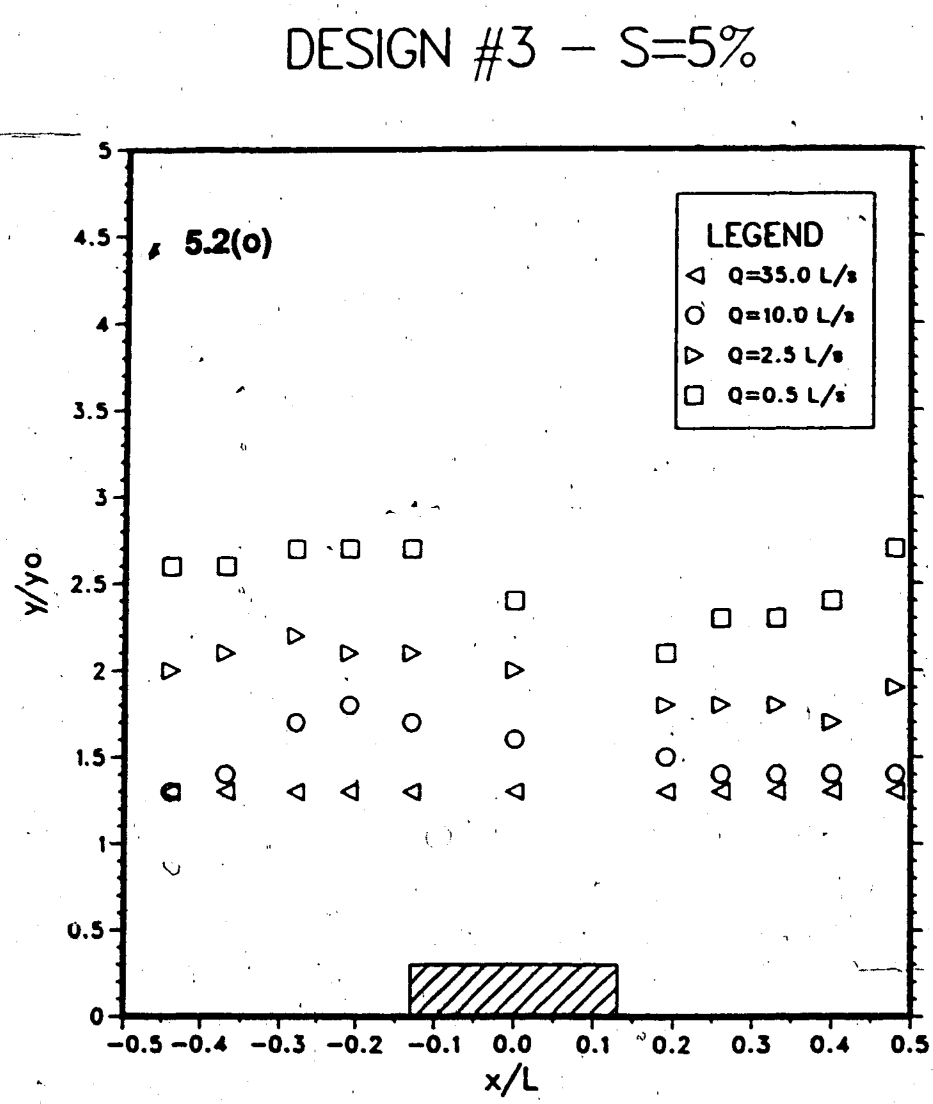


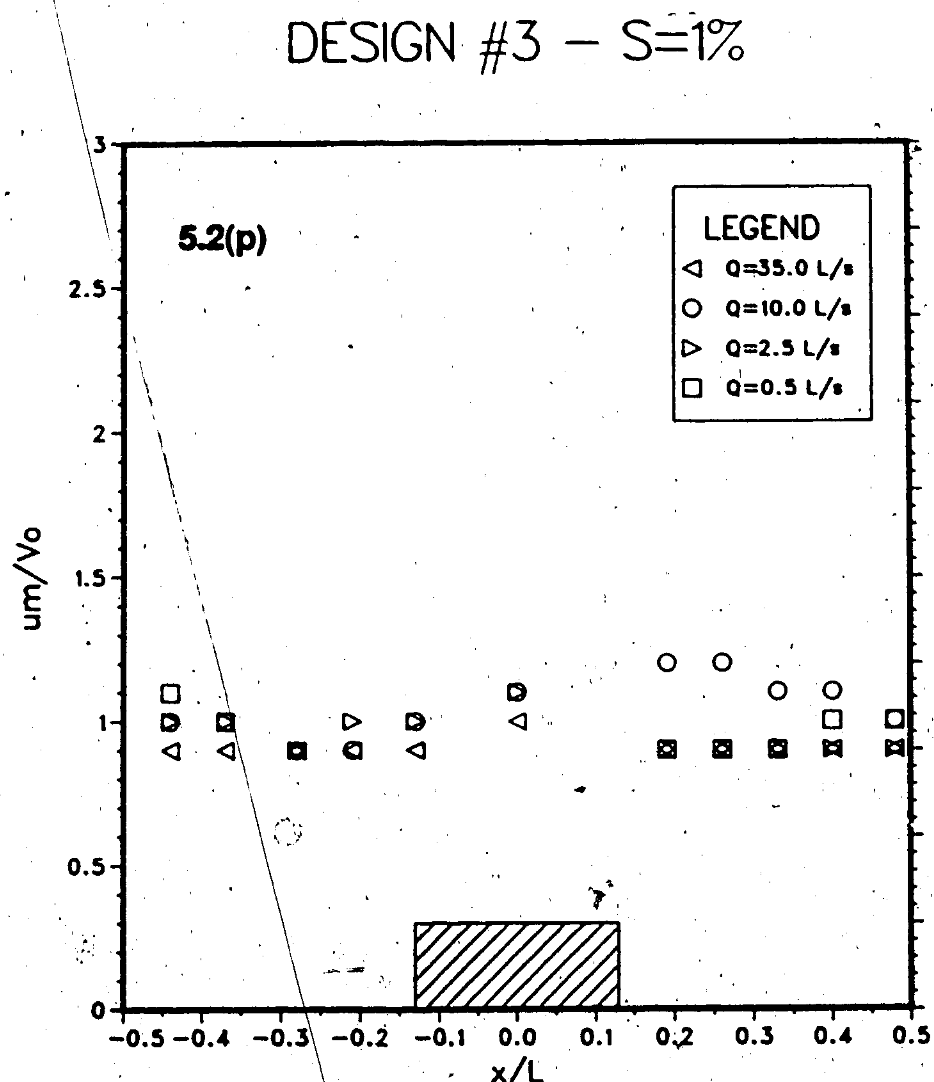
DESIGN #3 – S=1%

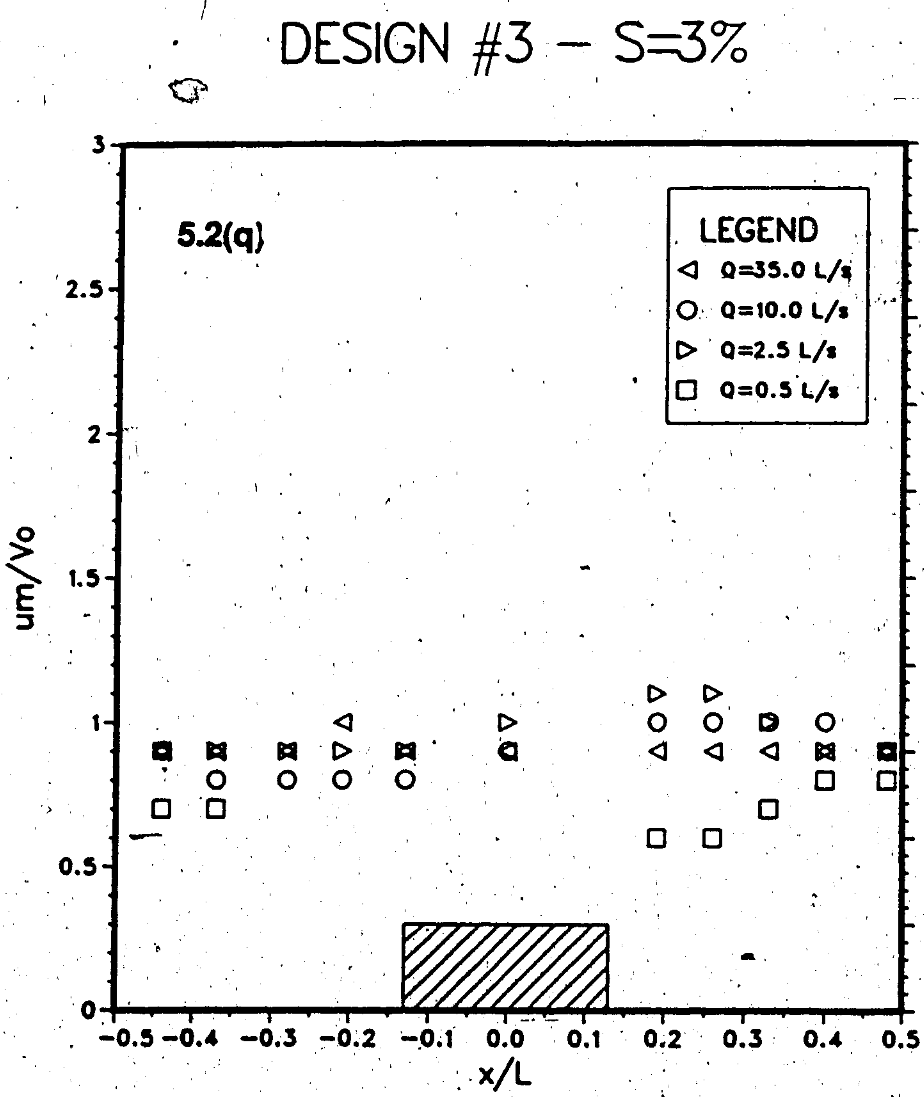

5.2(m)
LEGEND
Q=35.0 L/s
Q=10.0 L/s
Q=2.5 L/s
Q=0.5 L/s
y/yo
x/L
0
0.5
1.5
2
2.5
3
3.5
4
4.5
5
-0.5
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
0.5



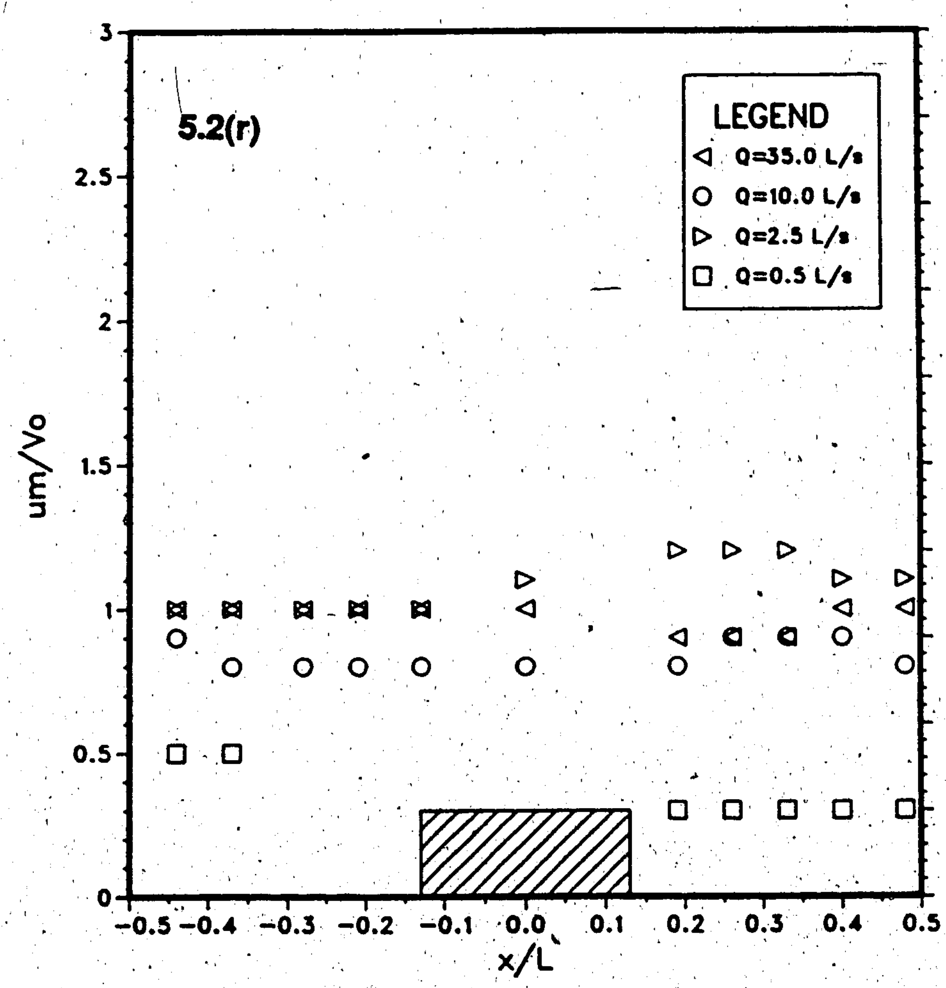
DESIGN #3 – S=3%
5.2(n)
LEGEND
Q=35.0 L/s
Q=10.0 L/s
Q=2.5 L/s
Q=0.5 L/s
y/yo
x/L


DESIGN #3 - S=5%
5.2(o)
LEGEND
Q=35.0 L/s
Q=10.0 L/s
Q=2.5 L/s
Q=0.5 L/s
y/yo
x/L
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
0.5

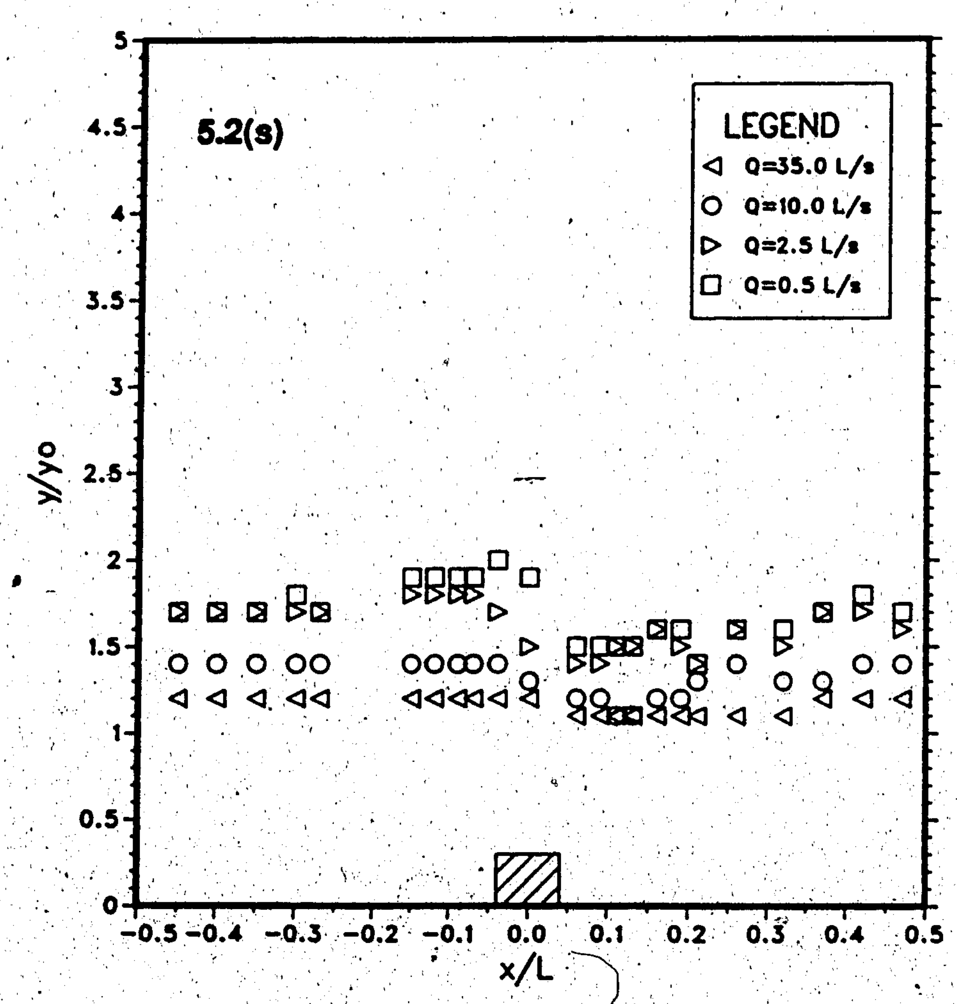

DESIGN #3 – S=1%
5.2(p)
LEGEND
Q=35.0 L/s
Q=10.0 L/s
Q=2.5 L/s
Q=0.5 L/s
um/Vo
x/L
0
0.5
1
1.5
2
2.5
3
−0.5
−0.4
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3
0.4
0.5


DESIGN #3 — S=3%
5.2(q)
LEGEND
Q=35.0 L/s
Q=10.0 L/s
Q=2.5 L/s
Q=0.5 L/s
um/Vo
x/L
0
0.5
1
1.5
2
2.5
3
-0.5
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
0.5

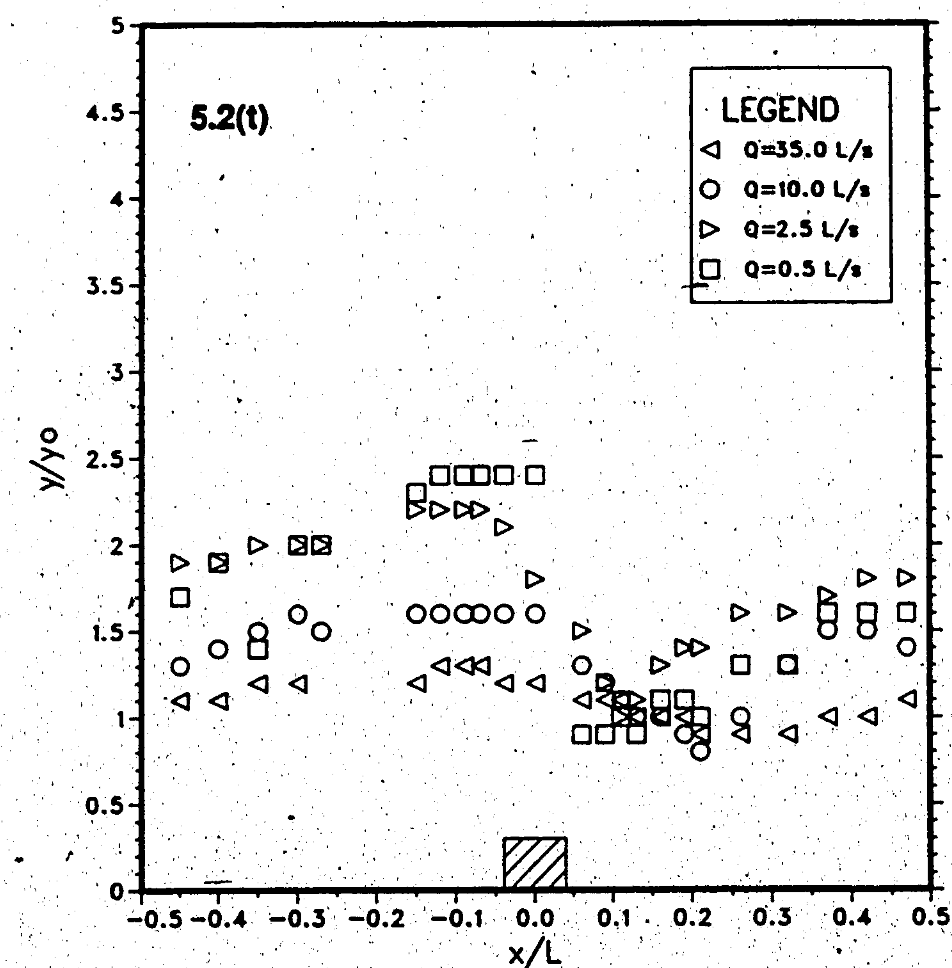
DESIGN #3 - S=5%


5.2(r)
LEGEND
Q=35.0 L/s
Q=10.0 L/s
Q=2.5 L/s
Q=0.5 L/s
um/Vo
x/L
3
2.5
2
1.5
1
0.5
0
-0.5
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
0.5

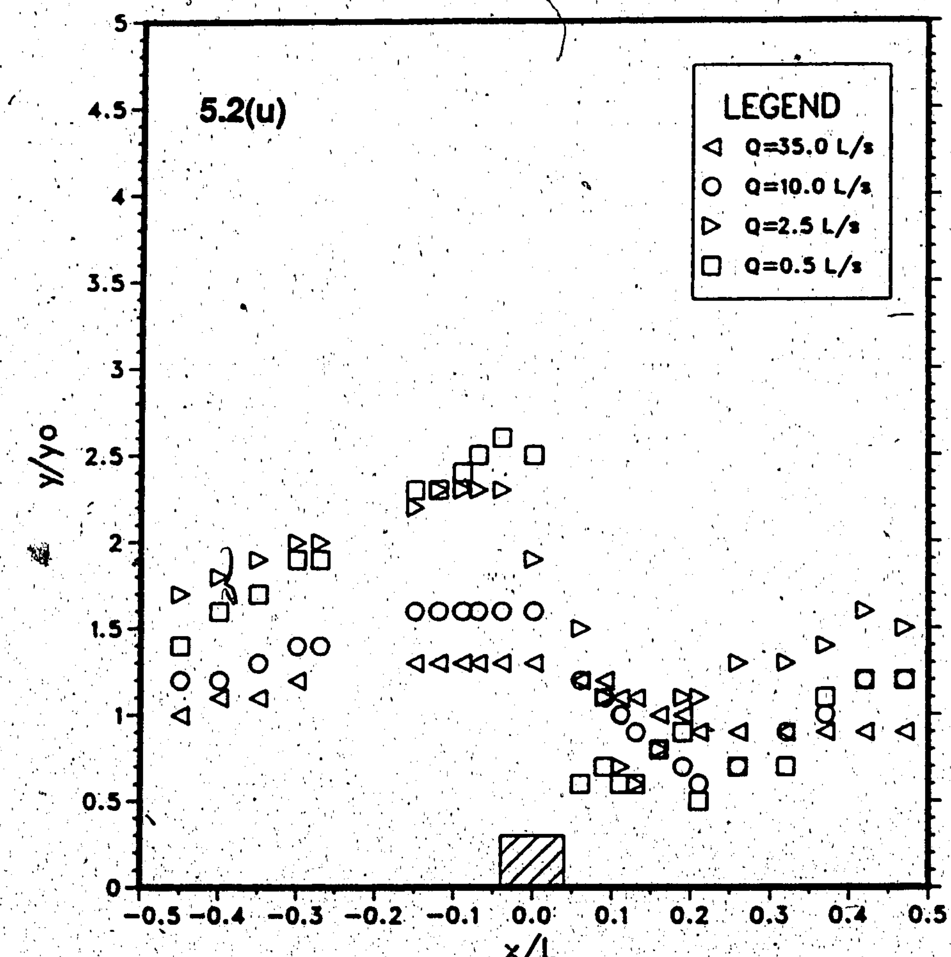
DESIGN #4 – S=1%


5.2(s)
LEGEND
Q=35.0 L/s
Q=10.0 L/s
Q=2.5 L/s
Q=0.5 L/s
y/yo
x/L
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
−0.5 −0.4 −0.3 −0.2 −0.1 0.0 0.1 0.2 0.3 0.4 0.5

DESIGN #4 – S=3%

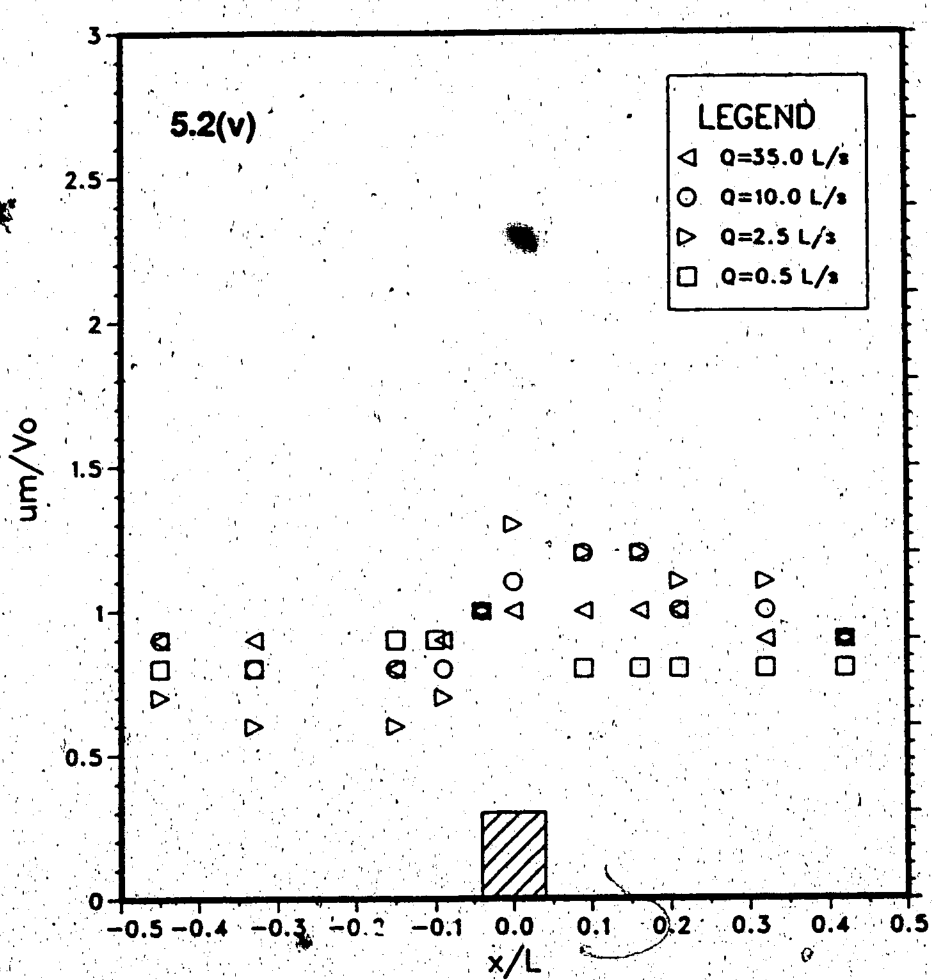

5.2(t)
LEGEND
Q=35.0 L/s
Q=10.0 L/s
Q=2.5 L/s
Q=0.5 L/s
y/yo
x/L
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
-0.5
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
0.5

DESIGN #4 – S=5%



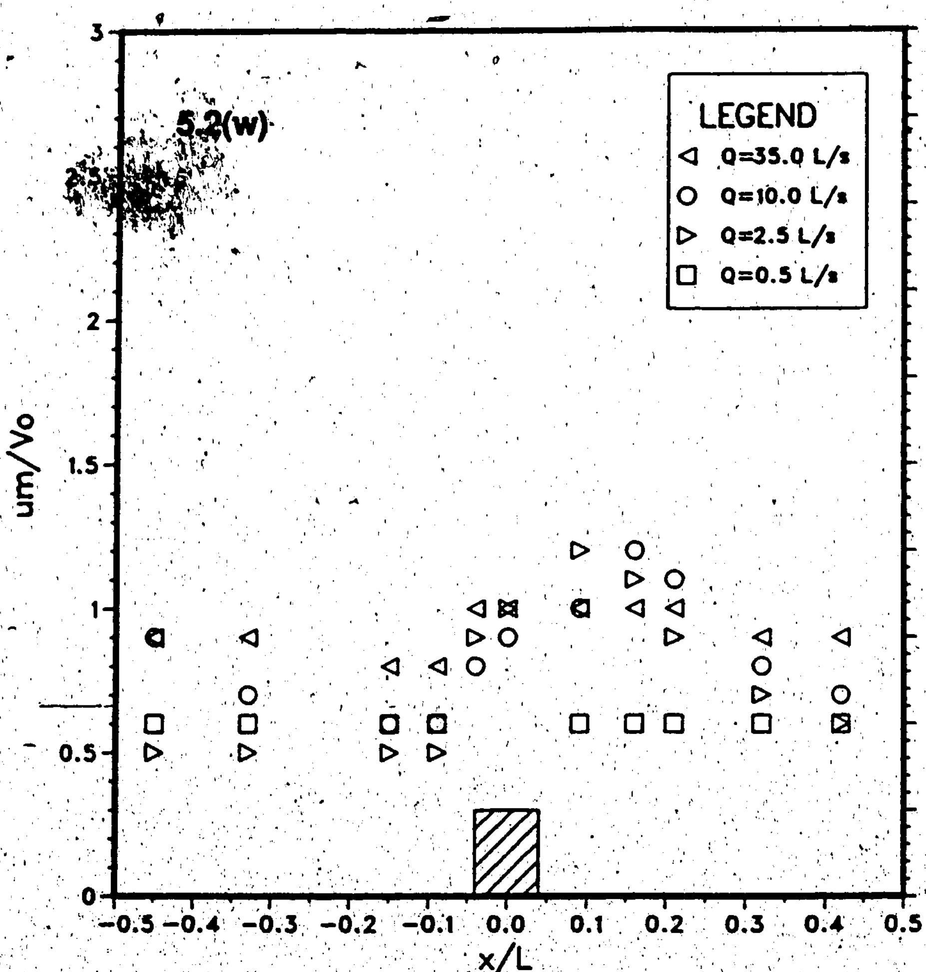
5.2(u)
LEGEND
Q=35.0 L/s
Q=10.0 L/s
Q=2.5 L/s
Q=0.5 L/s
y/yo
x/L
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
−0.5
−0.4
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3
0.4
0.5

DESIGN #4 – S=1%



5.2(v)
LEGEND
Q=35.0 L/s
Q=10.0 L/s
Q=2.5 L/s
Q=0.5 L/s
um/Vo
x/L
3
2.5
2
1.5
1
0.5
0
-0.5 -0.4 -0.3 -0.2 -0.1 0.0 0.1 0.2 0.3 0.4 0.5

DESIGN #4 — S=3%



5.2(w)
LEGEND
Q=35.0 L/s
Q=10.0 L/s
Q=2.5 L/s
Q=0.5 L/s
um/Vo
x/L
0
0.5
1
1.5
2
3
−0.5 −0.4 −0.3 −0.2 −0.1 0.0 0.1 0.2 0.3 0.4 0.5

DESIGN #4 – S=5%

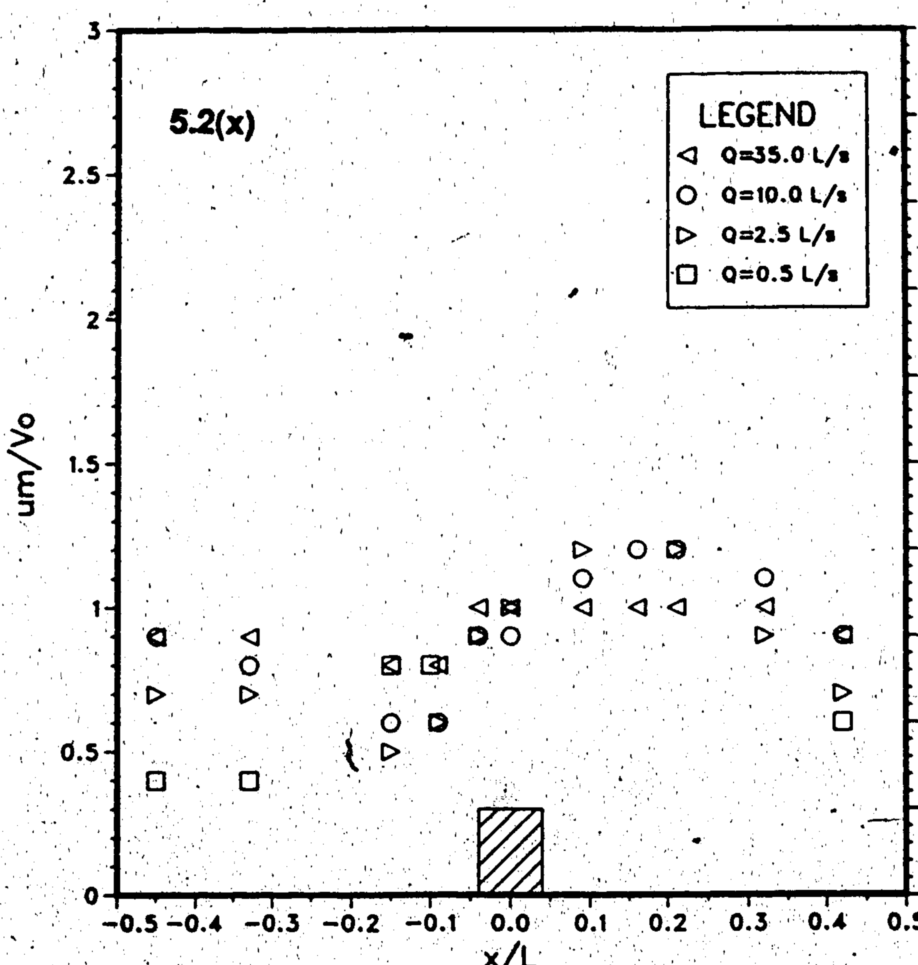
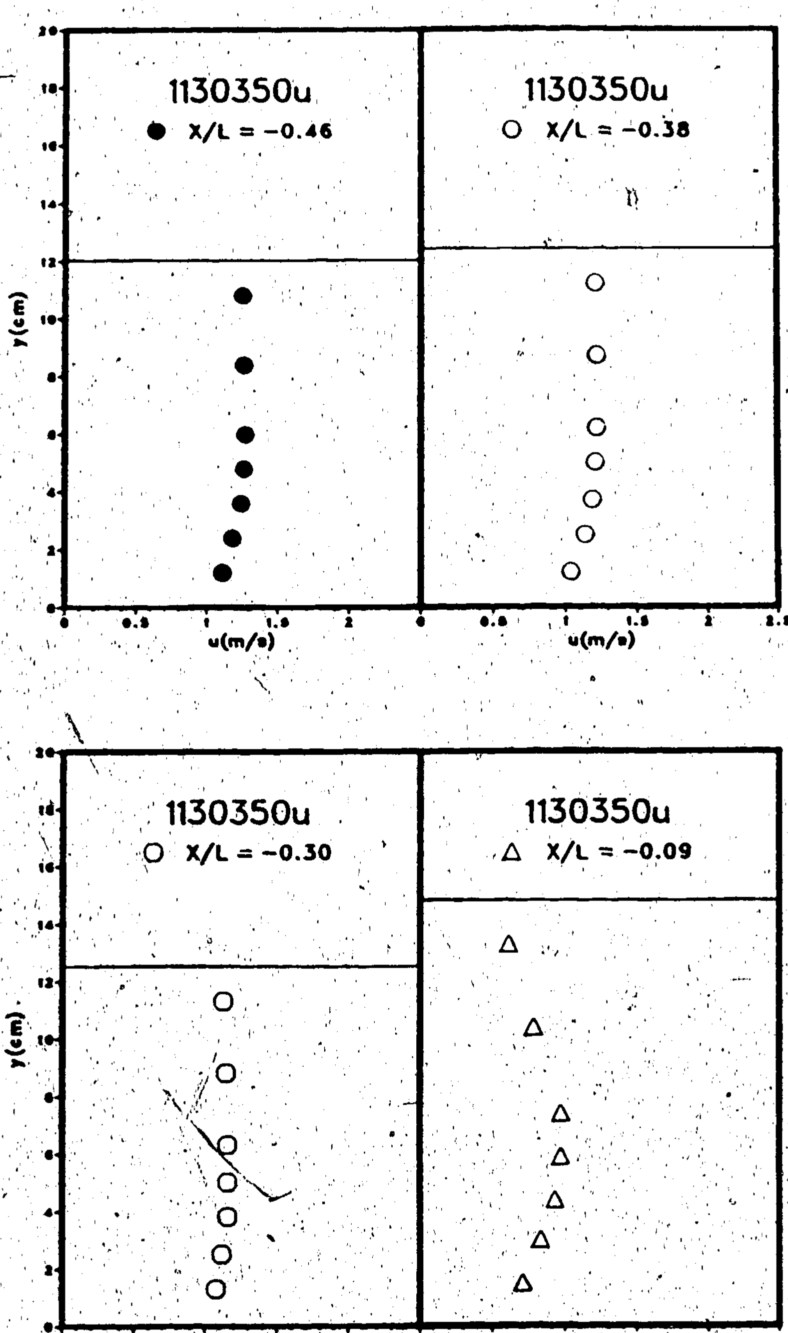
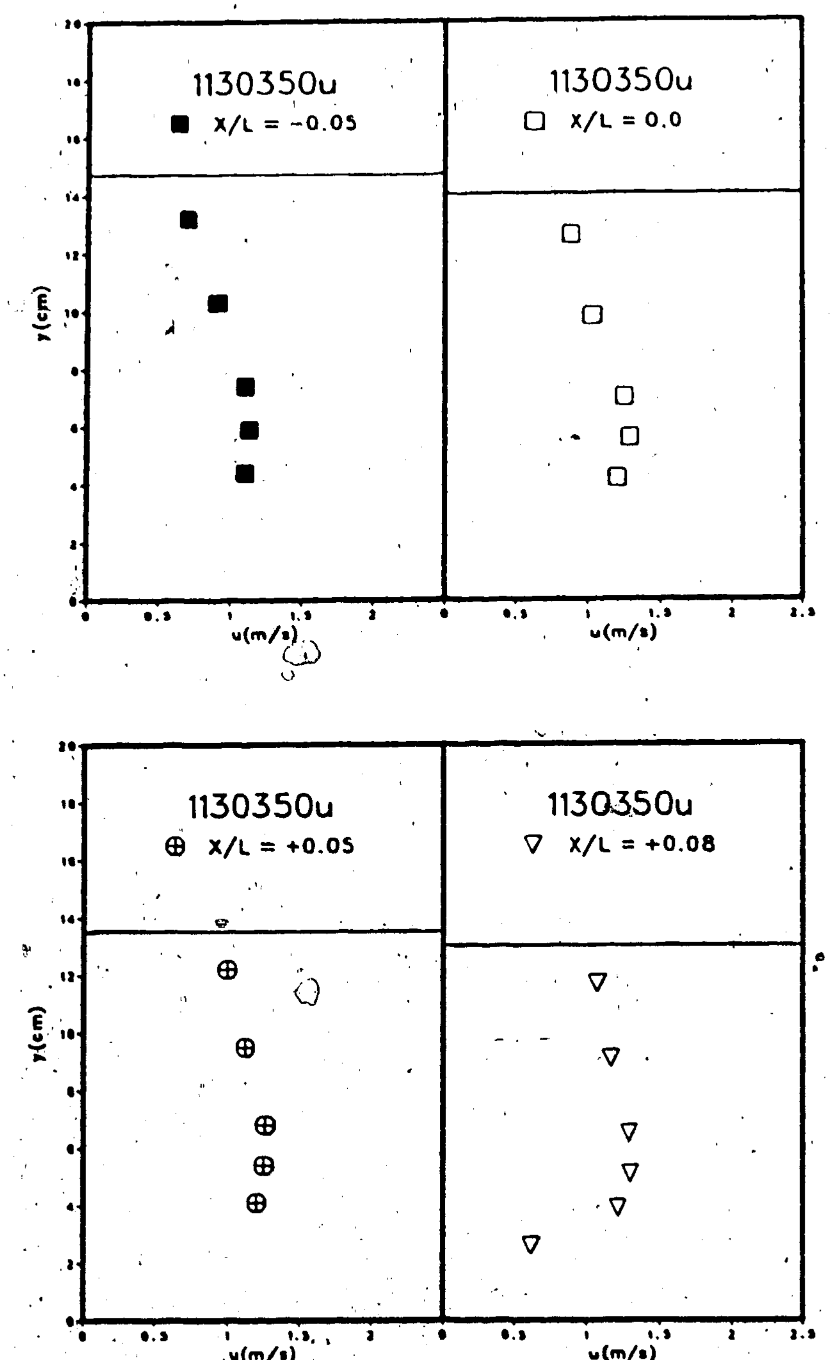

5.2(x)
LEGEND
Q=35.0 L/s
Q=10.0 L/s
Q=2.5 L/s
Q=0.5 L/s
um/Vo
x/L
0
0.5
1
1.5
2
2.5
3
−0.5
−0.4
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3
0.4
0.5

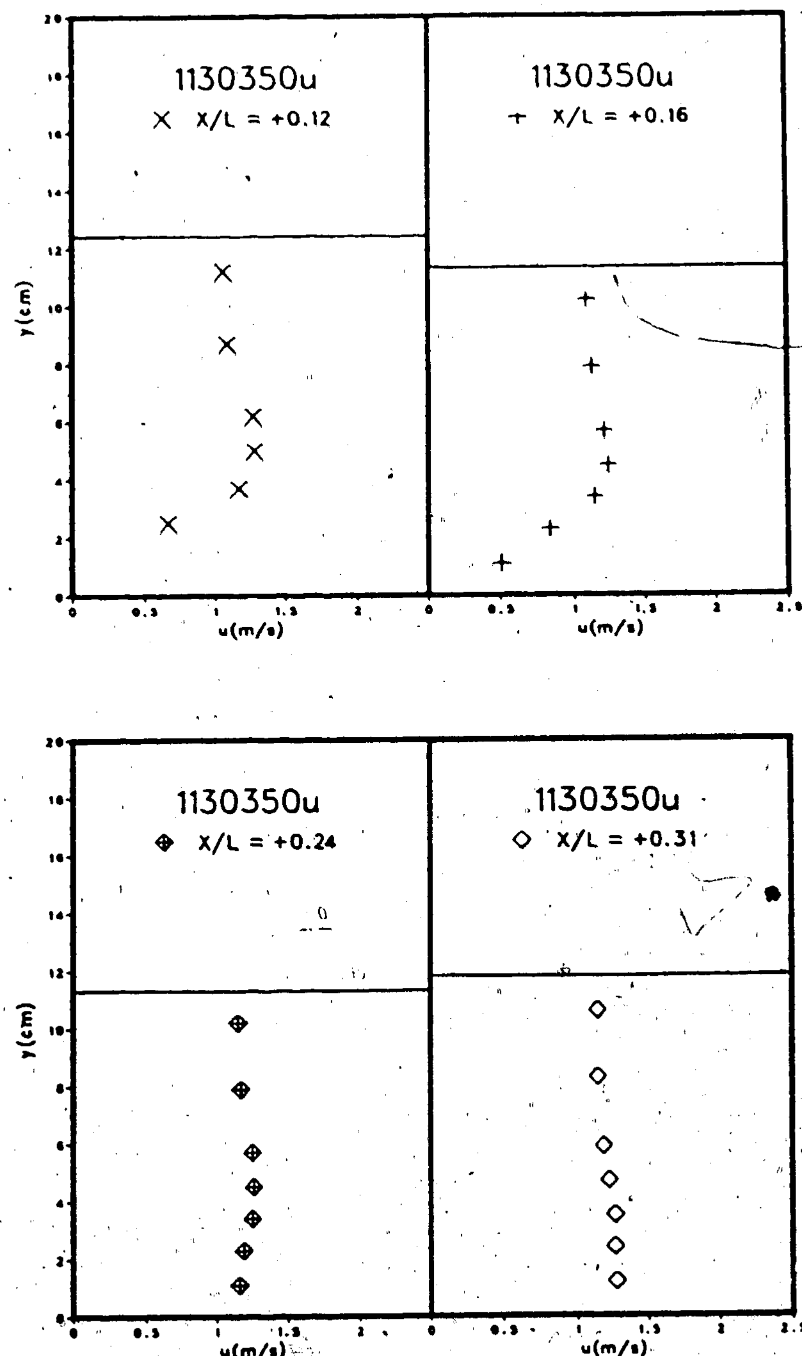
Figure 5.3 Velocity Profiles for Fish-weir Design #1 - Slope 3% and Discharge = 35.0 L/s for a 'cell'.


1130350u
X/L = -0.46
1130350u
X/L = -0.38
1130350u
X/L = -0.30
1130350u
X/L = -0.09
y(cm)
u(m/s)

5.3(a)


1130350u
X/L = -0.05
1130350u
X/L = 0.0
1130350u
X/L = +0.05
1130350u
X/L = +0.08
y(cm)
u(m/s)

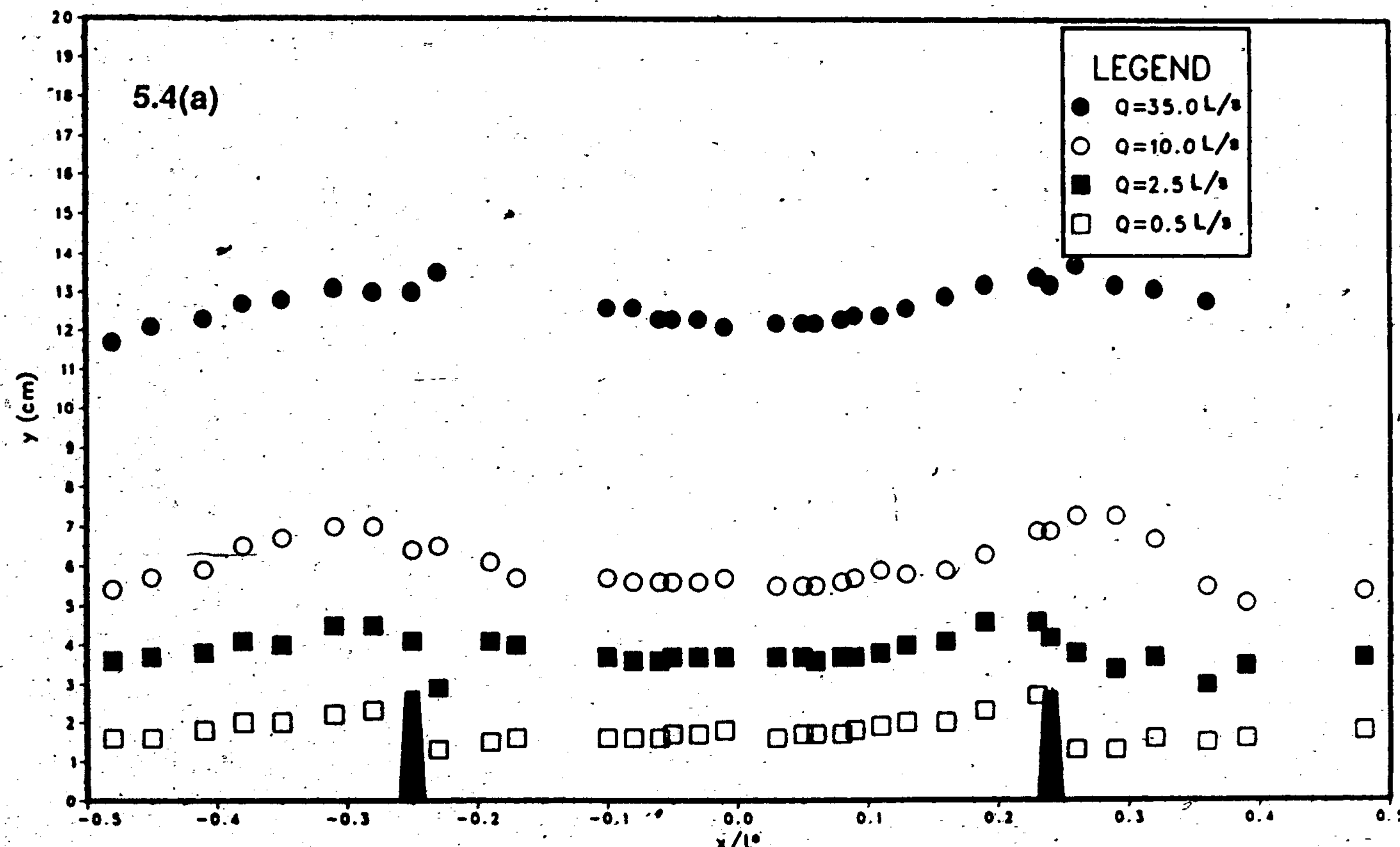
5.3(b)


1130350u
X/L = +0.12
1130350u
X/L = +0.16
1130350u
X/L = +0.24
1130350u
X/L = +0.31
y(cm)
u(m/s)

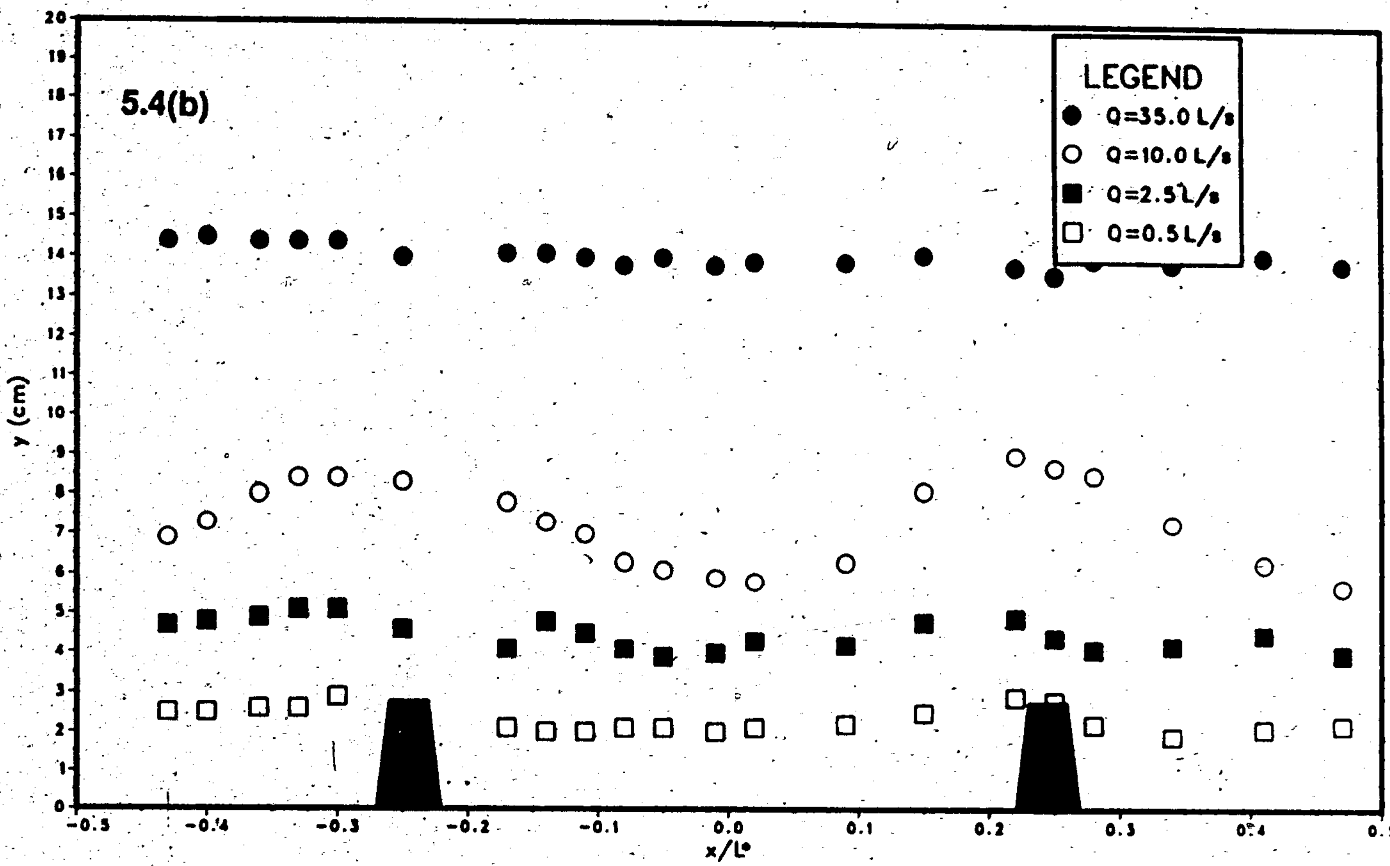
5.3(c)

Figure 5.4 Depth Profiles for Fish-baffle Design's #5, #6 and #7 at the 1% Slope.

DEPTH PROFILES FOR DESIGN #5 – So=1%



DEPTH PROFILES FOR DESIGN #6 – So=1%



DEPTH PROFILES FOR DESIGN #7 – So=1%

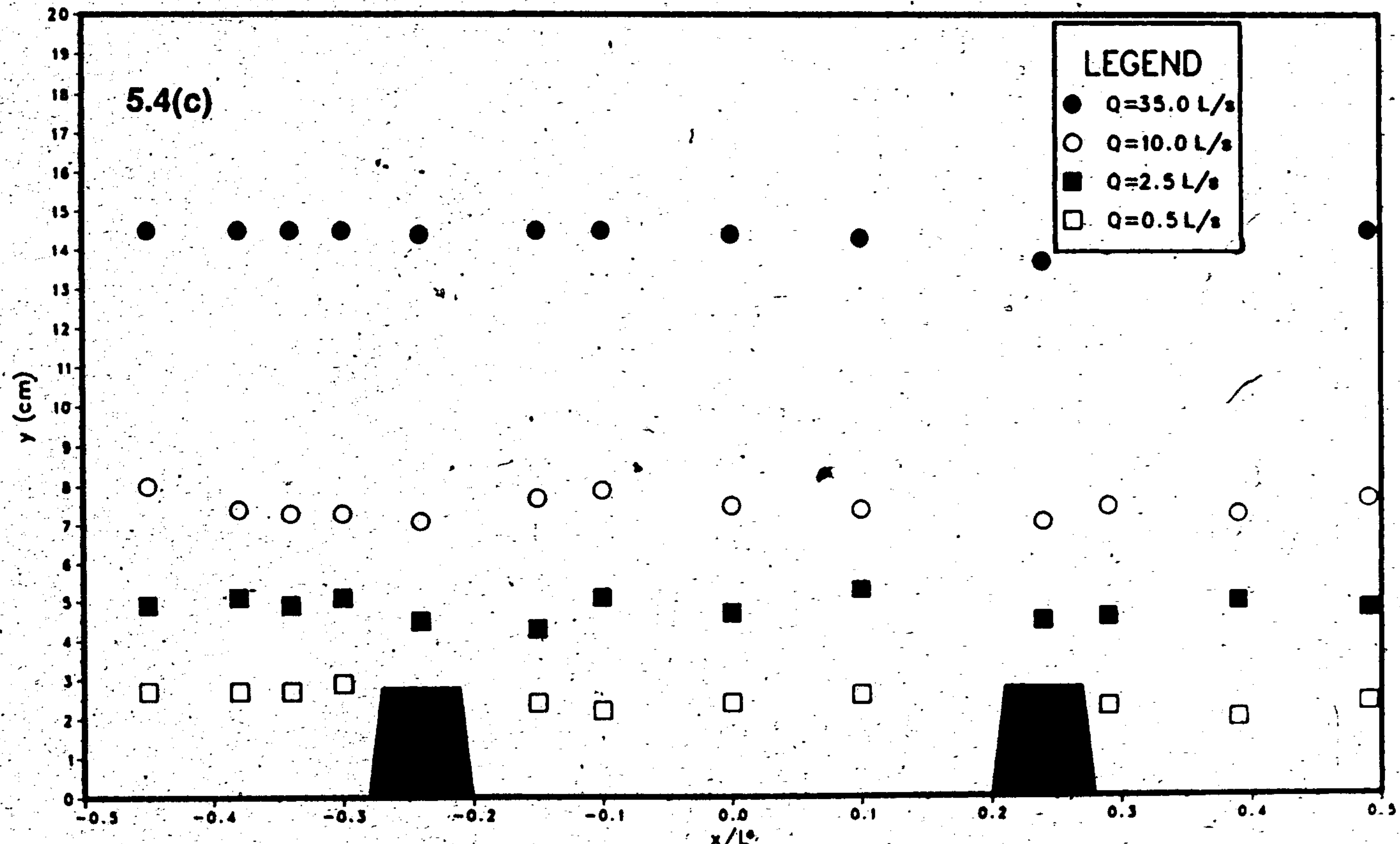
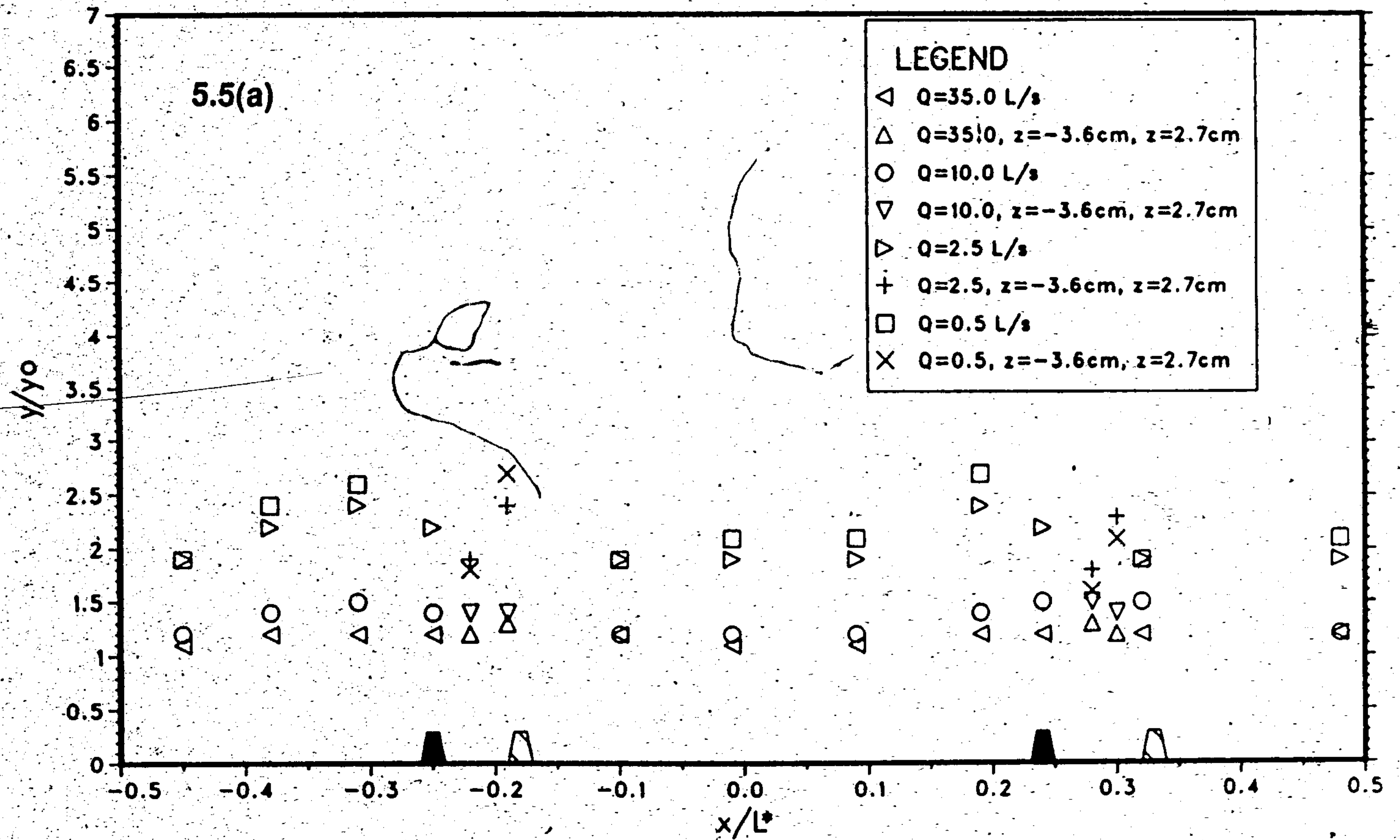
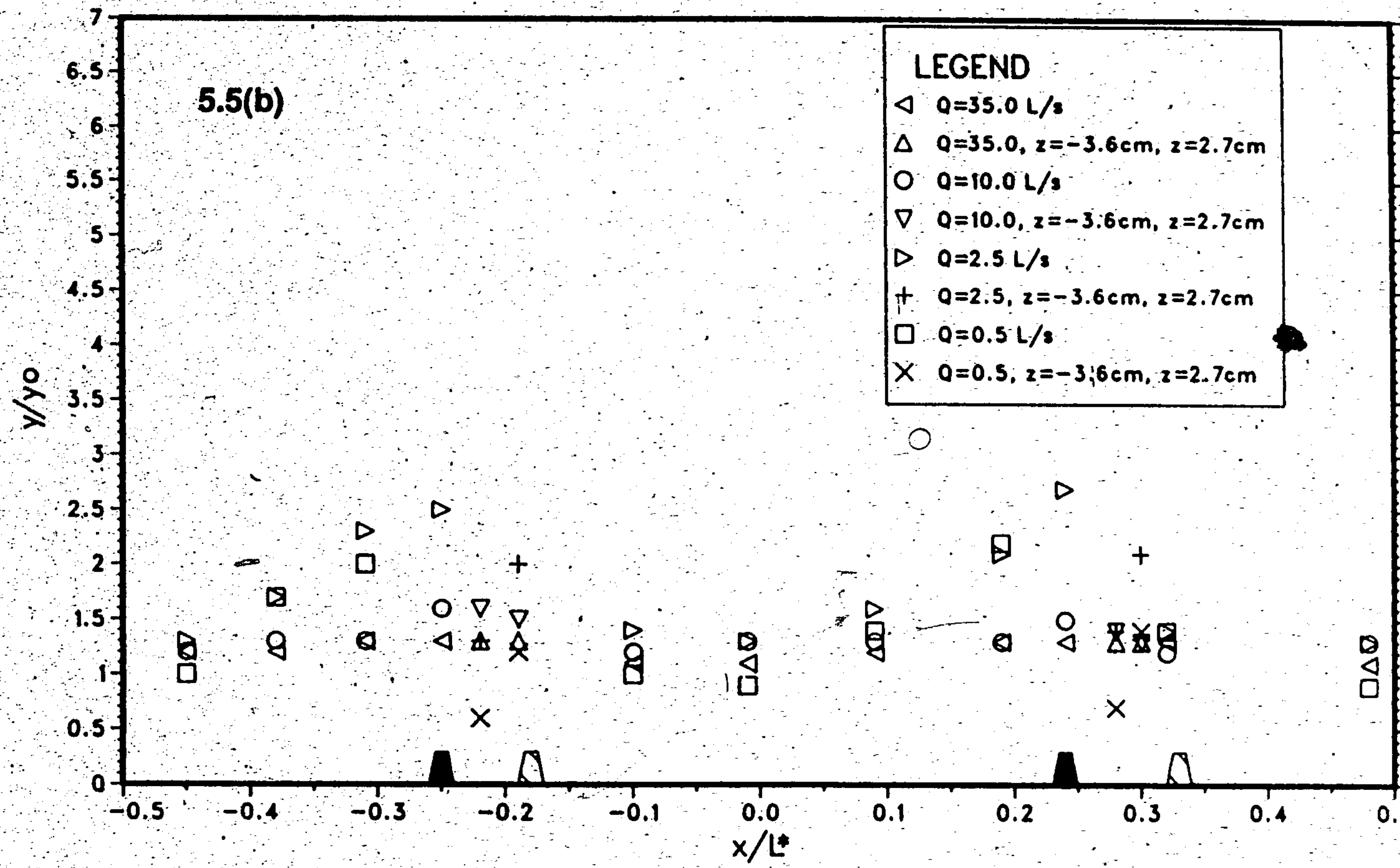


Figure 5.5 Dimensionless Depth and Characteristic Velocity Variations for Fish-baffle Design's #5 to #7.

DESIGN #5 – S=1%

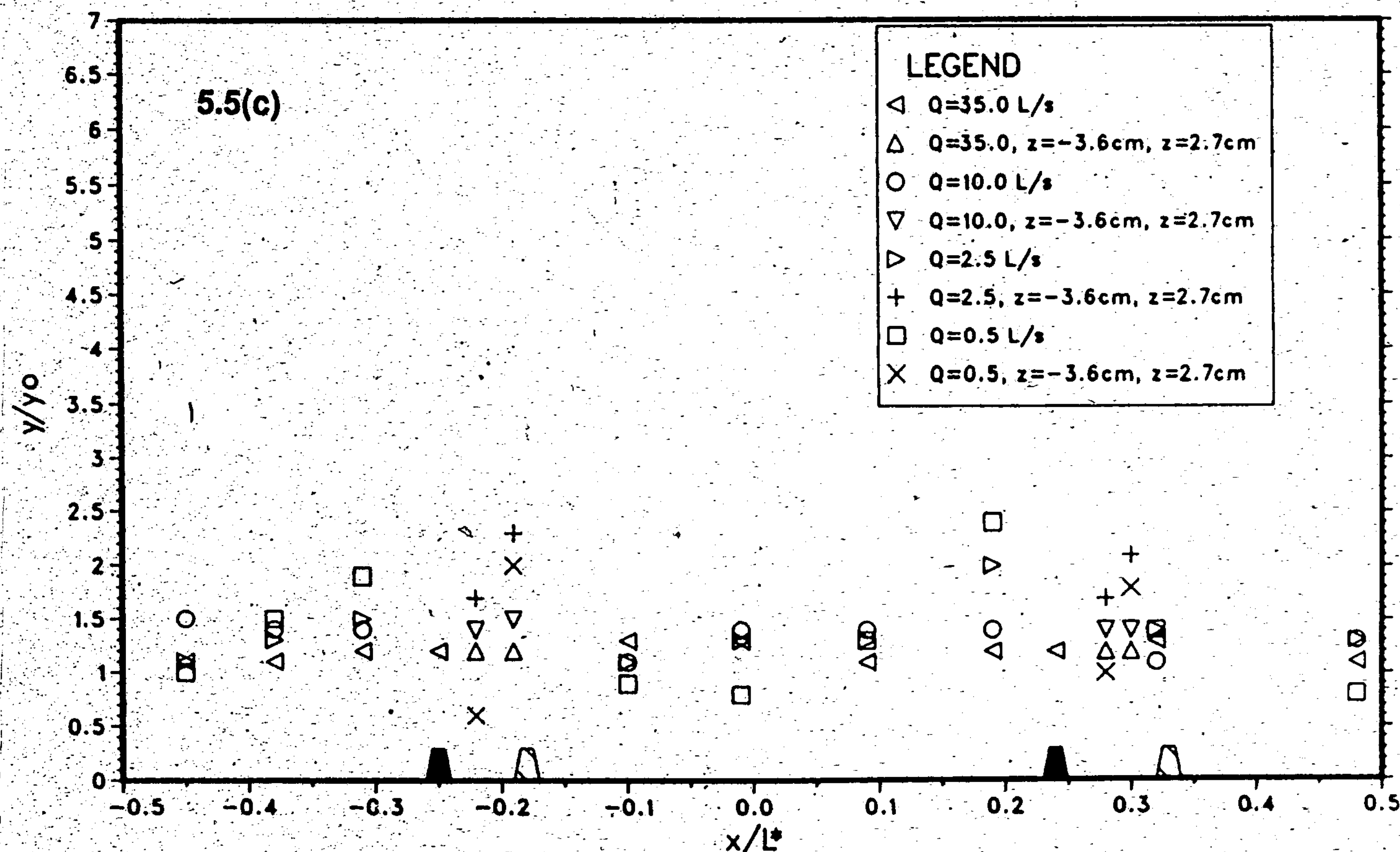

5.5(a)
LEGEND
Q=35.0 L/s
Q=35.0, z=−3.6cm, z=2.7cm
Q=10.0 L/s
Q=10.0, z=−3.6cm, z=2.7cm
Q=2.5 L/s
Q=2.5, z=−3.6cm, z=2.7cm
Q=0.5 L/s
Q=0.5, z=−3.6cm, z=2.7cm
y/yo
x/L*
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
−0.5
−0.4
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3
0.4
0.5

DESIGN #5 – S=3%

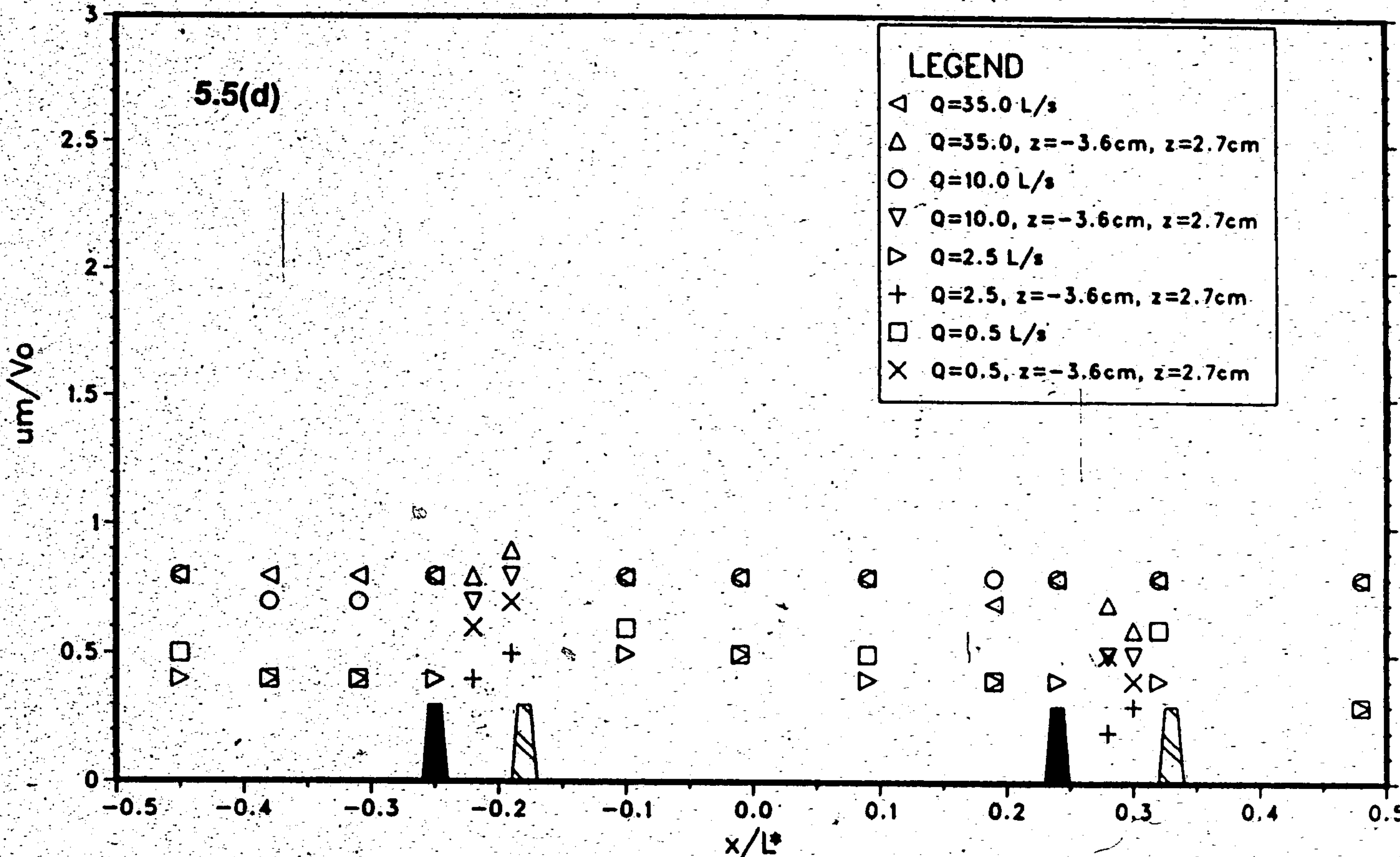


5.5(b)
LEGEND
Q=35.0 L/s
Q=35.0, z=-3.6cm, z=2.7cm
Q=10.0 L/s
Q=10.0, z=-3.6cm, z=2.7cm
Q=2.5 L/s
Q=2.5, z=-3.6cm, z=2.7cm
Q=0.5 L/s
Q=0.5, z=-3.6cm, z=2.7cm
y/yo
x/L*
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
-0.5
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
0.5

DESIGN #5 - S=5%

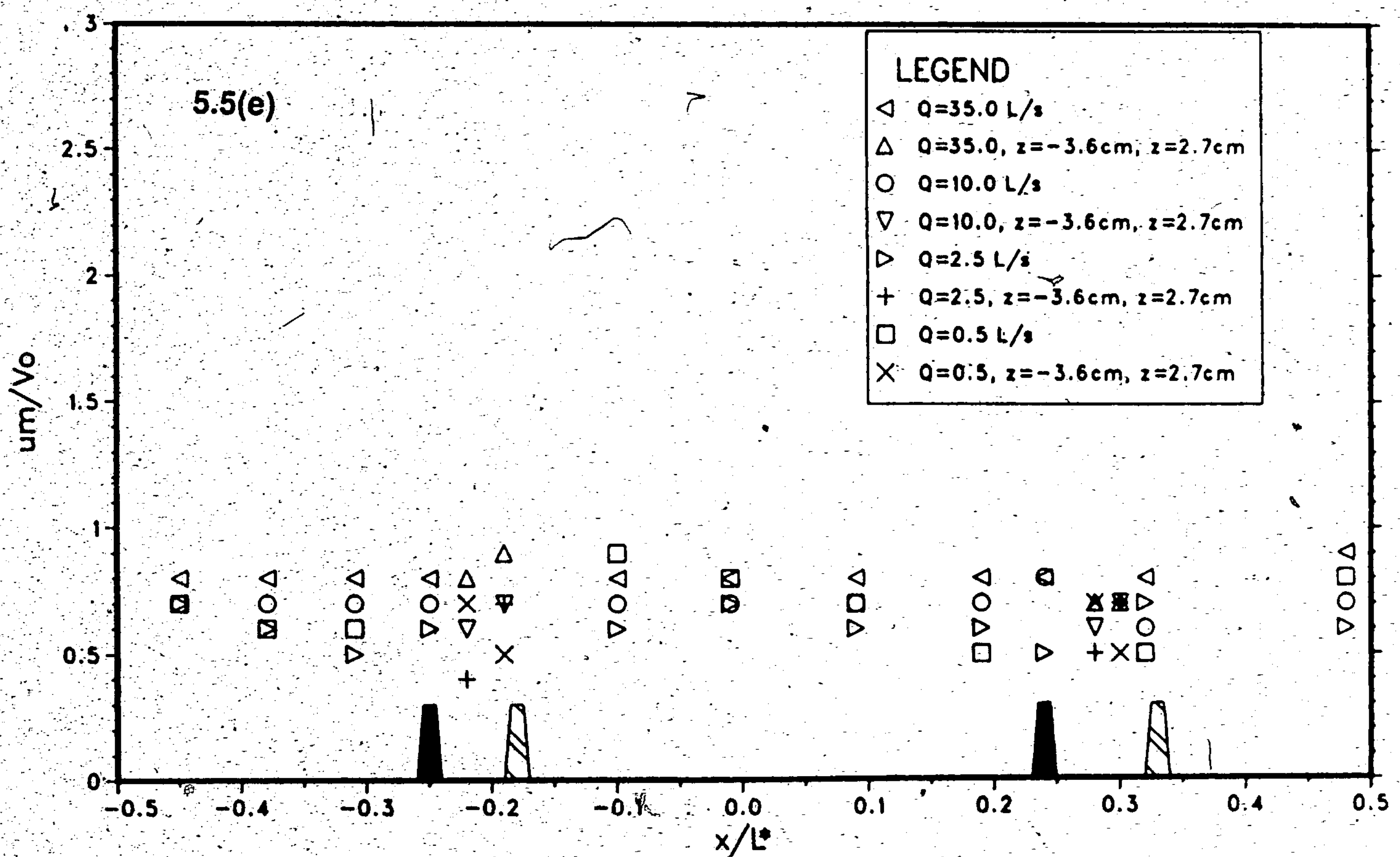

5.5(c)
LEGEND
Q=35.0 L/s
Q=35.0, z=-3.6cm, z=2.7cm
Q=10.0 L/s
Q=10.0, z=-3.6cm, z=2.7cm
Q=2.5 L/s
Q=2.5, z=-3.6cm, z=2.7cm
Q=0.5 L/s
Q=0.5, z=-3.6cm, z=2.7cm
y/yo
x/L*
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
-0.5
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
0.5

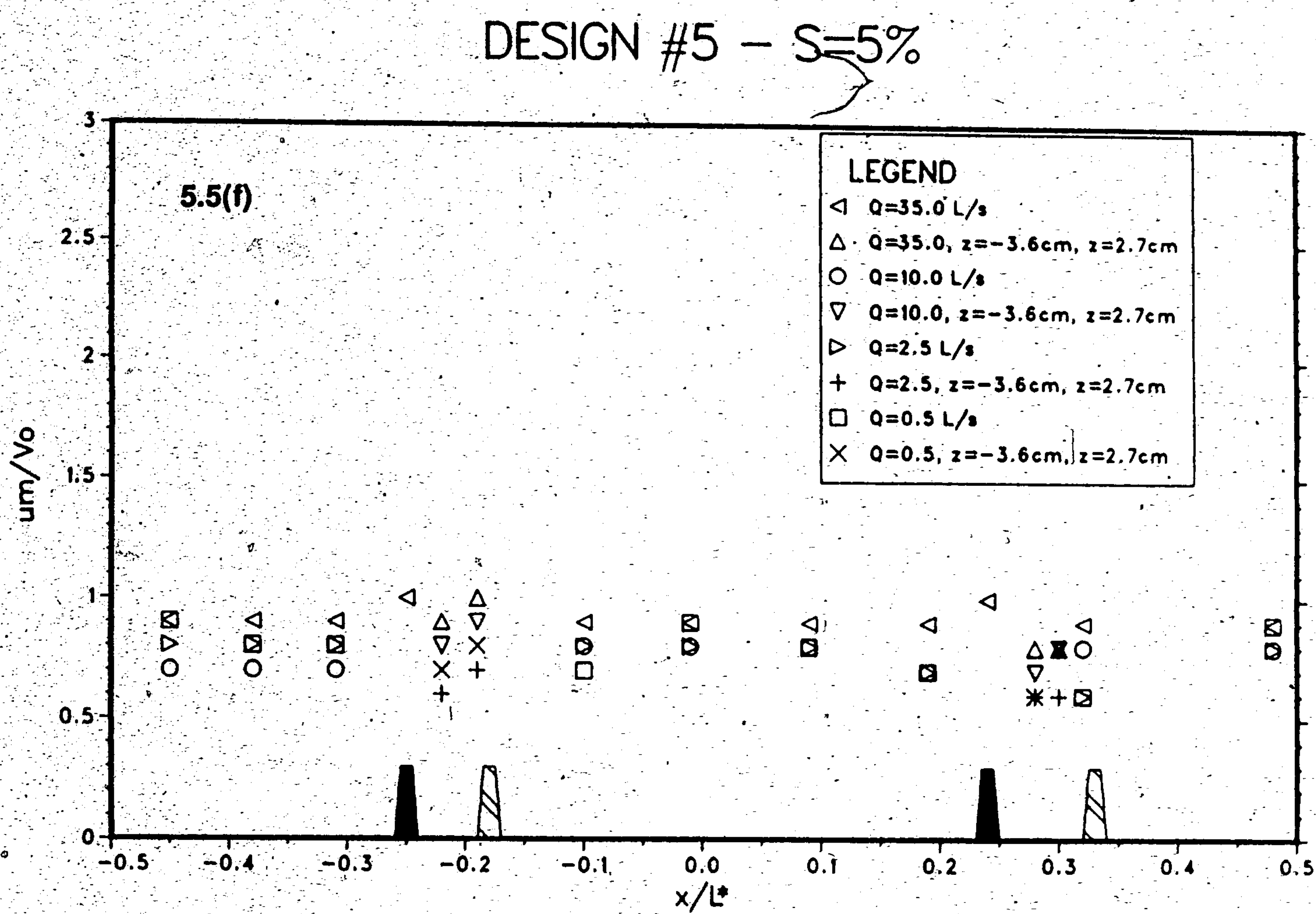
DESIGN #5 – S=1%



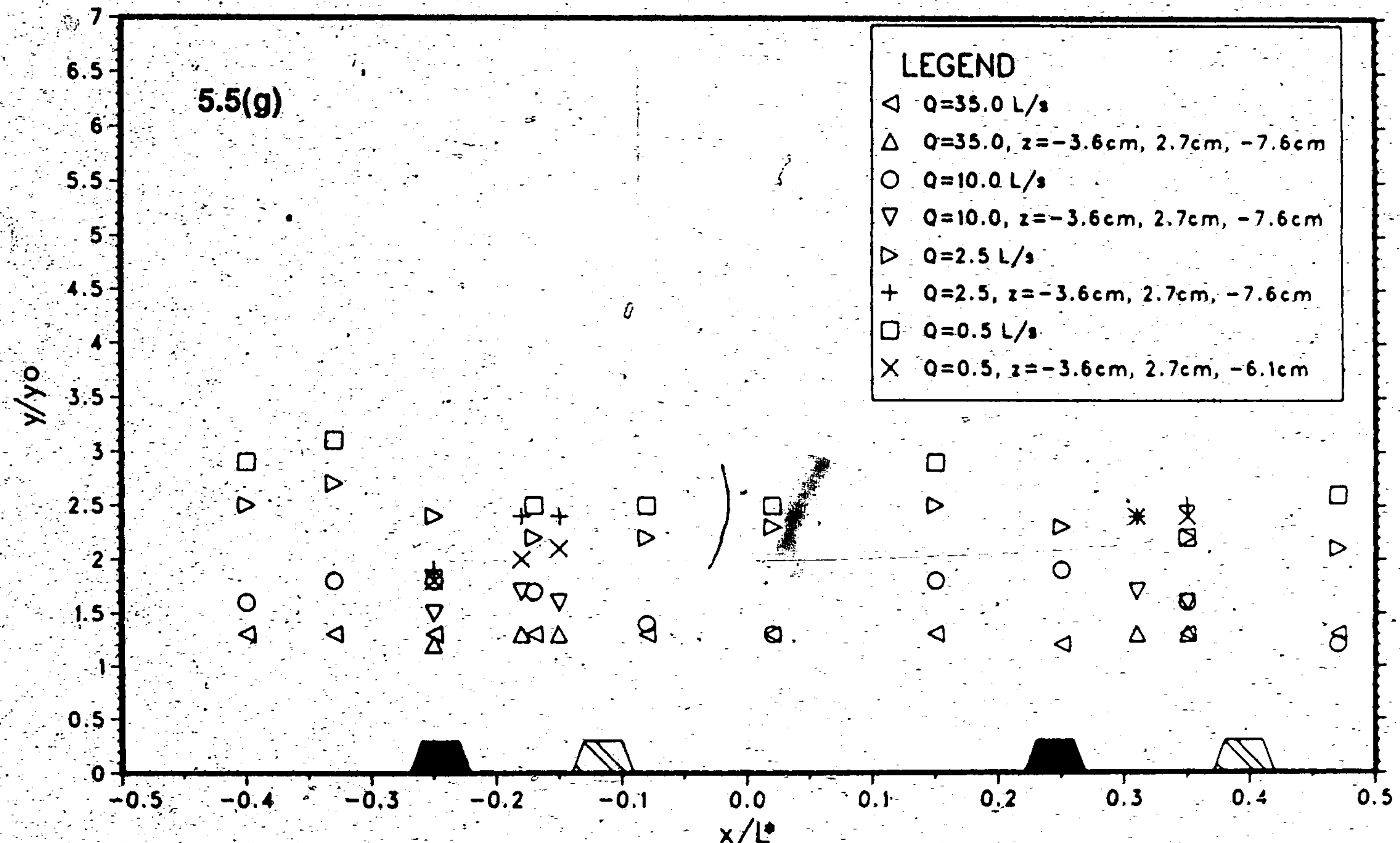
5.5(d)
LEGEND
Q=35.0 L/s
Q=35.0, z=−3.6cm, z=2.7cm
Q=10.0 L/s
Q=10.0, z=−3.6cm, z=2.7cm
Q=2.5 L/s
Q=2.5, z=−3.6cm, z=2.7cm
Q=0.5 L/s
Q=0.5, z=−3.6cm, z=2.7cm
um/Vo
x/L*
0
0.5
1
1.5
2
2.5
3
−0.5
−0.4
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3
0.4
0.5

DESIGN #5 – S=3%

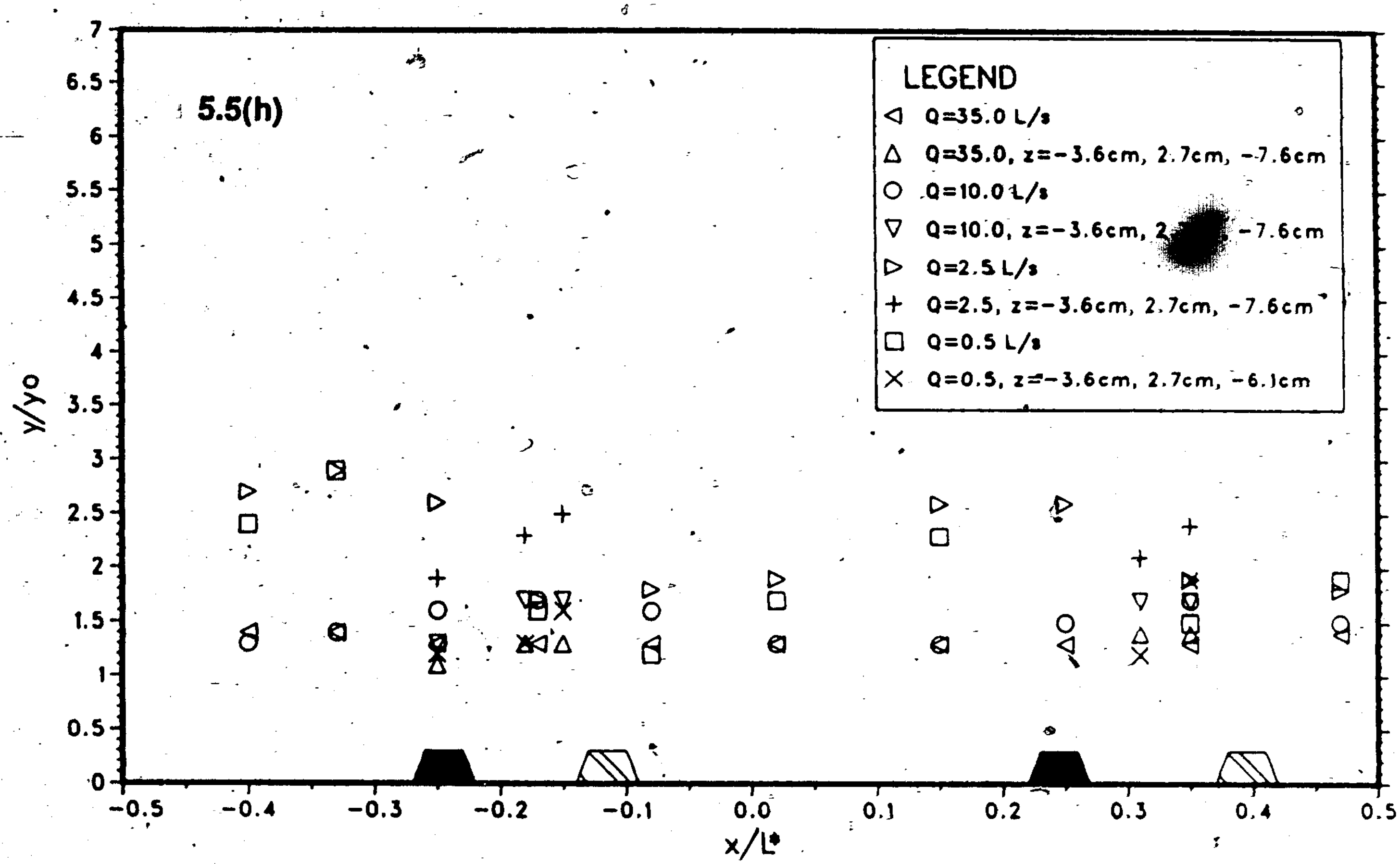

5.5(e)
LEGEND
Q=35.0 L/s
Q=35.0, z=-3.6cm, z=2.7cm
Q=10.0 L/s
Q=10.0, z=-3.6cm, z=2.7cm
Q=2.5 L/s
Q=2.5, z=-3.6cm, z=2.7cm
Q=0.5 L/s
Q=0.5, z=-3.6cm, z=2.7cm
um/Vo
x/L*
0
0.5
1
1.5
2
2.5
3
-0.5
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
0.5


DESIGN #5 – S=5%
5.5(f)
LEGEND
Q=35.0 L/s
Q=35.0, z=−3.6cm, z=2.7cm
Q=10.0 L/s
Q=10.0, z=−3.6cm, z=2.7cm
Q=2.5 L/s
Q=2.5, z=−3.6cm, z=2.7cm
Q=0.5 L/s
Q=0.5, z=−3.6cm, z=2.7cm
um/Vo
x/L*
0
0.5
1
1.5
2
2.5
3
−0.5
−0.4
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3
0.4
0.5

DESIGN #6 – S=1%

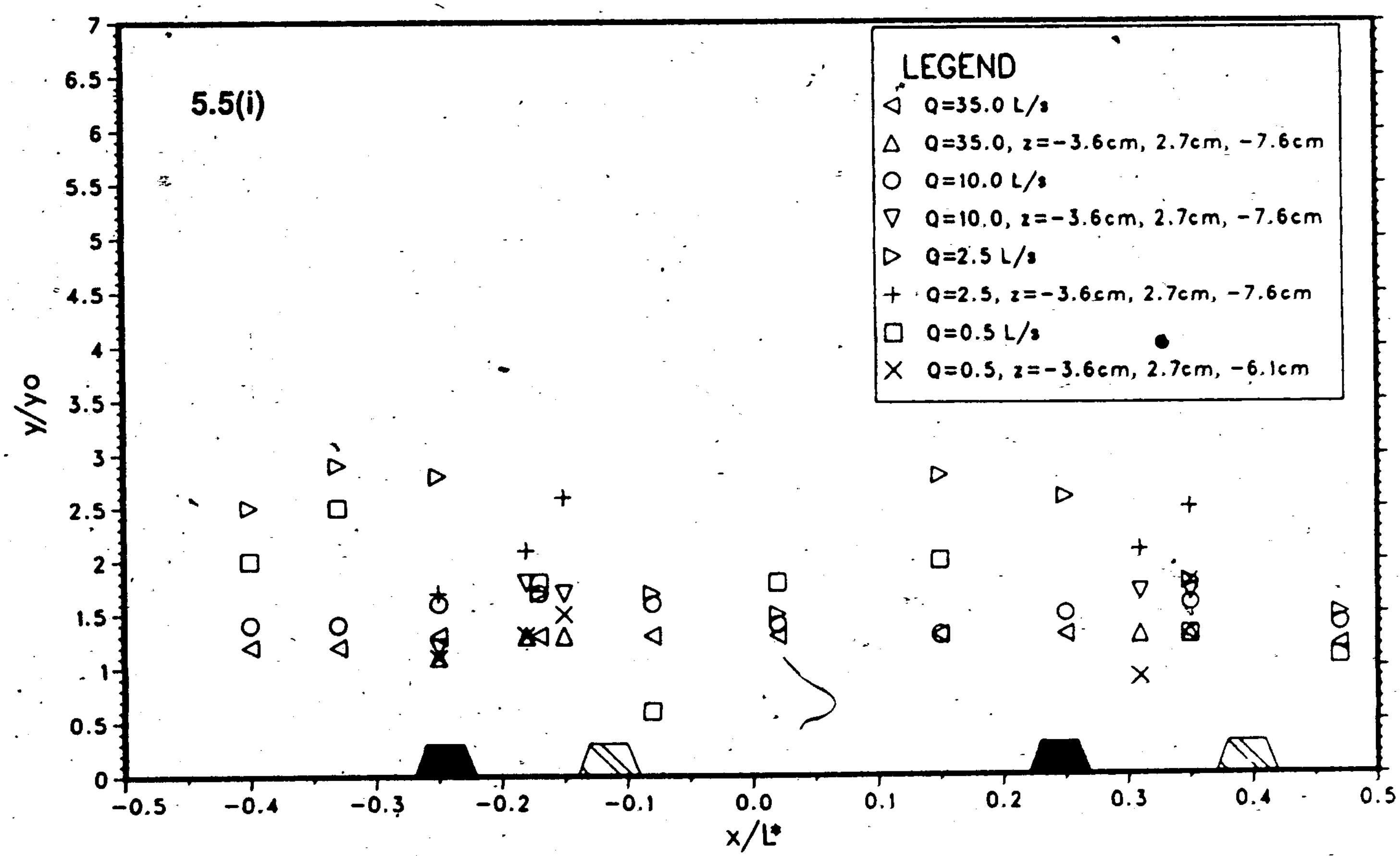

5.5(g)
LEGEND
Q=35.0 L/s
Q=35.0, z=−3.6cm, 2.7cm, −7.6cm
Q=10.0 L/s
Q=10.0, z=−3.6cm, 2.7cm, −7.6cm
Q=2.5 L/s
Q=2.5, z=−3.6cm, 2.7cm, −7.6cm
Q=0.5 L/s
Q=0.5, z=−3.6cm, 2.7cm, −6.1cm
y/yo
x/L*
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
−0.5
−0.4
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3
0.4
0.5

DESIGN #6 – S=3%

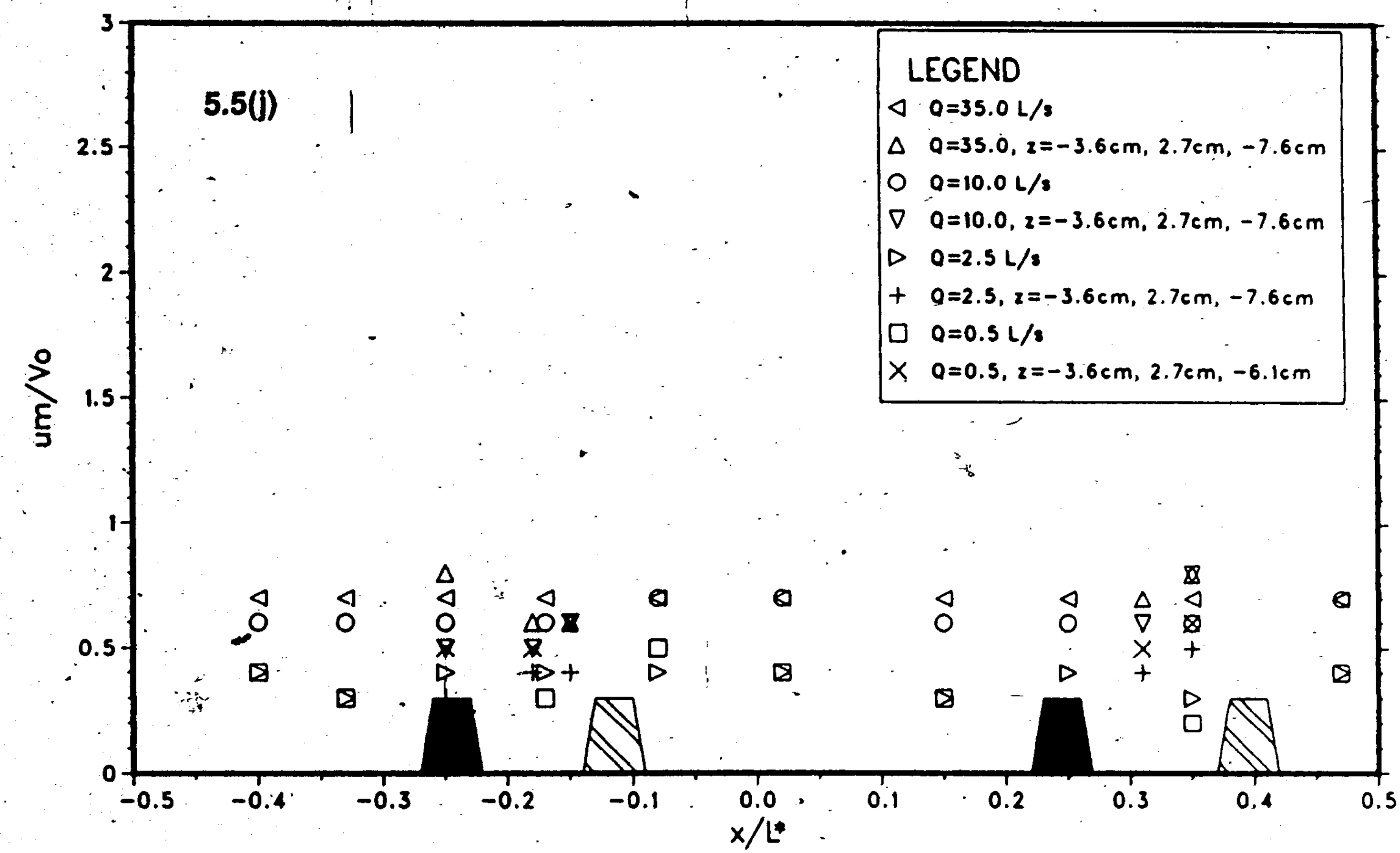


5.5(h)
LEGEND
Q=35.0 L/s
Q=35.0, z=-3.6cm, 2.7cm, -7.6cm
Q=10.0 L/s
Q=10.0, z=-3.6cm, 2 -7.6cm
Q=2.5 L/s
Q=2.5, z=-3.6cm, 2.7cm, -7.6cm
Q=0.5 L/s
Q=0.5, z=-3.6cm, 2.7cm, -6.1cm
y/yo
x/L*

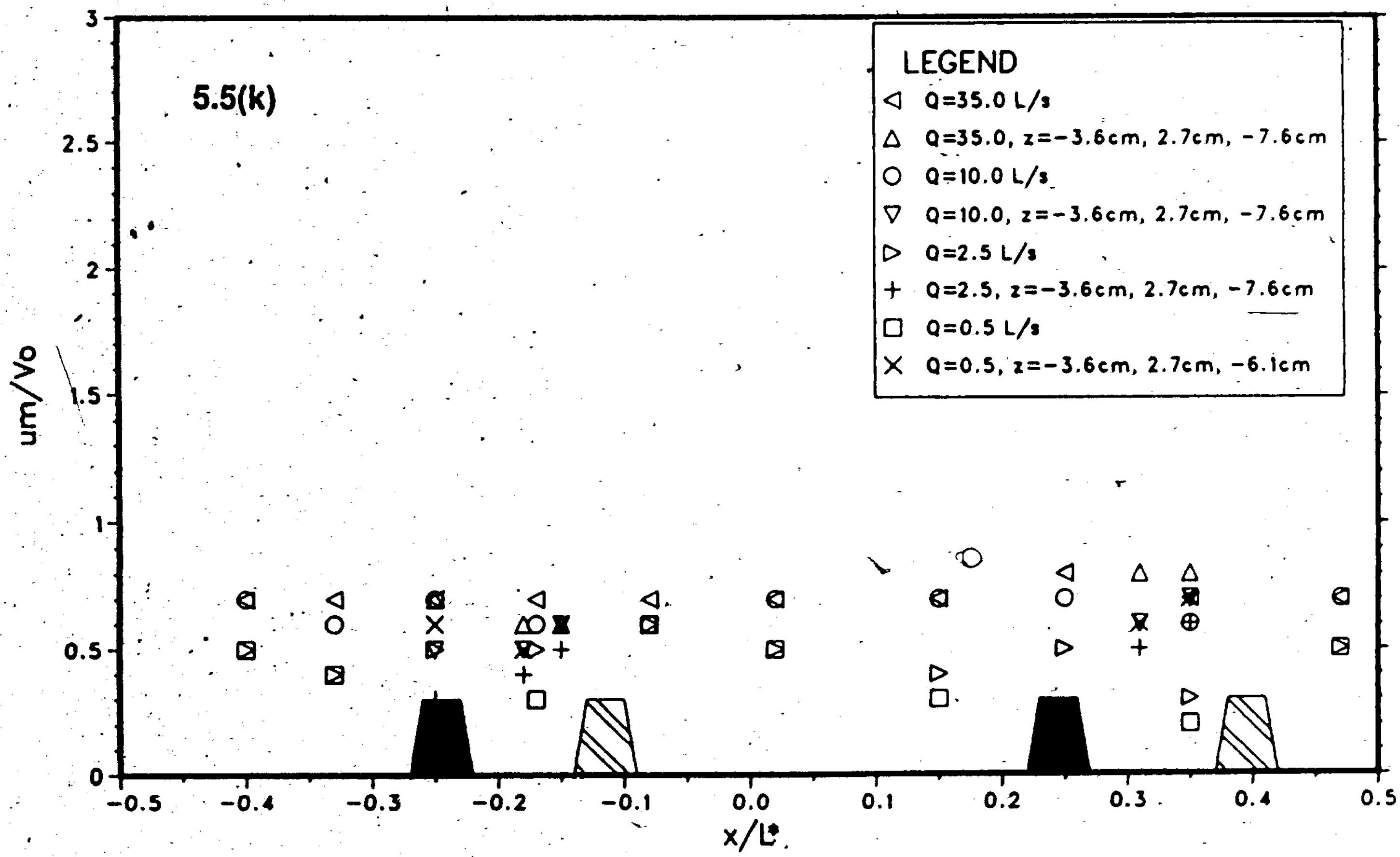
DESIGN #6 – S=5%


5.5(i)
LEGEND
Q=35.0 L/s
Q=35.0, z=-3.6cm, 2.7cm, -7.6cm
Q=10.0 L/s
Q=10.0, z=-3.6cm, 2.7cm, -7.6cm
Q=2.5 L/s
Q=2.5, z=-3.6cm, 2.7cm, -7.6cm
Q=0.5 L/s
Q=0.5, z=-3.6cm, 2.7cm, -6.1cm
y/yo
x/L*
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
-0.5
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
0.5

DESIGN #6 – S=1%

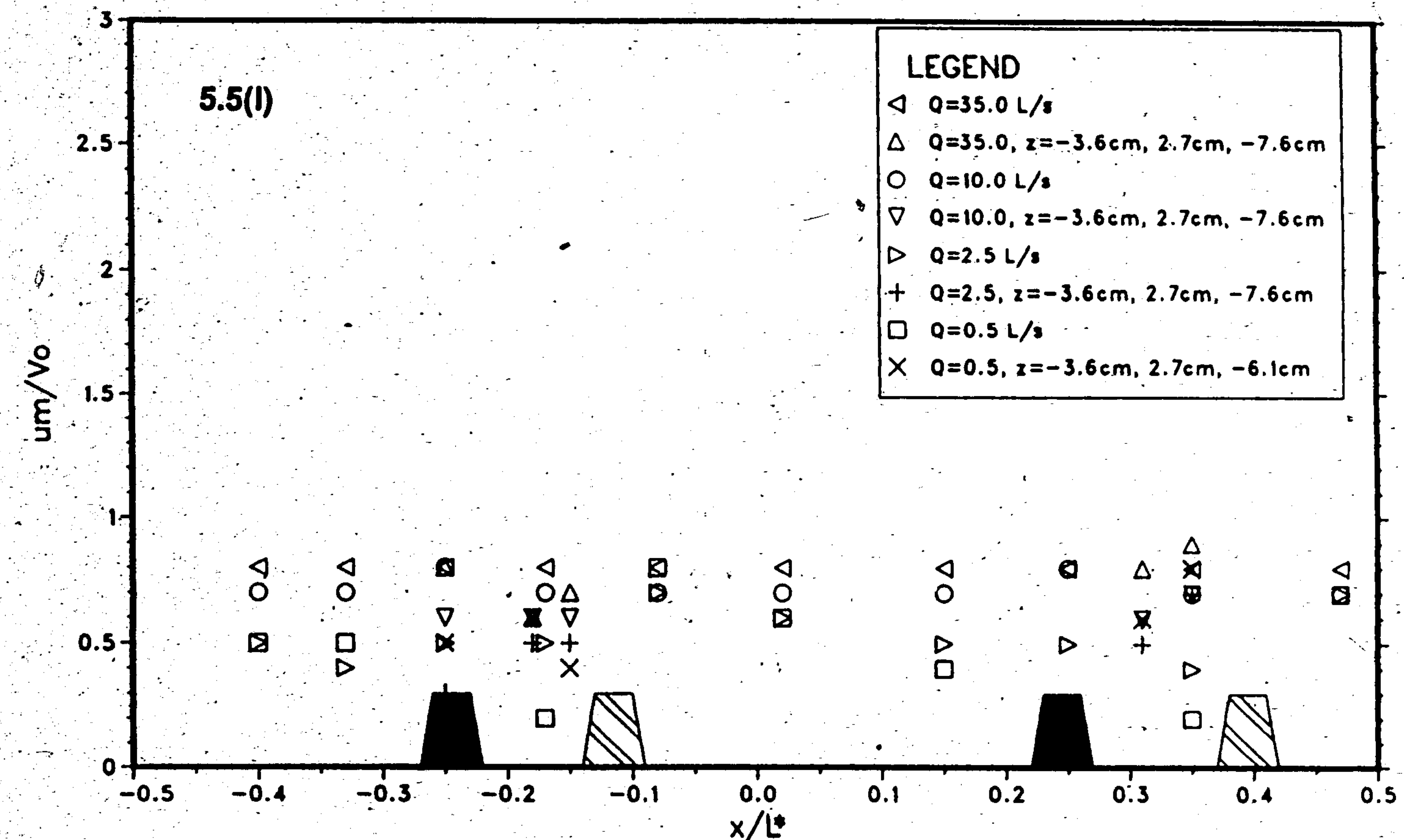

5.5(j)
LEGEND
Q=35.0 L/s
Q=35.0, z=-3.6cm, 2.7cm, -7.6cm
Q=10.0 L/s
Q=10.0, z=-3.6cm, 2.7cm, -7.6cm
Q=2.5 L/s
Q=2.5, z=-3.6cm, 2.7cm, -7.6cm
Q=0.5 L/s
Q=0.5, z=-3.6cm, 2.7cm, -6.1cm
um/Vo
x/L*
3
2.5
2
1.5
1
0.5
0
-0.5
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
0.5

DESIGN #6 – S=3%

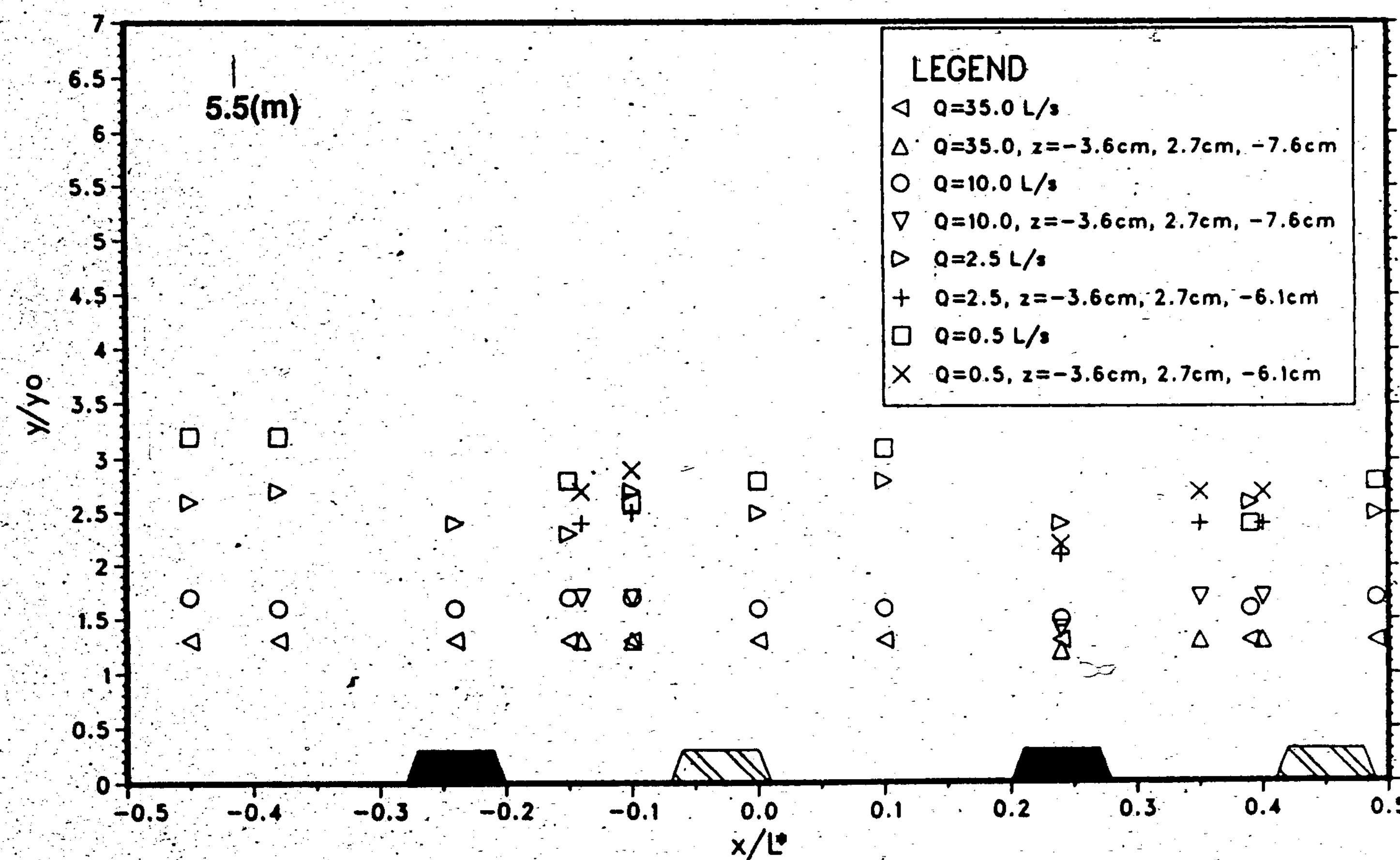


5.5(k)
LEGEND
Q=35.0 L/s
Q=35.0, z=-3.6cm, 2.7cm, -7.6cm
Q=10.0 L/s
Q=10.0, z=-3.6cm, 2.7cm, -7.6cm
Q=2.5 L/s
Q=2.5, z=-3.6cm, 2.7cm, -7.6cm
Q=0.5 L/s
Q=0.5, z=-3.6cm, 2.7cm, -6.1cm
um/Vo
x/L*
0
0.5
1
1.5
2
2.5
3
-0.5
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
0.5

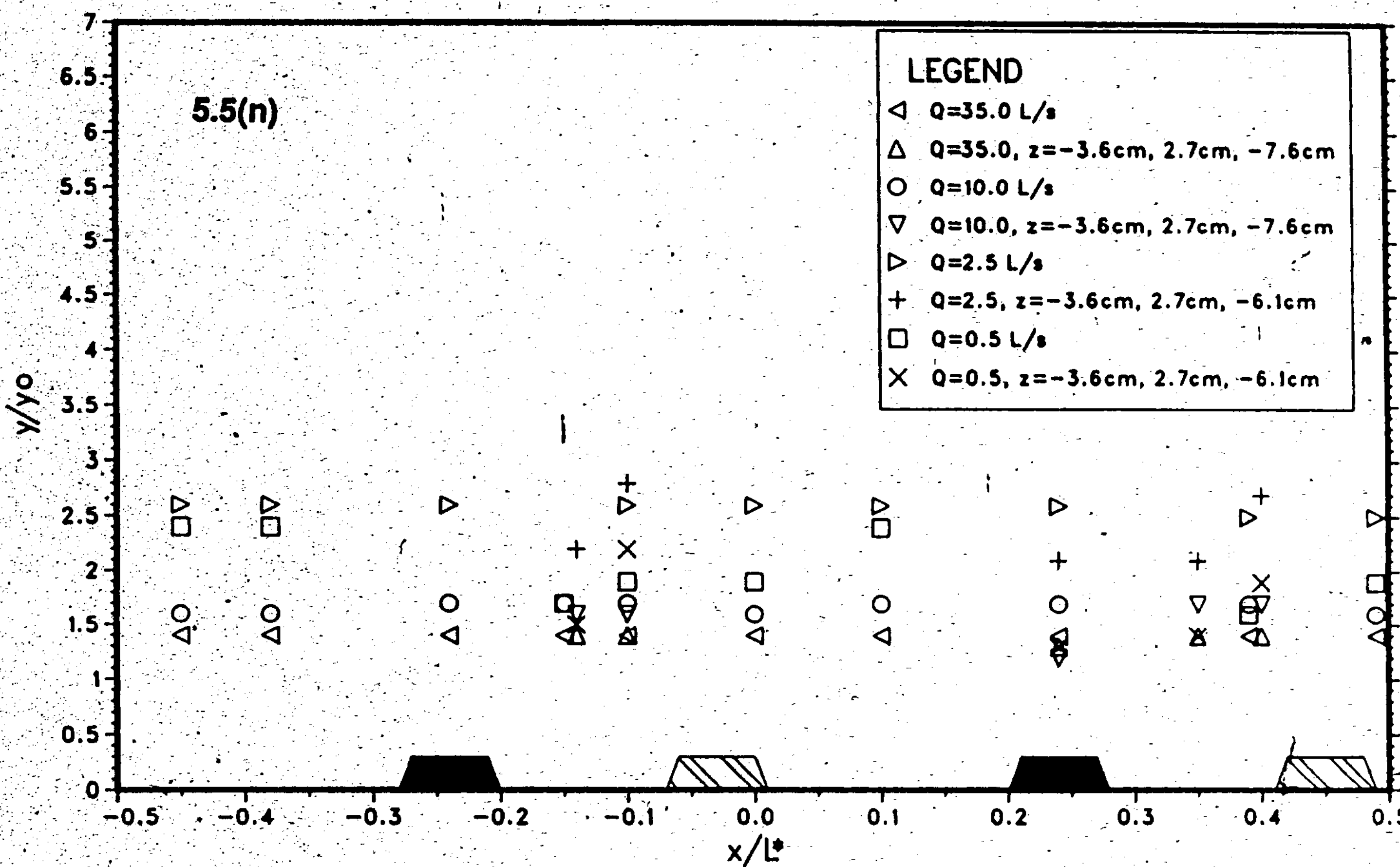
DESIGN #6 – S=5%


5.5(l)
LEGEND
Q=35.0 L/s
Q=35.0, z=−3.6cm, 2.7cm, −7.6cm
Q=10.0 L/s
Q=10.0, z=−3.6cm, 2.7cm, −7.6cm
Q=2.5 L/s
Q=2.5, z=−3.6cm, 2.7cm, −7.6cm
Q=0.5 L/s
Q=0.5, z=−3.6cm, 2.7cm, −6.1cm
um/Vo
x/L*
3
2.5
2
1.5
1
0.5
0
−0.5
−0.4
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3
0.4
0.5

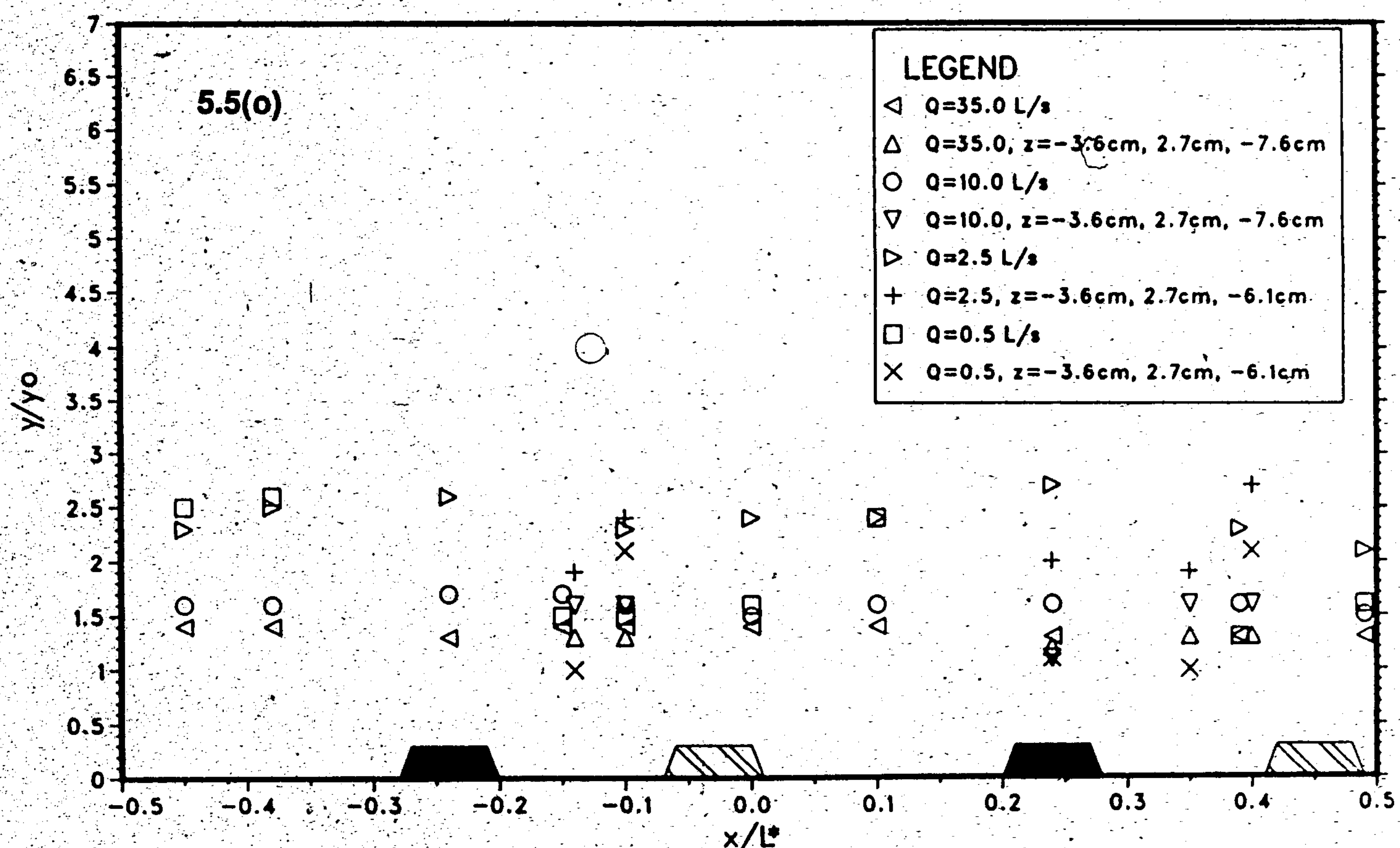
DESIGN #7 – S=1%


LEGEND
Q=35.0 L/s
Q=35.0, z=−3.6cm, 2.7cm, −7.6cm
Q=10.0 L/s
Q=10.0, z=−3.6cm, 2.7cm, −7.6cm
Q=2.5 L/s
Q=2.5, z=−3.6cm, 2.7cm, −6.1cm
Q=0.5 L/s
Q=0.5, z=−3.6cm, 2.7cm, −6.1cm
5.5(m)
y/yo
x/L*
−0.5
−0.4
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3
0.4
0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7

DESIGN #7 — S=3%

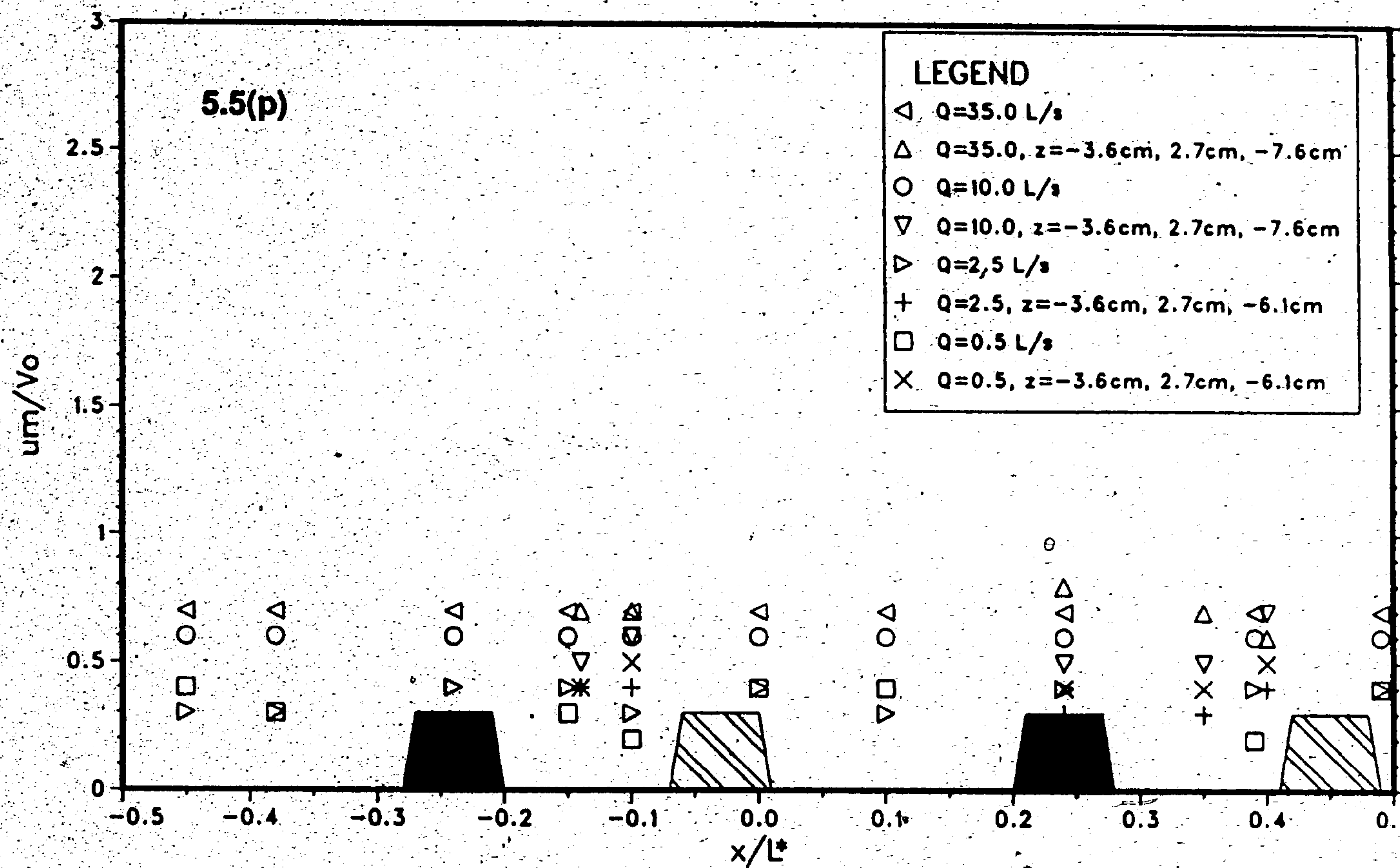

5.5(n)
LEGEND
Q=35.0 L/s
Q=35.0, z=−3.6cm, 2.7cm, −7.6cm
Q=10.0 L/s
Q=10.0, z=−3.6cm, 2.7cm, −7.6cm
Q=2.5 L/s
Q=2.5, z=−3.6cm, 2.7cm, −6.1cm
Q=0.5 L/s
Q=0.5, z=−3.6cm, 2.7cm, −6.1cm
y/yo
x/L*
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
−0.5
−0.4
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3
0.4
0.5

DESIGN #7 – S=5%

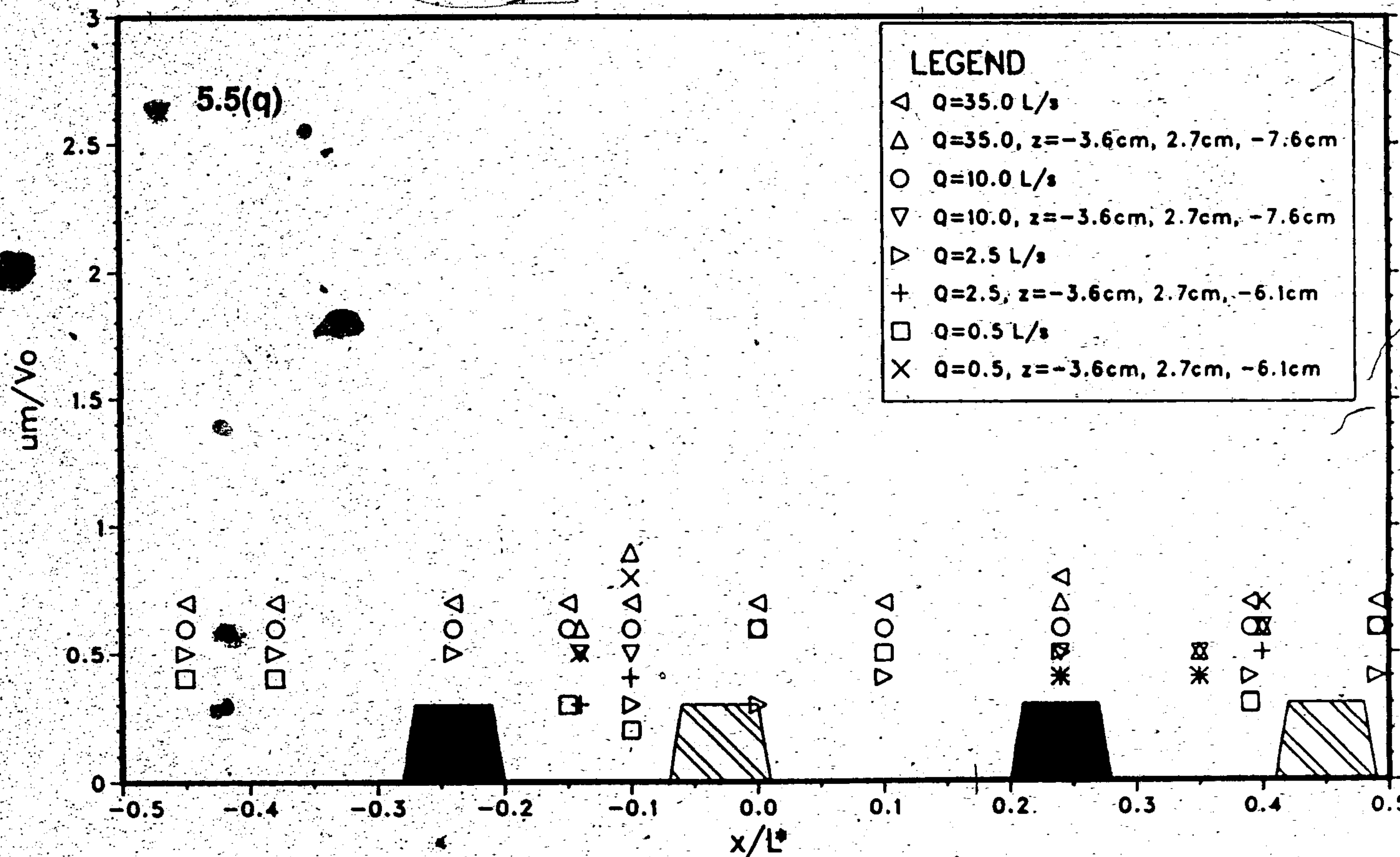


5.5(o)
LEGEND
Q=35.0 L/s
Q=35.0, z=-3.6cm, 2.7cm, -7.6cm
Q=10.0 L/s
Q=10.0, z=-3.6cm, 2.7cm, -7.6cm
Q=2.5 L/s
Q=2.5, z=-3.6cm, 2.7cm, -6.1cm
Q=0.5 L/s
Q=0.5, z=-3.6cm, 2.7cm, -6.1cm
y/yo
x/L*

DESIGN #7 – S=1%

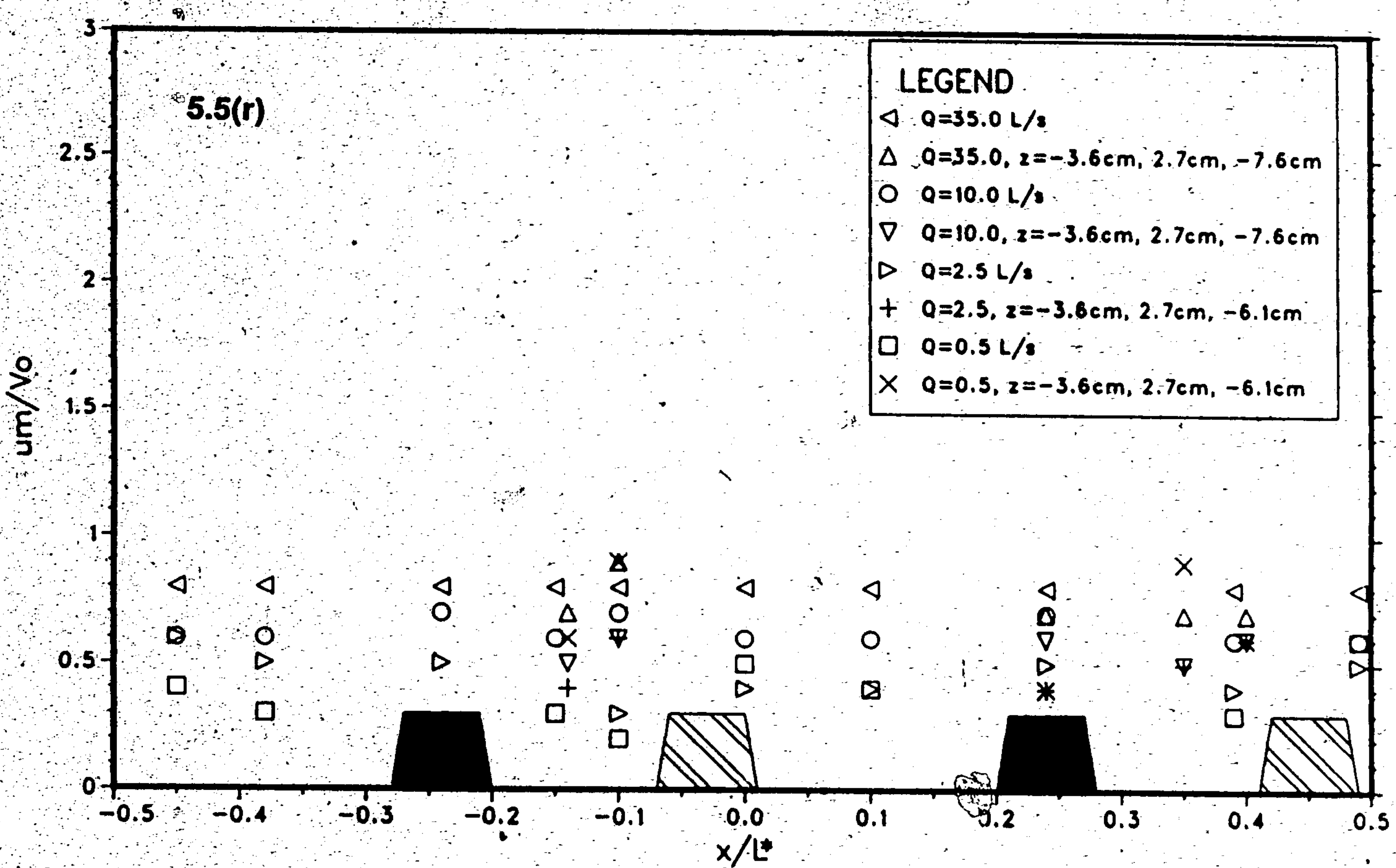

5.5(p)
LEGEND
Q=35.0 L/s
Q=35.0, z=-3.6cm, 2.7cm, -7.6cm
Q=10.0 L/s
Q=10.0, z=-3.6cm, 2.7cm, -7.6cm
Q=2,5 L/s
Q=2.5, z=-3.6cm, 2.7cm, -6.1cm
Q=0.5 L/s
Q=0.5, z=-3.6cm, 2.7cm, -6.1cm
um/Vo
x/L*
0
0.5
1
1.5
2
2.5
3
-0.5
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
0.5

DESIGN #7 - S=3%



5.5(q)
LEGEND
Q=35.0 L/s
Q=35.0, z=-3.6cm, 2.7cm, -7.6cm
Q=10.0 L/s
Q=10.0, z=-3.6cm, 2.7cm, -7.6cm
Q=2.5 L/s
Q=2.5, z=-3.6cm, 2.7cm, -6.1cm
Q=0.5 L/s
Q=0.5, z=-3.6cm, 2.7cm, -6.1cm
um/Vo
x/L*

DESIGN #7 – S=5%


5.5(r)
LEGEND
Q=35.0 L/s
Q=35.0, z=-3.6cm, 2.7cm, -7.6cm
Q=10.0 L/s
Q=10.0, z=-3.6cm, 2.7cm, -7.6cm
Q=2.5 L/s
Q=2.5, z=-3.6cm, 2.7cm, -6.1cm
Q=0.5 L/s
Q=0.5, z=-3.6cm, 2.7cm, -6.1cm
um/Vo
x/L*
3
2.5
2
1.5
1
0.5
0
-0.5
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
0.5

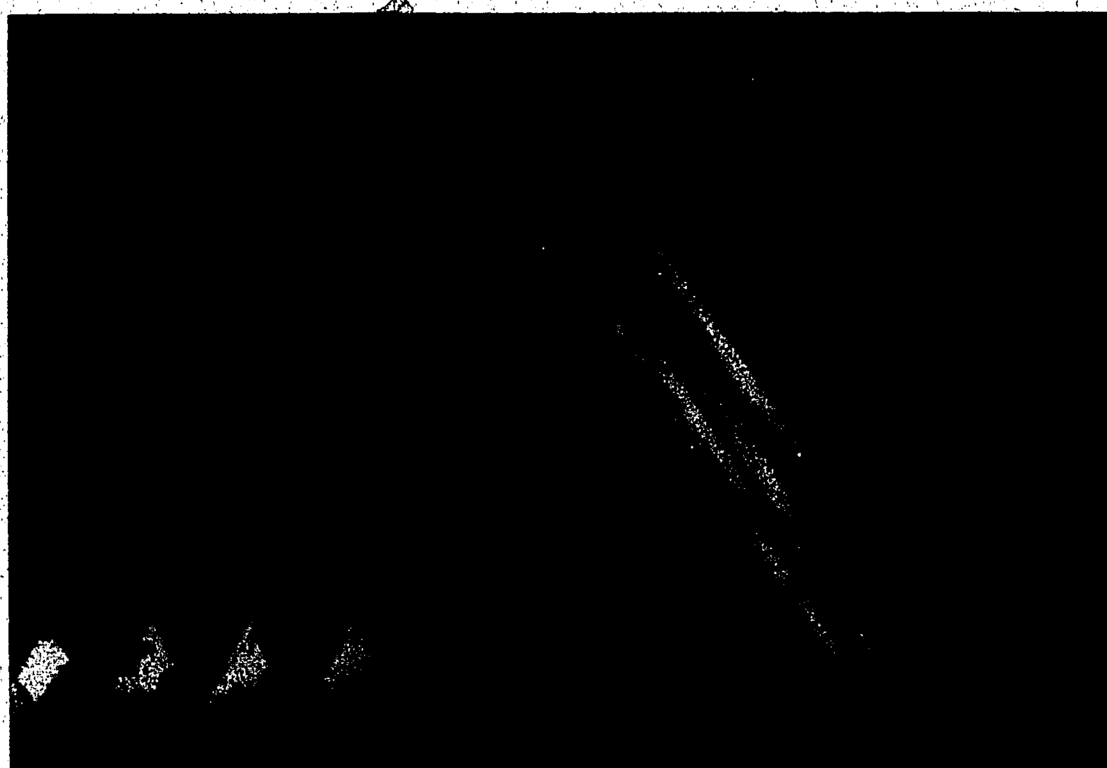


Plate 5.1 Flow around Fish-weirs - Design #1

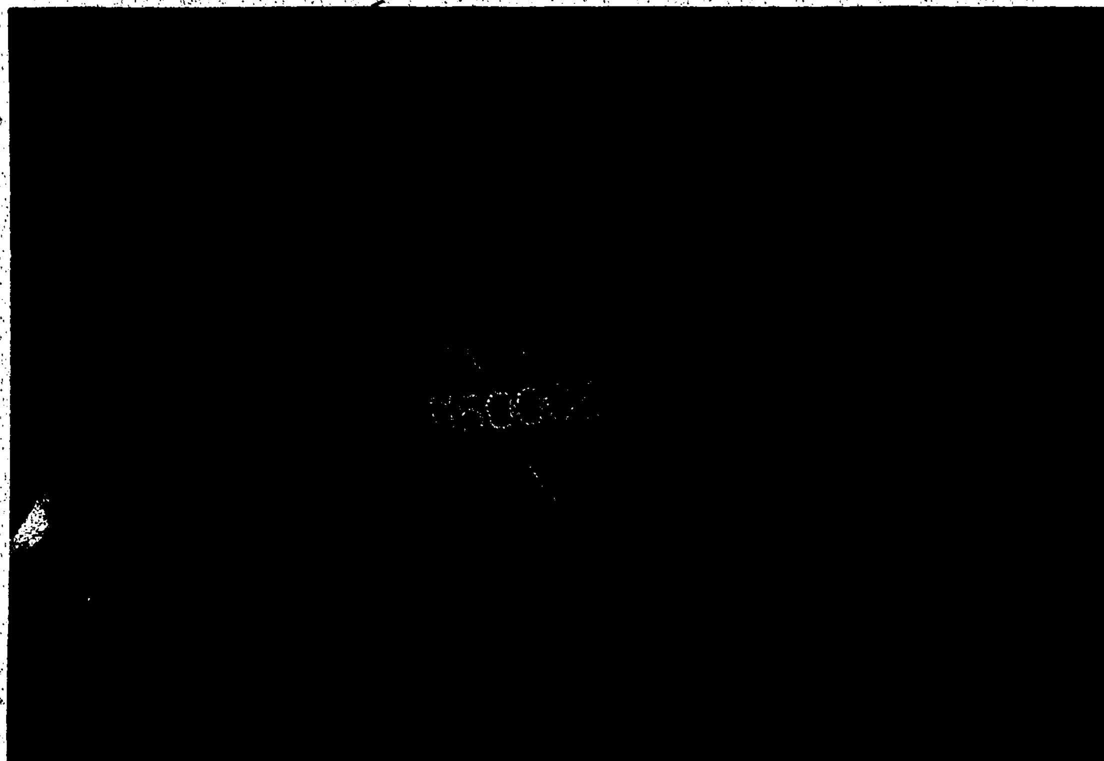


Plate 5.2 Flow around Fish-weirs - Design #1

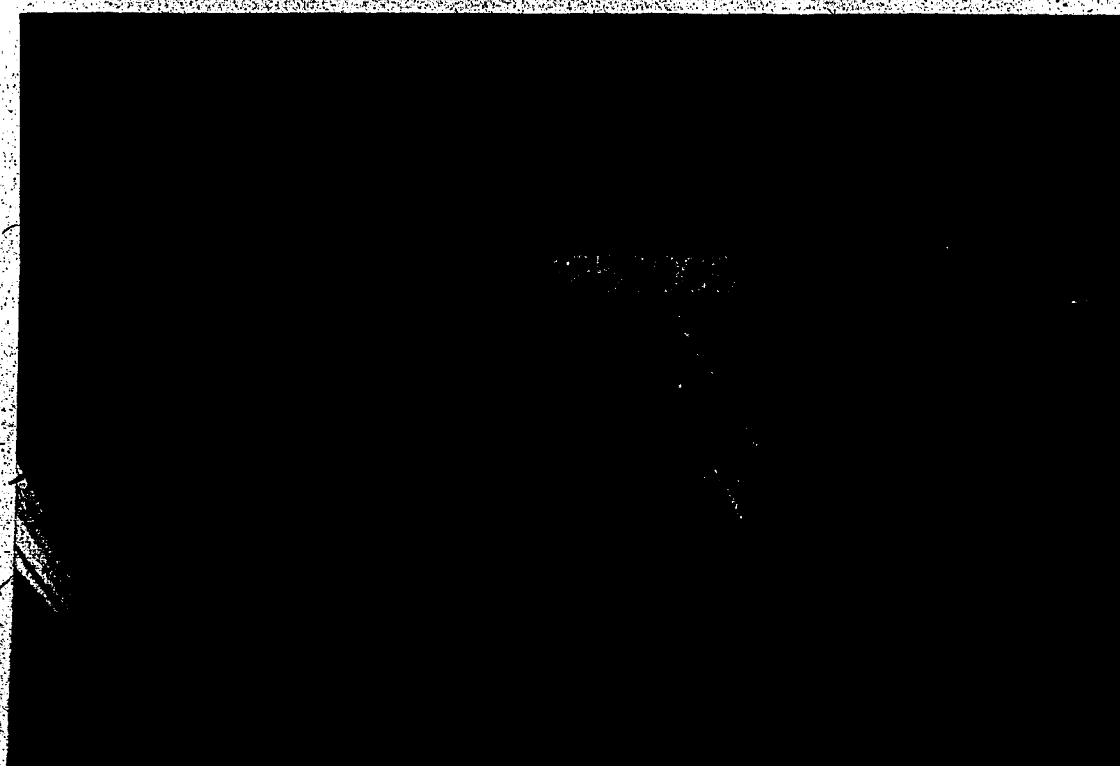


Plate 5.3 Flow around Fish-weirs - Design #2

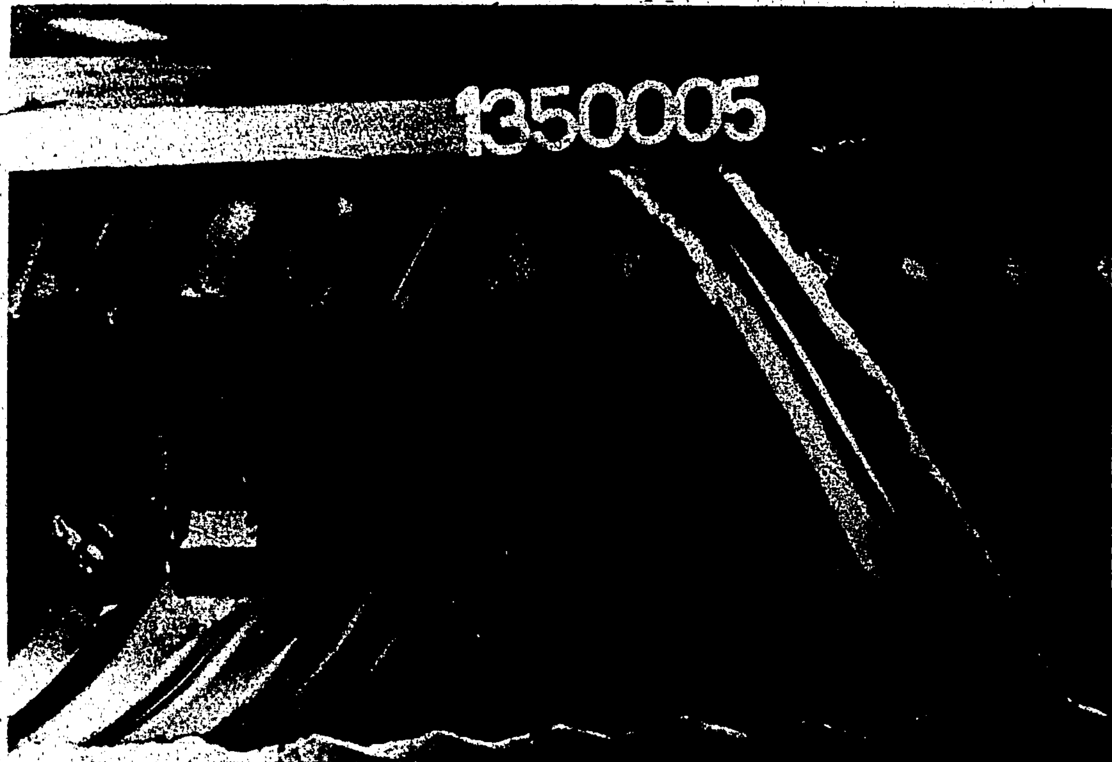


Plate 5.4 Flow around Fish-weirs - Design #3

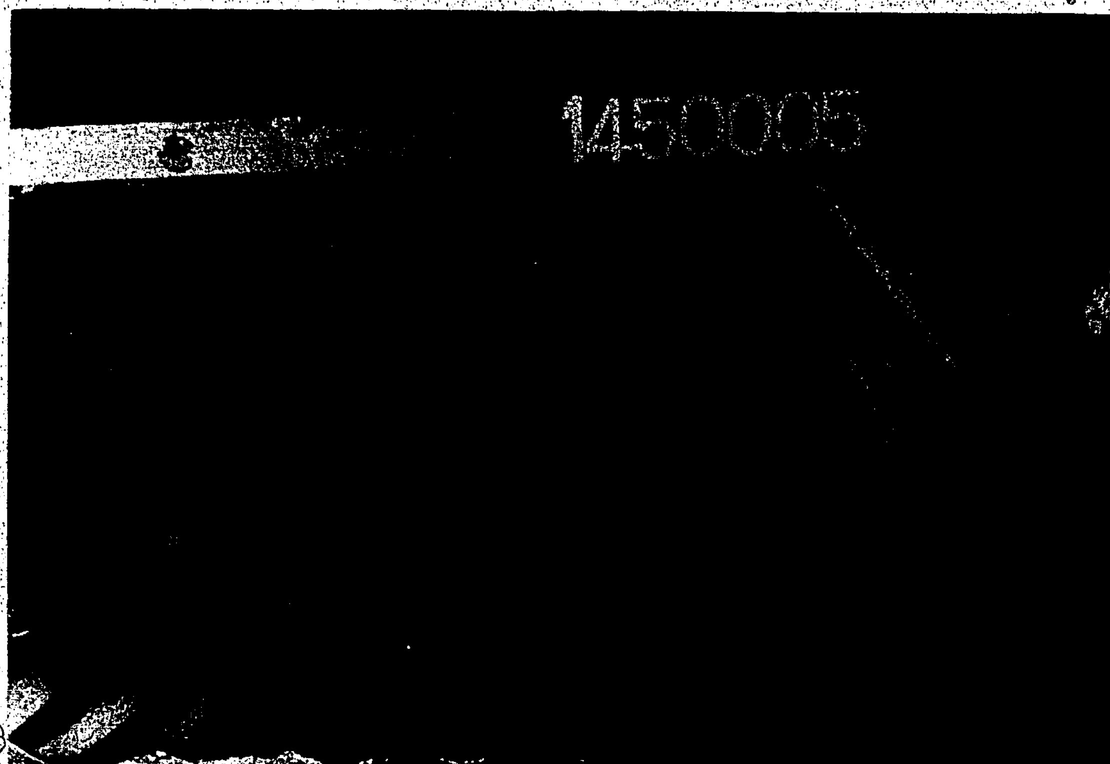


Plate 5.5 Flow around Fish-weirs - Design #4

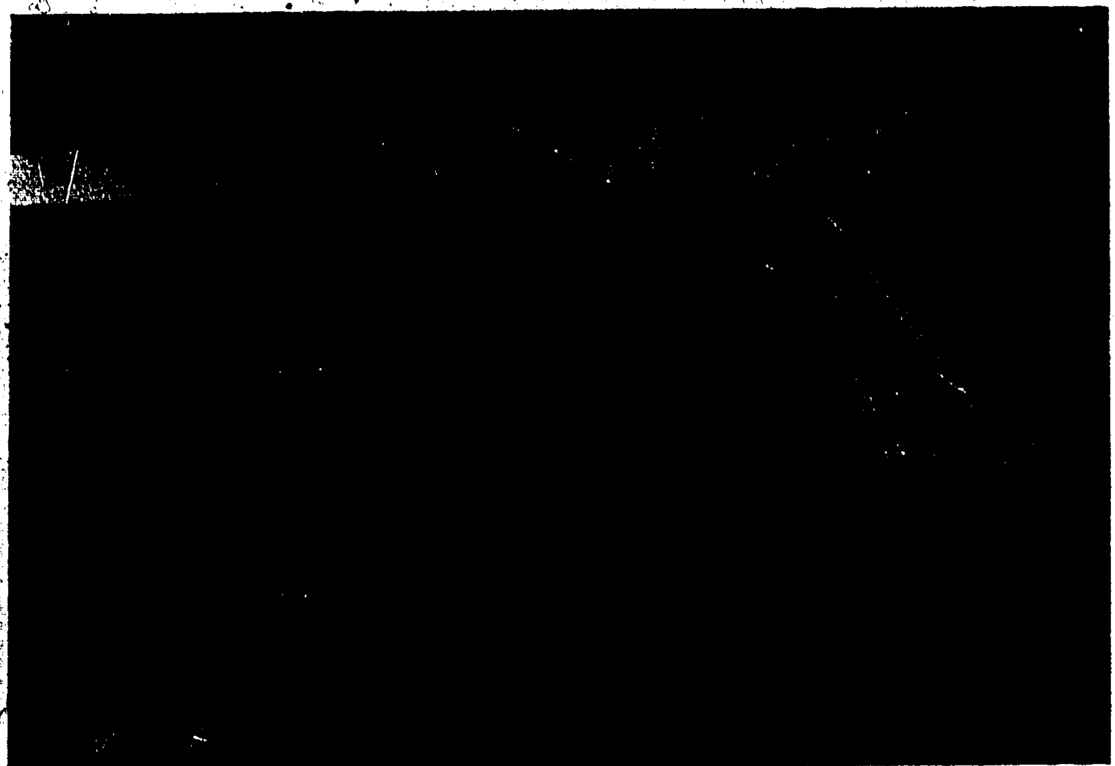


Plate 5.6 Flow around the Fish-baffles - Design #5

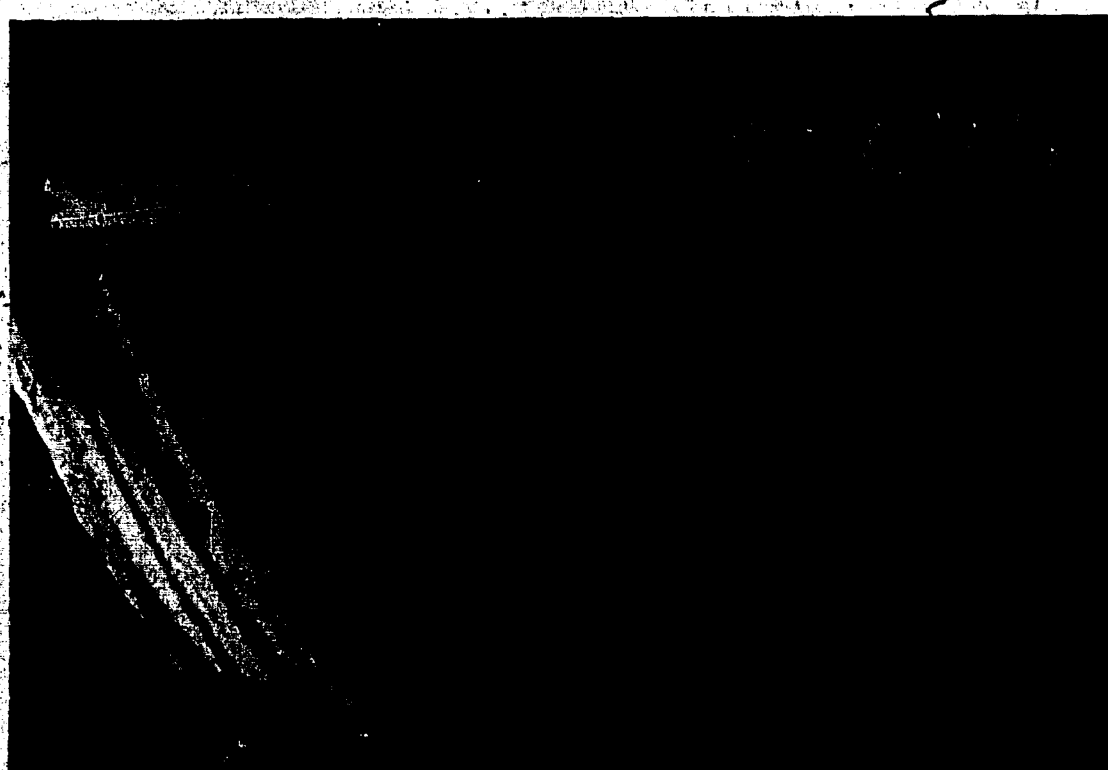


Plate 5.7 Flow around the Fish-baffles - Design #6

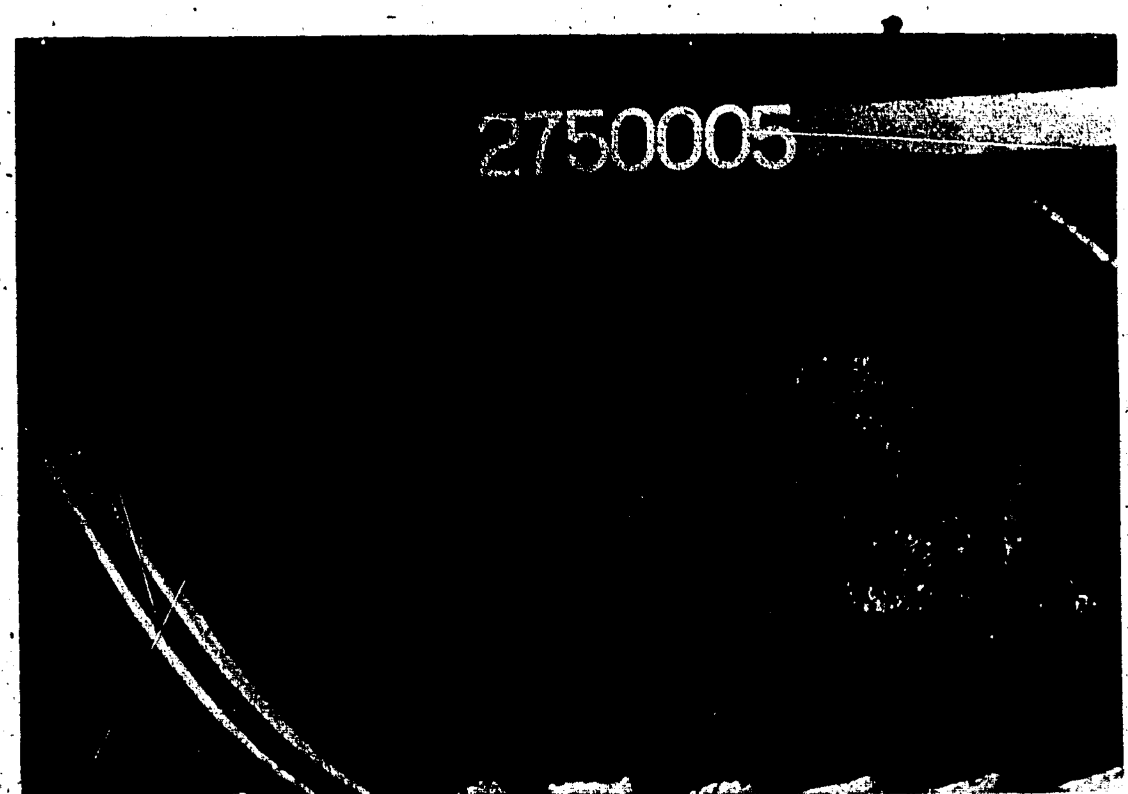


Plate 5.8: Flow around the Fish-baffles - Design #7

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Two types of culvert fishways (Fish-weirs and Fish-baffles) designed and used by Alberta Transportation were studied in a scale model study. This experimental study was undertaken to gain insight into the hydraulic performance of these two designs. Four fish-weir designs and three fish-baffle designs were tested for a number of slopes and discharges. Depths, velocities and flow patterns were recorded and analyzed. Based on the results of the experimental study presented, the following conclusions can be formulated.

The fish-weirs could be an obstacle to upstream fish movement at the lowest discharge since the depths over the central portion of the fish-weir and immediately downstream are lower than the recommended minimum depth of 6 inches (15 centimeters). The lowest discharge for this model study must be carefully examined to see if this discharge in the prototype is comparable to the minimum fish passage discharge for the particular fish species in question. This discharge may produce very low depths in natural conditions resulting in a natural barrier to fish passage.

Due to the low depths in some of the designs at the lowest discharge, the velocities could not be measured. The velocities that were measured were equal to or less than the maximum allowable velocities for trout (4 ft/sec - 1.2 m/s).

For the second lowest discharge (Q_M = 2.5 L/s - Q_P = 10.4 ft^3/s) the velocities were greater than the recommended maximum allowable velocities and could pose a problem to fish moving upstream at that discharge. An important aspect in the measuring of the water velocities is the length of the maximum velocities between fish-weirs as all fish have a maximum swimming distance for a particular water velocity before they must rest.

The fish-baffles do not function like the fish-weirs but simply increase the resistance to flow thereby producing larger depths of flow and reducing the maximum velocities one would find in a plain culvert. Yet, the depths at the lowest discharge for all the designs at all three slopes are less than recommended minimum depths of 6 inches (15 centimeters) (Table 5.4) which the fish require to maximize propulsion. Again, the question as to whether the lowest discharge for this study may already produce low depths in natural river conditions resulting in a natural barrier must be examined.

The majority of the velocities measured were less than the maximum allowable but there were some much greater than the maximum allowable. Since the fish-baffles do not span the entire width of the culvert, the fish moving upstream can choose its own path and may not have to contend with the maximum velocities at all times.

6.2 Recommendations

A number of recommendations for further research on the fish-weirs and fish-baffles can be made. A vast amount of data was collected and analyzed but more detailed analysis could be done on the data. First of all, the prototype dimensions of the fish-weirs and fish-baffles were fixed and were reduced by the scale factor of 6.75. Some parameters which could be analyzed in future studies are:

1. The side notches of the fish-weirs could be filled as the notches provided no benefit to the upstream movement for the fish.
2. The height of the center notch could be lowered to reduce the height of the jump at the lower discharges.
3. The width of the fish-weirs could be reduced,
4. The fixed spacing between each pair of fish-baffles could be increased or decreased.
5. The fish-baffles could be built as squares instead of tapered at the top which may increase the resistance to flow as well as the dimensions could be increased.

The above studies would be best done in a hydraulics laboratory.

Field studies are also necessary in evaluating the performance of culvert fishways in passing various fish species. Biological studies as well as hydraulic studies should be carried out in the field. Continuous interaction between field and laboratory studies should be ensured.

The effectiveness of this short study in undertaking the workings of these culvert fishways was surprising; nevertheless only a small part of the total field of the hydraulics of culvert fishways was investigated.

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APPENDIX A

Step-wise multiple regression is a statistical technique for analyzing a relationship between a dependent variable (y) and a set of independent variables $x_1, x_2, \ldots x_m$ in the order of importance. The criterion of importance is based on the reduction of sums of squares, and the independent variable most important in this reduction in a given step is entered into the regression. This statistical technique was acquired from the Scientific Subroutine Package (SSP) which can be obtained from MTS (Michigan Terminal System) at the University of Alberta.

Step-wise multiple regression was applied to seven variables slope (S_o), model discharge (Q_M), spacing length (L), minimum depth (y_{min}), maximum value of the maximum velocity (u_{mm}), centerline depth of the plain culverts (y_o) and ($Q/D^{5/2}$). It was used to obtain the best regression equation for y_{min} and the following four variables $Q/D^{5/2}$, S_o, y_o, L and between u_{mm} and the same four variables for the fish-weirs and the fish-baffles.

To obtain the best regression for y_{min} and u_{mm}, seven different functions were tested for y_{min} and u_{mm}:

1. y_{min} or $u_{mm} = f\{Q/D^{5/2}, y_o, S_o, L \text{ or } L*\}$
2. y_{min} or $u_{mm} = f\{Q/D^{5/2}, S_o, L \text{ or } L*\}$
3. y_{min} or $u_{mm} = f\{y_o, S_o, L \text{ or } L*\}$
4. y_{min} or $u_{mm} = f\{Q/D^{5/2}, S_o\}$
5. y_{min} or $u_{mm} = f\{Q/D^{5/2}, L \text{ or } L*\}$

6. y_{min} or u_{mm} = f{y_o, S_o}
7. y_{min} or u_{mm} = f{y_o, L or L*}

The best regression equations were chosen based on the multiple correlation coefficient, standard error of estimate and the computed T-value. There was no difference in the correlation coefficients for Q_M and $Q/D^{5/2}$ since there was no change in the culvert diameter. Thus the model discharge (Q_M) could have been used in the functions but $Q/D^{5/2}$ was chosen for this analysis.

For the fish-weirs, two regression equations were chosen for both y_{min} and u_{mm}:

$$y_{min} = 3.61 * (y_o)^{1.51}$$

where r=0.950, standard error of estimate=0.385 and the computed T-value for y_o=20.477

$$y_{min} = 0.16 * (Q/D^{5/2})^{0.73} * (S_o)^{-0.17}$$

where r=0.952, standard error of estimate=0.382 and the computed T-value for $Q/D^{5/2}$=20.859 and S_o=-2.019

$$u_{mm} = 18.93 * (y_o)^{0.65} * (S_o)^{0.31} * (L)^{0.15}$$

where r=0.938, standard error of estimate=0.199 and the computed T-value for y_o=17.186, S_o=7.249 and L=2.826

$$u_{mm} = 4.25 * (Q/D^{5/2})^{0.31} * (S_o)^{0.20} * (L)^{0.15}$$

where r=0.940, standard error of estimate=0.196 and the computed T-value for $Q/D^{5/2}$=17.506, S_o=4.683 and L=2.865

The calculated values for y_{min} and u_{mm} have been tabulated along with the observed values and are shown in table A.1. The calculated values for y_{min} and u_{mm} were compared to the observed values to show the magnitude of the discrepancies and these are shown in figures A.1 to A.4 respectively. The solid line in all the figures represents when the observed values equal the calculated values. Figures A.1 and A.2 show a large discrepancy at the higher discharges for y_{min} which could indicate a possible experimental error or the multiple regression package utilized was not the best choice and time did not permit the use of other multiple regression statistical techniques for comparison purposes. There is a slight difference in the calculated values between the two regression equations for y_{min}. Figures A.3 to A.4 show much scatter in the data which again could mean a poor choice in the statistical package and possible error in the experimental measurement. Again, there is very little difference in the calculated value's from the [illegible] regression equations for u_{mm}.

For the fish-baffles, two regression equations were chosen for both y_{min} and u_{mm}:

$$y_{min} = 0.50 * (y_o)^{0.99} * (S_o)^{-0.22} * (L*)^{-0.32}$$

where r=0.960, standard error of estimate=0.279 and the computed T-value for y_o=18.877, S_o=-3.121 and L*=-3.107

$$y_{min} = 0.05 * (Q/D^{5/2})^{0.56} * (S_o)^{-0.34} * (L*)^{-0.33}$$

where r=0.980, standard error of estimate=0.198 and the computed T-value for $Q/D^{5/2}$=27.090 and S_o=-6.969 and L*=-4.526

$$u_{mm} = 14.12 * (y_o)^{0.41} * (S_o)^{0.31} * (L*)^{0.18}$$

where r=0.982, standard error of estimate=0.085 and the computed T-value for y_o=25.717, S_o=15.023 and L*=5.842

$$u_{mm} = 5.29 * (Q/D^{5/2})^{0.23} * (S_o)^{0.26} * (L*)^{0.17}$$

where r=0.977, standard error of estimate=0.098 and the computed T-value for $Q/D^{5/2}$=22.853, S_o=11.215 and L*=5.054

The calculated values for y_{min} and u_{mm} have been tabulated along with the observed values and are shown in table A.2. The calculated values for y_{min} and u_{mm} again were compared to the observed values to show the magnitude of the discrepancies and these are shown in figures A.5 to A.8 respectively. Again, the solid line in all the figures represents when the observed values equal the calculated values. Figures A.5 and A.6 show a large discrepancy at the higher flow rates for y_{min} which could indicate a possible experimental error or the multiple regression package utilized was not the best choice. Figures A.7 to A.8 show little scatter in the data and a fairly good fit to the regression equation for u_{mm}. Again, there is slight difference in the calculated values for y_{min} from the two regression equations as well as for u_{mm}.

Table A.1 Calculated and observed values for y_{min} and u_{mm} for the fish-weirs.

DESIGN	S_o	Q	L	y_o	V_o	D	y_{min} (observed)	u_{mm} (observed)	y_{min} (calculated)		u_{mm} (calculated)	
	(%)	(m^3/s)	(m)	(m)	(m/s)	(m)	(m)	(m/s)	(m) (*1)	(m) (*2)	(m/s) (*3)	(m/s) (*4)
1	1	0.0350	0.985	0.133	0.94	0.406	0.127	1.01	0.172	0.157	1.22	1.20
2	1	0.0350	0.493	0.133	0.94	0.406	0.131	0.96	0.172	0.157	1.10	1.08
3	1	0.0350	0.246	0.133	0.94	0.406	0.138	0.90	0.172	0.157	0.99	0.98
4	1	0.0350	0.739	0.133	0.94	0.406	0.128	0.94	0.172	0.157	1.17	1.15
1	1	0.0100	0.985	0.072	0.65	0.406	0.064	0.79	0.068	0.063	0.82	0.81
2	1	0.0100	0.493	0.072	0.65	0.406	0.067	0.68	0.068	0.063	0.74	0.73
3	1	0.0100	0.246	0.072	0.65	0.406	0.069	0.76	0.068	0.063	0.67	0.66
4	1	0.0100	0.739	0.072	0.65	0.406	0.065	0.79	0.068	0.063	0.79	0.78
1	1	0.0025	0.985	0.037	0.43	0.406	0.031	0.65	0.025	0.023	0.53	0.53
2	1	0.0025	0.493	0.037	0.43	0.406	0.033	0.46	0.025	0.023	0.48	0.48
3	1	0.0025	0.246	0.037	0.43	0.406	0.034	0.46	0.025	0.023	0.43	0.43
4	1	0.0025	0.739	0.037	0.43	0.406	0.027	0.55	0.025	0.023	0.51	0.51
1	1	0.0005	0.985	0.017	0.26	0.406	0.008	0.35	0.008	0.007	0.32	0.32
2	1	0.0005	0.493	0.017	0.26	0.406	0.007	0.34	0.008	0.007	0.29	0.29
3	1	0.0005	0.246	0.017	0.26	0.406	0.004	0.29	0.008	0.007	0.26	0.26
4	1	0.0005	0.739	0.017	0.26	0.406	0.003	0.23	0.008	0.007	0.31	0.31
1	3	0.0350	0.985	0.110	1.30	0.406	0.110	1.35	0.129	0.130	1.52	1.50
2	3	0.0350	0.493	0.110	1.30	0.406	0.113	1.22	0.129	0.130	1.37	1.35
3	3	0.0350	0.246	0.110	1.30	0.406	0.109	1.25	0.129	0.130	1.23	1.22
4	3	0.0350	0.739	0.110	1.30	0.406	0.103	1.27	0.129	0.130	1.43	1.43
1	3	0.0100	0.985	0.057	0.90	0.406	0.049	1.09	0.048	0.052	0.99	1.01
2	3	0.0100	0.493	0.057	0.90	0.406	0.062	0.90	0.048	0.052	0.89	0.91
3	3	0.0100	0.246	0.057	0.90	0.406	0.064	0.88	0.048	0.052	0.80	0.82
4	3	0.0100	0.739	0.057	0.90	0.406	0.048	1.05	0.048	0.052	0.95	0.97
1	3	0.0025	0.985	0.030	0.59	0.406	0.028	0.88	0.018	0.019	0.65	0.66
2	3	0.0025	0.493	0.030	0.59	0.406	0.030	0.73	0.018	0.019	0.59	0.60
3	3	0.0025	0.246	0.030	0.59	0.406	0.027	0.66	0.018	0.019	0.53	0.54
4	3	0.0025	0.739	0.030	0.59	0.406	0.025	0.72	0.018	0.019	0.62	0.63
1	3	0.0005	0.985	0.014	0.36	0.406	0.008	0.43	0.006	0.006	0.40	0.40
2	3	0.0005	0.493	0.014	0.36	0.406	0.007	0.47	0.006	0.006	0.36	0.36
3	3	0.0005	0.246	0.014	0.36	0.406	0.002	0.28	0.006	0.006	0.32	0.33
4	3	0.0005	0.739	0.014	0.36	0.406	0.004	0.23	0.006	0.006	0.38	0.38
1	5	0.0350	0.985	0.099	1.42	0.406	0.093	1.55	0.110	0.119	1.66	1.66
2	5	0.0350	0.493	0.099	1.42	0.406	0.105	1.43	0.110	0.119	1.50	1.49
3	5	0.0350	0.246	0.099	1.42	0.406	0.098	1.40	0.110	0.119	1.35	1.35
4	5	0.0350	0.739	0.099	1.42	0.406	0.088	1.47	0.110	0.119	1.59	1.59
1	5	0.0100	0.985	0.054	0.97	0.406	0.044	1.16	0.044	0.048	1.12	1.12
2	5	0.0100	0.493	0.054	0.97	0.406	0.057	1.03	0.044	0.048	1.01	1.01
3	5	0.0100	0.246	0.054	0.97	0.406	0.059	0.87	0.044	0.048	0.91	0.91
4	5	0.0100	0.739	0.054	0.97	0.406	0.035	1.16	0.044	0.048	1.07	1.07
1	5	0.0025	0.985	0.028	0.64	0.406	0.019	1.01	0.016	0.017	0.73	0.73
2	5	0.0025	0.493	0.028	0.64	0.406	0.028	0.78	0.016	0.017	0.66	0.66
3	5	0.0025	0.246	0.028	0.64	0.406	0.025	0.79	0.016	0.017	0.59	0.59
4	5	0.0025	0.739	0.028	0.64	0.406	0.024	0.79	0.016	0.017	0.70	0.70
1	5	0.0005	0.985	0.013	0.39	0.406	0.009	0.40	0.005	0.005	0.44	0.44
2	5	0.0005	0.493	0.013	0.39	0.406	0.007	0.40	0.005	0.005	0.40	0.40
3	5	0.0005	0.246	0.013	0.39	0.406	0.002	0.20	0.005	0.005	0.36	0.36
4	5	0.0005	0.739	0.013	0.39	0.406	0.003	0.31	0.005	0.005	0.43	0.43

(*1) - $y_{min} = 3.61 \times (y_o)^{1.51}$

(*2) - $y_{min} = 0.16 \times (Q/D^{5/2})^{0.73} \times (S_o)^{-0.17}$

(*3) - $u_{mm} = 18.93 \times (y_o)^{0.65} \times (S_o)^{0.31} \times (L)^{0.15}$

(*4) - $u_{mm} = 4.25 \times (Q/D^{5/2})^{0.31} \times (S_o)^{0.20} \times (L)^{0.15}$

Table A.2 Calculated and observed values for y_{min} and u_{mm} for the fish-baffles.

DESIGN	S_o (%)	Q (m^3/s)	L* (m)	y_o (m)	V_o (m/s)	D (m)	y_{min} (observed) (m)	u_{mm} (observed) (m/s)	y_{min} (calculated) (m) (*1)	y_{min} (calculated) (m) (*2)	u_{mm} (calculated) (m/s) (*3)	u_{mm} (calculated) (m/s) (*4)
5	1	0.0350	1.176	0.1090	1.30	0.393	0.121	1.14	0.146	0.128	1.41	1.30
6	1	0.0350	0.588	0.1090	1.30	0.393	0.136	1.03	0.182	0.161	1.24	1.16
7	1	0.0350	0.388	0.1090	1.30	0.393	0.137	0.98	0.208	0.185	1.15	1.08
5	1	0.0100	1.176	0.0460	1.25	0.393	0.054	1.06	0.062	0.064	0.99	0.97
6	1	0.0100	0.588	0.0460	1.25	0.393	0.057	0.96	0.077	0.080	0.87	0.87
7	1	0.0100	0.388	0.0460	1.25	0.393	0.071	0.89	0.088	0.092	0.81	0.81
5	1	0.0025	1.176	0.0190	1.25	0.393	0.034	0.63	0.026	0.029	0.69	0.71
6	1	0.0025	0.588	0.0190	1.25	0.393	0.040	0.60	0.032	0.037	0.61	0.63
7	1	0.0025	0.388	0.0190	1.25	0.393	0.043	0.54	0.037	0.042	0.56	0.59
5	1	0.0005	1.176	0.0085	0.77	0.393	0.014	0.56	0.012	0.012	0.49	0.49
6	1	0.0005	0.588	0.0085	0.77	0.393	0.017	0.46	0.015	0.015	0.44	0.43
7	1	0.0005	0.388	0.0085	0.77	0.393	0.020	0.40	0.017	0.017	0.40	0.41
5	3	0.0350	1.176	0.0830	1.84	0.393	0.092	1.72	0.087	0.088	1.77	1.73
6	3	0.0350	0.588	0.0830	1.84	0.393	0.107	1.54	0.109	0.111	1.56	1.54
7	3	0.0350	0.388	0.0830	1.84	0.393	0.113	1.38	0.125	0.127	1.45	1.43
5	3	0.0100	1.176	0.0380	1.67	0.393	0.046	1.26	0.040	0.044	1.28	1.30
6	3	0.0100	0.588	0.0380	1.67	0.393	0.049	1.18	0.050	0.055	1.13	1.15
7	3	0.0100	0.388	0.0380	1.67	0.393	0.061	1.07	0.057	0.063	1.05	1.07
5	3	0.0025	1.176	0.0160	1.25	0.393	0.020	0.91	0.017	0.020	0.90	0.94
6	3	0.0025	0.588	0.0160	1.25	0.393	0.027	0.75	0.021	0.025	0.79	0.84
7	3	0.0025	0.388	0.0160	1.25	0.393	0.034	0.67	0.024	0.029	0.74	0.78
5	3	0.0005	1.176	0.0086	0.76	0.393	0.005	0.66	0.009	0.008	0.70	0.65
6	3	0.0005	0.588	0.0086	0.76	0.393	0.010	0.55	0.012	0.010	0.62	0.58
7	3	0.0005	0.388	0.0086	0.76	0.393	0.012	0.62	0.013	0.012	0.57	0.54
5	5	0.0350	1.176	0.0780	2.06	0.393	0.082	2.12	0.073	0.074	2.02	1.97
6	5	0.0350	0.588	0.0780	2.06	0.393	0.095	1.95	0.092	0.093	1.78	1.76
7	5	0.0350	0.388	0.0780	2.06	0.393	0.102	1.84	0.105	0.107	1.65	1.64
5	5	0.0100	1.176	0.0360	1.67	0.393	0.039	1.46	0.034	0.037	1.47	1.48
6	5	0.0100	0.588	0.0360	1.67	0.393	0.048	1.30	0.043	0.046	1.30	1.32
7	5	0.0100	0.388	0.0360	1.67	0.393	0.054	1.22	0.049	0.053	1.20	1.23
5	5	0.0025	1.176	0.0150	1.25	0.393	0.017	1.01	0.014	0.017	1.03	1.08
6	5	0.0025	0.588	0.0150	1.25	0.393	0.023	0.85	0.018	0.021	0.91	0.96
7	5	0.0025	0.388	0.0150	1.25	0.393	0.029	0.76	0.020	0.024	0.84	0.89
5	5	0.0005	1.176	0.0080	0.83	0.393	0.005	0.73	0.008	0.007	0.79	0.74
6	5	0.0005	0.588	0.0080	0.83	0.393	0.005	0.70	0.010	0.009	0.70	0.66
7	5	0.0005	0.388	0.0080	0.83	0.393	0.008	0.73	0.011	0.010	0.65	0.62

(*1) - $y_{min} = 0.50 \times (y_o)^{0.99} \times (S_o)^{-0.22} \times (L_*)^{-0.32}$

(*2) - $y_{min} = 0.05 \times (Q/D^{5/2})^{0.56} \times (S_o)^{-0.34} \times (L_*)^{-0.33}$

(*3) - $u_{mm} = 14.12 \times (y_o)^{0.41} \times (S_o)^{0.31} \times (L_*)^{0.18}$

(*4) - $u_{mm} = 5.29 \times (Q/D^{5/2})^{0.23} \times (S_o)^{0.26} \times (L_*)^{0.17}$

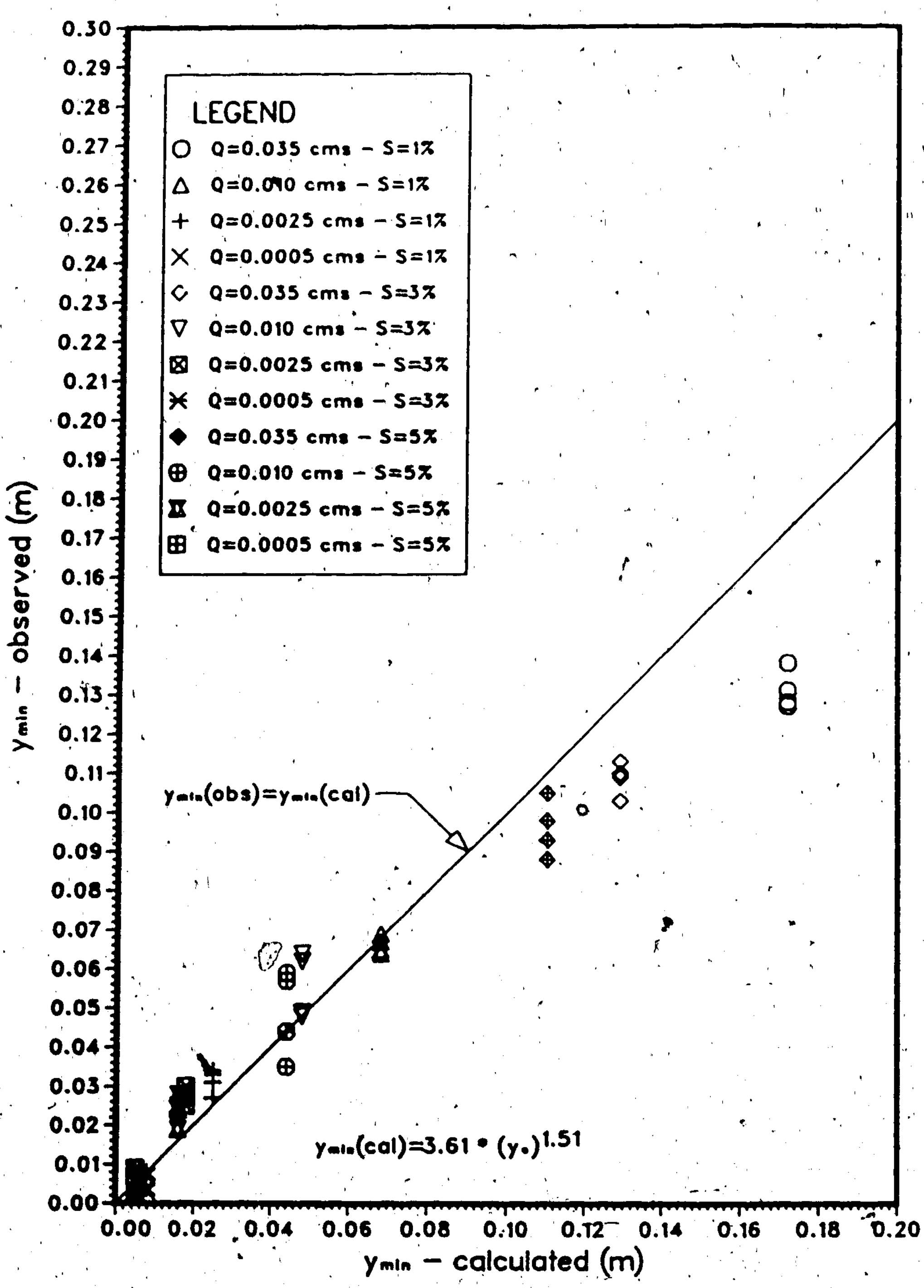

Figure A.1 Comparison between the calculated values based on $y_{min} = 3.61 * (y_o)^{1.51}$ and the observed values of y_{min}.

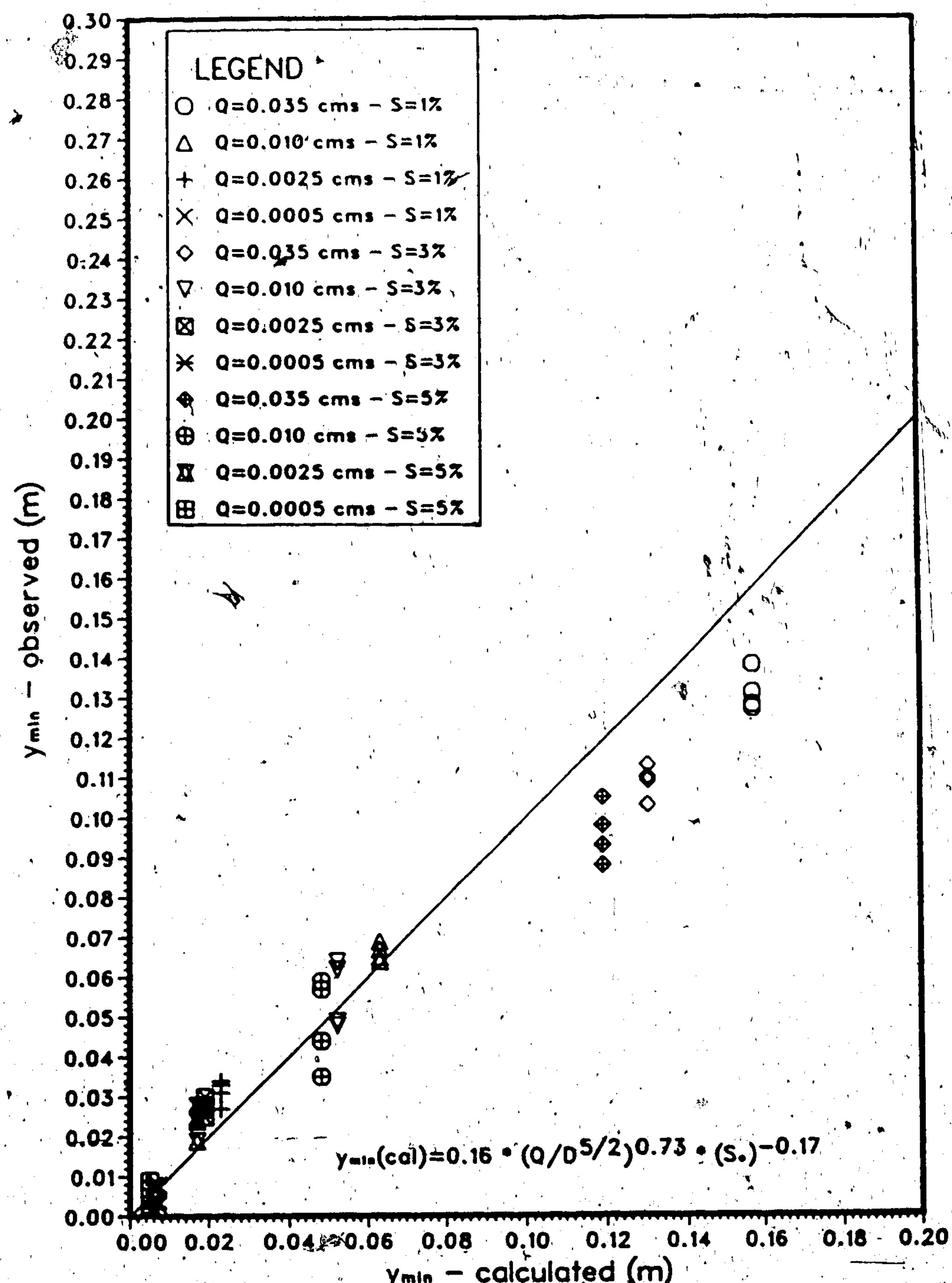

Figure A.2 Comparison between the calculated values based on $y_{min} = 0.16 * (Q/D^{5/2})^{0.73} * (S_o)^{-0.17}$ and the observed values of y_{min}.

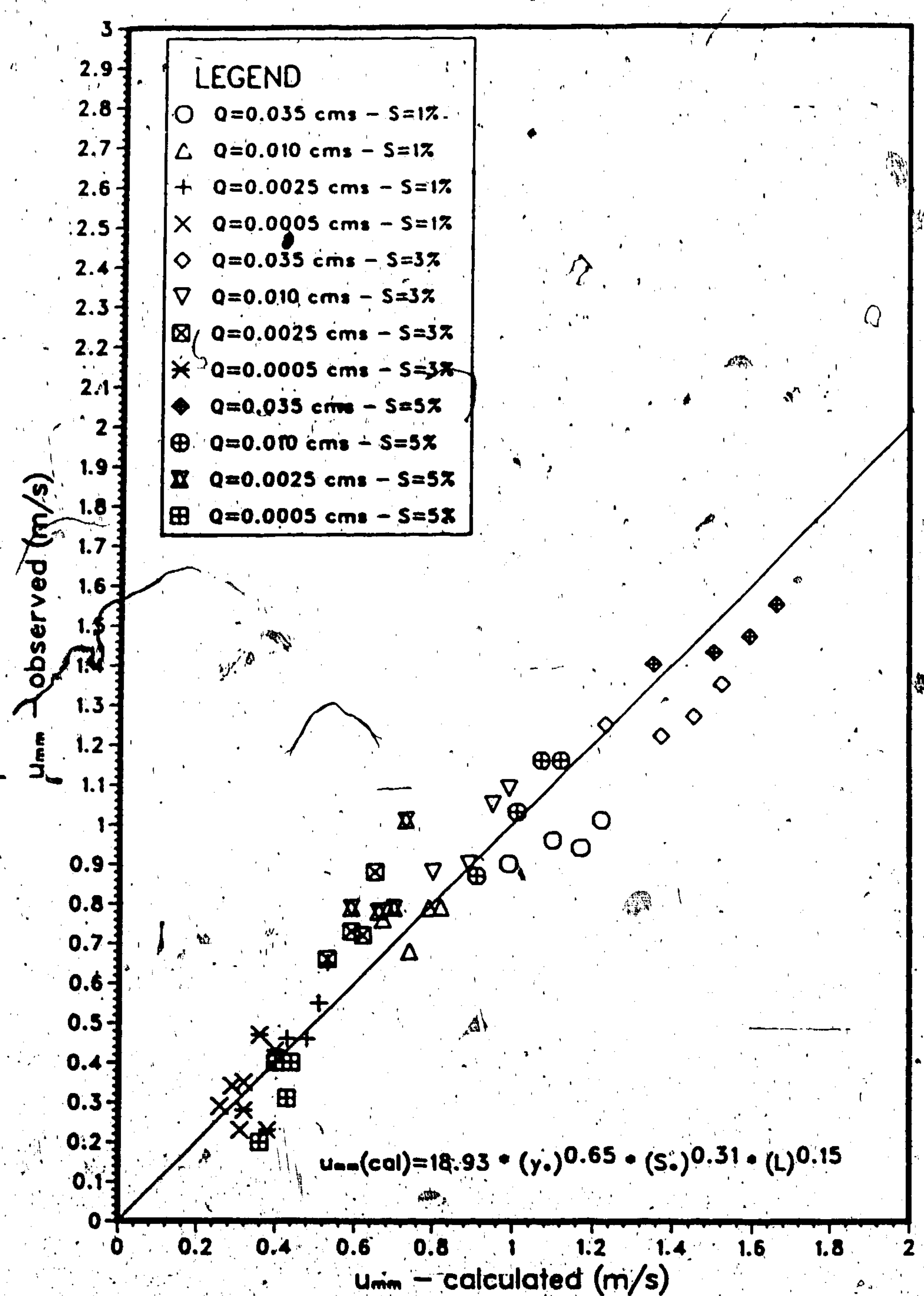

Figure A.3 Comparison between the calculated values based on $u_{mm} = 18.93 * (y_o)^{0.65} * (S_o)^{0.31} * (L)^{0.15}$ and the observed values of u_{mm}.

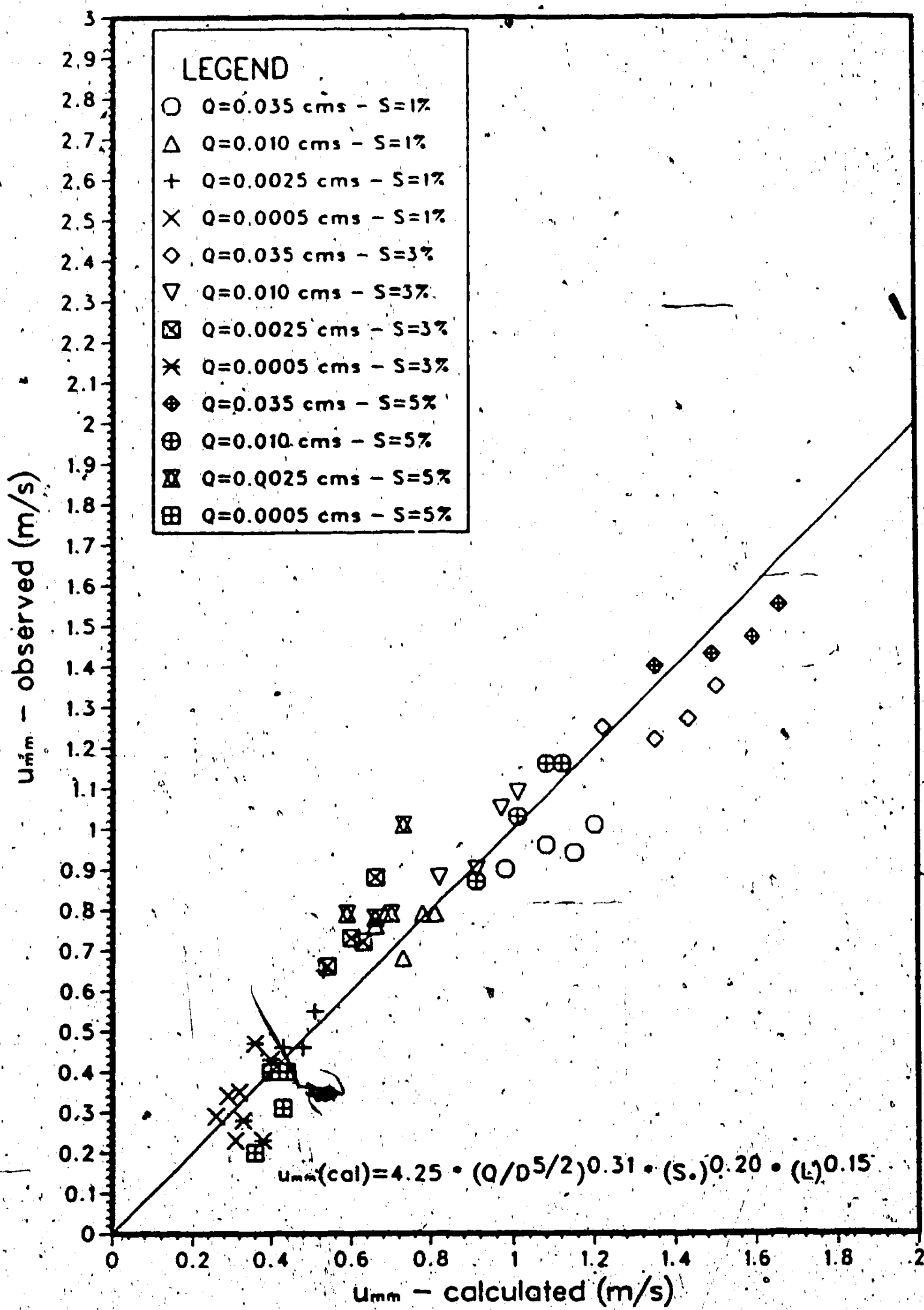

Figure A.4 Comparison between the calculated values based on $u_{mm} = 4.25 * (Q/D^{5/2})^{0.31} * (S_o)^{0.20} * (L)^{0.15}$ and the observed values of u_{mm}.

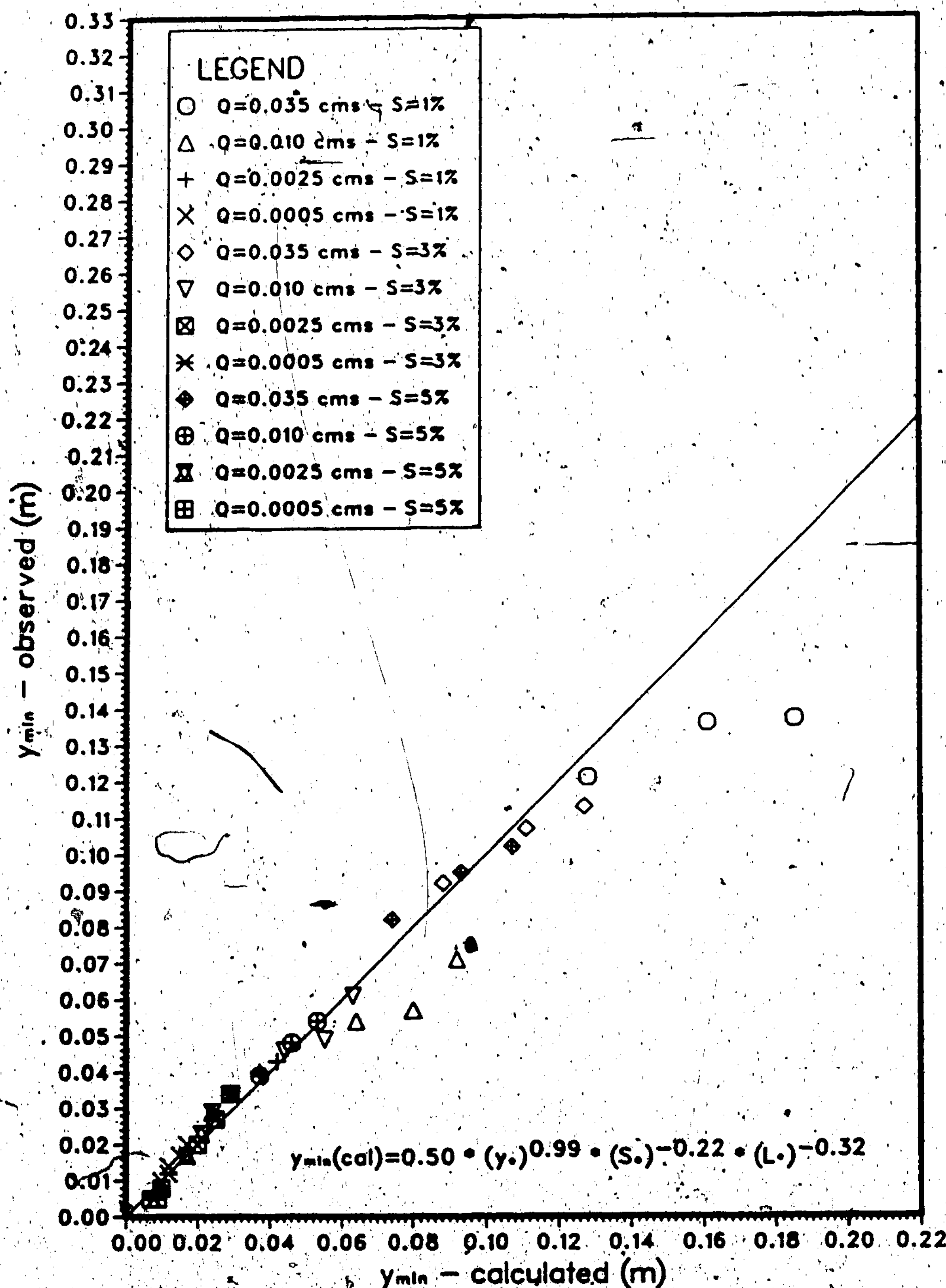

Figure A.5 Comparison between the calculated values based on $y_{min} = 0.50 * (y_o)^{0.99} * (S_o)^{-0.22} * (L*)^{-0.32}$ and the observed values of y_{min}.

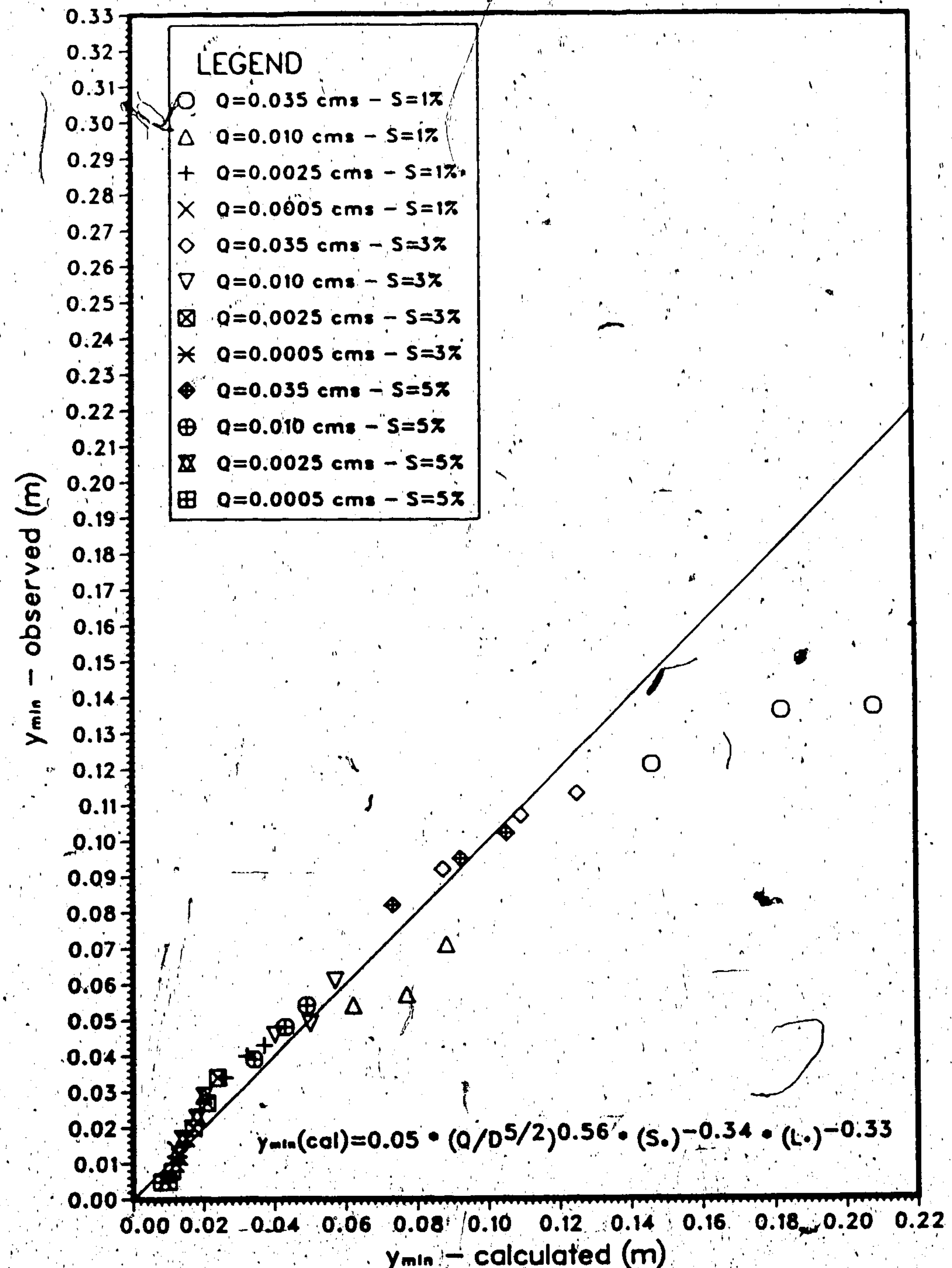

Figure A.6 Comparison between the calculated values based on $y_{min} = 0.05 * (Q/D^{5/2})^{0.56} * (S_o)^{-0.34} * (L*)^{-0.33}$ and the observed values of y_{min}.

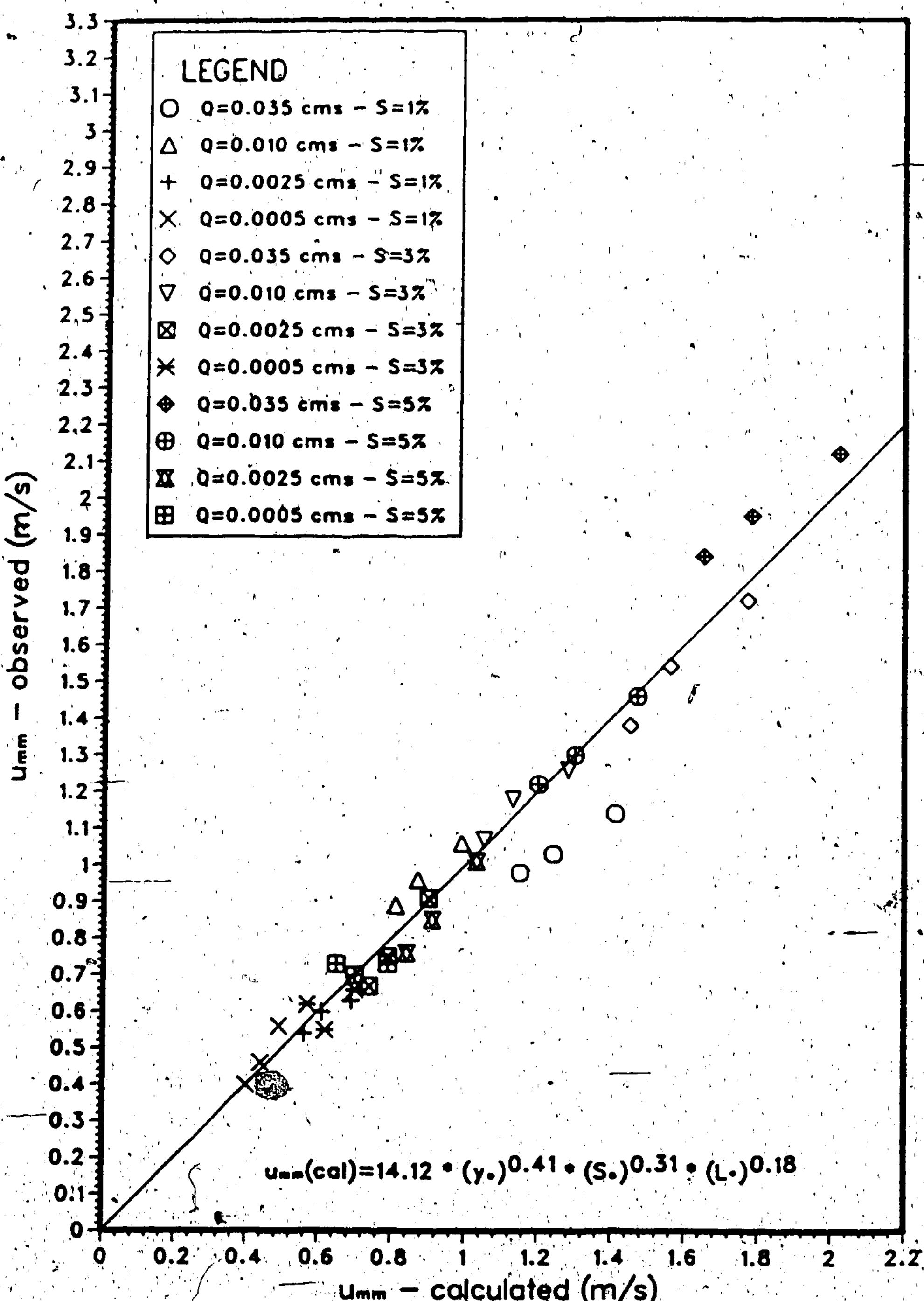

Figure A.7 Comparison between the calculated values based on $u_{mm} = 14.12 * (y_o)^{0.41} * (S_o)^{0.31} * (L*)^{0.18}$ and the observed values of u_{mm}.

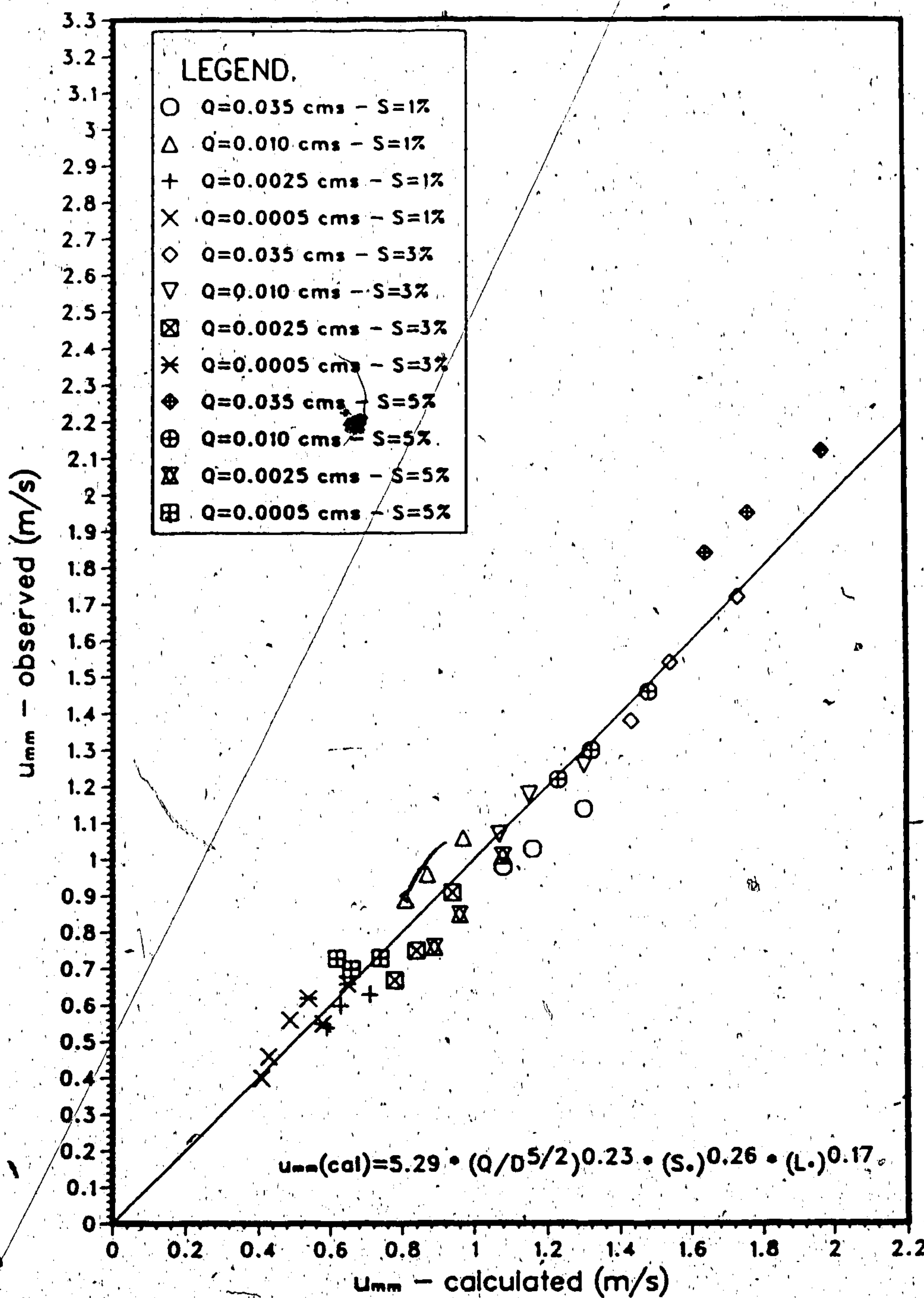

Figure A.8 Comparison between the calculated values u_{mm} = $5.29 * (Q/D^{5/2})^{0.23} * (S_o)^{0.26} * (L*)^{0.17}$ and the observed values of u_{mm}.