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A STUDY OF MODEL AND PROTOTYPE CULVERT BAFFLING FOR FISH PASSAGE

by

C. Katopodis, P. R. Robinson
and B. G. Sutherland

Western Region
Fisheries and Marine Service
Department of Fisheries and the Environment
Winnipeg, Manitoba R3T 2N6

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ABSTRACT

Katopodis, C., P. R. Robinson, and B. G. Sutherland. 1978. A study of model and prototype culvert baffling for fish passage. Can. Fish. Mar. Serv. Tech. Rep. 828: v + 78 p.

Most streams, crossed by roads or highways, are culverted. Many such crossings are impassable to migrating fish because of the culvert length and the high water velocities in them. A hydraulic model study tested and developed devices to aid fish passage through culverts. Based on the model study recommendations, Offset baffles and Spoiler baffles were designed and installed at the Mackenzie Highway crossing of the Redknife River.

Field testing showed good agreement, between model and prototype results. The effectiveness of both baffle types is inversely proportional to culvert slope. Maximum recommended slope is 5%. A method of judging baffle adequacy is provided. The Offset and Spoiler baffles are recommended, primarily for correcting existing culvert installations and for proposed stream crossings where alternative designs are neither practical nor economical. Minor problems were presented by ice, debris and sediment.

Unsuccessful attempts by Arctic grayling and longnose sucker, to enter the Redknife River culverts, were observed; their failures were attributed to overwhelming water velocities associated with elevated culvert outlets.

Key words: culverts; fish passage; fishways; fish barriers; baffles; grayling, Arctic; sucker, longnose; stream crossing; baffle design; baffle hydraulics.

RESUME

Katopodis, C., P. R. Robinson, and B. G. Sutherland. 1978. A study of model and prototype culvert baffling for fish passage. Can. Fish. Mar. Serv. Tech. Rep. 828: v + 78 p.

La plupart des cours d'eau traversés par des routes doivent couler dans des canaux tubulaires. Or, beaucoup de ces canaux tubulaires constituent une barrière infranchissable à la migration des poissons à cause de leur longueur et de la vitesse du courant. La modélisation hydraulique a permis d'éprouver et de mettre au point des dispositifs facilitant le passage des poissons. Les recommandations formulées par la suite ont été mises à profit pour la conception et l'installation de chicanes "Offset" et "Spoiler" à l'endroit où l'autoroute Mackenzie traverse la Redknife River.

Les essais sur le terrain ont confirmé les résultats obtenus avec le modèle. L'efficacité des deux types de chicanes est inversement proportionelle à la pente. La pente maximale recommandée est de 5%. Nous présentons une méthode qui permet de juger de l'utilité des chicanes employées. Les deux types de chicanes sont surtout destinés aux ouvrages en place et aux projets où les solutions de rechange ne sont ni pratiques, ni économiques. La glace, les débris, et les sédiments n'ont pas posés de problèmes sérieux.

Il nous a été donné d'observer des ombres arctiques et des meuniers rouges qui tentaient sans succès d'emprunter les ouvrages construits sur la Redknife River; ces échecs ont été attribués à la très grande vitesse du courant à la sortie des canaux tubulaires et à la position surplombante de ces derniers par rapport au lit de la rivière.

Mots-clés: canal tubulaire; passage des poissons; passes migratoires; barrières à poissons; chicanes; ombre arctique; meunier rouge; traversées des cours d'eau; conception des chicanes; études hydrauliques des chicanes.

INTRODUCTION

Presently there are many thousands of kilometers of roads and highways in the Prairie Provinces and the Northwest Territories (e.g. Manitoba, 74,000 km; N.W.T. 1300 km) and additional roads or highways are being built. Since culverting of highway stream crossings is very common and many impediments or complete blockages may await fish attempting to enter, pass through , or exit culverts, fish passage becomes critical to the maintenance of fisheries resources. Many existing culverts already present fish passage problems (e.g. Poplar River, Mosquito Creek, Redknife River, N.W.T.) and corrections are vital to maintaining the use of spawning areas and to open areas rendered inaccessible by culverting.

Excessive flow velocities, which hinder or block fish navigation through culverts, are a common problem. In natural streams, channel irregularities, protrusions, pools, meanders, etc. provide zones of slow water where fish can rest. In culverts, no such resting zones normally exist and therefore, the culverts must be designed to create either very low barrel velocities or adequate resting zones.

Baffles, consisting of blocks or plates attached to the barrel floor in regular patterns, have been recommended for simulating natural channel conditions (Dryden and Stein 1975; Evans and Johnston 1976; Gebhards and Fisher 1972; Lauman 1976; McKinley and Webb 1956; Metsker 1970; Renewable Resources Consulting Services Ltd. 1972; Slaney, F.F. and Company Ltd. 1972; Watts 1974). 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.

The Mackenzie Highway Environmental Working Group, an intergovernmental group comprised of representatives from the departments of Fisheries and the Environment, Energy Mines and Resources, Public Works and Indian and Northern Affairs, recognized the need to study the hydraulics of baffles in culverts and commissioned a hydraulic model study. The study was conducted by the Hydraulics Division, Canada Centre for Inland Waters, Burlington, Ontario who examined a number of baffle arrangements. Three types of baffles were recommended for fish passage and hydraulic data for their design was presented (Engel 1974). Based on these model study results, Fisheries and Marine Service (Winnipeg) in the fall of 1974 selected the Redknife River crossing on the Mackenzie Highway, N.W.T., as a field testing site (Fig. 1) and installed two types of baffles there in 1975. This site was chosen because it offered: a) testing on a constructed highway section; b) high spring flows (20-60 m^3/s); c) high culvert velocities (1.5-2.5 m/s); d) spring spawning runs; e) three culverts, allowing one control; f) accessibility. A field study was carried out in 1976 and tested the model-prototype flow relationships. Direct assessment of the baffle effectiveness to pass fish proved impossible in 1976, since the elevated culvert outlets combined with relatively high flows, during fish migrations, to prevent fish from entering the culverts.

This report is intended both as an analytical and a design tool. The designer will be particularly concerned with the report sections on Theory, Operational problems, Conclusions and recommendations, equations (29) and (30), Fig. 2, 3, 35, and 36 and Appendices 1, 2 and 6.

THEORY

THE FUNCTION OF BAFFLES

In natural streams meandering, pools and riffles, boulders etc. provide zones of low water velocities where fish can rest. Fish therefore are obliged to traverse only short distances against high water velocities. In culverts, velocities are nearly uniform throughout their length and usually greater than in natural channels. Culverts, therefore, force fish to traverse long distances without any rest. Traversable water velocity becomes severely restricted (Bainbridge 1960, 1962: Blaxter 1969; Brett 1964, 1967; Jones et al 1973, 1974; Katopodis 1977; Webb 1975). Dryden and Stein (1975) recommend that average culvert velocities not exceed 0.9 m/s (3.0 ft/s) for fish passage. Ensuring such velocities by culvert oversizing and low gradient is not always practical or economical.

In a culvert with baffles, fish may use their burst speeds to advance from one resting zone to another and their cruising speeds to swim through resting zones. Such mode of motion allows fish to travel much longer distances, without overtaxing their biokinetic potential; it also raises the allowable level of culvert water velocities. There are indications that, alternating periods of burst swimming and resting, is a highly economical and efficient mode of motion for fish. Such swimming may result in large savings in the energy required to traverse a given distance (Weihs 1974).

McKinley and Webb (1956) developed the Offset baffle system, after model testing with rectangular culverts. Unfortunately, the approach taken by McKinley and Webb (1956) was entirely empirical and no hydraulic relationships were derived. Nevertheless, the Offsets have been used extensively in the states of Washington, Oregon and California (Kay and Lewis 1970; McClellan 1970; Webb, letter to L. Edgeworth, 1968) and are recommended for general use. These baffles have also been used in British Columbia. Engel (1974) adapted the Offsets for circular culverts (Fig. 2) and studied their hydraulics in model. Similarly, Engel (1974) reported results for a Spoiler baffle system (Fig. 3). The objectives in developing these baffles were to: a) provide regions of low enough water velocities for fish to rest, b) achieve low enough jet velocities to permit fish to advance from one resting zone to the next and c) create a minimum of additional roughness.

In elliptical and arch culverts, one may easily adapt the Offsets by maintaining the relative dimensions of Fig. 2. One may also adapt the Spoilers by adding extra ones to compensate for the larger culvert perimeter (resulting from the greater span) while maintaining their relative dimensions and lateral spacing as shown in Fig. 3.

HYDRAULICS OF CIRCULAR CULVERTS

The basic hydraulic parameters of Cross-sectional Area, A , Hydraulic Radius, R, and Top Width, B, of a circular culvert are defined by its geometry. They depend on the relative depth, δ, and the diameter of the culvert D. The following expressions are derived in Appendix 1:

$$A = \lambda_a D^2 \quad (1)$$

$$R = \lambda_r D \quad (2)$$

$$B = \lambda_b D \quad (3)$$

where λ_a, λ_r and λ_b are functions of relative depth only

These basic hydraulic parameters and some fundamental flow parameters, such as discharge, Q, water surface slope, S, and roughness coefficient (e.g. Manning's n, Chezy's C or Darcy-Weisbach's dimensionless f) combine to describe the flow conditions in an open channel.

In the case of uniform flow, that is, when the velocity remains constant (in magnitude and direction) with respect to distance and time, Chezy's equation, (4) and Manning's formula, (5) are most commonly used:

$$Q = CA\sqrt{RS} \quad (4)$$

$$Q = \frac{\zeta}{n} AR^{2/3} S^{1/2} \quad (5)$$

The constant ζ depends only on the unit system. It is equal to 1.0 for m-s and to 1.49 for ft-s units.

Chezy's equation may also be written in terms of Darcy-Weisbach's f (g = acceleration of gravity):

$$Q = A\sqrt{\frac{8g}{f}}\sqrt{RS} \quad (6)$$

For uniform flow the water surface slope equals the channel bottom slope. Water depth is constant for the entire length of the channel, for a given discharge, and is called the normal depth. Utilizing equations (1) and (2), for a circular culvert, equation (5) reduces to:

$$\lambda_a \lambda_r^{2/3} = \frac{nQ}{\zeta S^{1/2} D^{8/3}} \quad (7)$$

This equation enables the estimation of the normal depth by trial and error (Appendix 1).

Uniform flow seldom exists under natural conditions. Gradually varied flow, often, presents a more realistic picture of flow conditions. This flow occurs when velocity changes with distance but not with time. Further the velocity changes so slowly that any accelerating effects may be neglected.

Backwater curves describe the water surface in open channels for this type of flow. The water surface may have a positive or a negative slope, depending on the slope of the channel bottom and the magnitude of water depth with respect to the normal depth and the critical depth.

Critical depth occurs when the ratio of inertia forces to the gravity forces, acting on a water segment, is equal to unity. This ratio is known as the Froude number (Fr) and is given by:

$$Fr = \frac{V}{\sqrt{gd}} \quad (8)$$

When Fr = 1.0, critical depth occurs and the flow is termed critical flow. The flow is supercritical for $Fr > 1.0$ and subcritical for $Fr < 1.0$. Appendix 1 presents an expression for the critical depth in circular culverts and ways to compute it. In gradually varied flow, a channel reach is divided in small segments, of length Δx, and the water surface slope for each segment is approximated with a straight line. The smaller the Δx, the greater the accuracy but the slower the speed of computation.

In Appendix 1, the reader will find the derivation of the following two equations, from basic principles. Ways to solve them are also indicated.

$$\Delta x = \frac{1}{fM_1 - M_2} \quad (9)$$

$$f = \frac{\xi n^2}{D^{1/3}} \frac{1}{\lambda^{1/3}} \quad (10)$$

where f = Darcy-Weisbach's friction coefficient

n = Manning's roughness coefficient

$\xi = \frac{8g}{\zeta^2} = \{78.5 \text{ for m-s units}\}\ \{117 \text{ for ft-s units}\}$

The parameters M_1 and M_2 depend on relative depths, diameter, discharge and bottom slope. An HP-67 calculator was programmed to solve equations (9) and (10).

HYDRAULICS OF BAFFLES

Fish ascending a baffled culvert, encounter two types of flow, i.e. jet flow and leeward flow. For the Offsets (Fig. 2), jet flow is found at the slot between the sill ends and leeward flow extends downstream behind the back of the sills. For the Spoilers (Fig. 3), jet flow occurs in the lateral spaces between the blocks and leeward flow extends along a line from heel to toe of adjacent baffle rows. Use of least resistance paths is expected by upstream moving fish.

The following criteria were set for successful baffle operation (Engel 1974):

(1) Resting zone velocities should be no greater than 0.15 m/s (0.50 ft/s) and should allow enough space for an average size fish, i.e. 38 cm (15in).

(2) Maximum swimming distance against jet currents should be equal to, or greater than, the distance required to clear the obstruction imposed by a given baffle arrangement.

(3) Maximum distance, fish must swim against leeward currents, be equal to, or greater than, the longitudinal spacing between two successive obstacles imposed by baffles.

It was found that, if jet velocities were adequate, the other criteria for leeward velocities and length of resting zones were met also. The jet Froude number may be expressed as a function of culvert slope:

$$F = \frac{V_j}{\sqrt{gR_p}} \qquad (11)$$

where F = jet Froude number

V_j = jet velocity

R_p = hydraulic radius of culvert without baffles

The fish swimming distance in the jet flow (S^*) depends on barrel size, because baffle dimensions are proportional to culvert diameter. The minimum baffle height recommended is 0.30 m (1 ft). Therefore, the following conditions may be derived from the above second criterion and Figs. 2 and 3.

Offsets

$$S^* = 0.30W = 0.18D,\ D > 3\,\text{m}\ (10\ \text{ft}) \qquad (12)$$

$$S^* = 0.55\ \text{m}\ (1.80\ \text{ft}),\ D \leq 3\ \text{m}\ (10\ \text{ft}) \qquad (13)$$

Spoilers

$$S^* = 0.20D,\ D > 4\ \text{m}\ (13\ \text{ft}) \qquad (14)$$

$$S^* = 0.80\ \text{m}\ (2.5\ \text{ft}),\ D \leq 4\ \text{m}\ (13\ \text{ft}) \qquad (15)$$

Maximum swimming distance of fish in the burst range, should be greater than S^*, to ensure that fish can pass through the slots between two spoiler blocks or the offset sills and return to leeward flow.

The total roughness with baffles may be expressed as:

$$f_t = f_p + f_b \qquad (16)$$

where f_t = total friction factor

f_p = friction factor due to plain pipe only

f_b = friction factor due to baffles only

Using basic hydraulic principles of uniform flow and equating the discharge through a culvert with and without baffles (Appendix 1):

$$\frac{f_t}{f_p} = \frac{A_t{}^2R_t}{A_p{}^2R_p} = \frac{\lambda_{at}^2\lambda_{rt}}{\lambda_{ap}^2\lambda_{rp}} \qquad (17)$$

or

$$\frac{n_t}{n_p} = \frac{A_tR_t{}^{2/3}}{A_pR_p{}^{2/3}} = \frac{\lambda_{at}\lambda_{rt}^{2/3}}{\lambda_{ap}\lambda_{rp}^{2/3}} \qquad (18)$$

where subscripts t and p denote conditions with and without baffles respectively

Hydraulic similitude laws (Yalin 1971) relate model and prototype results. Since gravitational forces predominate, Froudian similitude may be assumed:

$$V_r = L_r^{1/2} \qquad (19)$$

$$n_r = L_r^{1/6} \qquad (20)$$

with $V_r = \frac{V'}{V}$, $n_r = \frac{n'}{n}$, and $L_r = \frac{D'}{D}$

where V = water velocity

n = Manning's roughness coefficient

D = culvert diameter for the prototype

' indicates the corresponding model quantities

The hydraulic efficiency of the baffled culvert, as compared to the plain culvert, may be measured by:

$$\eta(\%) = \frac{\delta_p}{\delta_t} \times 100 \qquad (21)$$

where δ_p = relative depth without baffles

δ_t = relative depth with baffles

MATERIALS AND METHODS

DESCRIPTION OF THE STUDY AREA

The Mackenzie Highway crosses the Redknife River at Mile 186, approximately midway between Hay River to the east and Fort Simpson to the west (Fig. 1 and 4). The crossing consists of three 4.27 m (14 ft), circular, structural plate, corrugated steel pipes, 44.5 m (146 ft) long. The culverts were installed in 1968 with a camber (average slope 1%); fish passage was not considered in their design.

A drainage area of 1425 km^2 (550 mi^2) was estimated for the Redknife River basin above the highway crossing. The river drains the northern edge of the Alberta Plateau flowing through the boreal forest in the discontinuous permafrost zone. The Redknife Hills, rising to an elevation of 800 m (2625 ft) above sea level in the southwest, consist of tertiary sandstones and clays and form the headwaters of the Redknife River. Below the crossing the basin is part of the Great Slave Plain. The escarpment, separating the two physiographic regions, traverses the river, 2.5 km (1.5 mi) upstream of the Mackenzie Highway crossing. The escarpment forms a limestone canyon, 30 m (100 ft) deep, with numerous narrow rapids and chutes. The canyon starts 5 km (3 mi) upstream of the stream crossing and forms 5 m (16 ft) high falls. These falls would act as a natural obstruction to fish movement (Fig.4).

Upstream of the crossing, the river contains gravel, cobble and boulders, thereby being almost continuous riffle; downstream of the crossing, there are alternating pool and riffle areas. Stream meandering and pool areas increase near the Mackenzie River confluence and culminate in a sand delta approximately 11.5 km (7.2 mi) downstream of the crossing.

At the highway crossing, the river is contained within a 90 m (300 ft) wide and 22 m (72 ft) deep valley. The valley sides rise on a 15% slope to form another, 400 m (1300 ft) wide valley. The river has cut a channel 1.5 m(5 ft) deep in the middle of the flood plain. The river bed is underlain with limestone bedrock at a depth of 0.6 m(2 ft).

ENGINEERING

Using the meager hydrologic information available, field observations, a mean invert slope of 1% and the model study results (Engel 1974), Offset and Spoiler baffles were designed for two of the Redknife River culverts. Jet velocities were estimated to be within the capabilities of adult Arctic grayling. Appendix 2 provides details on baffle materials, design, installation techniques, fabrication and installation costs. Figures 5 and 6 show the Offsets and Spoilers as they were installed.

Catwalks, approximately 7 m (23 ft) in length were installed on each culvert (Fig. 7). They were essential for making hydraulic measurements within the culverts.

Three water level staff gauges were installed one upstream of the culvert inlets and two downstream of the culvert outlets (Fig. 8).

Water velocities within the culverts were measured with a full size Ott (C31 - 10.002) horizontal axis meter, secured to a 20 mm wading rod. A "fast", 0.50 m (1.6 ft) pitch, 125 mm (4.9 in) diameter propeller was used to measure velocities greater than 1.5 m/s (4.7 ft/s). A "slow", 0.25 m (0.8 ft) pitch, 125 mm (4.9 in) diameter propeller was used to measure velocities less than 1.5 m/s (4.7 ft/s). The wading rod was marked at 30 mm (0.1 ft) intervals. At high flows a full size Price type, vertical axis meter with cable suspension and an 18 kg (40 lb) bomb, was used. The meter-bomb assembly was raised and lowered using a field-fabricated winch.

Level circuits were run with a KERN GK1, small engineer's level and a Wild N10 engineer's compact level. Metric level rods were read to the nearest cm and estimated to the nearest mm. Hydrometric stations are shown in Fig. 8.

MEASUREMENTS

Hydrometric

A discharge metering section was established 125 m (410 ft) downstream of the culvert outlets (Fig. 8). The section was metered on April 26, May 19 and June 14 using the Ott meter, hand held on the wading rod. The April 26 metering was discontinued because of ice movements and rapidly increasing flows. A boat discharge measurement was also taken on May 1, using a Price current meter with cable-bomb assembly.

River discharges were calculated using the standard midsection method. The two-point method (i.e. mean velocity is the mean of the velocities at 0.2 and 0.8 of the total water depth) determined the mean velocity at each vertical; for the May 1 measurements, the 0.6 method estimated the mean velocity.

The three staff gauges (Fig. 8) were read twice daily to the cm and estimated to the 0.5 cm. Other water levels were measured directly from level circuits at the culvert inlets, outlets and 43 and 58 m (140 and 190 ft) downstream of the outlets.

Water levels inside the culverts were measured by determining the distance from the culvert crown to the water level. Water depths were then determined, to the nearest cm, by subtracting the distance to the water surface from the difference in elevation between crown and invert.

All elevations were tied into the highway reference benchmark 1994, located 0.4 km (0.25 mi) west of the Redknife River crossing, along the Mackenzie Highway.

Two monitoring stations were established in each culvert (Fig. 7). Flow depths and water velocities were measured in the upper and lower sections of each culvert. Table 1 indicates the length and slope of each culvert section. The metering stations, in the upper culvert sections, were located as far downstream of the inlet turbulence and as far upstream of the invert slope change as possible. Similarly, in the lower sections metering stations were located as far upstream of the outlets and as far downstream of the transitional zone caused by the slope change, as physical limitations would allow.

In the control culvert each station consisted of one cross-section, and in the baffled culverts each station consisted of three cross-sections. Cross-section "A" (Fig. 7) was positioned immediately upstream of a row or set of baffles. This section was chosen to determine jet velocities at the upstream ends of the slots and whether leeward velocities extended that far downstream. Cross-section "B" was selected to determine how far downstream the leeward velocities extended and for estimating culvert discharges. Cross-section "C" (Fig. 7), immediately downstream of a row or set of baffles, was selected to measure the maximum expected jet velocities.

Current metering within the culverts was accomplished using different schemes to accomodate the various flow conditions (Table 2):

A. A crosswalk, made of four 3.3 m (10 ft) long 5.1 cm x 15.2 cm (2 in x 6 in) wooden studs bolted together, was placed on and perpendicular to the catwalk. The crosswalk, its center lined up by eye with the culvert crown, supported a ladder down to the water surface. The Ott meter, secured at the end of the wading rod, was held with two pairs of vice grips by a person on the ladder . The ladder edge supported the wading rod, also. Depth measurements were made by determining the distance left or right of the centerline. This method was extremely awkward and time consuming. It was not possible to measure velocities in the center region because the ladder could not be placed directly beneath the catwalks.

B. This method was the same as A except that an additional cross beam was placed beneath the catwalk. It was supported by the ladder at one end and by an additional support at the other end. This arrangement allowed measurements in the central portion of the culvert. The wading rod was hung down through the holes of the catwalk planking and supported, at the water surface, by the cross bar. Depth measurements were made by zeroing the wading rod at the water surface, using the crosswalk as a reference point, and then lowering the rod the required distance. All other measurements were made as in method A.

C. The ladder was discarded. Instead a 3 m (10 ft) long, 5.1 cm x 15.2 cm (2 in x 6 in) wooden stud was positioned, perpendicular to the direction of the flow, about 25 cm (10 in) above and parallel to the water surface. The ends of the beam were cut to fit snugly in the culvert corrugations. The wading rod, still held by vice grips, was supported by this beam across the full culvert width. Measurements were made the same way as in B. This method proved less cumbersome than the previous two, but it could only be used when the water depth was low enough to expose the inward sloping culvert sides and allow the cross beam to fit securely.

D. The crosswalk was taken down from the catwalk and was placed directly across the flow, its ends resting on the culvert sides. Measurements were made similar to the other methods.

E. The crosswalk was placed on the catwalk perpendicular to the flow. The Price current meter, with a 18 kg (40 lb) bomb assembly, was suspended by cable from a winch secured to the crosswalk. The meter was lowered to the water surface and zeroed. The end of a tape measure was held on the wire where it intersected the catwalk. The meter was then lowered until the derived length of tape (i.e. depth) was reeled out. Width measurements were made by placing the winch on the marks along the edges of the crosswalk.

The meter-bomb assembly was swept downstream because of very high water velocities and the relatively small size of the bomb. This resulted in overestimated depth measurements. Water depths calculated from the profiles provided actual depths so that corrections could be made as follows (Fig. 9):

$$\cos \theta = \frac{d''}{d'} \tag{22}$$

where d'' = depth from profiles

d' = measured depth

Assuming that the meter was swept downstream at an angle proportional to the depth of submergence, the corrected water depth (d) was estimated as:

$$d = d' \cos \frac{m \cdot \theta}{n+1} \tag{23}$$

where m = number of measurements from the surface

n = number of measurements made

No total depth measurements were made during test one using the meter and cable. Depth corrections were made based on extrapolated θ values derived from tests two and three. Method E had the greatest inaccuracies in depth measurement.

F. The Ott current meter was used, hand held on the wading rod. Depth measurements were made from the wading rod. Because of extremely low flow, width was only estimated.

The extremely turbulent nature of flow in the baffled culverts did not allow for discharge calculation, from hydrometric measurements by standard methods. Instead, each velocity measurement was weighted with depth (Bolter, Parish and Trimble Ltd. 1974) and the calculated discharges were correlated to the mean upstream water level, for the duration of the measurement. The culvert rating curves developed were then combined to produce the river rating curve. Mean discharges were determined from the two hydrographs and all rating curves were adjusted. The rating curve of each plain pipe was assumed to be that of the 1976 control culvert; the river rating curve, with the culverts free of baffles, was thus developed by combining three such rating curves.

Hydrological

Maximum and minimum air temperatures were read twice daily from a Taylor maximum-minimum thermometer secured on a tree near the campsite. Temperatures were recorded in °F and later converted to °C. Daily precipitation totals were measured at the highway crossing using the inner copper collection tube from a standard Canadian Rain Gauge. Water was emptied into a tapered graduated cylinder for measurement.

Biological

From May 3 to May 13, 1975, five locations were sampled during the spawning runs of Arctic grayling (*Thymallus arcticus*) and longnose sucker (*Catostomus catostomus*). Three downstream locations (1, 3, 5) and two upstream locations (2, 4) were established (Fig. 8). Initial sampling of all locations involved the use of gill nets. Upstream ponding allowed continuous effort at locations 2 and 4 using 22.9 m (25 yd) lengths of net. These nets were stretched from shore as perpendicular to the stream flow as possible, checked twice daily and replaced if debris laden. Netting of downstream areas was irregular depending on location conditions, i.e. presence of ice and/or debris. Generally shorter lengths of net were used as the locations were often short pools or back-eddies. Downstream effort was concentrated at Location 1 (Fig. 8) where a trap net was installed with the funnel facing downstream. The trap net was checked twice daily for fish.

Water temperatures were recorded twice daily using a pocket thermometer to the nearest 0.5°C. In 1976 concentrated fishing effort was initiated on April 21 and continued until June 1. Upstream continuous effort with gill nets commenced April 30 when ice and debris conditions subsided to warrant net setting. Locations 2 and 4 as per 1975 and a new location 6 were utilized (Fig. 8). Location 6 was later discontinued when upstream ponding subsided and conditions at Locations 2 and 4 improved such that nets could be stretched perpendicular to the stream flow.

Downstream gill netting was initiated April 21 at Location 1 (Fig. 8) but on an irregular basis due to ice and debris coming down the river. Runoff conditions improved by April 27 and daily setting of gill nets at Locations 1 and 5 commenced. First fish (grayling) were taken at Location 1 on April 29 and the fish trap and fence were installed April 30 (Figs. 8 and 10). The trap site was in a channel 10.7 m (35 ft) wide ranging in depth from 0.3 m to 1.2 m (1-4 ft) and swift flowing. The trap and fence remained operational until May 22 at which time after several negative captures and receding water levels it was removed from the river. Gill netting at Locations 1 and 7 were resumed near mid-May in order to capture fish still present in downstream pools and to determine fish condition tagging success. Three locations (9, 11, 13) downstream and two locations upstream (8, 10) were sampled in mid-May (Fig. 8) to determine fish species present and hopefully recapture tagged fish. Access to these sites was by helicopter and 24 hour gill net sets were employed.

In 1976 water temperatures were recorded to the nearest 0.1°C using a submersible Ryan thermograph (Model G) with a 15-day interval chart. This recorder was initially set at Location 1 then moved to the trap site when the trap was installed. The thermograph charts were changed weekly.

The highway crossing site was visited periodically during the summer and fall (both 1975 and 1976). Sampling consisted of beach seining downstream and upstream of the culverts. Fish captured alive and having a fork length greater than 150 mm (6 in) were tagged at the posterior base of the dorsal fin. Sequential numbered tags consisting of vinyl tubing (floy tags) were inserted by means of a tagging gun. Some released fish in 1976 were not tagged but fin coded by punching a small hole(s) in the dorsal fin. Some grayling were adipose fin clipped. Tagging and fin coding were conducted to determine fish movements and to assist in determination of an anticipated delay period associated with fish passage through the culverts. All tagged and clipped fish were placed in the holding pen located beside the trap and later released if swimming normally.

All fish fork lengths were measured to the nearest mm and a small scale sample taken from behind the dorsal fin. During the spawning run all fish were squeezed anterior to the vent to determine the degree of ripeness. All dead fish were sampled for length, sex and maturity. For Arctic grayling, otoliths and a scale sample were taken for later laboratory age determination. Fish captured by seining were identified, counted by species and a small subsample preserved in 10% formalin solution for later laboratory reference.

FISH SAMPLING PROGRAM

Fish sampling by means of gill nets, beach seines, a trap net and a fish counting trap and fence was conducted. Angling and dip netting were conducted but to a lesser extent. Except where noted sampling periods were May 3 to May 13 in 1975 and April 21 to May 30 in 1976. Sampling dates and methods utilized are given in Appendix 3.

Gill nets were generally of the following dimensions: 22.9 m (25 yd) length and 1.52 m (5 ft) depth. All nets were of 7.6 cm (3 in) nylon stretched mesh and set for 24 hours. A beach seine of length 9.2 m (30 ft) depth 1.22 m (4 ft) and 0.3 cm (0.125 in) mesh was used in pools and low flow areas.

During spring 1975 a trap net was operated downstream of the highway crossing at Location 1 (Fig. 8). The trap net pot was 1.83 m (6 ft) in length, 1.22 m (4 ft) wide and 1.22 m (4 ft) deep. Wings of 22.9 m (25 yd) were attached to form the funnel leading to the pot entrance. Netting of the pot and wings was of 2.54 cm (1 in) stretched nylon mesh.

For the spring of 1976 a fish fence and trap were installed downstream of the highway crossing (Figs. 8 and 10). The trap consisted of a 5.1 cm x 10.2 cm (2 in x 4 in) frame of 1.5 m (5 ft) length, 1.22 m (4 ft) depth and 1.22 m (4 ft) width. A plywood bottom was attached and sides and back consisted of wire mesh fabric of 2.54 cm^2 (1 in^2) mesh stapled to the frame. The entrance to the trap was a funnel made from 2.54 cm (1 in) mesh of a beach seine. The funnel was stapled to the trap frame and stretched into position by means of guy ropes. The fence leading to the trap was of 1.5 m (5 ft) height wire mesh fabric (2.54 cm, 1 in) with a 0.3 m (1 ft) mesh skirting attached to the bottom at a right angle. The fence was installed in the channel using 1.83 m (6 ft) steel posts spaced 1.22 m (4 ft) apart and imbedded in the stream bottom to a depth of 0.6 m (2 ft). The wire mesh fence was attached to these posts with wound wire and weighted down by placing rock-filled burlap bags upon the fence skirting. A fish holding pen of similar dimensions and material as the trap was placed alongside the trap (Fig. 10).

For upstream conditions three traps of similar dimensions and materials were constructed. These were to be positioned slightly upstream of the three culvert inlets in order to capture fish making passage of the culverts, however water depths and flow conditions were such that intensive gill netting upstream was deemed more feasible.

RESULTS AND DISCUSSION

OBSERVATIONS

Icing

The Redknife River was first visited by Fisheries and Marine Service personnel in the spring of 1974. Ice was observed inside the culverts with water flowing under it (Fig. 11).

Inspection of the Redknife River crossing on February 26, 1975, revealed that a tributary stream (named "Devil Creek") maintained year-round flow. The crossing constriction ponded most of the ice upstream, where about 2 m (6.5 ft) of ice was present. Icing had progressed through the middle culvert to about 200 m (650 ft) downstream. The side culverts contained less ice than the middle one.

Field observations, on May 17, 1974, and May 1, 1975, indicated that culvert ice, undermined by flowing water, moved out in large chunks. There was no evidence that water flowed over the culvert ice. Average surface velocities of 2.5 m/s

(8.2 ft/s), at the culvert inlets, and of 3.5 m/s (11.5 ft/s), at the culvert outlets, were estimated by current metering. Culvert camber, revealed by a survey in the summer of 1975, explained this flow nonuniformity. Ponded upstream water levels were also recorded.

The study area was inspected twice during the winter of 1975-76, after the baffles were installed. Icing depth, upstream of the culverts, was 0.85 m (2.8 ft) on December 3, 1975 and 1.3 m (4.3 ft) on February 3, 1976. Each culvert contained, approximately, 0.8 m (2.6 ft) of ice at the centerline. The culvert with the Offsets had the most ice (0.92 m, 3.0 ft) and the one with the Spoilers had the least ice (0.73 m, 2.4 ft) at the centerline. Layers of ice and snow had formed to a depth of 0.75 m (2.5 ft) at the culvert outlets. On March 31, 1976, ice depth was 2.2 m (7.2 ft) upstream, 1.7 m (5.6 ft) at centerline and 1.4 m (4.6 ft) downstream of the culverts. Figure 12 shows inlet icing on April 10, 1976.

Snowmelt

On March 31, 1976 there was 90 cm (36 in) of snow present at the Bouvier Creek Crossing, Mile 174 of the Mackenzie Highway (12 miles from the Redknife crossing), 51 cm (26 in) of snow in Hay River and 68 cm (27 in) in Fort Simpson. There was negligible precipitation during the snowmelt period. At the Redknife River crossing mean daily minimum and maximum air temperatures, from April 21 to May 3, were -1.5°C (29°F) and 15.8°C (60°F) respectively. By May 3, except for drifts in the trees, the snow had completely melted along the Mackenzie Highway between Fort Simpson and the Redknife River.

Ice break-up

In 1976, flow over the upstream ice began on April 13. The river channel and all three culverts were completely free of ice by April 27. Holes drilled at the inlets, on April 5, revealed solid ice to the culvert invert in the Offset and Spoiler culverts and 0.2 m (0.65 ft) of free flowing water below an ice thickness of 0.3 m (1.0 ft), in the unbaffled culvert. On April 16, water from "Devil Creek" was flowing over the ice through the Spoiler culvert. Redknife River water appeared over the ice on April 18. Complete break-up of "Devil Creek" occurred on April 20, sending a wave of ice, mud and debris over the ice in the Redknife River channel. On April 21, water was flowing over the ice in all three culverts and more debris and large chunks jammed upstream of the crossing during the Redknife River break-up. Figure 13 shows inlet conditions on April 23, 1976.

The culvert ice, regressing from the outlets towards the inlets, exposed the baffles to the full force of the mass of water, debris and ice, sweeping down off the top of the culvert ice sheet (Fig. 14). Some damage was inflicted upon the Offsets but none upon the Spoilers (Appendix 2). Many chunks of solid blue ice (≈70 cm x 70 cm x 40 cm) started moving downstream through the culverts, on April 26. The upstream ice jam released and a wave of debris and ice roamed downstream moving on top of the culvert ice (Fig. 15). All three culverts were free of ice by April 27, but upstream ice was still moving through on April 28.

DATA AND ANALYSIS

Hydrometric

Hydrometric measurements made within the culverts are presented in Table 3. Discharge calculations, from the downstream station and from in-culvert measurements, allowed the comparison of two independent measurements of the river hydrograph. The two hydrographs agreed well for discharges less than 30 m³/s (1060 cfs). At peak, the downstream discharge was 39 m³/s (1375 cfs) and the discharge through the culverts was 42 m³/s (1485 cfs) , resulting in a maximum discrepancy of 7.5%. Adjusted rating curves are shown in Table 4 and Fig. 16. Hydrological data for the Redknife River, including hydrographs, precipitation and temperatures, are shown in Table 5 and Fig. 17. Daily precipitation totals for the Redknife basin were weighted as follows: Redknife basin precipitation = 0.5 Redknife Crossing + 0.3 Fort Simpson airport + 0.2 Hay River airport.

Water surface profiles for each culvert, over the range of flows tested are shown in Fig. 18, 19, 20. Location of the hydraulic jump is also indicated, except for tests five to seven. Water was diverted through one culvert at a time, during these tests and therefore the resulting downstream conditions were not considered representative.

Water velocity distributions showing the size and shape of resting zones, the jet velocities created by baffles and the extent to which velocities were measured are presented in Appendix 4. Mean velocities, calculated for each culvert and discharge, appear in Fig. 21.

Velocity measurements at the downstream discharge station were used to plot the velocity distribution in the natural channel, a mild riffle river section over a limestone cobble bed. Appendix 4 contrasts in-culvert and natural velocity distributions.

Backwater calculations

To allow comparison of model and prototype and transferability of results to similar situations, uniform flow conditions were estimated through backwater calculations (eq. 9, 10, and Appendix 1). Manning's roughness coefficient was calculated from the control culvert, for the plain pipe condition and from the other two culverts for the condition with baffles. Equations (7) and (18) gave normal relative depths for the plain and baffled culverts, using these calculated values of Manning's n.

Table 6 summarizes the corrected discharge and depth values used in the backwater calculations and the results obtained. The prototype plain pipe roughness of 0.037 was related to the model plain pipe roughness of 0.027 using (20) and the model total pipe roughness was recalculated from (18). Tables 7 and 8 exhibit the results of these calculations.

Flow characteristics

Offsets: Two distinct regions were noted at the water surface of the culvert with the Offset baffles. Boiling near the culvert wall followed by spiraling toward the culvert centerline characterized the flow over the long baffles. In contrast, a series of troughs and waves formed over the short baffles.

The waves were not in phase with the location of the short baffles (Figs. 22, 23).

Spoilers: First noticeable water surface disturbances formed at the end baffles, i.e. the first and last of each row of spoilers. The rows of waves were not in phase with the rows of spoilers (Figs. 24, 25 and 26).

Control culvert: Smooth water surface conditions were observed in both sections of the culvert during all tests. Water accelerated as it moved out of the culvert (Fig. 27). Appendix 5 provides detailed descriptions of the water surface at each measured discharge for the three culverts.

Biology

On-site visual observations during spring break-up, in May 1974, indicated that spawning runs of Arctic grayling and longnose sucker (Figs. 28 and 29) were present. Sampling during break-up in 1975 confirmed these observations. Figure 30 summarizes biophysical measurements for 1976. The high culvert outlet velocities appeared to defeat passage attempts by fish both in 1975 and 1976 (Figs. 31, 32, and 33). Fish were observed swimming up and attempting entrance to all three culvert outlets, but were repeatedly thrown back by the water force. Many sport fishermen fished downstream of the crossing (Fig. 34).

The spring spawning run of Arctic grayling and its arrival below the highway crossing coincided almost exactly with peak river discharge in 1976 (Fig. 30A). The grayling arrived at the highway crossing near or at spawning condition (Fig. 30B). Fry emergence indicated that spawning occurred in most areas immediately downstream of the crossing. Fry were sighted at downstream sampling locations on May 22.

The spring spawning run of longnose sucker and its arrival below the highway crossing occurred four to seven days after the grayling appearance and coincided with decreasing discharges (Fig. 30). Prevented from proceeding further upstream, spawning occurred downstream of the crossing. Fry emergence sightings were made on May 30 at downstream sampling locations. Some sucker fry at this time had remaining traces of the yolk sac.

By the time of arrival of peak numbers of longnose sucker, the Arctic grayling spawning was virtually completed and the adult grayling tended to drop downstream beyond the study area. It is assumed that the majority of adults retreat to the Mackenzie River and Mills Lake area for summer and winter feeding.

During the summer and early fall (June to mid-September) culvert discharges were such that upstream migration was possible for immature and the young-of-the-year fish of Arctic grayling, longnose sucker and northern pike. This was confirmed by upstream seining catches (Appendix 3).

Appendix 3 includes a list of common and scientific names of the fish species encountered during the study, species tagged, fin coded or dead sampled, mean lengths, length-frequency distributions and a summary of fish species captured at the Redknife River crossing. The report deals specifically with the spawning runs of Arctic grayling and longnose sucker. The other species captured are probably indigenous to both upstream and downstream areas of the river or their biology is such that if runs occur they take place late during lower levels, for example in June.

COMPARISON OF MODEL AND PROTOTYPE

In the model Reynolds number ranged from 2×10^5 to 2×10^6 and uniform flow conditions were assumed. Tailwater levels were manipulated to achieve uniform flow although the presence of waves made this difficult, if not impossible at times (Engel 1974). In the prototype Reynolds number ranged from 4×10^5 to 6.5×10^6. Uniform flow conditions were estimated by backwater calculations (Table 7). Figures 35 and 36 present data from Tables 7 and 8 graphically.

Figure 35 shows good agreement between model and prototype for the Offset baffles, whereas prototype measurements tend to be somewhat high in the case of the Spoilers. In the model average maximum jet velocities were plotted, whereas in the prototype maximum measured jet velocities were used. Offset jet velocity measurements were reduced by partial debris blockage of the baffle slot at the higher discharges.

To explain the point scatter of Fig. 36, particularly for the Offsets, the backwater program was checked for (a) effect of the kinetic energy coefficient α, and (b) error sensitivity to depth measurements. Velocity contours for each discharge (Appendix 4) were used to estimate α. A mean value of 1.17 was arrived at for the control culvert and values ranging from 1.10, at high flows, to 2.20 at low flows, for the baffled culverts. The corresponding decreases in Manning's n for the plain culvert or the baffled culvert, of 0.1% to 0.2%, were not significant. However, calculated n values for the baffled culvert were sensitive to depth measurement errors. In the steeper culvert sections depth errors of 1 cm affected baffled culvert n by approximately 5%. The presence of waves, which made depth measurements difficult, explain, therefore, the point scatter of Fig. 36. Close examination of Fig. 36 reveals that, particularly for the Offsets, points representing the lower (steeper) culvert section plot consistently below the points representing the upper (milder) culvert section. There is no apparent explanation for this. The increase in water depth is of concern only at high relative depths, when the maximum culvert capacity may be reduced. Figure 36 indicates that the depth increase levels off at high relative depths and a good estimate of the culvert capacity reduction may be obtained. A rigorous examination of the phenomenon, therefore, becomes of academic interest only.

Regression analysis of jet velocity and flow depth increase (Tables 7 and 8, Figs. 35 and 36) reveals (S is the culvert slope):

Offsets (model and prototype):

$$\frac{V_j}{\sqrt{gR_p}} = 5.638S^{0.469} \tag{24}$$

$(r^2 = 0.892,\ N = 14,\ P>0.001)$

$$\frac{\delta_t}{\delta_p} = 1.719 - 0.315 \ell n \frac{\delta_t}{\lambda} \qquad (25)$$

$(r^2 = 0.868,\ N = 14,\ P>0.001)$

Spoilers (model and prototype):

$$\frac{V_j}{\sqrt{gR_p}} = 7.978 S^{0 \cdot 539} \qquad (26)$$

$(r^2 = 0.738,\ N = 13,\ P>0.01)$

$$\frac{\delta_t}{\delta_p} = 1.641 - 0.358 \ell n \frac{\delta_p}{\lambda} \qquad (27)$$

$(r^2 = 0.831,\ N = 13,\ P>0.001)$

All results combined:

$$\frac{V_j}{\sqrt{gR_p}} = 6.267\, S^{0 \cdot 489} \qquad (28)$$

$(r^2 = 0.820,\ N = 27,\ P>0.001)$

or by rearranging and rounding off:

$$V_j = 6.3 \sqrt{g}\, R_p{}^{1/2} S^{1/2} \qquad (29)$$

$$\frac{\delta_t}{\delta_p} = 1.7 - 0.35 \ell n \frac{\delta_p}{\lambda} \qquad (30)$$

$(r^2 = 0.809,\ N = 27,\ P>0.001)$

The success of baffles as fish passage aids is judged, primarily, by the ability of the fish to swim against the jet velocities created. Figure 35 and eq. (29) show that jet velocities are proportional to culvert slope and therefore the baffle effectiveness reduces as slope increases, reaching an upper limit at a slope of approximately 5%.

WATER VELOCITY DISTRIBUTION

Figure 37 compares the flow area available at different water velocities in the natural channel riffle section, the baffled and unbaffled culverts. These graphs can only be interpreted qualitatively since the values indicated are based on isovels whose locations are at best approximate. However, Fig. 37, illustrates that at high flood flows there are significant areas within the natural channel where velocities are less than 0.5 m/s (1.6 ft/s). In the unbaffled control culvert there are no such areas even at low flows. The addition of baffles does improve the availability of slow water areas, although such areas are small and their size is highly variable along the culvert length and baffle configurations.

BIOPHYSICAL RELATIONSHIPS

In 1975 and 1976 willing, concerted, but unsuccessful efforts, by Arctic grayling and longnose sucker, to enter the Redknife River culverts were observed. High culvert outlet velocities, caused mainly by the elevated inverts are assumed to have prevented fish entrance during hydraulic testing. Therefore, one can neither directly assess the baffle effectiveness nor discriminate between the two types of baffles, from the fish passage point of view.

Dryden and Stein (1975) recommend a three-day impassable period should not be exceeded during the mean annual flood and a seven-day impassable period should not be exceeded more than once in a design period of 50 years. Both these periods were greatly exceeded at the Redknife River due to overwhelming culvert outlet velocities. These delay periods were intended for coinciding peak discharges and fish movement past the culvert site.

As shown in Fig. 30A the spawning run of Arctic grayling coincides almost exactly with peak discharges. Arctic grayling are at or near ripeness upon arrival below the highway crossing (Fig. 30B). This makes the three-day delay period of critical importance for the Arctic grayling of the Redknife River.

The situation is somewhat different for the longnose sucker spawning run as their arrival at the highway coincides with decreasing discharges (Fig. 30A). Figure 30B shows that female suckers exhibit a delay between arrival and ripeness, suggesting the three-day delay period would be acceptable if outlet velocities were reduced.

OPERATIONAL PROBLEMS

No debris of any sort was observed anywhere in the spoiler culvert in 1976. Some small rocks collected immediately downstream of each spoiler beneath the upstream crown. The spoiler culvert was isolated from the main flow during the period of heaviest debris movement by an ice jam at the inlet.

During break-up, the offset culvert carried the major portion of the heavily debris-laden water. Numerous small sticks, weeds, etc. were caught by the upstream edge of the long baffles. The fourth baffle pair (Fig. 7, counting from downstream end) caught a log and debris which jammed across the inlet to the fourth jet. This situation, revealed after water levels had dropped, may have caused lower jet velocities to be measured.

The spoilers did not appear to sustain any damage from ice or debris. The rounded upstream edge was certainly a factor in reducing direct impact. Some rusting of the spoilers was noted. Large ice chunks damaged the first three (Fig. 7, counting from the downstream end) short offset baffles, by direct impact, as they came down on top of the culvert ice and fell on the baffles (Fig.38). The baffle plates were bent vertically and horizontally and were loose on their mounts. The second long baffle was also bent at the upstream edge and two bolts were missing from the stabilizer bar.

An inspection of the Redknife River crossing in the summer of 1978, three years after the baffles were installed, revealed minimal rusting and debris accumulation in either baffle system, while the Offsets and Spoilers were structurally sound.

CONCLUSIONS AND RECOMMENDATIONS

1. The hydraulics of two prototype baffle sets, the Offsets and the Spoilers, were studied in the field. Figures 35 and 36 are recommended for the hydraulic design of such baffles.

2. Good agreement was found between model and prototype results (Figs. 35 and 36).

3. The effectiveness of Offsets or Spoilers is inversely proportional to the culvert slope and may allow fish passage for slopes up to 5% (Fig. 35).

4. Baffled culverts afford slow water areas where fish can rest, while plain culverts do not afford such resting zones (Fig. 37).

5. A minimum baffle height of 0.3 m (1 ft) is recommended and baffle adequacy may be judged by checking (a) jet velocities (Fig.35 or eq. 29) and jet distances (conditions 12, 13, 14, 15) against swimming capabilities of the species involved; (b) effects of hydraulic efficiency reduction (eq. 21) and headwater increase (Fig. 36 or eq. 30).

6. Spoilers proved less prone to damage by ice and debris than the Offsets; galvanization or a more rust-proof metal may be considered for the Spoilers and better attachment methods as well as stronger plates are recommended for the Offsets.

7. Spoiler or Offset baffles are recommended, primarily, in modifying existing culvert installations where water velocities overtax or block fish *within* the pipe barrel, and in stream crossings where it is not practical or economical to meet culvert fish passage criteria.

8. Determined but unsuccessful attempts by Arctic grayling and longnose sucker to enter the Redknife River culverts were observed; failures were attributed to high water velocities at the culvert outlets.

9. Downstream weirs are recommended to allow fish to enter the culverts of the Redknife River.

10. Following such installation of weirs a hydraulic-biological study is recommended to directly assess the fish passage effectiveness of the baffles and weirs and field test the biokinetics of Arctic grayling and longnose sucker.

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Table 1. Location and slope of culvert sections.

Culvert Section	Section Location (Distance from culvert outlet, m)	Section Slope
Control - Lower	0-28	1.42%
Control - Upper	28-44.5	0.14%
Offset - Lower	0-22.3	1.86%
Offset - Upper	22.3-44.5	0.47%
Spoiler - Lower	0-20	1.88%
Spoiler - Upper	20-44.5	0.63%

Table 2. Current metering methods.

Station Number Location	Test Number 1	2	3	4	5	6	7
One - Spoilers Upper	A	B	B	C	-	D	F
Two - Spoilers Lower	A	B	B	C	-	D	F
Three - Control Upper	E	E	E	C	D	D	F
Four - Control Lower	E	E	E	C	D	D	F
Five - Offsets Upper	A	B	B	C	-	D	F
Six - Offsets Lower	A	B	B	B	-	D	F

Table 3. Prototype, hydrometric measurements.

Test Number	Date		Calculated Discharge (m^3/s)		Upstream Water Elevation (m)		Mean Velocity (m/s)	
	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower
				CONTROL				
1	May 8	May 9	12.50	12.95	119.59	119.56	2.56	3.25
2	May 16	May 16	7.75	7.81	119.11	119.10	2.13	3.00
3	May 22	May 22	4.56	4.98	118.74	118.74	1.95	2.67
4	May 28	May 28	3.71	3.96	118.57	118.57	1.80	2.42
5	Aug. 3	Aug. 3	1.19	1.22	118.07	118.07	1.04	1.58
6	July 25	July 25	0.53	0.55	117.86	117.86	0.80	1.19
7	Sept. 18	Sept. 18	0.07	0.04	117.69	117.66	0.08	0.59
				OFFSETS				
1	May 6	May 7	10.20	12.37	119.64	119.66	2.05	2.42
2	May 14	May 15	6.54	6.79	119.16	119.22	1.36	1.99
3	May 20	May 21	3.49	3.98	118.78	118.85	1.04	1.41
4	May 27	May 27	2.49	2.26	118.58	118.59	0.84	1.13
6	July 24	July 24	0.48	0.50	118.10	118.10	0.38	0.50
7	Sept. 18	Sept. 18	0.06	0.06	117.77	117.77	0.07	0.15
				SPOILERS				
1	May 10	May 11	11.15	-	119.50	119.45	2.34	2.71
2	May 17	May 18	6.28	5.41	119.04	118.97	1.74	2.19
3	May 23	May 24	3.69	3.54	118.70	118.65	1.23	1.67
4	May 30	May 31	2.52	2.45	118.52	118.49	1.01	1.41
6	July 26	July 26	0.49	0.47	118.03	118.03	0.41	0.56
7	Sept. 18	Sept. 18	0.06	-	117.75	117.75	0.07	0.10

Table 4. Rating curve equations.

Relationship	Elevation (m) (used as 0 discharge and 0 stage)	Equation: Q = discharge (m^3/s) S = stage (m)
Total River Discharge vs Water Level at downstream discharge metering section.	116.20	$Q = 44.46\ S^{2.423}$
Ponded upstream water level vs:		
a) Total River Discharge with 2 baffled and 1 control culvert.	117.44	$Q = 6.44\ S^{2.307}$
b) Total River Discharge with 3 control culverts.	117.44	$Q = 7.69\ S^{2.106}$
c) Offset Culvert Discharge.	117.49	$Q = 1.77\ S^{2.495}$
d) Spoiler Culvert Discharge.	117.50	$Q = 2.30\ S^{2.412}$
e) Control Culvert Discharge.	117.44	$Q = 2.83\ S^{1.974}$

Table 5. Hydrograph data (1976).

A. Hydrograph:

Volume of Runoff April 20 to May 31:

67.2 million m^3

Fastest Rate of Discharge Increase:

68.5 m^3/s/day between 12:40 and 16:00 on April 26.

Fastest Rate of Discharge Decrease:

2.8 m^3/s/day between 9:15 and 18:30 on May 12.

Miscellaneous Discharge Measurements (m^3/s) 1976:

June 15	9.5
June 24	6.5
June 26	5.4
June 29	4.6
July 20	0.56
July 25	0.70
Aug. 1	1.2
Aug. 3	1.4
Aug. 24	0.64
Oct. 28	3.2

B. Precipitation:

Total Precipitation April 17 to June 7, 1976.

42.1 mm

Average Daily Precipitation.

0.8 mm

Table 6. Depth values used in prototype backwater calculations.

Culvert Slope	Distance Upstream (m)	Test Number					
		1	2	3	4	5	6
		CONTROL					
Mean Discharge (m^3/s)		12.6	7.49	4.80	3.75	1.20	0.55
0.14%	31.1	1.65	1.28	1.04	0.91	0.57	0.38
(Upper)	38.1	1.71	1.36	1.12	1.00	0.62	0.44
1.42%	4.1	1.34	1.02	0.83	0.73	0.52	0.34
(Lower)	11.9	1.40	1.05	0.83	0.72	0.48	0.32
		OFFSETS					
Mean Discharge (m^3/s)		12.1	6.83	3.57	2.14	-	0.47
0.47%	31.2	1.83	1.49	1.22	1.03	-	0.61
(Upper)	38.1	1.88	1.57	1.26	1.07	-	0.64
1.86%	4.1	1.49	1.23	0.97	0.82	-	0.48
(Lower)	9.1	1.58	1.28	1.01	0.85	-	0.50
		SPOILERS					
Mean Discharge (m^3/s)		12.4	6.36	3.55	2.20	-	0.48
0.63%	30.6	1.62	1.30	1.08	0.94	-	0.58
(Upper)	38.1	1.63	1.34	1.10	0.94	-	0.59
1.88%	4.1	1.38	1.08	0.87	0.73	-	0.49
(Lower)	9.3	1.43	1.12	0.90	0.77	-	0.51

Table 7. Prototype: flow depth increase and jet velocities (V_j), n_p = 0.037.

Culvert Slope	Test Number	δ_p	n_t	δ_t	$\frac{\delta_p}{\lambda}$	$\frac{\delta_t}{\delta_p}$	V_j (m/s)	$\frac{V_j}{\sqrt{gR_p}}$
			OFFSETS					
0.47% (Upper)	1	0.46	0.047	0.53	4.8	1.15	-	-
	2	0.34	0.069	0.48	3.5	1.41	1.46	0.52
	3	0.24	0.075	0.35	2.5	1.46	1.39	0.57
	4	0.19	0.092	0.30	2.0	1.58	1.12	0.51
	6	0.091	0.139	0.17	0.95	1.87	0.58	0.37
1.86% (Lower)	1	0.32	0.054	0.39	3.3	1.22	-	-
	2	0.24	0.062	0.31	2.5	1.39	2.35	0.97
	3	0.17	0.075	0.25	1.8	1.47	2.00	9.95
	4	0.14	0.088	0.21	1.4	1.50	1.65	0.88
	6	0.066	0.132	0.12	0.69	1.82	1.10	0.82
			SPOILERS					
0.63% (Upper)	1	0.43	0.031	0.39	5.6	0.91	-	-
	2	0.30	0.047	0.34	3.9	1.13	1.88	0.70
	3	0.23	0.055	0.28	2.9	1.22	1.53	0.65
	4	-	-	-	-	-	1.18	0.57
	6	0.086	0.109	0.15	1.1	1.74	0.86	-
1.88% (Lower)	1	0.32	0.043	0.35	4.2	1.09	-	-
	2	0.23	0.047	0.26	3.0	1.13	2.74	1.15
	3	0.17	0.057	0.21	2.2	1.24	2.17	1.03
	4	0.14	0.069	0.18	1.8	1.29	1.90	1.01
	6	0.066	0.125	0.12	0.86	1.82	1.29	0.97

Table 8. Model: flow depth increase and jet velocities (V_j), n_p = 0.027.

δ_p	n_t	δ_t	$\frac{\delta_p}{\lambda}$	$\frac{\delta_t}{\delta_p}$
		OFFSETS		
0.30	0.047	0.40	3.1	1.33
0.40	0.042	0.51	4.2	1.28
0.50	0.040	0.64	5.2	1.28
0.60	0.034	0.71	6.3	1.18
		SPOILERS		
0.30	0.036	0.35	3.9	1.17
0.40	0.032	0.44	5.2	1.10
0.50	0.031	0.54	6.5	1.08
0.60	0.030	0.64	7.8	1.07

δ_p	Slope (%)	V_j (m/s)	$\frac{V_j}{\sqrt{gR_p}}$
	OFFSETS		
0.15	4.0	0.86	1.18
0.20	2.0	0.70	0.85
0.20	4.0	1.03	1.25
0.30	0.5	0.36	0.37
0.30	1.0	0.58	0.58
0.30	2.0	0.95	0.96
	SPOILERS		
0.30	0.5	0.42	0.43
0.30	1.0	0.61	0.62
0.30	2.0	0.80	0.81
0.50	0.5	0.40	0.33
0.50	1.0	0.67	0.56
0.50	2.0	0.97	0.81

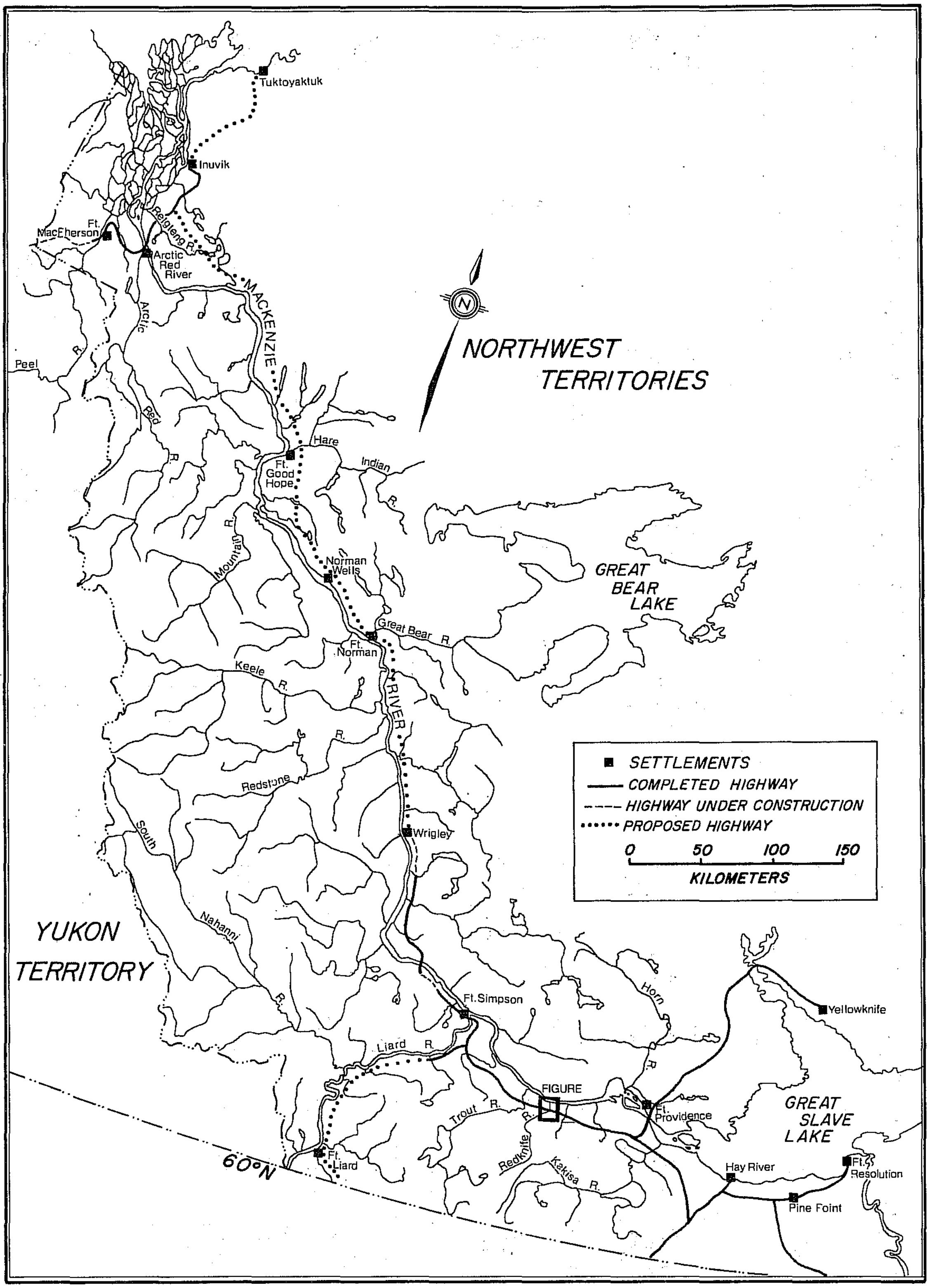


Fig. 1. Redknife River in relation to the Mackenzie Valley.

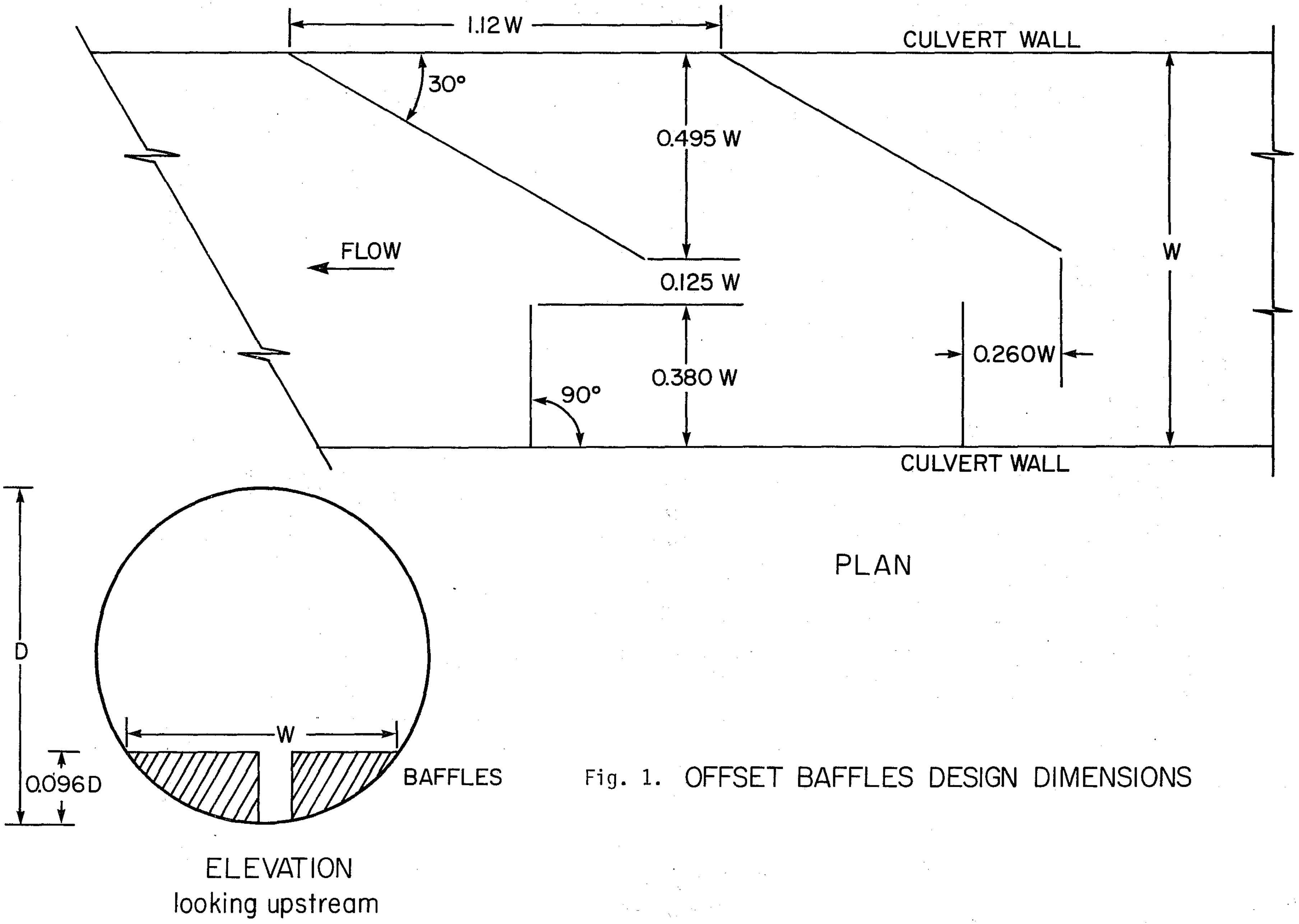


Fig. 1. OFFSET BAFFLES DESIGN DIMENSIONS

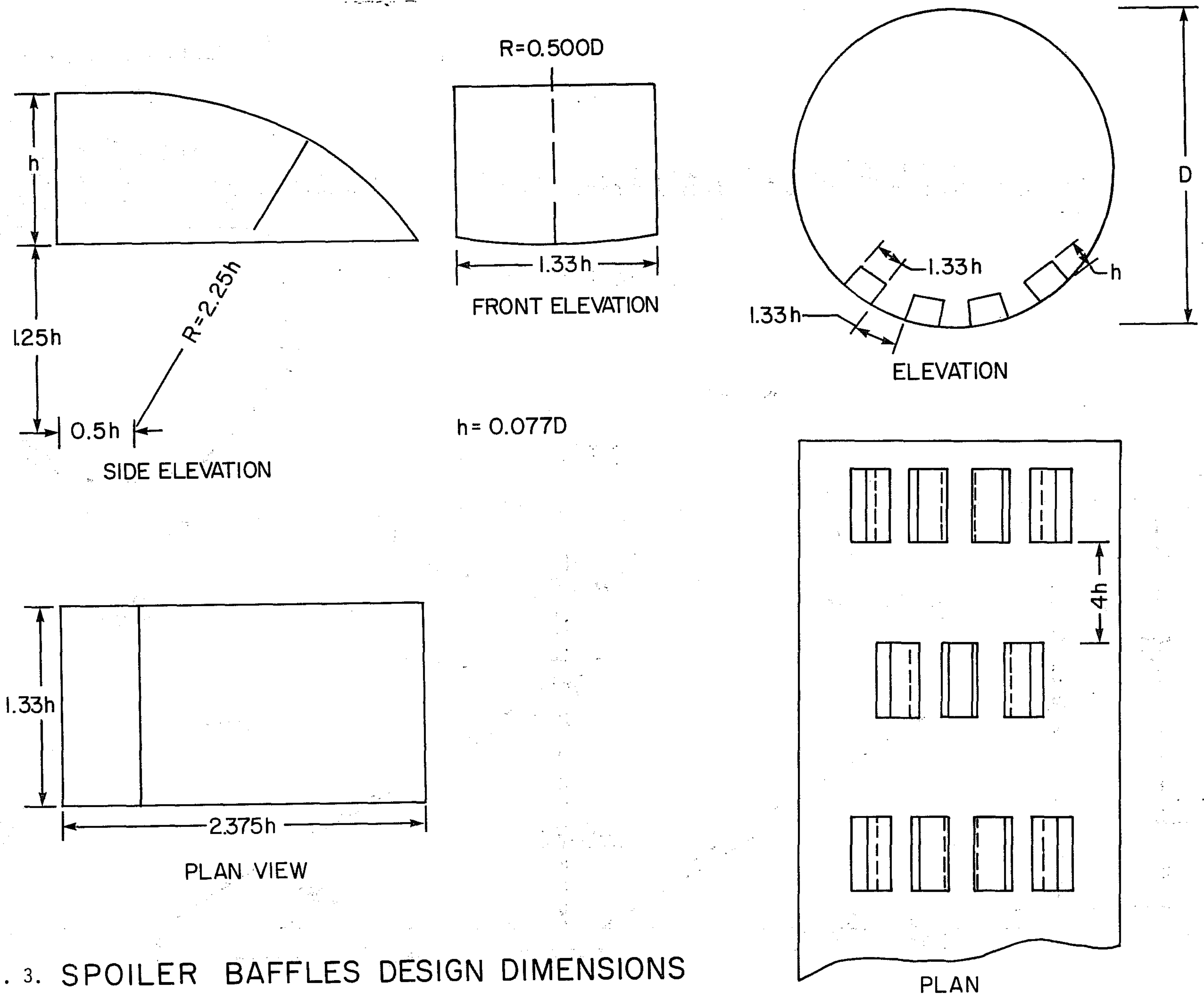


Fig. 3. SPOILER BAFFLES DESIGN DIMENSIONS

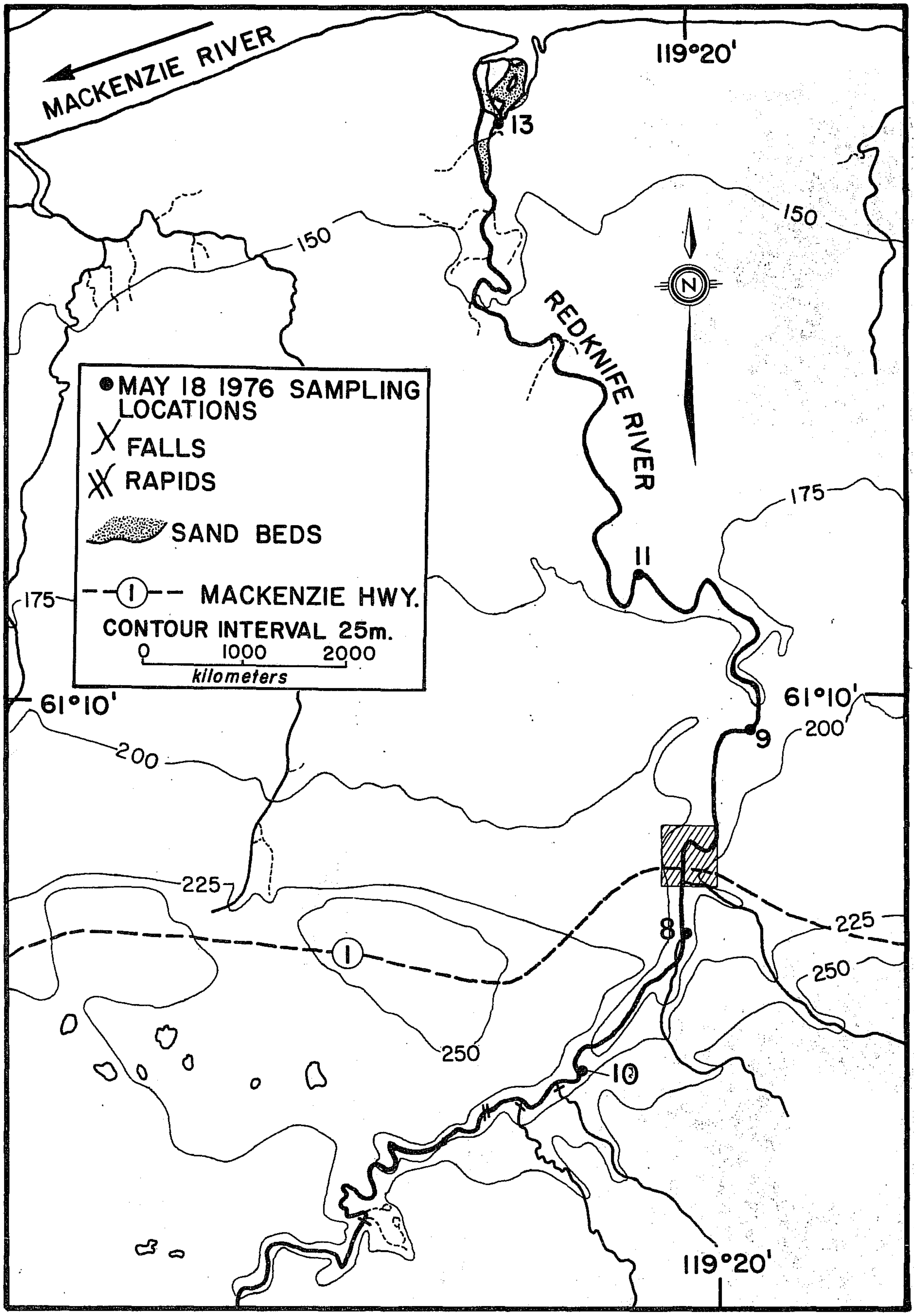


Fig. 4. Redknife River.

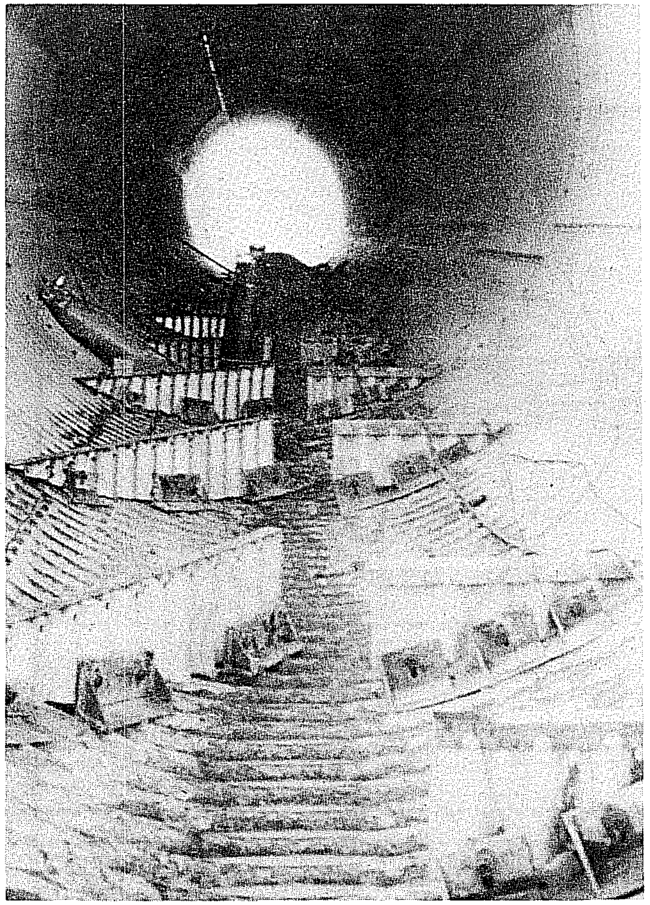


Fig. 5. Installation of Offsets (looking upstream).

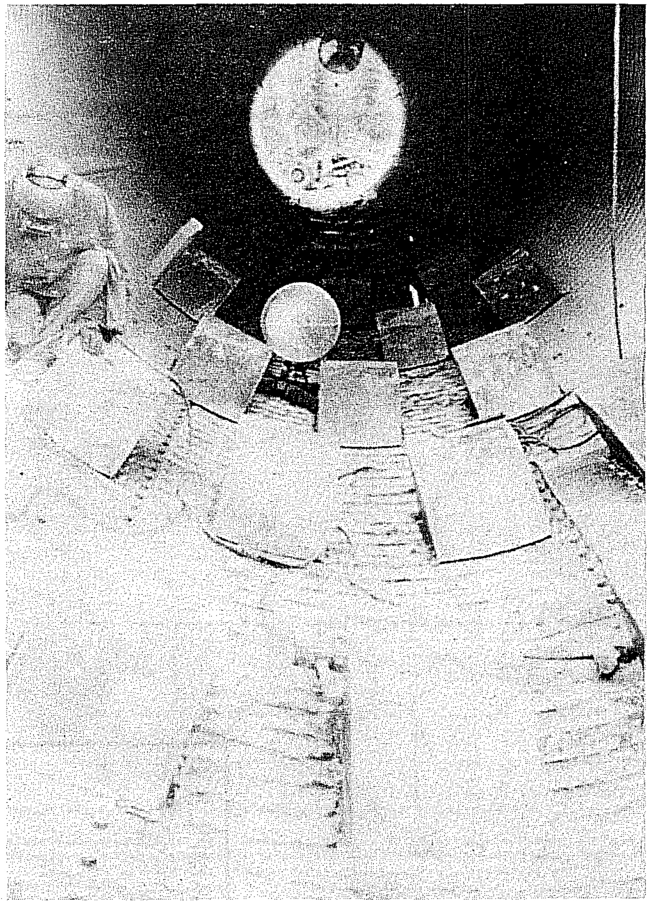


Fig. 6. Installation of Spoilers (looking downstream).

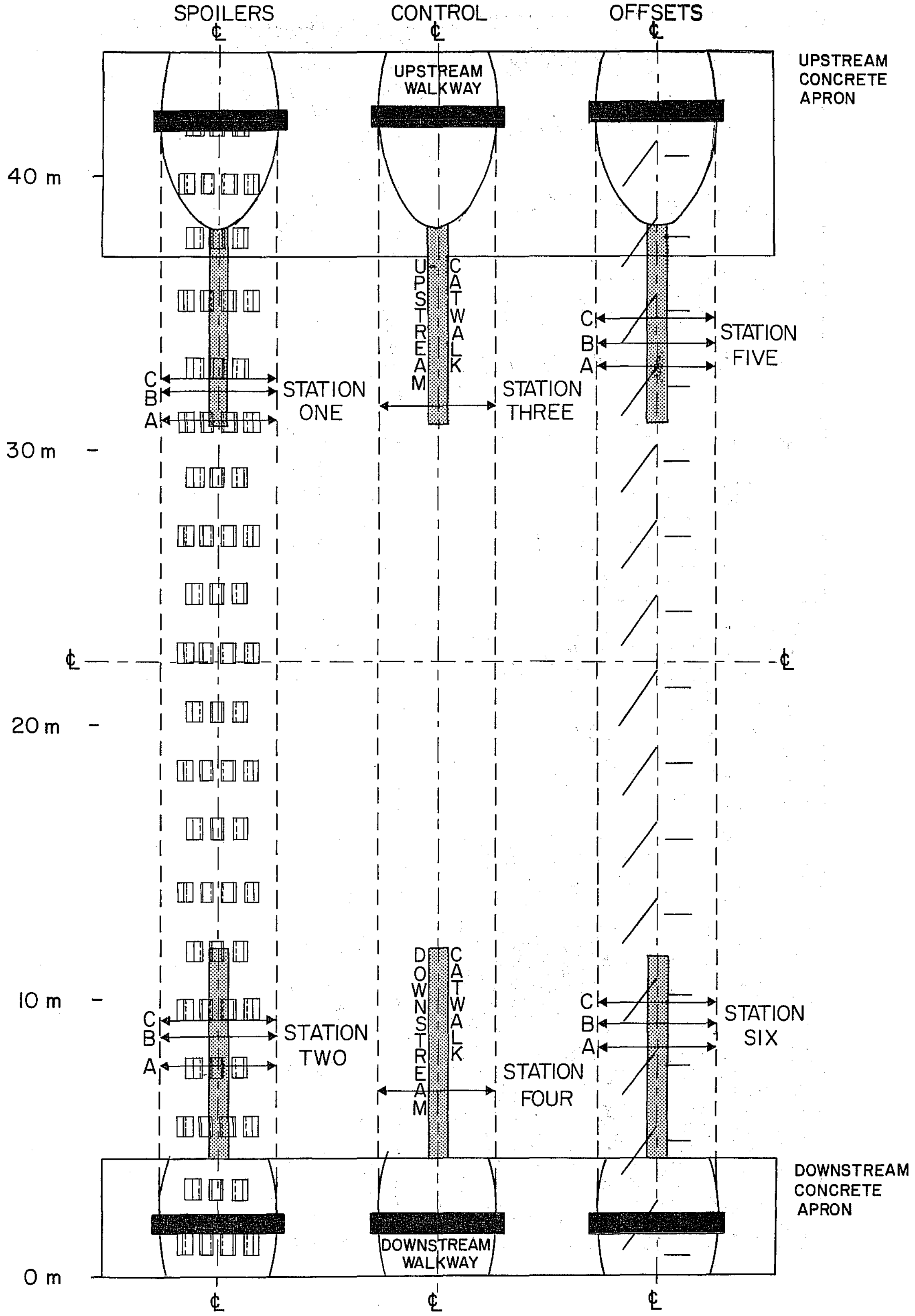


Fig. 7. Culvert monitoring facilities and stations.

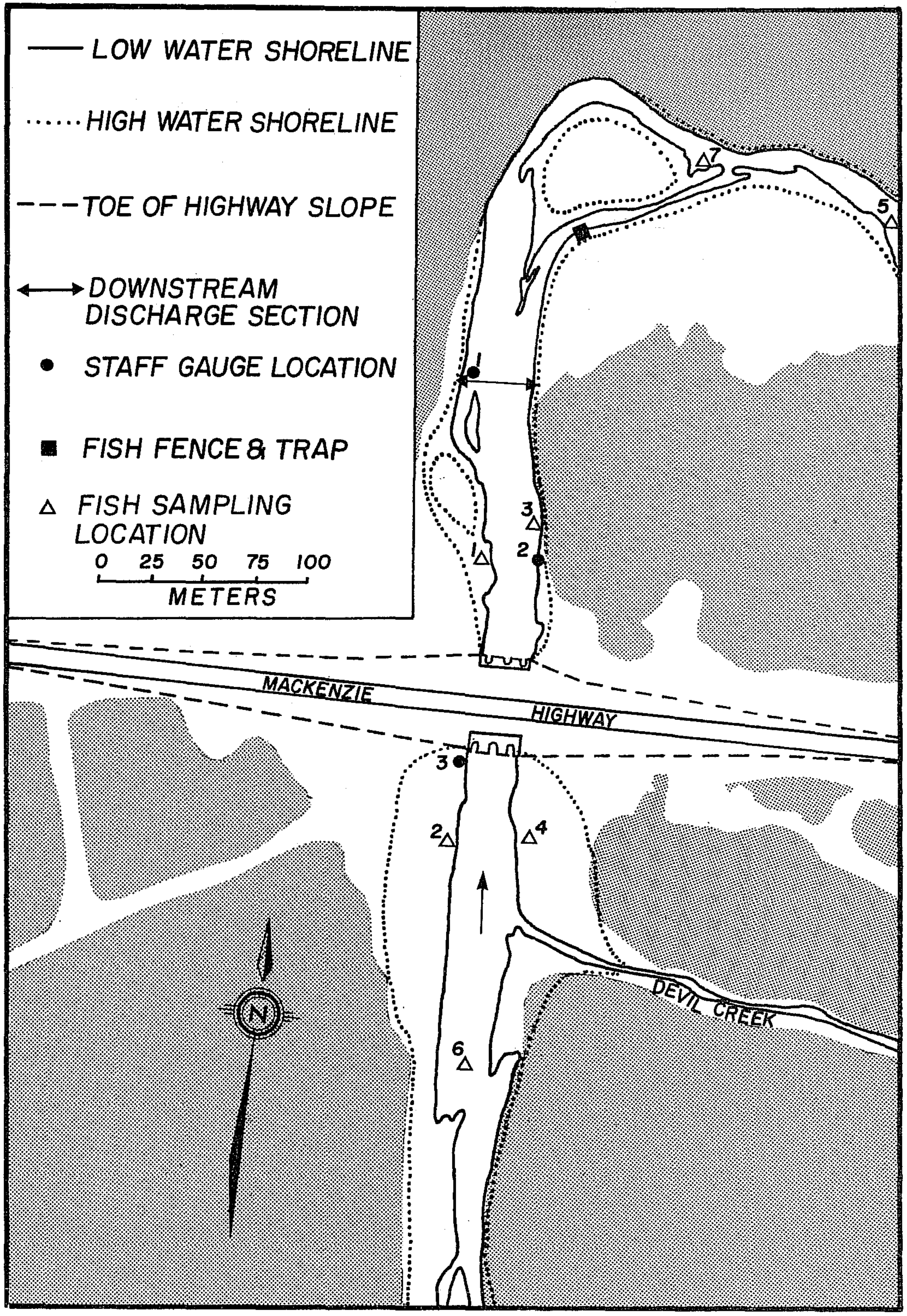


Fig. 8. Measuring and sampling stations.

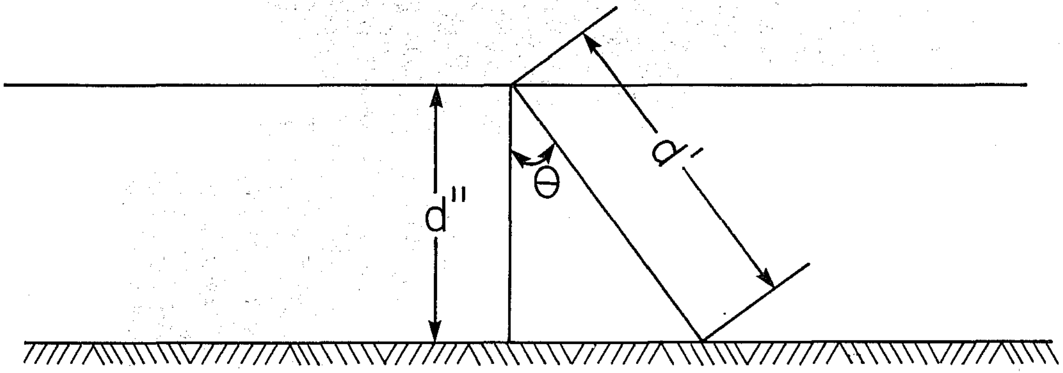


Fig. 9. Depth measurement correction.

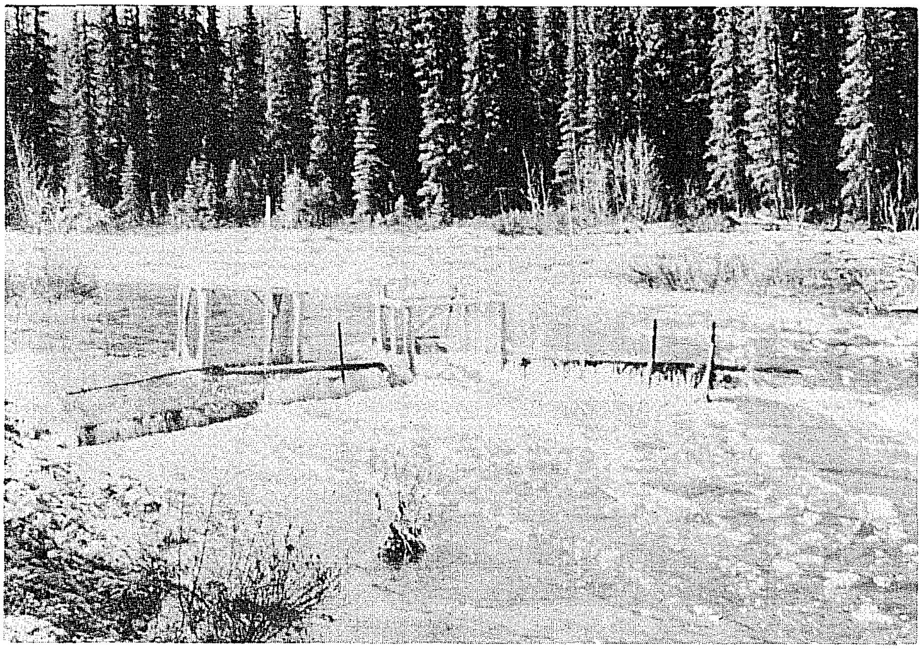


Fig. 10. Fish fence, trap and holding pen.

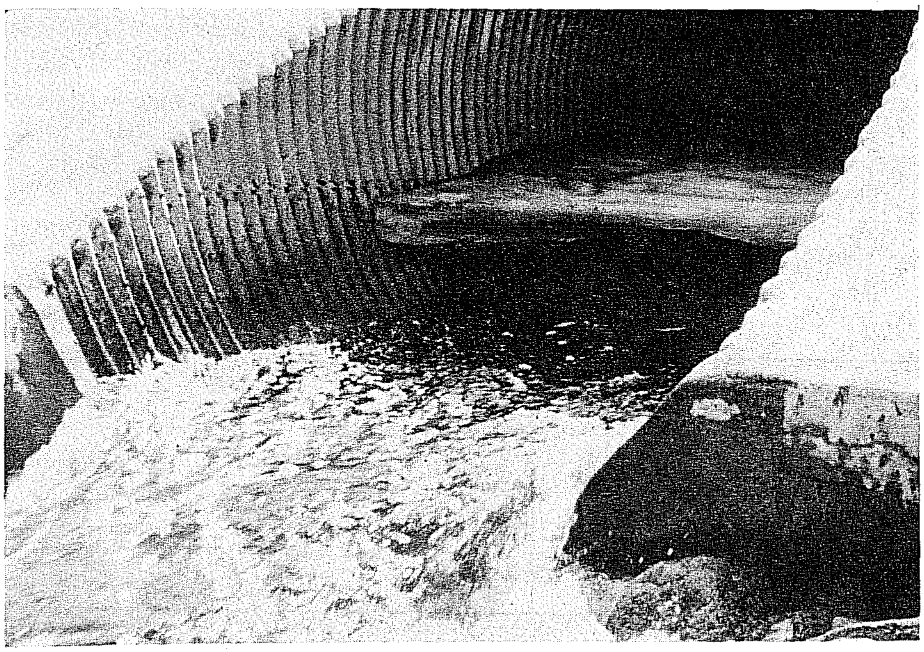


Fig. 11. Icing at outlet of west (offset) culvert, May 15, 1974 (no baffles present).

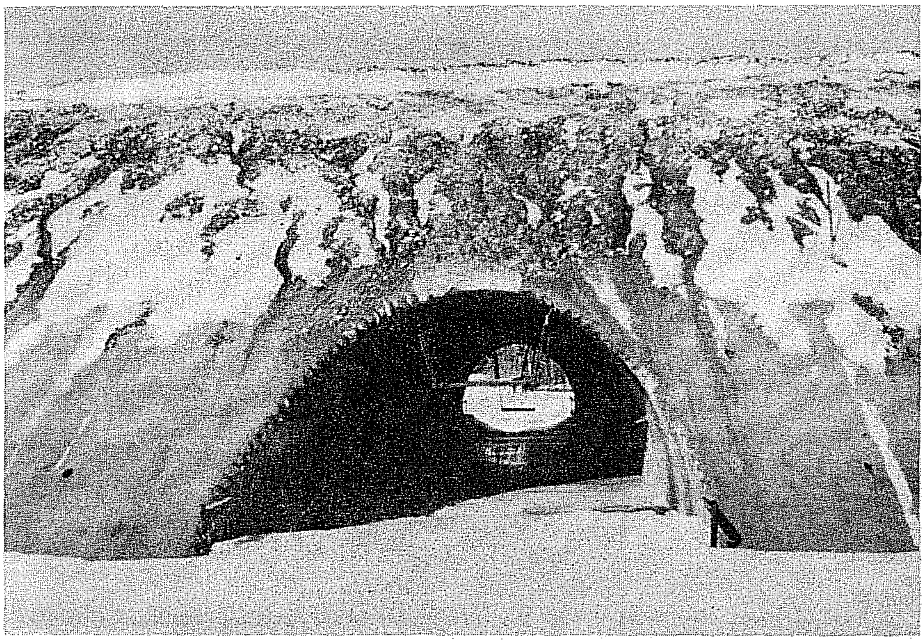


Fig. 12. Inlet icing of control culvert, April 10, 1976.

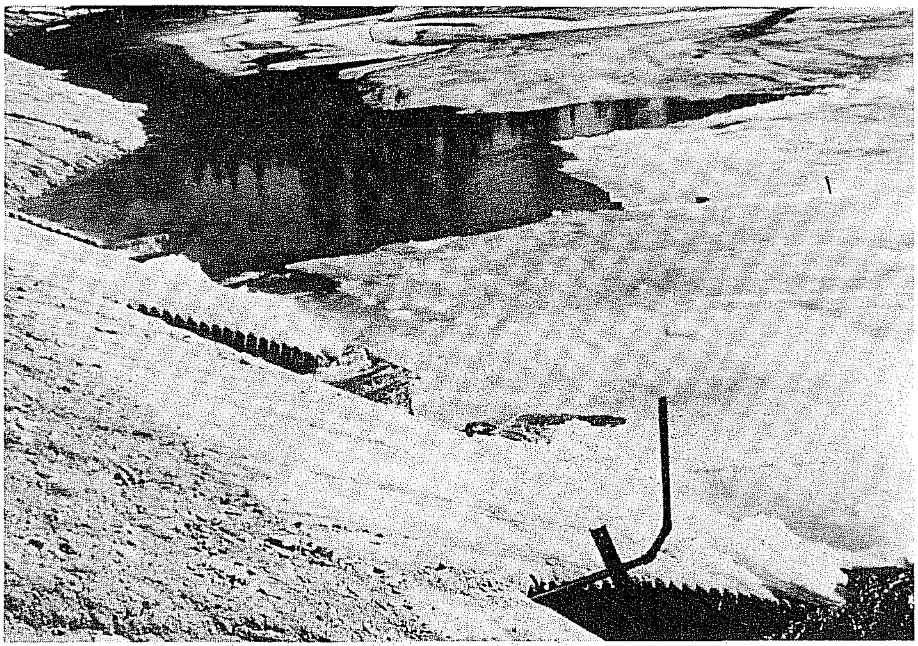


Fig. 13. Inlet conditions, April 23, 1976 (looking southeast).

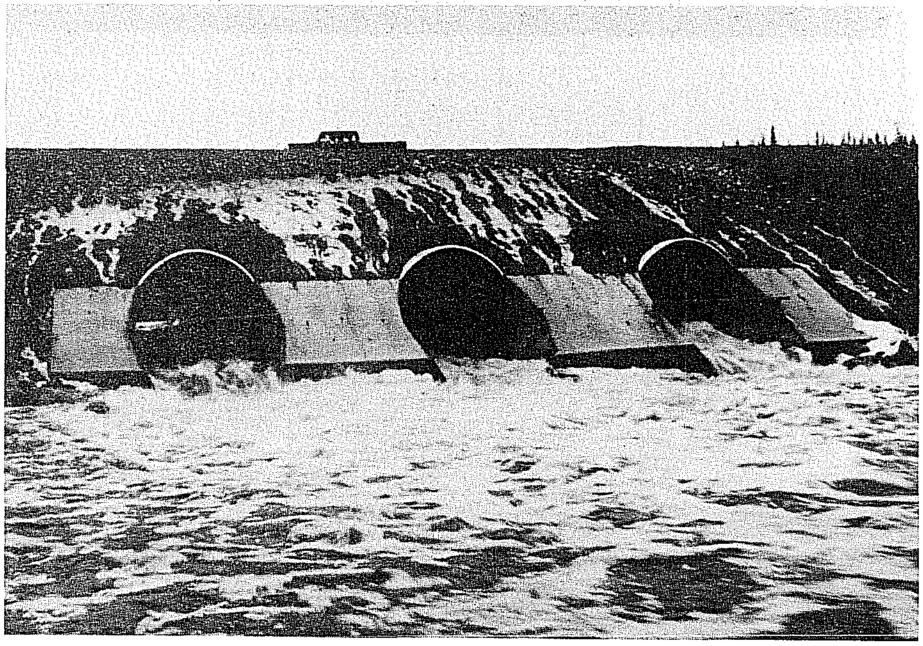


Fig. 14. Outlet conditions, April 25, 1976.

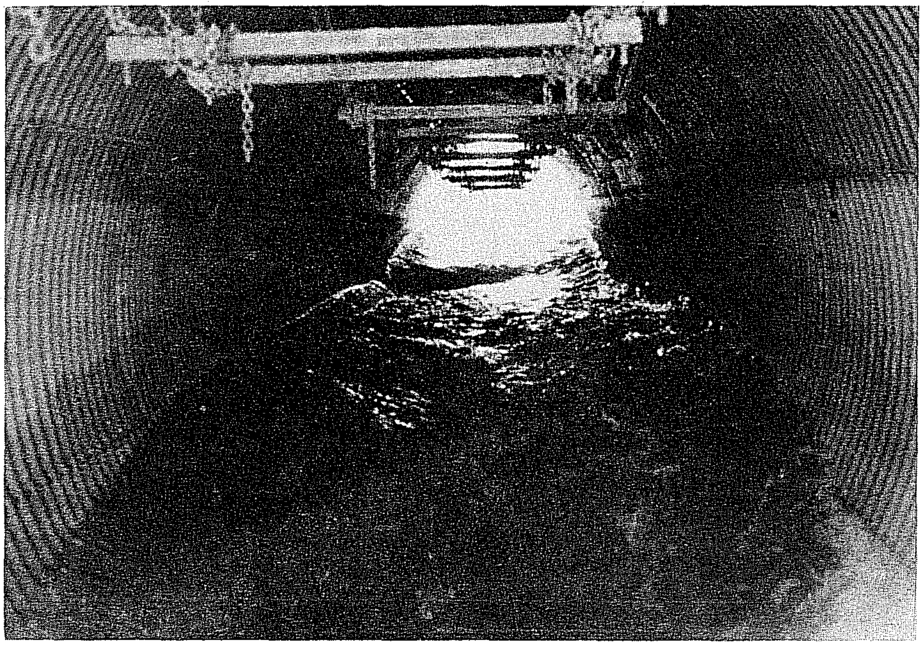


Fig. 15. Water flowing over the ice in culvert with Offsets, April 26, 1976.

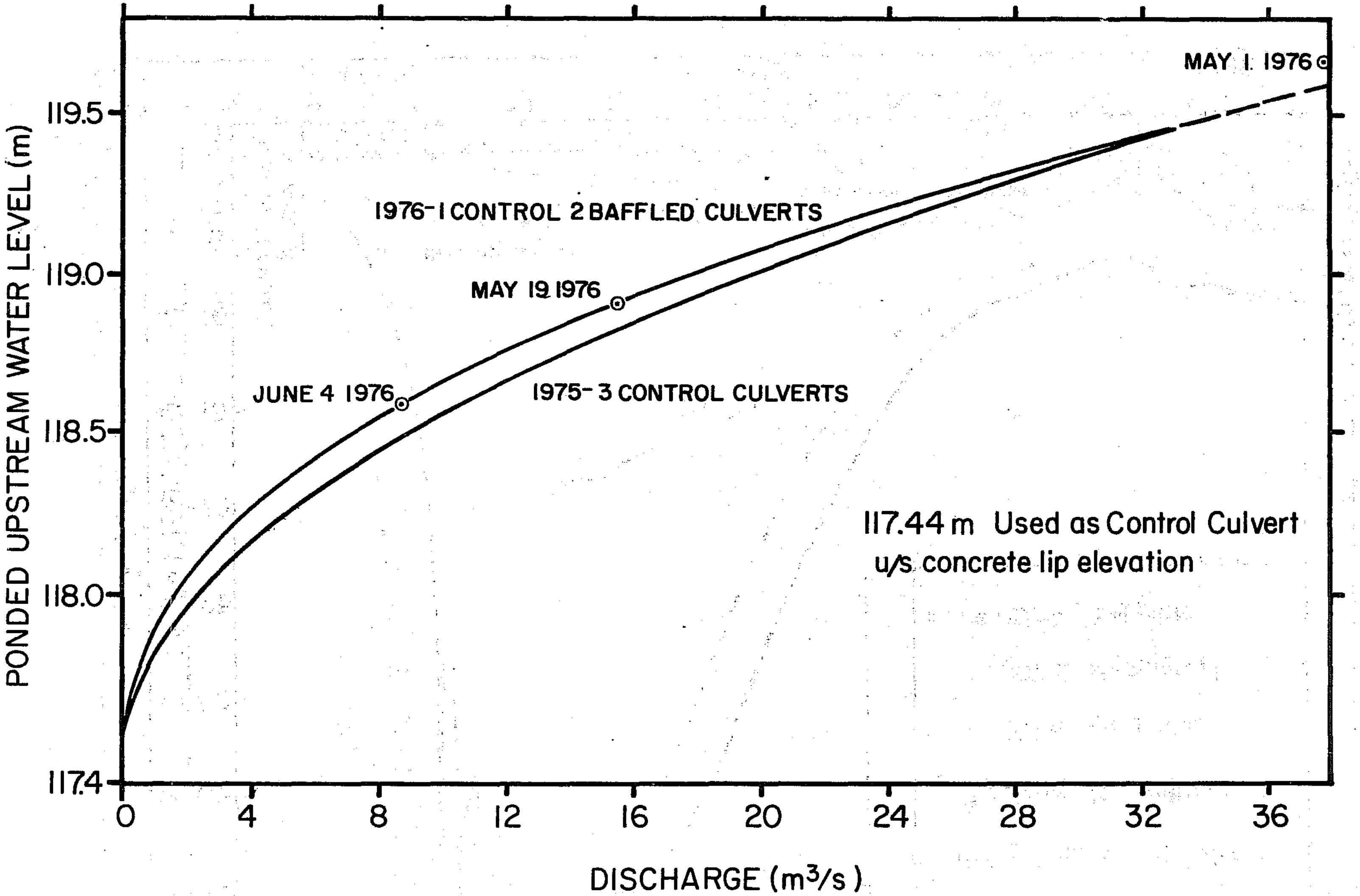


Fig. 16. Discharge rating curves for the Redknife River culverts.

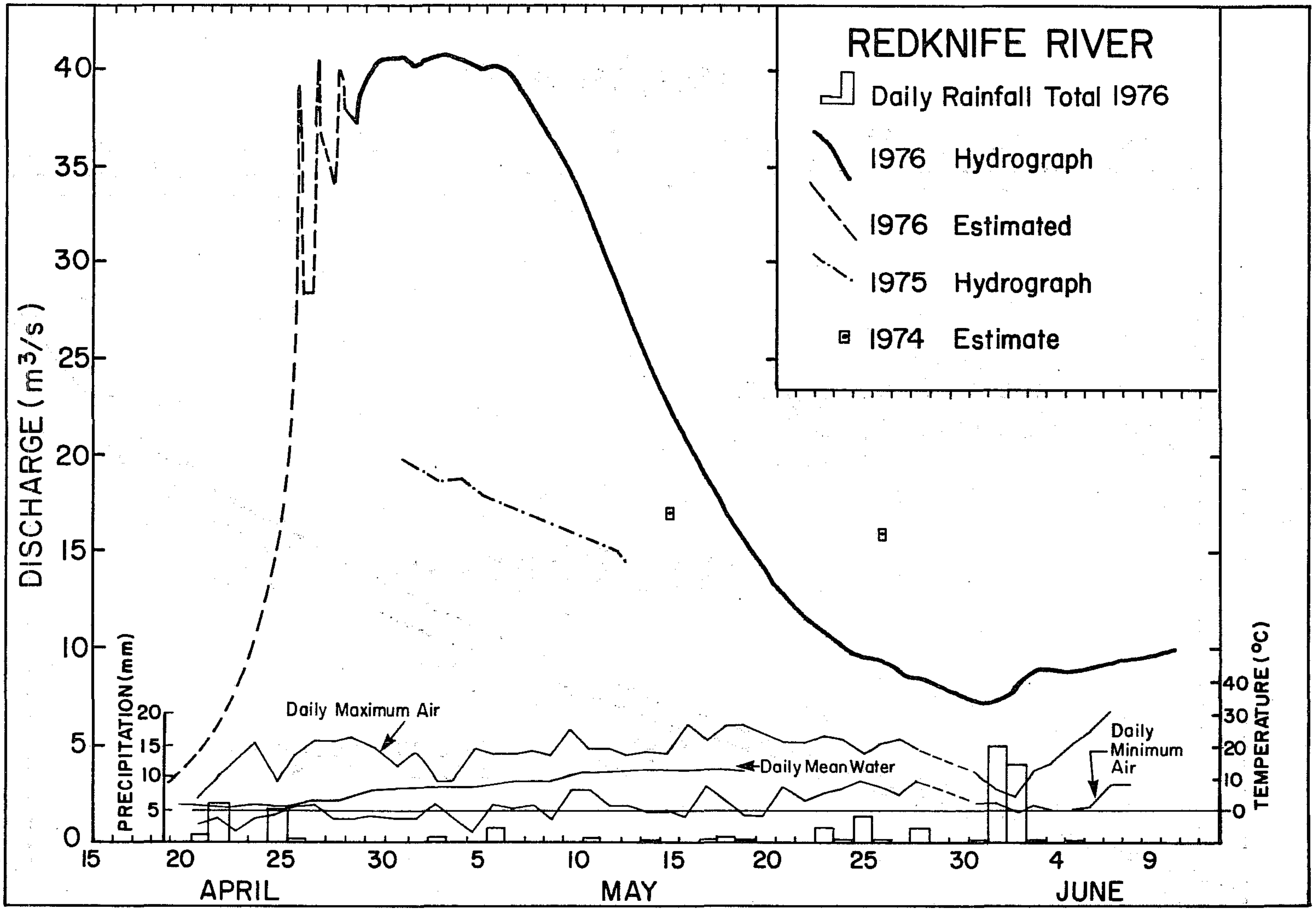


Fig. 17. Hydrological data for the Redknife River crossing.

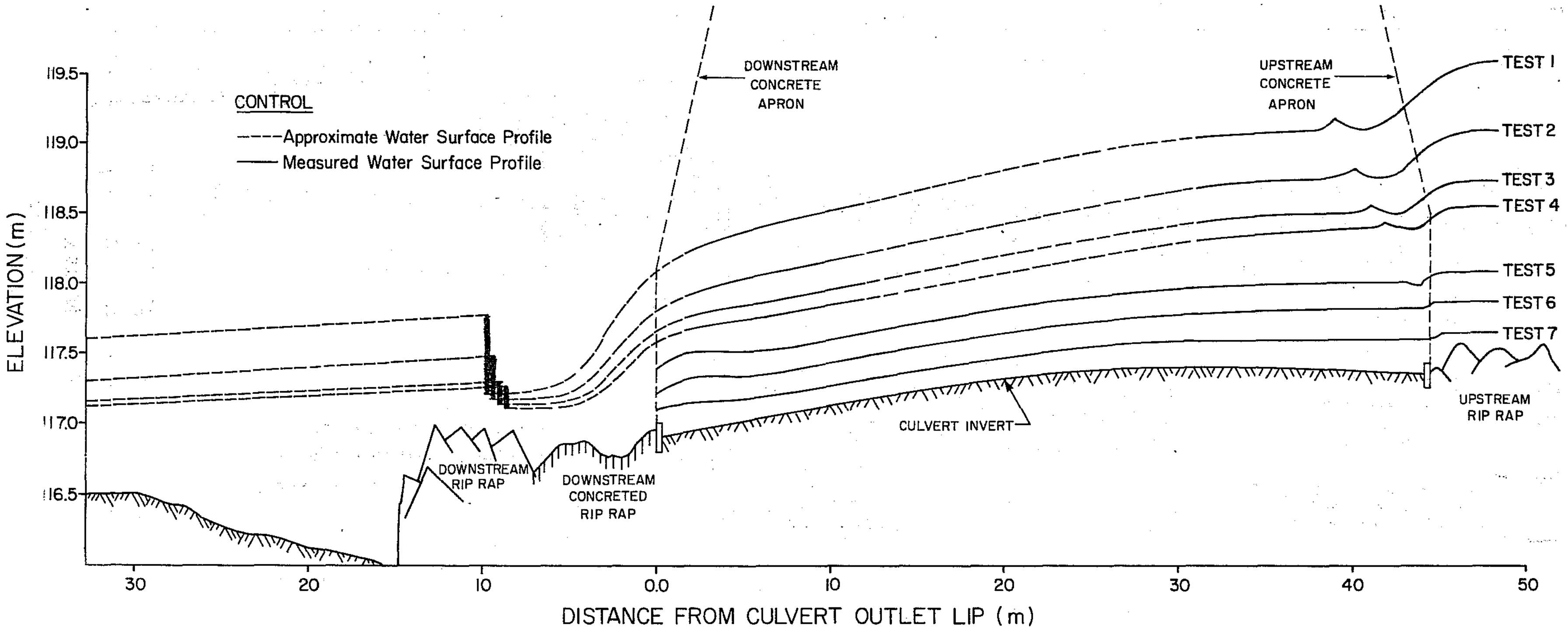


Fig. 18. Water surface profiles for control culvert.

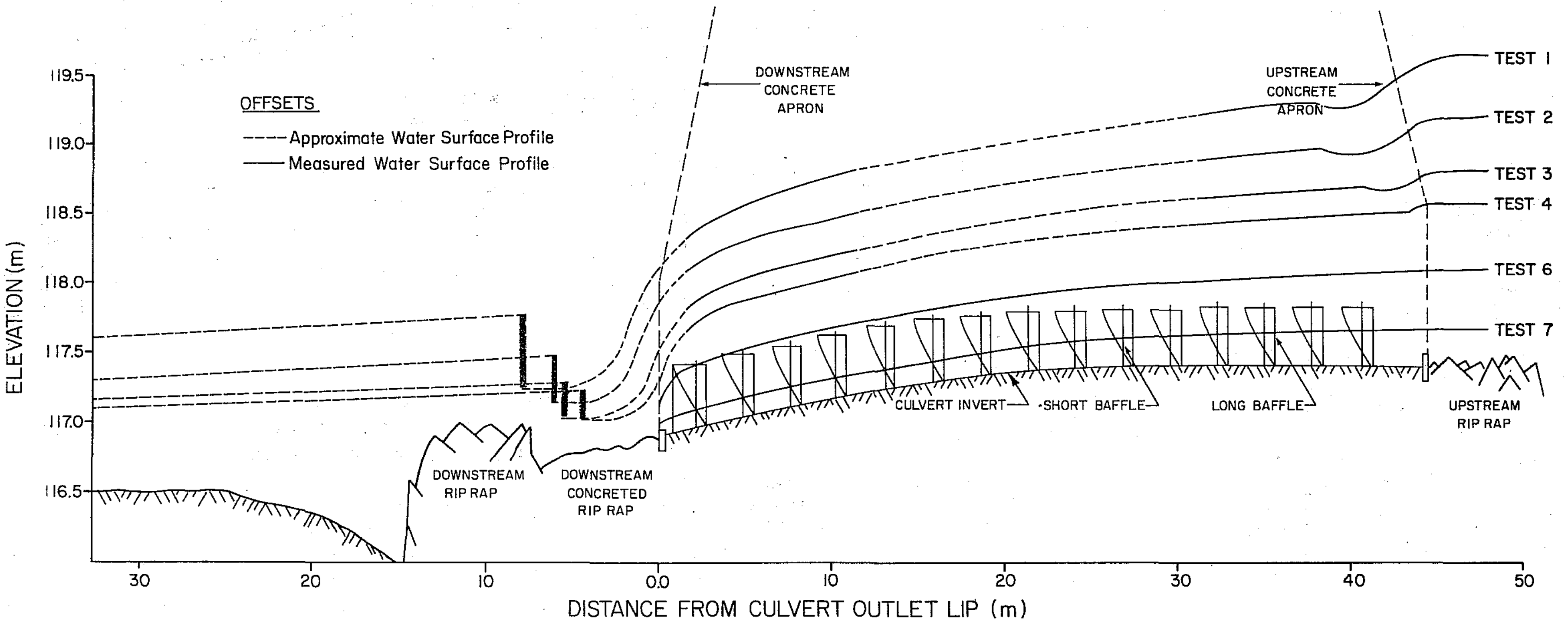


Fig. 19. Water surface profiles for the Offset culvert.

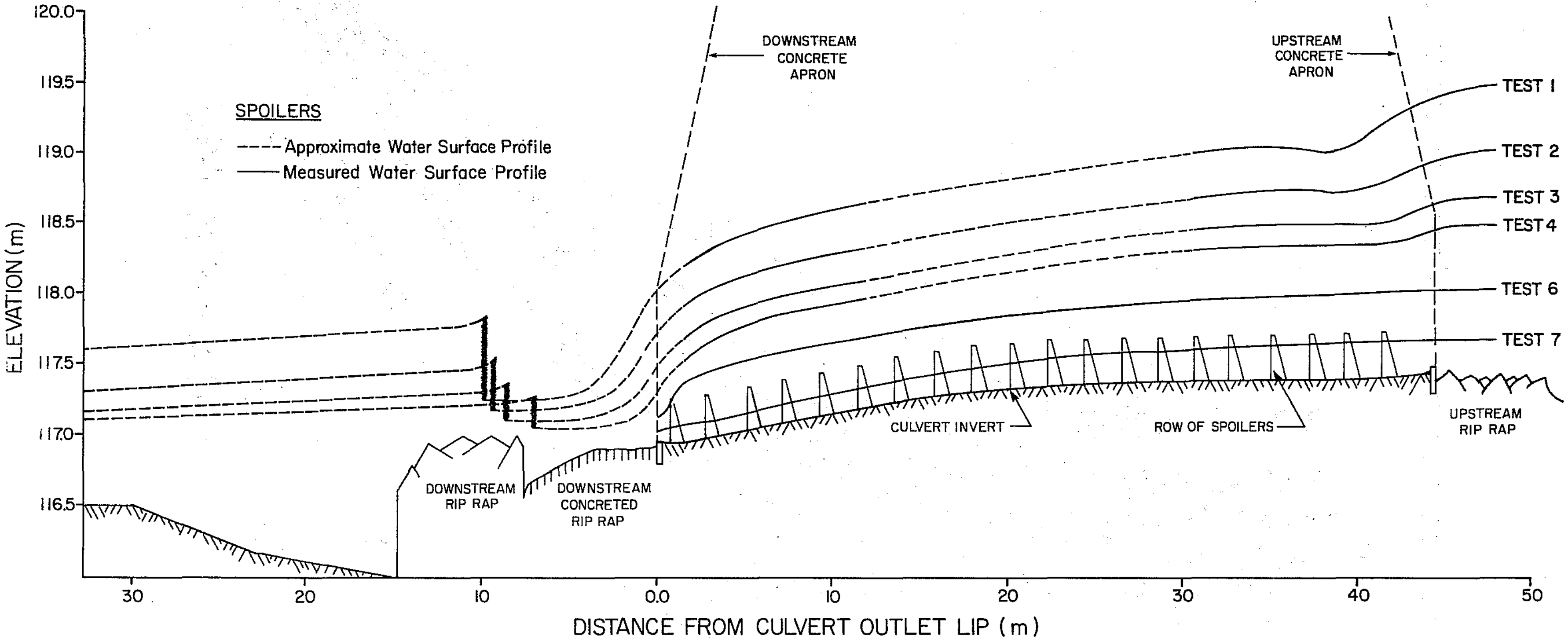


Fig. 20. Water surface profiles for the Spoiler culvert.

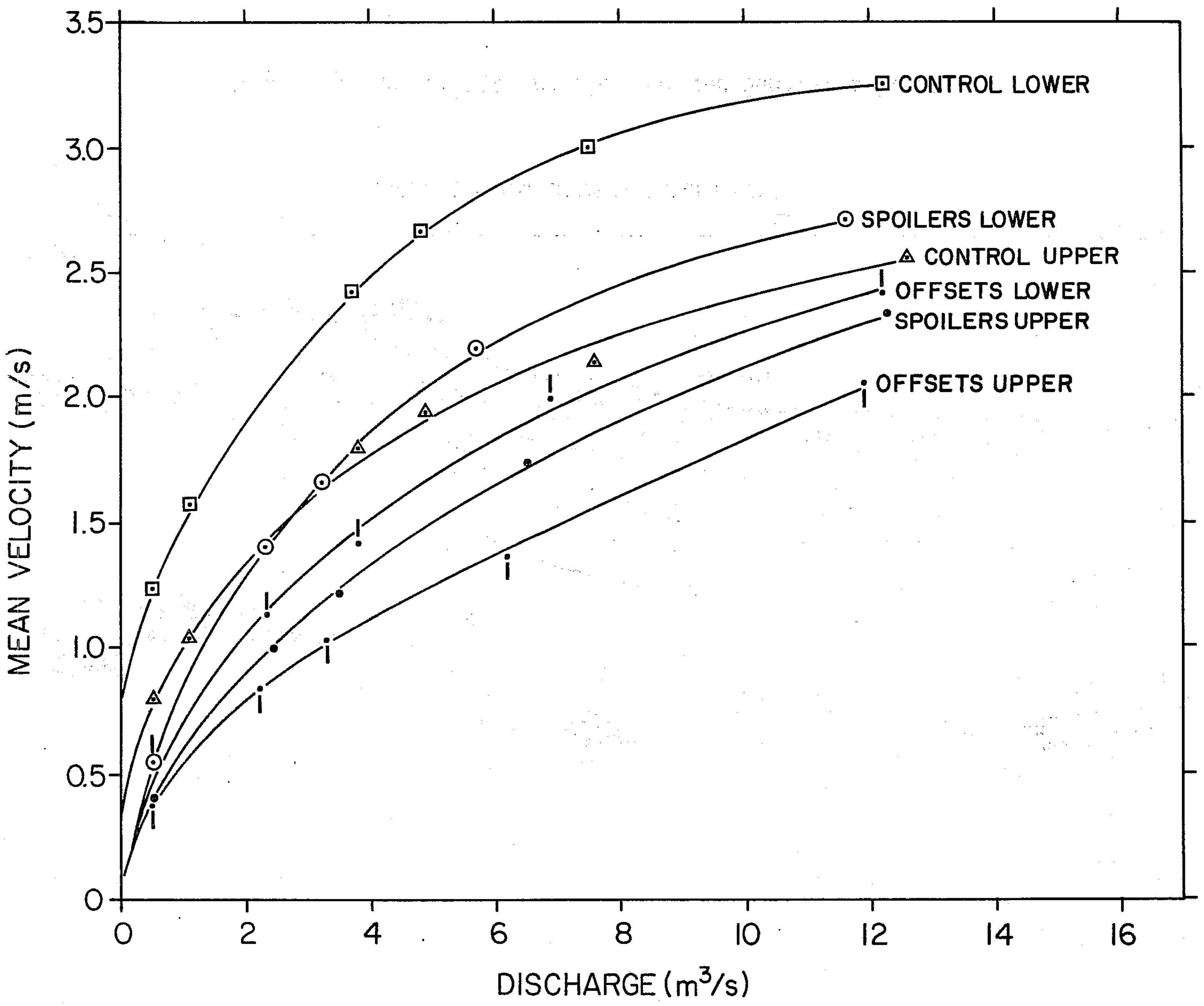


Fig. 21. Mean water velocities through the culverts.

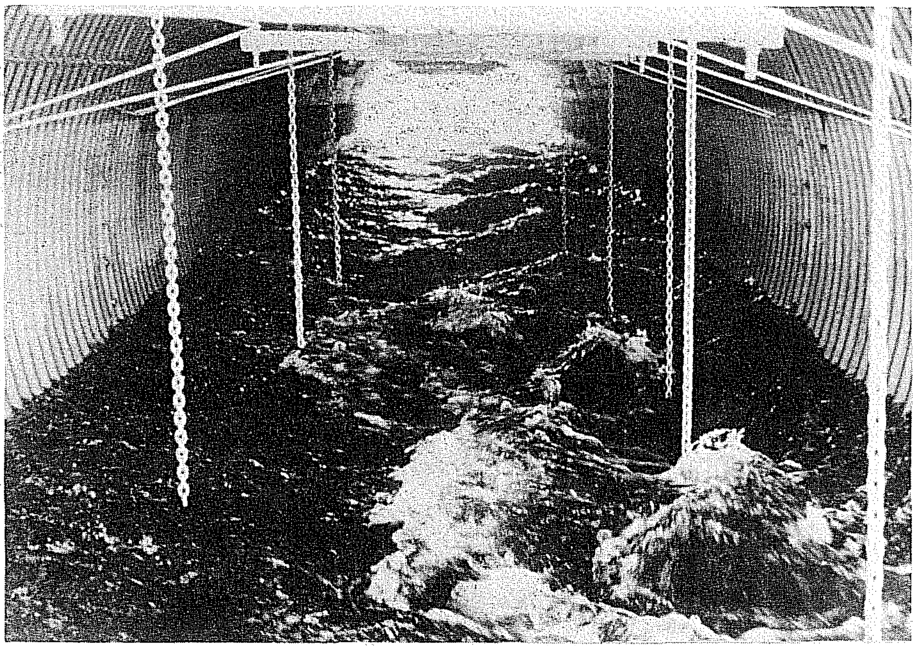


Fig. 22. Flow over Offsets, test 1, May 7, 1976 (looking upstream).

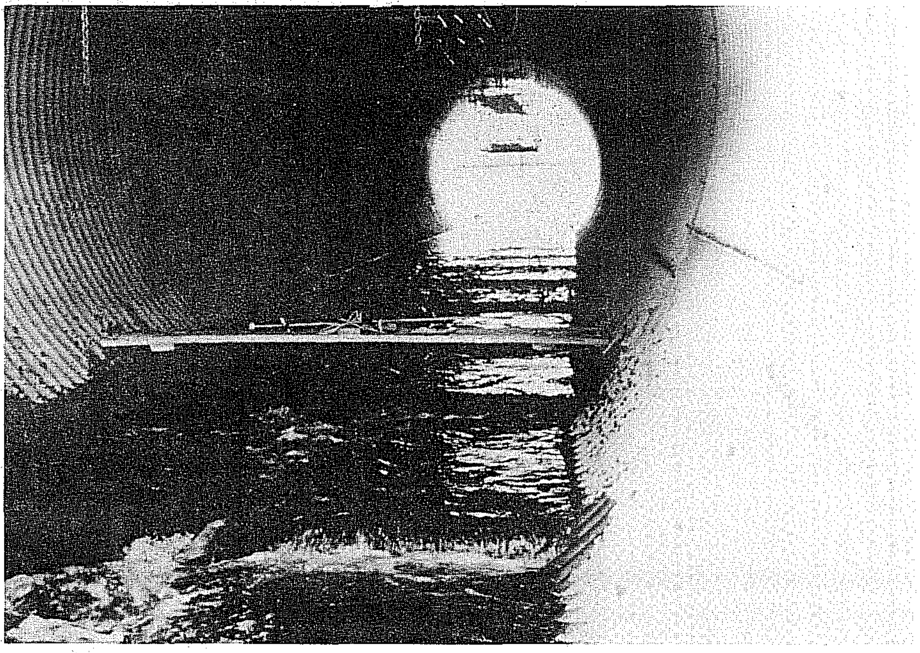


Fig. 23. Flow over Offsets, test 6, July 24, 1976.

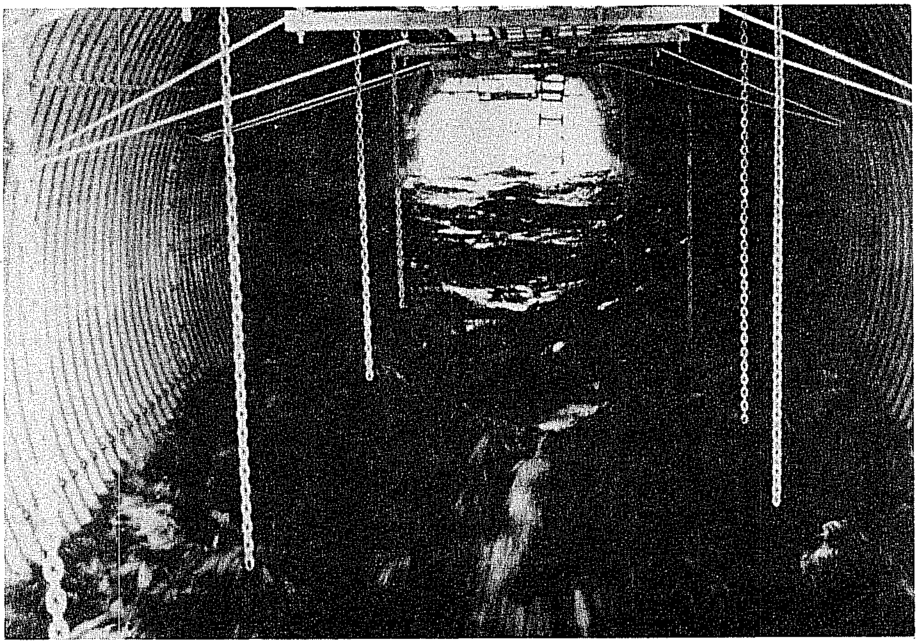


Fig. 24. Flow over Spoilers, test 1, May 10, 1976 (looking upstream).

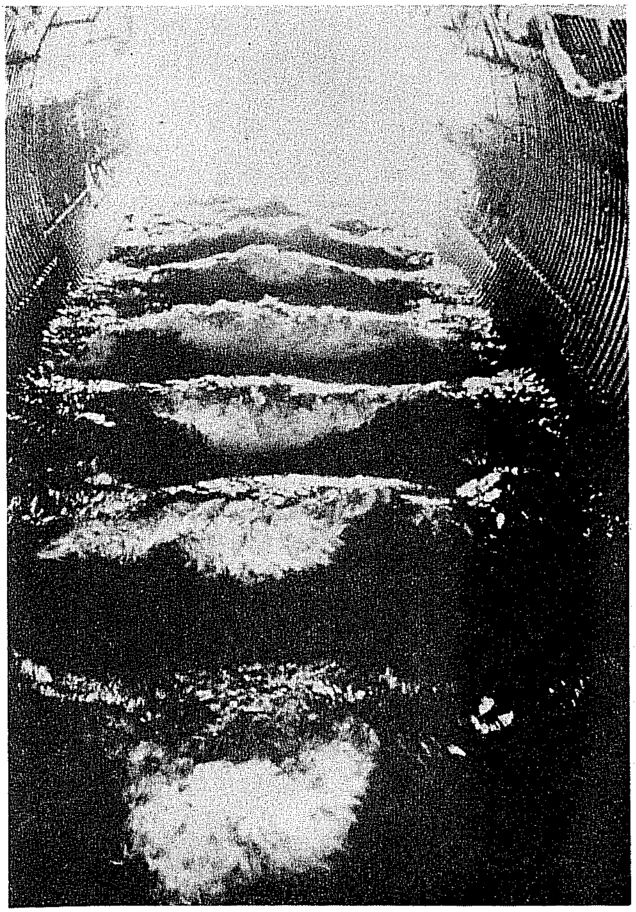


Fig. 25. Flow over Spoilers, test 3, May 23, 1976 (looking upstream).

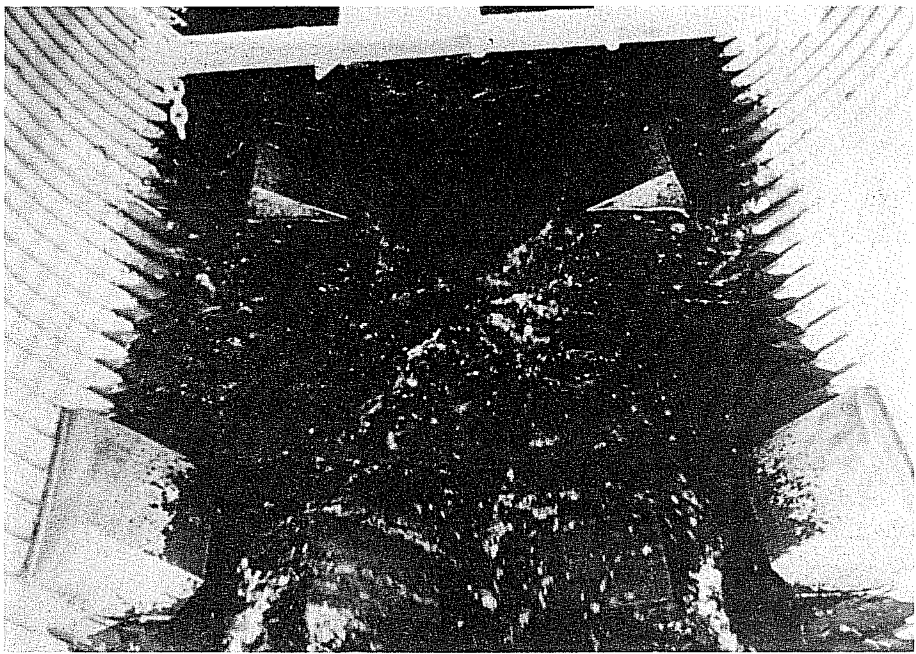


Fig. 26. Flow in culvert with Spoilers, test 6, July 26, 1976 (3rd and 4th row of Spoilers, looking upstream).

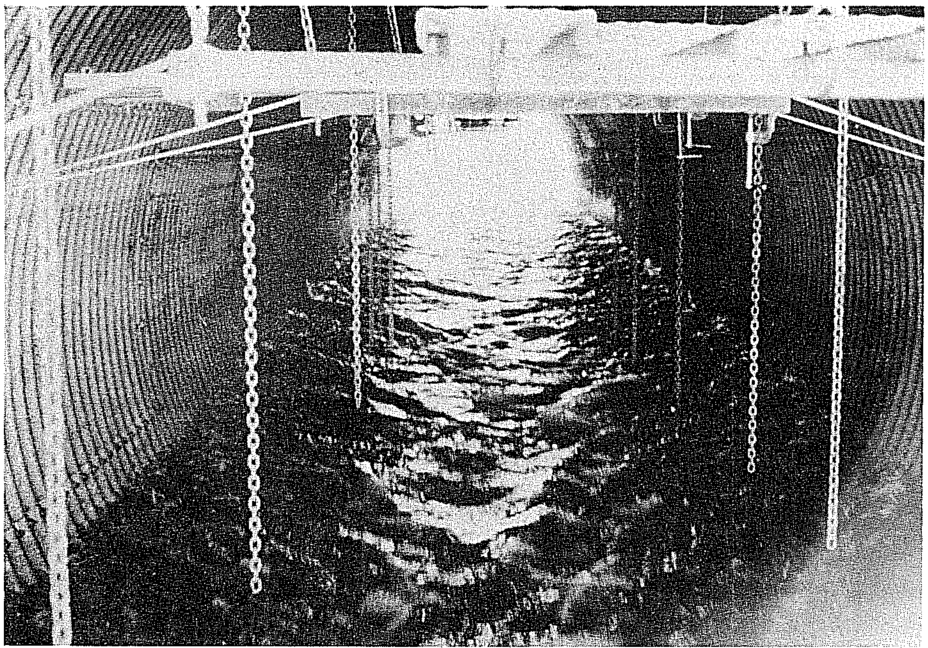


Fig. 27. Flow in control culvert, test 1, May 9, 1976 (looking upstream).

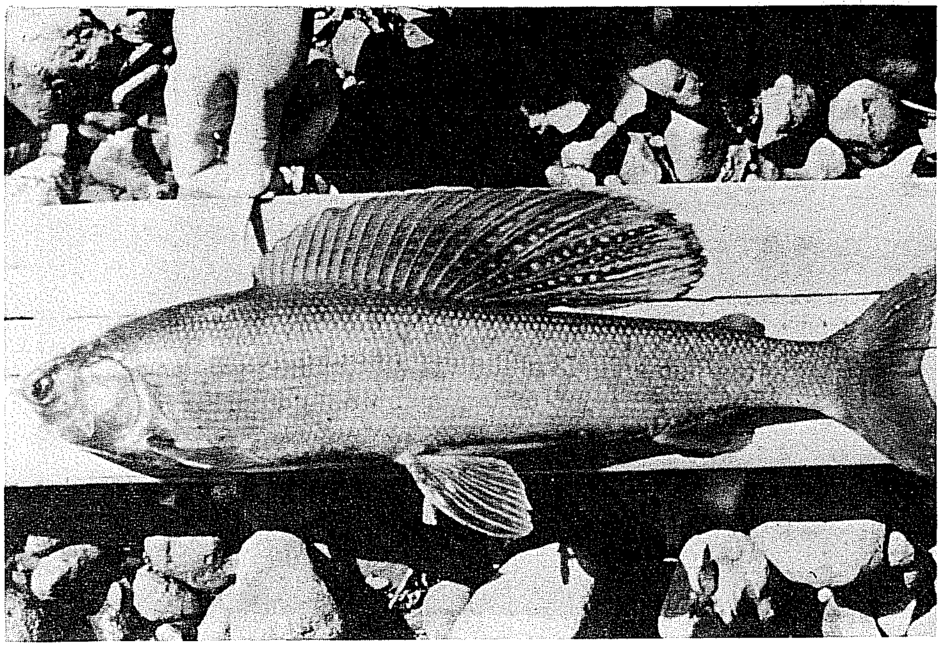


Fig. 28. Arctic grayling (*Thymallus arcticus*).

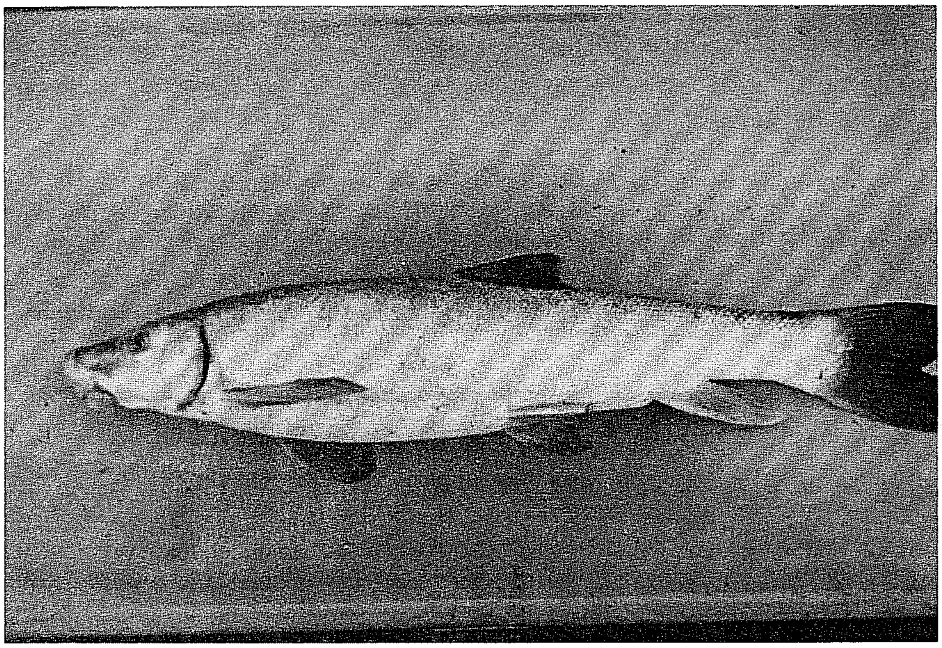


Fig. 29. Longnose sucker (*Catostomus catostomus*).

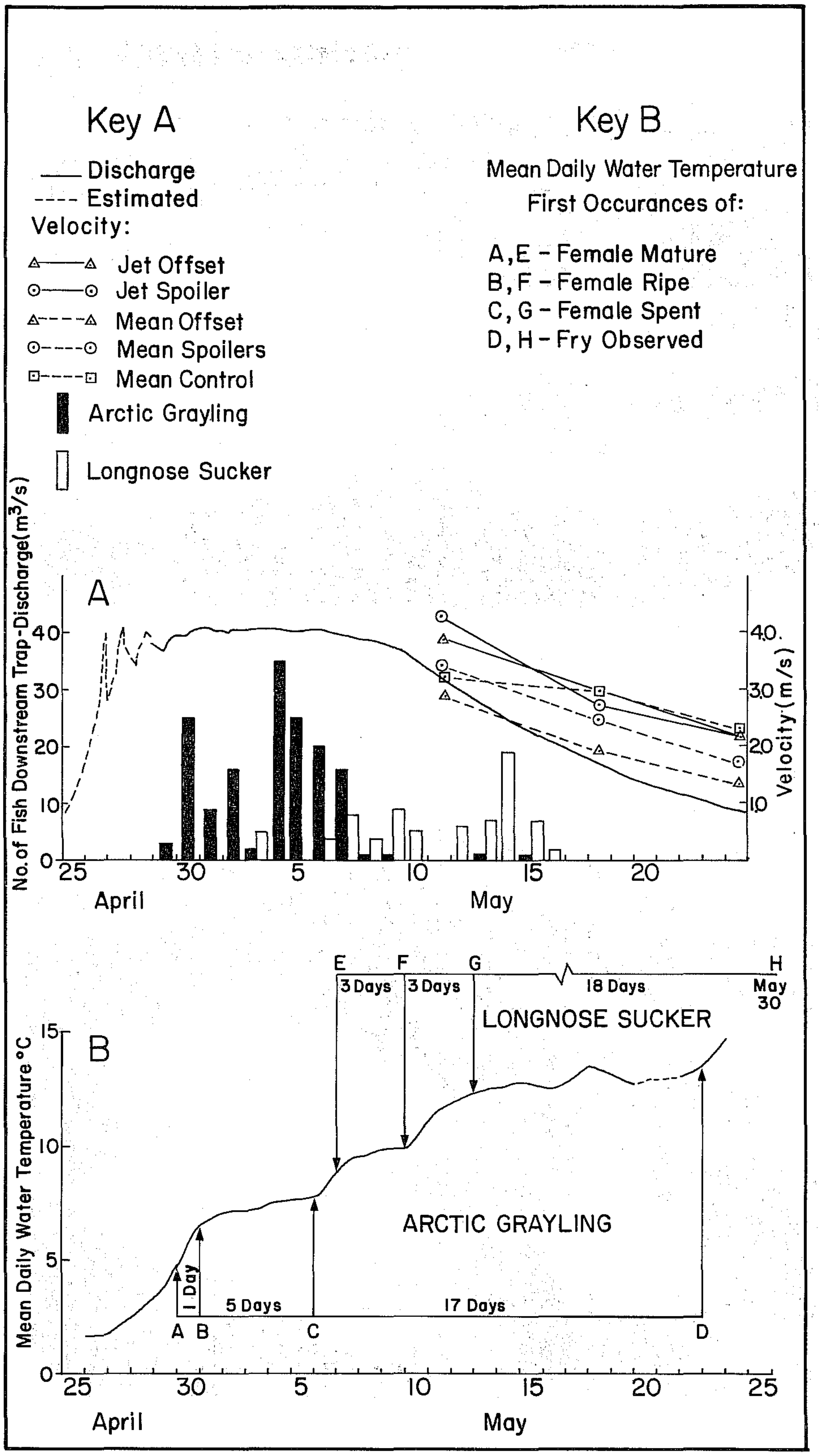


Fig. 30. Biophysical relationships for spring fish migrations in the Redknife River (1976).

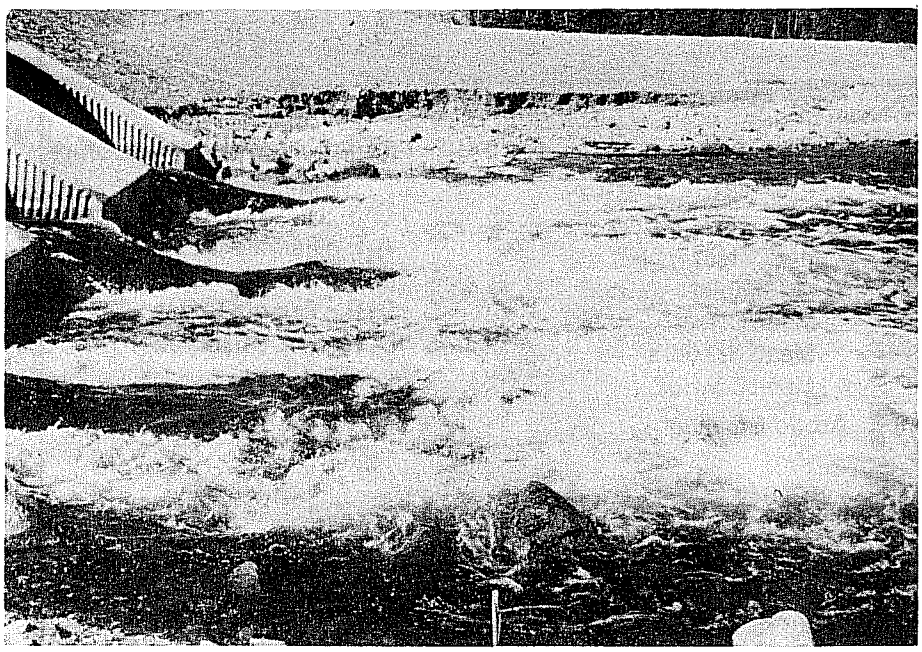


Fig. 31. Culvert outlets during fish migration, May 9, 1975.

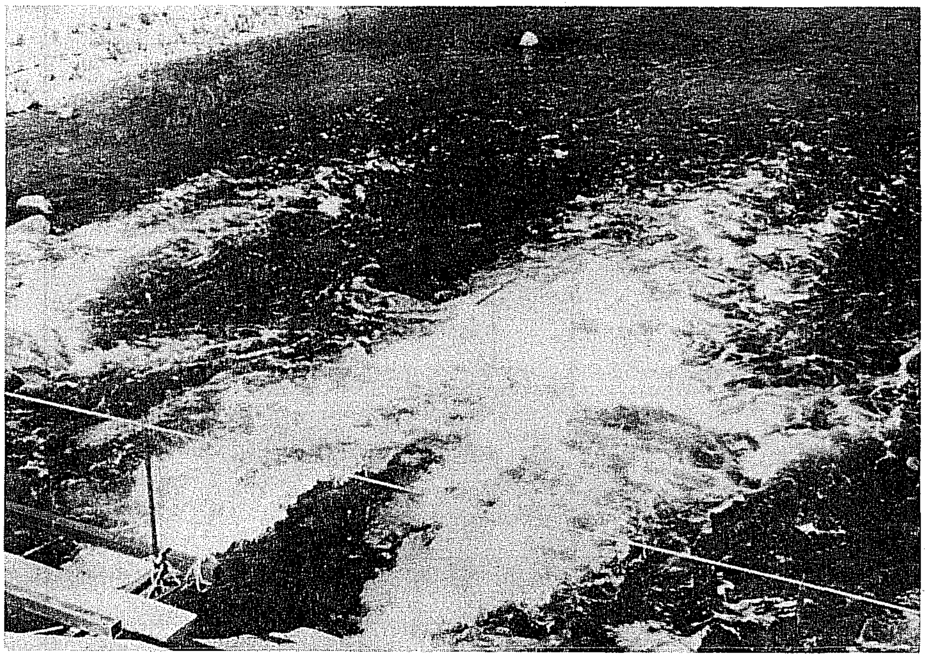


Fig. 32. Culvert outlets during fish migration, June 5, 1976.

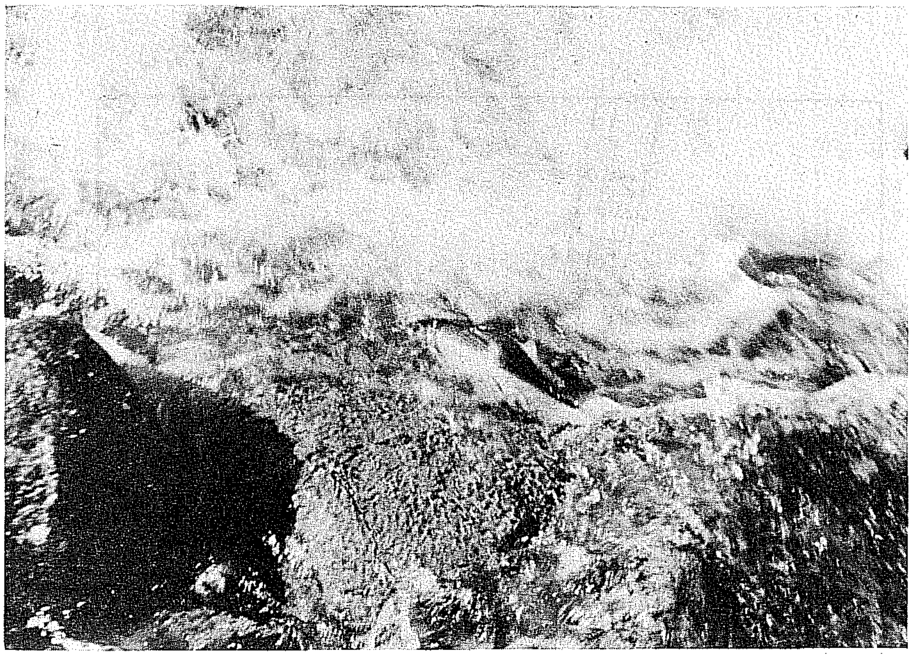


Fig. 33. Arctic grayling attempting to enter culvert with Spoilers, May 1, 1976.

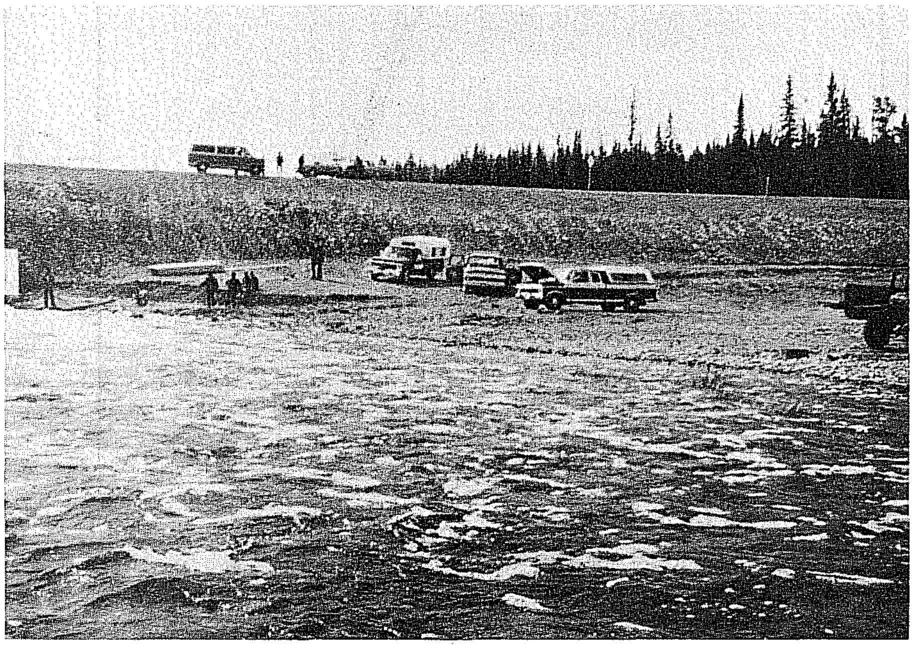


Fig. 34. Fishermen downstream of the culverts , May 2, 1976.

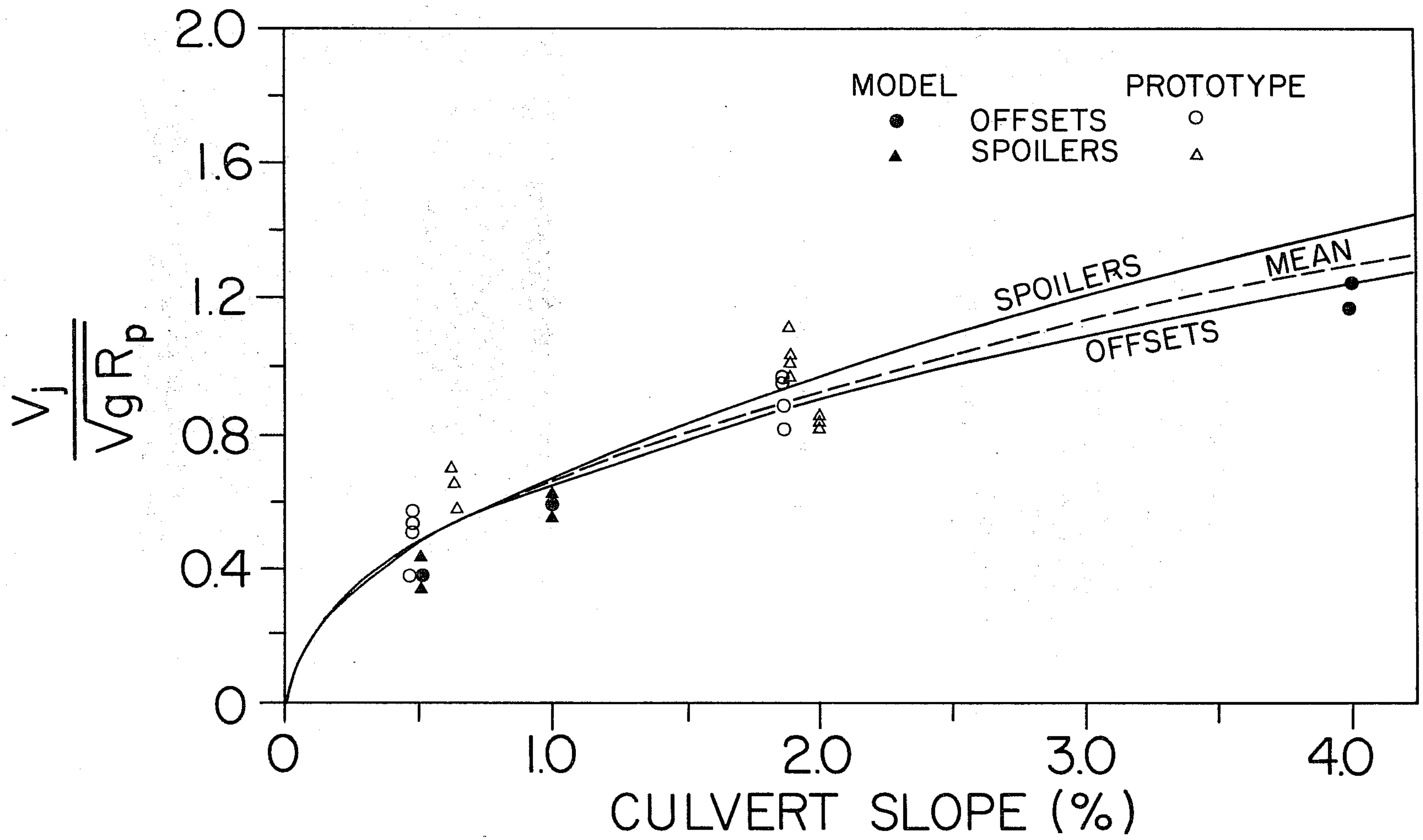


Fig. 35. Jet velocities for the Offsets and Spoilers.

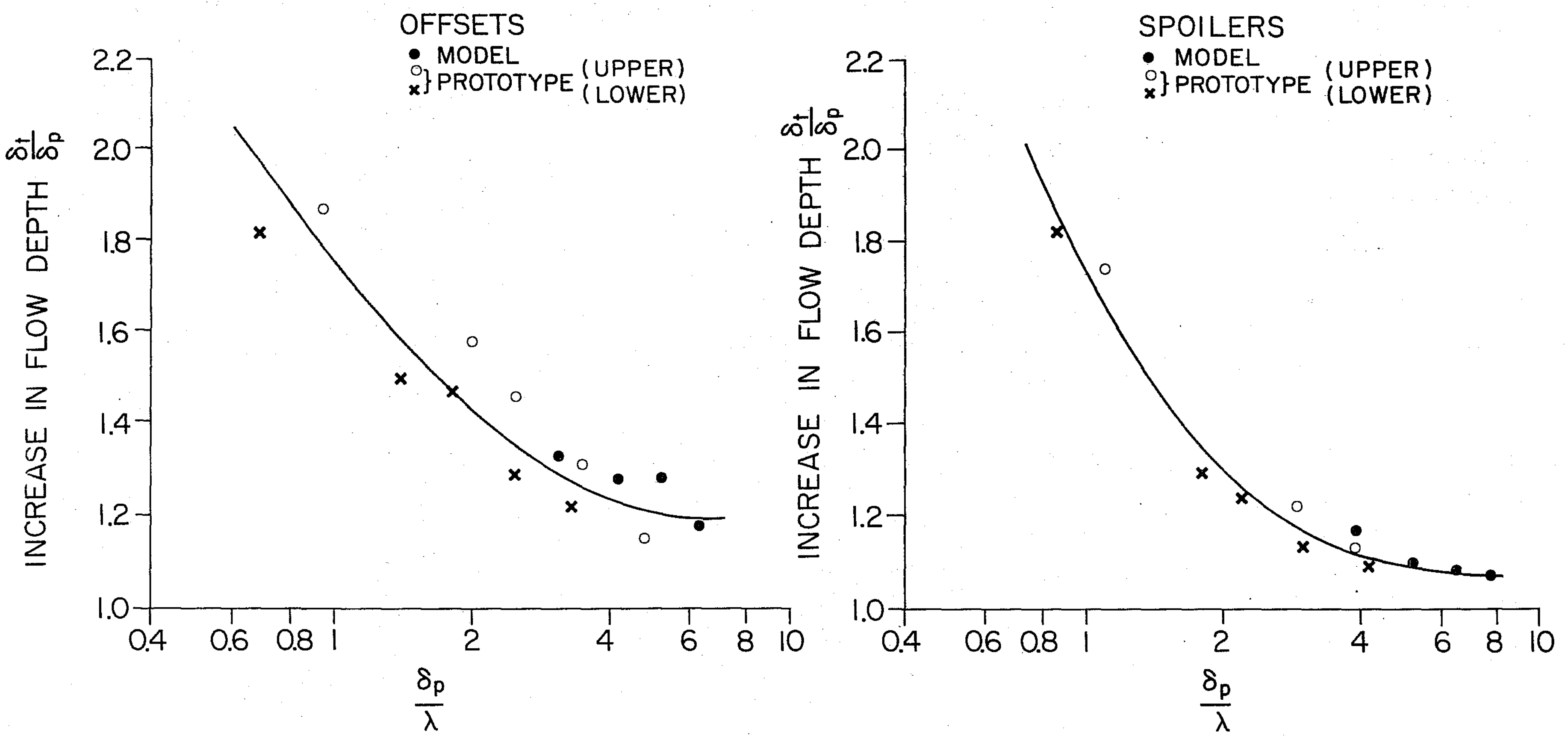


Fig. 36. Increase in flow depth for the Offsets and Spoilers.

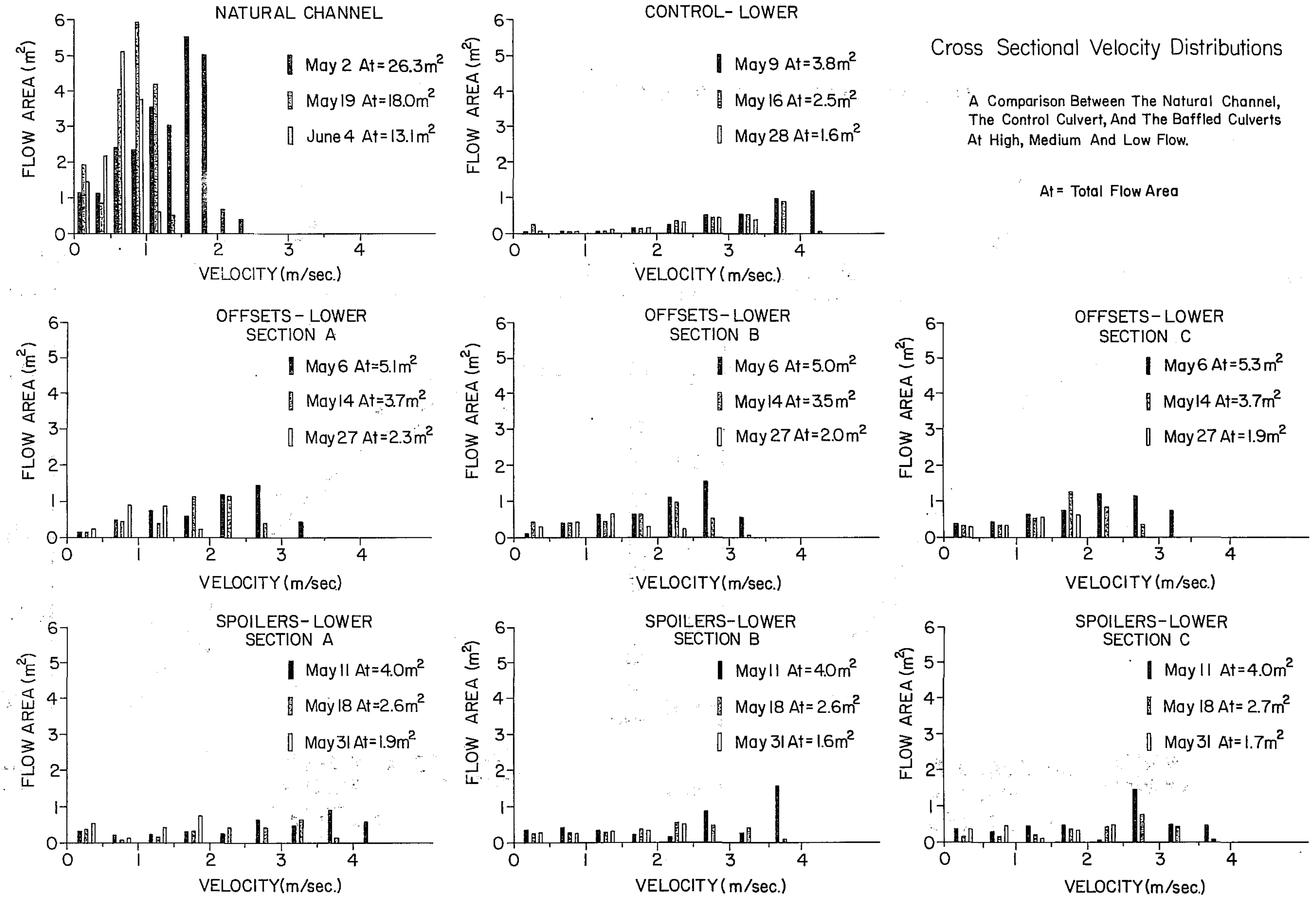


Fig. 37. Cross-sectional velocity distributions.

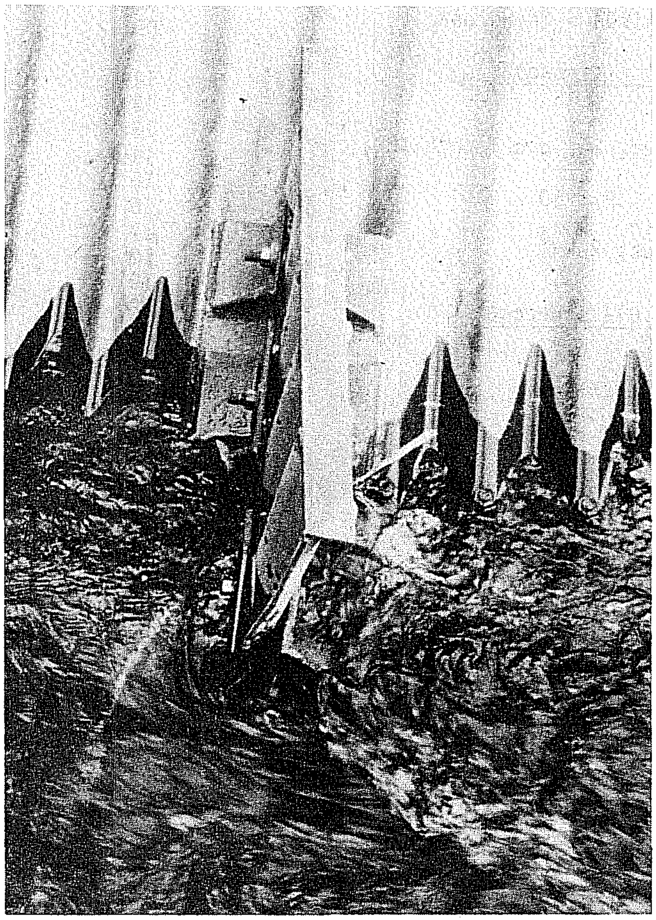


Fig. 38. Damaged short Offset baffle (outlet).

APPENDIX 1: HYDRAULICS OF CIRCULAR CULVERTS AND BAFFLES

BASIC HYDRAULIC PROPERTIES OF CIRCULAR CULVERTS

Cross-sectional Area, A = area of sector OXCZO - area of triangle XOZ, (θ in radians) (Fig. A1.1).

$$A = (D/2)^2\ \theta - \frac{(D/2)^2 \sin 2\theta}{2} = \frac{D^2}{4} \{\theta - \frac{\sin 2\theta}{2}\}$$

Since $\sin 2\theta = 2\sin\theta\cos\theta$

$$A = \{\frac{\theta - \sin\theta\cos\theta}{4}\}\ D^2 \qquad (1)$$

Wetted Perimeter, P = arc length XCZ,

$$P = \theta D \qquad (2)$$

Hydraulic Radius, $R = \frac{A}{P}$

$$R = \{\frac{\theta - \sin\theta\cos\theta}{4\theta}\}\ D \qquad (3)$$

Top width, B = 2 (XY)

$$B = D\sin\theta \qquad (4)$$

Relative depth, $\delta = d/D$, is related to θ as follows:

$$\cos\theta = \frac{OY}{OX} = \frac{D/2 - d}{D/2} = 1 - 2\ (d/D)$$

$$\text{or } \cos\theta = 1-2\delta \qquad (5)$$

$$\text{and, } \sin\theta = \sqrt{1-\cos^2\theta} \qquad (6)$$

Equations (1), (2), (3) and (4) may also be written as:

$$A = \lambda_a\ D^2 \qquad (7)$$

$$P = \lambda_p\ D \qquad (8)$$

$$R = \lambda_r\ D \qquad (9)$$

$$B = \lambda_b\ D \qquad (10)$$

where:

$$\lambda_a = \frac{\theta - \sin\theta\cos\theta}{4} \qquad (11)$$

$$\lambda_p = \theta \qquad (12)$$

$$\lambda_r = \frac{\theta - \sin\theta\cos\theta}{4\theta} = \frac{\lambda a}{\theta} \qquad (13)$$

$$\lambda_b = \sin\theta \qquad (14)$$

Since θ depends on relative depth (δ) only (eq. 5) and λa, λ_p, λ_r and λ_b depend on θ only (eq. 11, 12, 13, 14), it follows that λ_a, λ_p, λ_r and λ_b depend on relative depth (δ) only.

An HP-55 desk computer was programmed to calculate λ_a, λ_p, λ_r and λ_b given the relative depth δ. The key sequence is as follows:

BHPC (Basic Hydraulic Properties for Circular Culverts)

Line	Key Entry	Comments
01	Enter	δ is entered
02	2	
03	X	
04	CHS	
05	1	
06	+	
07	STO	
08	3	$\cos\theta$
09	f	
10	RAD	
11	g	
12	$\cos^{-1}$	
13	STO	
14	4	$\theta = \lambda_p$
15	f	
16	sin	
17	STO	
18	5	$\sin\theta = \lambda_b$
19	RCL	
20	3	
21	X	
22	CHS	
23	RCL	
24	4	
25	+	
26	4	
27	÷	
28	STO	
29	1	λ_a
30	RCL	
31	4	
32	÷	
33	STO	
34	2	λ_r
35	GTO-00	

NORMAL DEPTH

Normal depth may be calculated from Manning's formula, as follows:

$$Q = \frac{\zeta}{n} AR^{2/3}\ {}^{1/2} \qquad (15)$$

$$\text{or } AR^{2/3} = \frac{nQ}{\zeta S^{1/2}} \qquad (16)$$

Using (7) and (9) we get

$$\lambda_a\ D^2\ \lambda_r^{2/3}\ D^{2/3} = \frac{nQ}{\zeta S^{1/2}}$$

$$\text{or } \lambda_a\ \lambda_r^{2/3} = \frac{nQ}{\zeta S^{1/2} D^{8/3}} \qquad (17)$$

$\zeta = 1.0$ if m-s units are used and $\zeta = 1.49$ if ft-s units are used.

Equation (17) may be solved by trial and error to determine the relative normal depth, δ_n, and therefore the normal depth d_n. A trial value of δ is assumed and the product $\lambda_a \lambda_r^{2/3}$ is calculated. The value of this product is then compared to the right hand side of equation (17). The value of δ_n is determined when for a trial δ, (17) is satisfied.

The following key sequence may be added to the BHPC program to facilitate this calculation:

Line	Key Entry	Comments
35	RCL	Store the value 2/3 in register 0 before running the program.
36	0	
37	y^x	
38	RCL	
39	1	
40	X	
41	STO	
42	6	$\lambda_a \lambda_r^{2/3}$
43	GTO-00	

CRITICAL DEPTH

For critical flow, the following relationship can be derived (see texts on Fluid Mechanics or Hydraulics):

$$\frac{\alpha Q^2 B_c}{g A_c^3} = 1.0$$

where: α = kinetic energy coefficient.
A_c, B_c are A, B at critical flow.

Equation (18) can also be written as:

$$\frac{B_c}{A_c^3} = \frac{g}{\alpha Q^2} \tag{19}$$

Using (7) and (9), (19) may be rewritten as:

$$\frac{\lambda_b}{\lambda_a^3} = \frac{g D^6}{\alpha Q^2} \tag{20}$$

This equation may be solved, by trial and error, to yield δ_c, and therefore the critical depth, d_c.

The following key sequence may be added to BHPC for this purpose:

Line	Key Entry	Comments
35	RCL	
36	1	
37	3	
38	y^x	
39	1/x	
40	RCL	
41	5	
42	X	
43	STO	
44	6	λ_b/λ_a^3
45	GTO-00	

BACKWATER CALCULATIONS

Figure A1.2 illustrates a channel reach sufficiently short so that the water surface can be approximated by a straight line.

The Bernoulli energy equation between points 1 and 2 is:

$$\alpha \frac{V_2^2}{2g} + d_2 + S_o \Delta x = \alpha \frac{V_1^2}{2g} + d_1 + S_f \Delta x \tag{21}$$

By rearranging (21):

$$(S_f - S_o)\Delta x = \alpha \{\frac{V_2^2}{2g} - \frac{V_1^2}{2g}\} + (d_2 - d_1) = \alpha \Delta \frac{V^2}{2g} + \Delta d \tag{22}$$

The slope S_f, may be approximated as the average friction slope between points 1 and 2 and may be estimated from Chezy's (equivalent to Manning's):

$$V = C\sqrt{RS} = \sqrt{\frac{8g}{f}}\sqrt{RS} \tag{23}$$

where f is Darcy-Weisbach's dimensionless friction factor. From (23), the slope S may be determined:

$$S = \frac{fV^2}{8gR} = \frac{f(Q/A)^2}{8gR} = \frac{fQ^2}{8gRA^2}$$

or using (7) and (9)

$$S = \frac{fQ^2}{8gD^5\lambda_a^2\lambda_r} \tag{24}$$

Therefore:

$$S_f = \frac{S_1 + S_2}{2} = \frac{fQ^2}{16gD^5} \{\frac{1}{\lambda_{a1}^2 \lambda_{r1}} + \frac{1}{\lambda_{a2}^2 \lambda_{r2}}\}$$

$$\text{or } S_f = \frac{fQ^2}{16gD} M_f \tag{25}$$

$$\text{and } M_f = \frac{1}{\lambda_{a1}^2 \lambda_{r1}} + \frac{1}{\lambda_{a2}^2 \lambda_{r2}} \tag{26}$$

Similarly, the change in velocity head, in equation (22), may be expressed in terms of basic hydraulic properties:

$$\Delta \frac{V^2}{2g} = \frac{1}{2g}\{\frac{Q^2}{A_2^2} - \frac{Q^2}{A_1^2}\} = \frac{Q^2}{2gD^4}\{\frac{1}{\lambda_{a2}^2} - \frac{1}{\lambda_{a1}^2}\}$$

$$\text{or } \Delta \frac{V^2}{2g} = \frac{Q^2}{2gD^4} M_v \tag{27}$$

$$\text{where: } M_v = \frac{1}{\lambda_{a2}^2} - \frac{1}{\lambda_{a1}^2} \tag{28}$$

Utilizing (25) and (27), (22) may be written:

$$\{\frac{fQ^2 M_f}{16gD^5} - S_o\}\Delta x = \alpha \frac{Q^2 M_v}{2gD^4} + \Delta d$$

$$\text{or } \frac{fQ^2 M_f - 16gD^5 S_o}{16gD^5}\Delta x = \frac{\alpha Q^2 M_v + 2gD^4 \Delta d}{2gD^4}$$

$$\text{or } \Delta x = \frac{8D\alpha Q^2 M_v + 16gD^5 \Delta d}{fQ^2 M_f - 16gD^5 S_o} \tag{23}$$

Dividing both numerator and denominator by $Q^2 M_f$ ($\neq 0$), (23) yields:

$$\Delta x = \frac{8D\alpha M_v/M_f + (16gD^5/Q^2M_f)\ \Delta d}{f - (16gD^5/Q^2M_f)\ S_o} \quad (24)$$

$$\text{Set } M_c = \frac{16gD^5}{Q^2M_f} \quad (25)$$

then (24) becomes:

$$\Delta x = \frac{8D\alpha M_v/M_f + M_c\ \Delta d}{f - M_c\ S_o} = \frac{M'}{f - M''} \quad (26)$$

where: $M' = 8D\alpha M_v/M_f + M_c\ \Delta d$
$M'' = M_c\ S_o$

Finally, dividing numerator and denominator of (26) by M' ($\neq 0$):

$$\Delta x = \frac{1}{fM_1 - M_2} \quad (27)$$

where: $M_1 = \frac{1}{M''}$
$M_2 = \frac{M''}{M'}$

From equation (27), it is clear that for given D, S_o, and Q M_1 and M_2 depend on relative depths δ_1 and δ_2 only.

Equation (27) may be used directly to calculate Δx, if f is known or it may be used to calculate f, if Δx is known (trial and error).

The relationship between Darcy-Weisbach's f, and Manning's n, may be derived from:

$$C = \sqrt{\frac{8g}{f}} \quad (28)$$

$$C = \frac{\zeta R^{1/6}}{n} \quad (29)$$

where; C is Chezy's coefficient. From (28) and (29):

$$n = \frac{\zeta}{\sqrt{8g}} \sqrt{f}\ R^{1/6}$$

$$\text{or } n = \frac{\sqrt{f}\ D^{1/6}}{\sqrt{\xi}} \lambda r^{1/6} \quad (30)$$

$$\text{and } f = \frac{\xi n^2}{D^{1/3}} \frac{1}{\lambda_r^{1/3}} \quad (31)$$

$$\text{where: } \xi = \frac{8g}{\zeta^2}$$

For m-s units $\zeta = 1.0$, $g = 9.81$ m/s^2 and therefore $\xi = 78.5$. For ft-s units $\zeta = 1.49$, $g = 32.2$ ft/s^2, and $\xi = 117$.

Manning's n is usually assumed not to vary with relative depth, but f does as indicated by (31). Equations (27) and (31) may therefore be used to estimate the average value of n for a culvert section AB. The section is divided in small subsections of length Δx and n is assumed constant for the entire section. Starting with a known depth at A, d_A, and n is assumed and Δx's are calculated for small depth increments, Δd. When d_B is arrived at, all Δx's are summed up and compared to the known distance AB. If the two do not agree, a new n is assumed and the process repeated until they do.

An HP-67 (the HP-55 does not allow enough key entries) was programmed to solve equations (27) and (30). The key sequence in the BCP (Backwater Computations Program) is as follows:

Line	Key Entry	Comments
001	f LBL A	depth d_1 is entered
002	STO 0	to start the program.
003	4	
004	.	Culvert
005	2	diameter
006	6	in
007	7	m.
008	2	
009	STO 5	
010	5	
011	h y^x	
012	1	
013	6	
014	x	
015	9	
016	.	g in
017	8	m/s^2
018	1	
019	x	
020	STO 9	
021	1	
022	2	Q in
023	.	m^3/s
024	1	
025	g x^2	
026	h 1/x	
027	RCL 9	
028	x	
029	STO 6	16 gD^5/Q^2
030	RCL 0	
031	RCL 5	
032	÷	
033	f GSB 1	
034	RCL 1	λ_{a1}
035	g x^2	
036	h 1/x	
037	STO 7	$1/\lambda^2{}_{a1}$
038	RCL 2	r_1
039	h 1/x	
040	RCL 7	
041	x	
042	STO 8	$1/\lambda^2{}_{a1}\ \lambda_{r1}$
043	RCL 0	
044	0	
045	.	Δd
046	0	(in m)
047	1	
048	0	
049	STO 9	
050	+	
051	RCL 5	
052	÷	$\delta_2 = (d_1 + \Delta d)/D$
053	f GSB 1	
054	RCL 1	λ_{a2}
055	g x^2	
056	h 1/x	$1/\lambda^2_{a2}$
057	RCL 7	
058	—	
059	STO 7	M_v
060	RCL 2	λ_{r2}

Line	Key Entry	Comments
061	h 1/x	
062	RCL 4	
063	x	$1/\lambda_{a2}^2\ \lambda_{r2}$
064	RCL 8	
065	+	
066	STO 8	M_f
067	RCL 7	
068	RCL 8	
069	÷	M_v/M_f
070	RCL 5	
071	x	
072	8	
073	x	
074	STO A	$8D\ (M_v/M_f)$
075	RCL 6	
076	RCL 8	
077	÷	
078	STO D	M_c
079	RCL 9	
080	x	
081	RCL A	
082	+	
083	STO E	M'
084	h 1/x	
085	STO B	M_1
086	RCL D	
087	0	
088	.	Bottom
089	0	Slope
090	1	(S_o)
091	8	
092	6	
093	x	
094	RCL E	
095	÷	
096	STO C	M_2
097	1	
098	ENTER	
099	3	
100	÷	
101	STO E	1/3
102	0	
103	.	Manning's
104	0	n
105	5	
106	3	
107	g x^2	
108	7	
109	8	
110	.	ξ
111	5	
112	x	
113	STO D	
114	RCL 5	
115	RCL E	
116	h y^x	
117	h 1/x	
118	RCL D	
119	x	
120	STO A	$\xi n^2/D^{1/3}$
121	RCL 9	
122	2	
123	÷	
124	RCL 0	
125	+	
126	RCL 5	
127	÷	$\delta_m = (d_1 + \Delta d/2)/D$
128	f GSB 1	
129	RCL 2	λ_{rm}
130	RCL E	
131	h y^x	
132	RCL A	

Line	Key Entry	Comments
133	x	
134	STO A	f
135	RCL B	
136	x	
137	RCL C	
138	—	
139	h 1/x	
140	h ST I	Δx
141	h RTN	
142	f LBL 1	Subroutine, similar to BHPC
143	ENTER	
144	2	
145	x	
146	CHS	
147	1	
148	+	
149	STO 3	$\cos\theta$
150	h RAD	
151	g $\cos^{-1}$	
152	STO 4	θ
153	f sin	
154	RCL 3	
155	x	
156	CHS	
157	RCL 4	
158	+	
159	4	
160	÷	
161	STO 1	λ_a
162	RCL 4	
163	÷	
164	STO 2	λ_r
165	h RTN	

INCREASE IN FLOW DEPTH WITH BAFFLES

The increase in flow depth in culverts with baffles may be obtained by equating the discharge through the culvert with and without baffles:

$$Q = \sqrt{\frac{8g}{f_p}}\, A_p\sqrt{R_pS} = \sqrt{\frac{8g}{f_t}}\, A_t\sqrt{R_tS} \tag{32}$$

where: t denotes condition with baffles
p denotes condition of plain culvert

By squaring both sides of (32) and rearranging:

$$\frac{f_t}{f_p} = \frac{{A_t}^2R_t}{{A_p}^2R_p} \tag{33}$$

Utilizing (7) and (9):

$$\frac{f_t}{f_p} = \frac{\lambda_{at}^2\ \lambda_{rt}D^5}{\lambda_{ap}^2\ \lambda_{rp}D^5}$$

$$\text{or } \lambda_{at}^2\ \lambda_{rt} = \frac{f_t}{f_p}\,\lambda_{ap}^2\ \lambda_{rp} \tag{34}$$

By trial and error (34) gives δ_t and therefore d_t. Similarly, if Manning's equation is used:

$$Q = \frac{\zeta}{n_p}\, A_p{R_p}^{2/3}S^{1/2} = \frac{\zeta}{n_t}\, A_t{R_t}^{2/3}S^{1/2} \tag{35}$$

$$\text{or } \frac{n_t}{n_p} = \frac{A_t R_t^{2/3}}{A_p R_p^{2/3}} = \frac{\lambda_{at}\, \lambda_{rt}^{2/3}\, D^{8/3}}{\lambda_{ap}\, \lambda_{rp}^{2/3}\, D^{8/3}}$$

$$\text{or } \lambda_{at}\, \lambda_{rt}^{2/3} = \frac{n_t}{n_p}\, \lambda_{ap}\, \lambda_{rp}^{2/3} \qquad (36)$$

This equation may also be used to determine d_t. For equation (34) the following keys may be added to the BHPC program:

Line	Key Entry	Comments
35	RCL	
36	1	λ_a
37	g	
38	x^2	
39	RCL	
40	2	λ_r
41	x	
42	STO	
43	6	$\lambda_a^2\, \lambda_r$
44	GTO-00	

For equation (36) add the same keys as for the normal depth calculation.

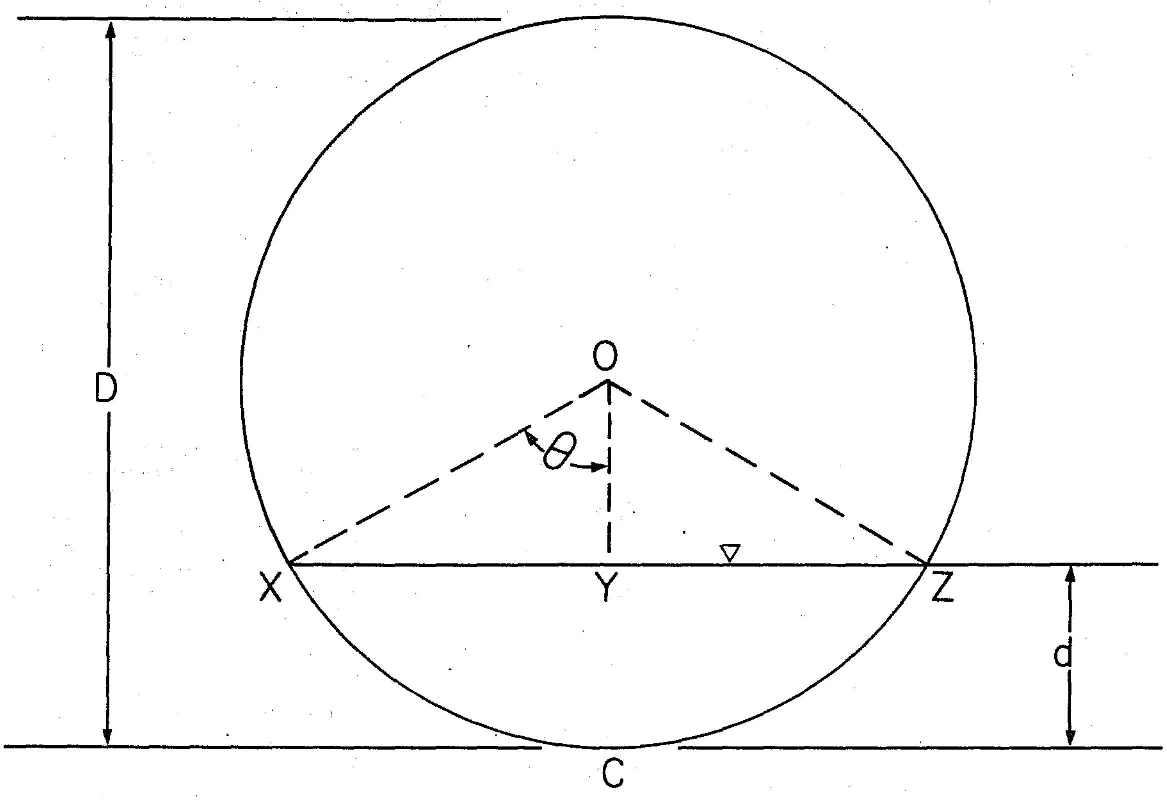


Fig. A1.1. Basic hydraulic parameters in culverts.

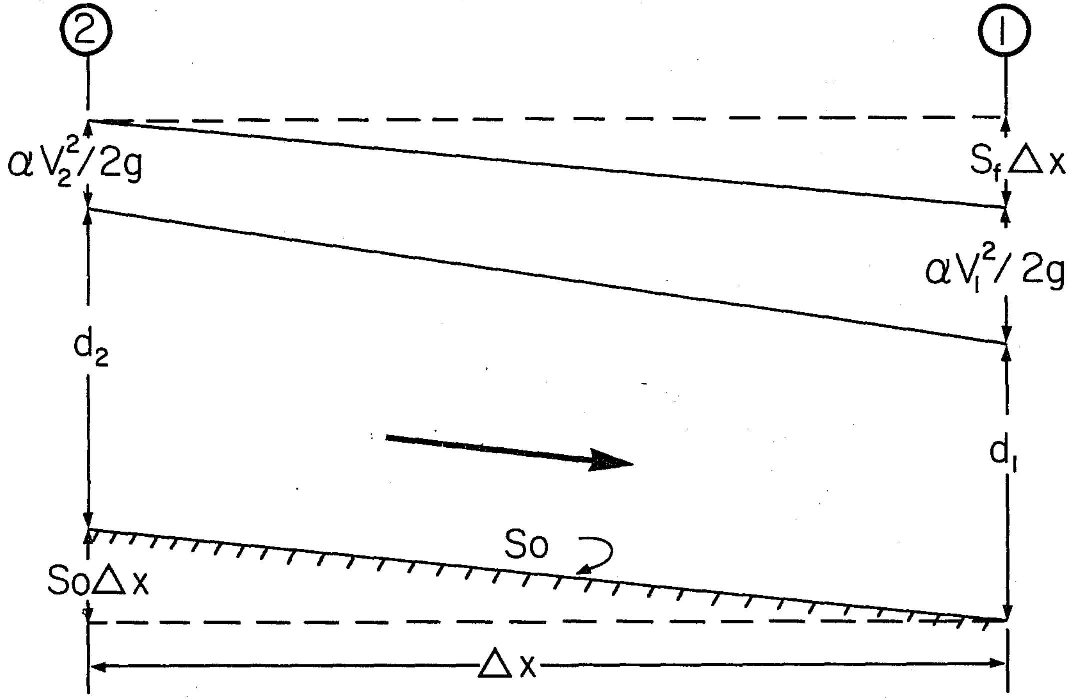


Fig. A1.2. Basic hydraulic parameters in gradually varied flow.

APPENDIX 2: BAFFLE MATERIALS, COSTS AND INSTALLATION TECHNIQUES

BAFFLE MATERIALS

The Spoilers were fabricated using 4.8 mm (3/16 in) steel plate. Two 38 mm x 38 mm x 6 mm (1½ in x 1½ in x ¼ in) pieces of angle iron were welded across the inside of the spoiler tops for added strength. Pieces of similar size angle iron were also welded to the sides of the baffles to aid in attaching them to the culverts. The Offsets were fabricated from corrugated metal plates. Figures A2.1 and A2.2 show fabrication dimensions and Figs. 5 and 6 show the baffles as they were installed at the Redknife River. All baffle materials were fabricated to a tolerance of ± 6 mm (¼ in).

BAFFLE INSTALLATION

Attachment Methods

Spoilers: The general method of attachment was welding, using No. 7018 welding rods. Continuous welding of the upstream edge to the corrugation tops and 10 cm (4 in) from each side along the downstream edge to the corrugation top was the major position of the work. The flanges along the sides of the spoilers were spot welded at the corrugation tops.

Offsets: The general method of attachment was to weld the baffle mount to the culvert and then to bolt the baffle plate to the baffle mount. The short baffle mount was continuously welded along the upstream and downstream sides which conform to the corrugation tops. The short baffle plate was then placed into the mount adjusted for a proper horizontal and vertical fit. Three holes for 19 mm (3/4 in) machine bolts were cut in the baffle plate at the slots in the baffle mount. Installation was completed by inserting and tightening the 3 19 mm x 127 mm (3/4 in x 5 in) machine bolts complete with 2 flat washers.

The long baffle plate was tack welded at the upstream edge to the culvert centerline. The plate was isolated until it was level and conformed to a 30° angle. Some cutting of the lower edge of the baffle plate was necessary to ensure a proper fit. The upstream baffle mounts were cut and bent to a proper fit and then tack welded to the culvert. The downstream baffle mounts were similarly fitted. Holes for the five 19 mm (3/4 in) bolts were cut in the baffle plate to align with the slots in the baffle mounts. The bolts were inserted and tightened with 2 flat washers. Gussets were cut and continuously welded to the upstream and downstream mounts. The baffle mounts were finally welded at all accessible contact points with the culvert side. The flame cut through mount's legs was filled.

Deviations from Design During Installation

Spoilers: The front and rear plates were approximately 1 cm (0.4 in) too short. It was not therefore possible to continuously weld the rear plate without excessive filling. The front plate and the side flanges were hammered down to make a snugger fit. The location of wires of bolts connecting the various culvert plates necessitated the relocation of rows of spoilers upstream or downstream one corrugation crest 152 mm (6 in). Rows 2, 15 and 18 were moved downstream, row 8, 16 and 17 were moved upstream.

Offsets: Minor deviations from the specified 30° angle are inherent in the long baffle installation method. A slight fabrication defect in the shape of the short baffles resulted in space being left under the short baffle at the centerline and the short baffles being higher than the corresponding long baffle. This shape discrepancy is possible due to the 5% vertical elongation of the culverts.

Fabrication and Installation Costs

The fabrication contract was awarded in February 1975 to an Edmonton firm for $25,894.65. Unit break-down costs are given in Table A2.1. Rigid time factors requiring fabrication be complete within three weeks of the award date increased costs considerably.

The installation contract was awarded in August 1975 to a Hay River contractor for $35,000. The contract consisted of the items and costs listed on Table A2.3 . The novel nature and the relatively remote area of the work combined to escalate costs. The work was completed easily in one week using three welders. Costs next time will be considerably reduced.

Design Modifications

The method of attaching the Offsets to the culvert should be reconsidered to reduce installation time. These baffles could be strengthened by using two plates instead of one. The economics of using other materials (e.g. corrugated metal) and mass production of two or three standard block sizes should be investigated for the Spoilers.

Table A2.1. Fabrication contract, unit breakdown.

	Item	Cost
1.	70 Culvert Spoilers	$ 8,000.00
2.	16 Long Culvert Baffles	
3.	16 Short Culvert Baffles	3,150.00
4.	64 Long Baffle Mounts - Large	1,380.00
5.	32 Long Baffle Mounts - Small	478.00
6.	16 Short Baffle Mounts	1,685.00
7.	6 Walkway Supports - Right Hand	
8.	6 Walkway Supports - Left Hand	265.00
9.	12 Hand Rail Posts	180.00
10.	50 Walkway Crossbeam Assemblies c/w Eyebolts and Chains	1,655.00
11.	250 Walkway Hanger Bracket Assemblies c/w Split Ring and Grab Hook	
12.	75 Walkway Hanger Brackets only	1,318.00
13.	8 Beam Handles	10.00
14.	12 Beam Stops	98.00
15.	140 Fixture Mounting Braces	76.00
16.	Fixture Mounting Plate: (a) 12 Sections 46 cm (1.5 ft) long (b) 14 Sections 61 cm (2.0 ft) long (c) 2 Sections 107 cm (3.5 ft) long (d) 2 Sections 122 cm (4.0 ft) long (e) 2 Sections 198 cm (6.5 ft) long	510.00
17.	50 Steam Line Brackets	220.00
18.	4 Catwalks - Complete Assemblies	454.00
19.	Stock Items (Table 2)	3,254.00
		$22,733.00
	Freight	2,025.00
	Tax @ 5%	1,136.65
		$25,894.65

Table A2.2. Fabrication contract, stock items.

1. 140 - 1.90 cm (3/4") x 12.7 cm (5") Long Machine Bolts each with one nut.
2. 1000 - Heavy Flat Washers for 1.90 cm (3/4") Bolt.
3. 15 - 1.1 cm (7/16") x 7.6 cm (3") Long Machine Bolts each with one nut and two Flat Washers.
4. 8 - Pieces of Angle Iron 6.4 cm (2 1/2") x 6.4 cm (2 1/2") x 0.5 cm (3/16") 3.05 m (10 ft) long.
5. 2 - Pieces of 10.2 cm (4") x 20.3 cm (8") Rectangular Tubing 3.7 m (12') long, 0.5 cm (3/16") wall thickness.
6. 85 - 3.7 m (12') long section of 22.9 cm (9") wide Metal Planking.

Table A2.3. Installation contract items and costs.

	Installation Item	Cost
1.	Board and lodging for Engineer's Staff (2)	$ 1,500.00
2.	Installation of Spoilers	8,000.00
3.	Installation of Short Baffles	5,000.00
4.	Installation of Long Baffles	6,000.00
5.	Installation of Walkway Supports	3,000.00
6.	Installation of Stop Log Supports	6,500.00
7.	Installation of Walkway Hanger Brackets	2,000.00
8.	Installation of Stream Lines	3,000.00
		$35,000.00

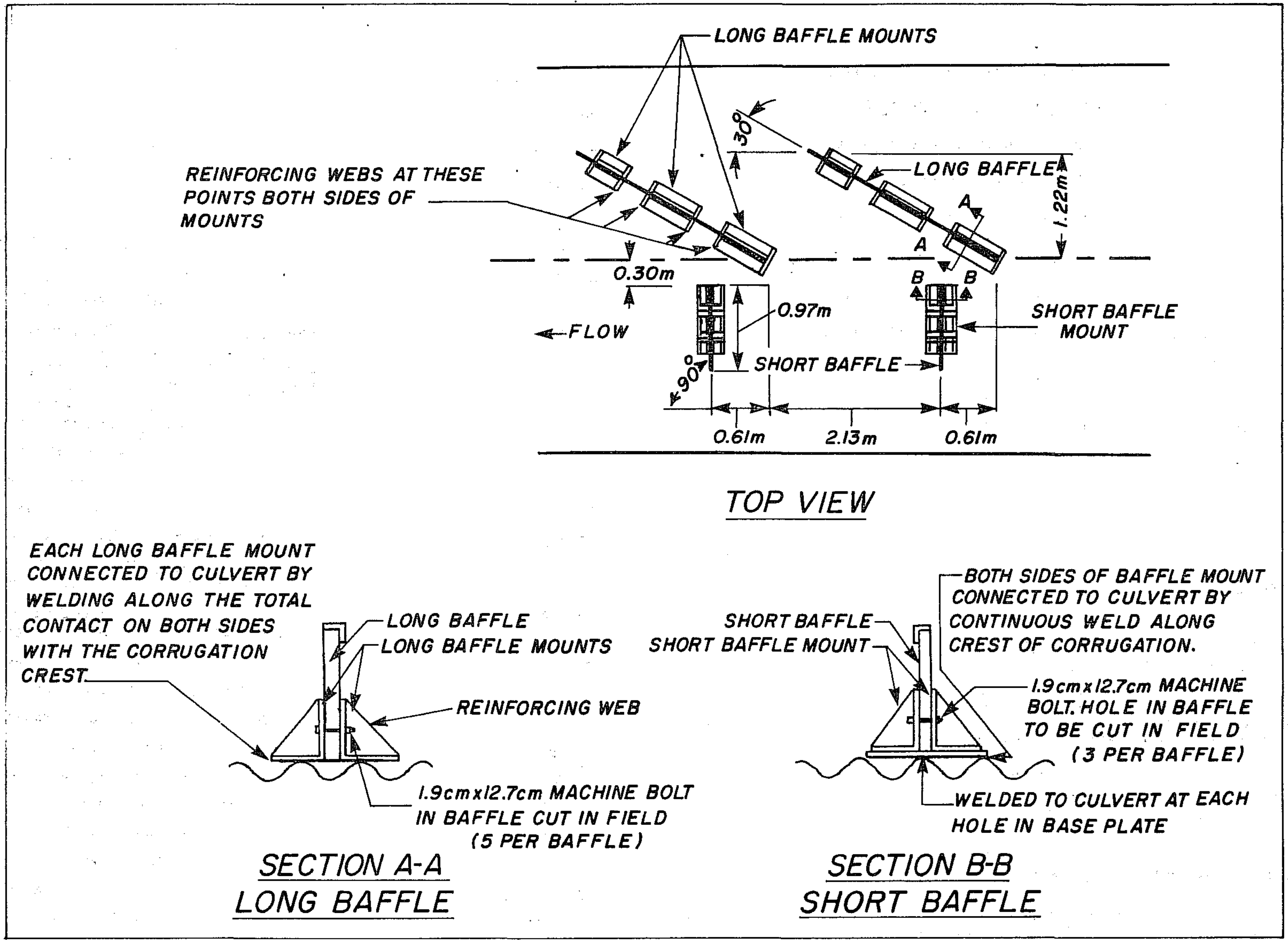


Fig. A2.1. Offset Baffles.

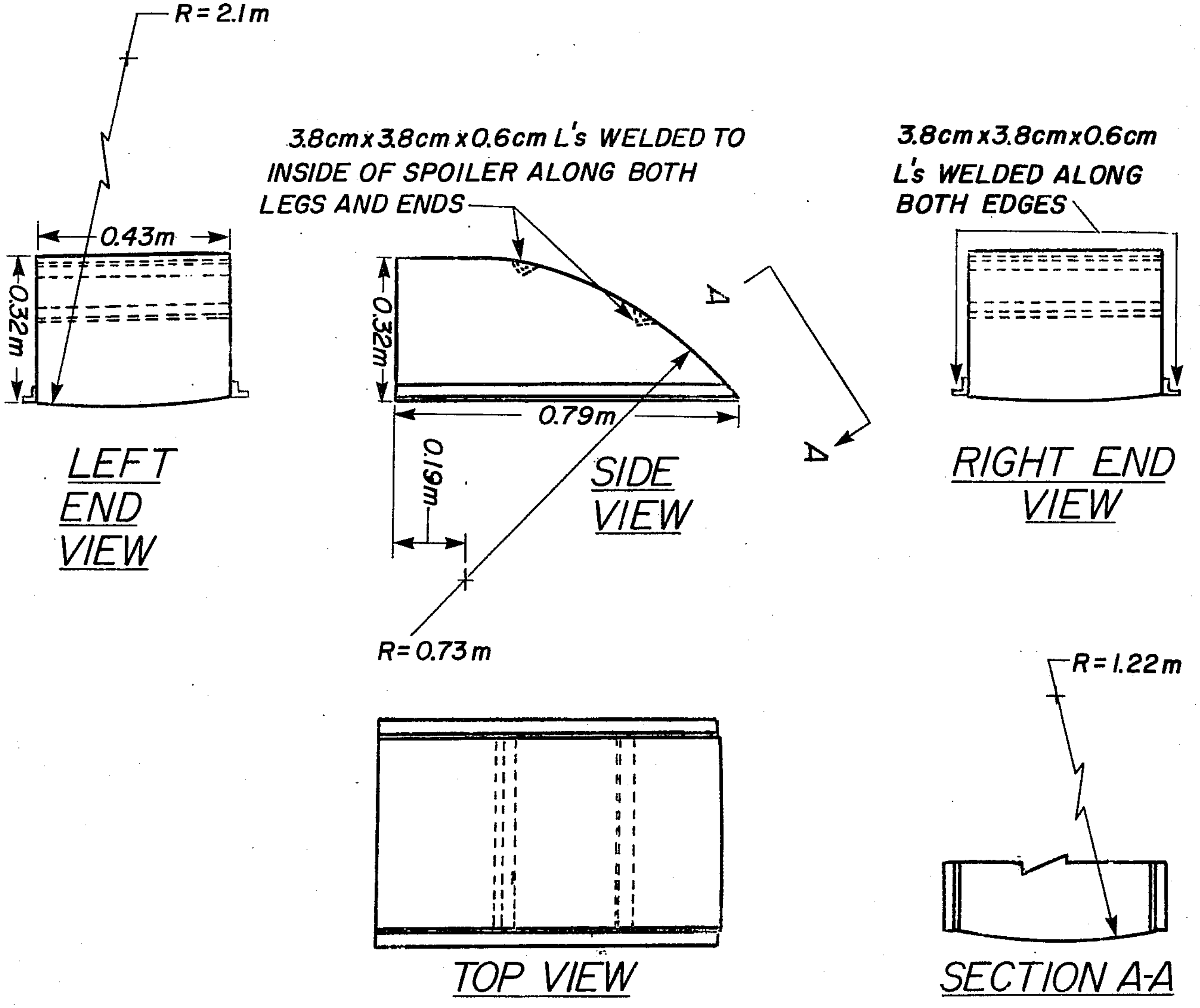


Fig. A2.2. Spoiler Baffles.

APPENDIX 3: BIOLOGICAL DATA OF REDKNIFE RIVER FISH SPECIES

CATCH SUMMARY

From the summary below note that total catches are low. For the purposes of this study we did not intend to obtain detailed population numbers but only relative abundance of the populations. Intensive downstream sampling would create a further stress on the fish population. The blockage at the culverts coupled with the sports fishery exploitation are already stress factors.

Downstream of Highway Crossing

Arctic grayling	1975	1976	Total
# tagged & released	43	56	99
# fin coded & released	-	85	85
# dead sampled	14	36	50
TOTAL	57	177	234

Longnose sucker	1975	1976	Total
# tagged & released	37	77	114
# dead sampled	2	11	13
	39	88	127

Upstream of Highway Crossing

	1975*	1976**
Arctic grayling	1	0
Longnose sucker	0	0
Burbot	1	0

*based on 422.25 hrs (16.9 days) fished with total gill net length 342.9 m (375 yds).

**based on 943.25 hrs (39.3 days) fished with total gill net length 850.4 m (930 yds).

Table A3.1 lists the fish species captured the Redknife River, while Table A3.2 provides a detailed account of the species captured during 1974-76. Species numbers, method of capture and location and comments on fish size are given.

AGE AND GROWTH

Arctic grayling

A total of 72 adult grayling were aged and ranged from 4 to 8 years. The age groups of 5, 6 and 7 years accounted for 94% of those aged. Table A3.3 presents the mean length by age group for Redknife River grayling. Also shown for comparison are length-age groupings from the Kakisa River, N.W.T. (Falk and Dahlke 1975) and from the Great Bear River-Wolverine Creek study 1974 (Chang-Kue and Cameron, in press). Table A3.4 presents the length-frequency data on Arctic grayling catches of 1975 and 1976.

Longnose sucker

No aging of this species was conducted due to the small number that were dead sampled. The length-frequency results for 1975 and 1976 are shown in Table A3.5. The mean fork length of 126 longnose suckers for the Redknife River spawning runs of 1975 and 1976 was 465.2 mm. For comparison McPhail and Lindsey 1970 report a longnose sucker from Great Slave Lake of 483 mm fork length was 10 years of age. Jessop et al. 1973 reports on longnose suckers of the Rabbitskin River, N.W.T.: males mature at age 4 and 5; minimum length 246 mm and females mature at age 6 and 7; minimum length of 257 mm. For comparison Stein et al. 1973 report for longnose suckers in the Fort Simpson, N.W.T. area ages and mean length as follows: 10 years, 360 mm; 11 years, 430 mm; 12 years 466 mm.

Table A3.1. Alphabetical list of common names and associated generic names for fish species captured in the Redknife River 1974-76.

Arctic grayling - *Thymallus arcticus* (Pallas)

Brook stickleback - *Culaea inconstans* (Kirtland)

Burbot - *Lota lota* (Linnaeus)

Lake chub - *Couesius plumbeus* (Agassiz)

Longnose sucker - *Catostomus catostomus* (Forster)

Ninespine stickleback - *Pungitius pungitius* (Linneaus)

Northern pike - *Esox lucius* Linneaus

Northern redbelly dace - *Chrosomus eos* Cope

Slimy sculpin - *Cottus cognatus* Richardson

Yellow walleye - *Stizostedion vitreum vitreum* (Mitchill)

Table A3.2. Summary of fish species captured at the Redknife River Highway Crossing and other locations 1974-76.

Date	Location	Fishing Method	Species Captured	#	Comments
21/07/74	d/s Loc. 1	observation	northern pike	5	immature 8" - 1' length
21/07/74	u/s Loc. 4	seine	longnose suckers	56	immature
			lake chub	9	adult
			grayling	1	immature
			brook stickleback	2	adult
			redbelly dace	1	adult
			cyprinid fry	15	tentative lake chub
04/05/75	Loc, 1, 5	trap net	grayling	57	adult spawning run
04/05/75	d/s	gill net angling	longnose suckers	39	adult spawning run
12/05/75	Loc. 2, 4 u/s	gill net	grayling	1	adult*
			burbot	1	adult**
31/08/75	Loc. 1 d/s	seine	grayling	2	immature
			longnose sucker	2	immature
			lake chub	8	adult
31/08/75	Loc. 4 u/s	seine	grayling	3	immature
			longnose sucker	1	immature
			lake chub	81	adults & immature
			brook stickleback	1	adult
			slimy sculpin		adult
10/09/75	Loc. 4 u/s	seine	grayling	1	immature
			lake chub	150	adults & immature
		observation	northern pike	6	immature 6 - 8" length
29/04/76	Loc. 1,3, 5,7 trap site	gill net angling	grayling	174	adult spawning run
29/05/76	d/s	seine trap & fence	longnose sucker	88	adult spawning run
30/04/76	Loc. 2,4, 6	gill net	negative		
24/05/76	u/s				
19/05/76	Loc. 13 d/s Redknife mouth @ Mackenzie	gill net	grayling	1	immature
			longnose sucker	2	male & female spent
			northern pike		female spent
			yellow walleye		male spent
	Loc. 11 d/s	gill net	grayling	2	females spent, immature
			northern pike	2	females spent
	Loc. 9 d/s	gill net	negative		
	Loc. 8 u/s	gill net	negative		
	Loc. 10 u/s	gill net	negative		
22/05/76	Loc. 1,3 trap site d/s	observation	grayling fry		first sighting after emergence
31/05/76	Loc. 1 d/s	dipnet	grayling	10	fry
			longnose sucker	26	fry
15/06/76	Loc. 1,3 d/s	seine	grayling	50	fry
			sculpins	2	adults
			lake chub	20	adults
	Loc. 4 u/s	seine	longnose sucker		immature
29/06/76	Loc. 1,3 d/s	seine	longnose sucker	11	immature
			grayling	4	immature
			lake chub	15	adults
			sculpins	2	adults
	Loc. 4	seine	longnose sucker	8	immature
			lake chub	1	adults
			brook stickleback	1	adults
24/08/76	Loc. 1,3 d/s	seine	sculpin	2	adults
			longnose sucker	3	immature
			lake chub	2	adults
	Loc. 4 u/s	seine	sculpin	1	adults
			longnose sucker	7	immature
			lake chub	14	adults
			brook stickleback	2	adults
24/08/76	Loc. 4 u/s	seine	ninespine stickleback	1	adult
08/10/76	Loc. 1,3 d/s	seine	grayling	4	immature
			sculpins	1	adult
			longnose suckers	2	immature
			pike	3	immature

*Adult grayling may have been one grayling that was transported across the highway to test effectiveness of upstream netting.

**Adult burbot assumed to be an overwintered upstream fish.

Table A3.3. Mean length by age group for Arctic grayling: A. Redknife River 1975 and 1976; B. Kakisa River 1971-74; C. Great Bear River 1974.

Parameter		Age (yr)	
	5	6	7
A. N	14	39	15
Mean Length	345.4	387.6	420.8
Range	324 - 365	360 - 412	406 - 450
S.E.^{1} Length	3.9	2.8	3.3
B. N	17	37	37
Mean Length	364.7	396.4	426.1
S.E. Length	5.8	4.0	3.5
C. N	51	85	71
Mean Length	364.5	403.7	413.0
Range	290 - 417	324 - 456	376 - 452
S.D.^{2} Length	31.5	21.5	15.9

S.E.^{1}: Standard Error
S.E.^{2}: Standard Deviation
A: This report
B: Falk and Dahlke 1975.
C: Chang-Kue and Cameron (in press).

Table A3.4. Length-frequency distributions for Arctic grayling from the Redknife River, 1975 and 1976.

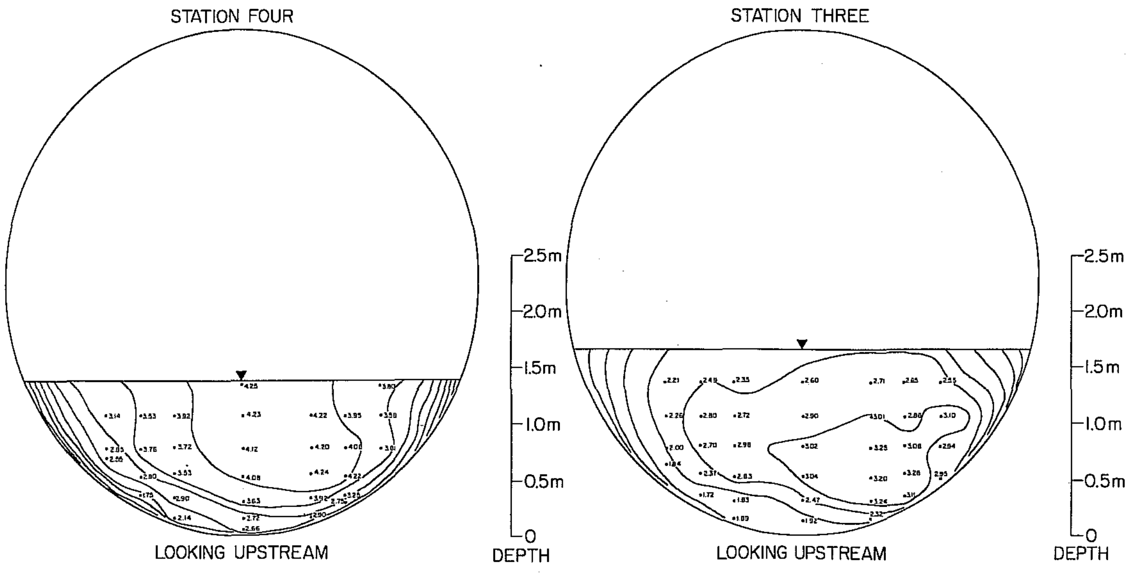
Fork Length Interval (mm)	1975		1976		1975 and 1976	
	No.	%	No.	%	No.	%
231 - 240			1	0.6	1	0.4
241 - 250			1	0.6	1	0.4
251 - 260						
261 - 270						
271 - 280			1	0.6	1	0.4
281 - 290						
291 - 300			2	1.1	2	0.9
301 - 310			5	2.8	5	2.1
311 - 320			5	2.8	5	2.1
321 - 330	1	1.8	16	9.0	17	7.3
331 - 340	1	1.8	11	6.2	12	5.2
341 - 350	3	5.4	19	10.7	22	9.4
351 - 360	2	3.6	17	9.6	19	8.2
361 - 370	5	8.9	20	11.3	25	10.7
371 - 380	6	10.7	10	5.6	16	6.9
381 - 390	6	10.7	13	7.3	19	8.2
391 - 400	7	12.5	21	11.9	28	12.0
401 - 410	7	12.5	21	11.9	28	12.0
411 - 420	9	16.1	8	4.5	17	7.3
421 - 430	5	8.9	5	2.8	10	4.3
431 - 440	2	3.6	1	0.6	3	1.3
441 - 450	2	3.6			2	0.9
TOTAL	56		177		233	

Table A3.5. Length-frequency distributions for longnose suckers from the Redknife River, 1975 and 1976.

Fork Length Interval (mm)	1975		1976		1975 and 1976	
	No.	%	No.	%	No.	%
371 - 380			1	1.1	1	0.8
381 - 390	1	2.6	2	2.3	3	2.4
391 - 400			1	1.1	1	0.8
401 - 410	1	2.6	5	5.7	6	4.8
411 - 420			9	10.2	9	7.1
421 - 430	2	5.3	9	10.2	11	8.7
431 - 440	2	5.3	11	12.5	13	10.3
441 - 450	3	7.9	9	10.2	12	9.5
451 - 460	1	2.6	9	10.2	10	7.9
461 - 470	4	10.5	4	4.5	8	6.3
471 - 480	5	13.2	7	8.0	12	9.5
481 - 490	4	10.5	3	3.4	7	5.6
491 - 500	5	13.2	6	6.8	11	8.7
501 - 510	3	7.9	2	2.3	5	4.0
511 - 520	1	2.6	3	3.4	4	3.2
521 - 530	4	10.5	4	4.5	8	6.3
531 - 540	1	2.6	1	1.1	2	1.6
541 - 550			1	1.1	1	0.8
551 - 560			1	1.1	1	0.8
561 - 570	1	2.6			1	0.8
TOTAL	38		88		126	

APPENDIX 4: VELOCITY DISTRIBUTION

Isovels, plotted from point velocities measured within the culverts for the full range of flows experienced in 1976, are shown in Figs. A4.1 to A4.15. The relative depth (d/D) given is a mean water depth at each station. These velocity distributions show the size and shape of resting zones, the jet velocities created by baffles and the extent to which velocities were measured. Velocity distribution in the natural channel, plotted from velocity measurements at the downstream discharge section, are shown in Fig. A4.16. The above figures contrast in-culvert and natural velocity distributions for a mild riffle river section over a limestone cobble bed.



CONTROL

Test - One

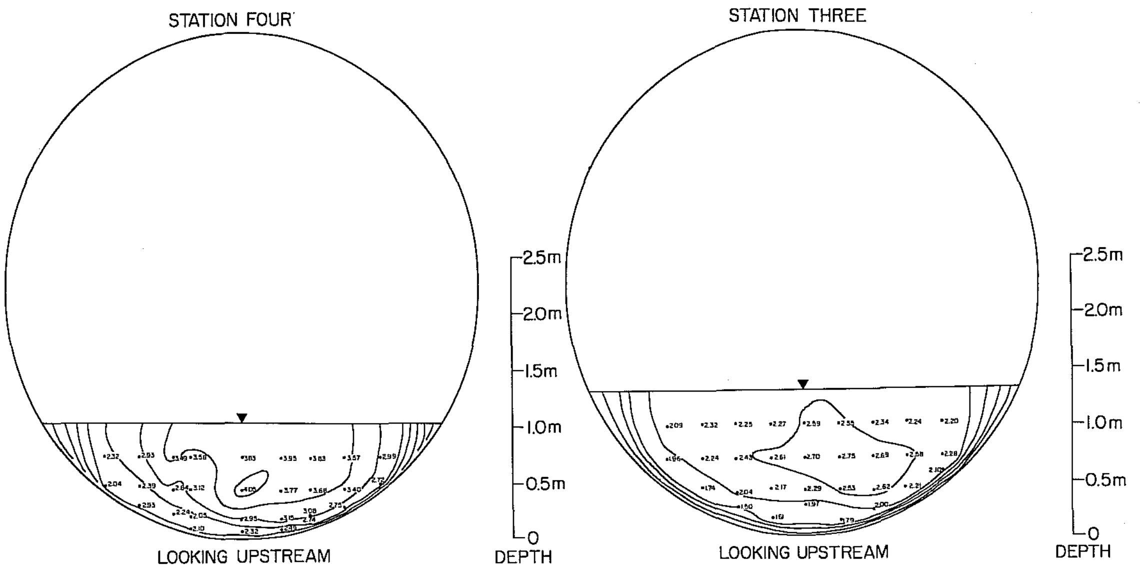
Station - Four
May 9 1976
Discharge = 12.2 c.m.s.
Mean Velocity $\frac{Q}{A}$ = 3.3 m.p.s.
$d/D = 0.32$

Station - Three
May 8 1976
Discharge = 12.6 c.m.s.
Mean Velocity $\frac{Q}{A}$ = 2.6 m.p.s.
$d/D = 0.38$

Water level in culvert - ▼

Isovel interval = 0.5 m.p.s.
• 4.25 - measured velocity (m.p.s.)

0 0.5m 1.0m 1.5m
Figure



CONTROL

Test - Two

Station - Four
May 16 1976
Discharge = 7.5 c.m.s.
Mean Velocity $\frac{Q}{A}$ = 3.0 m.p.s.
$d/D = 0.24$

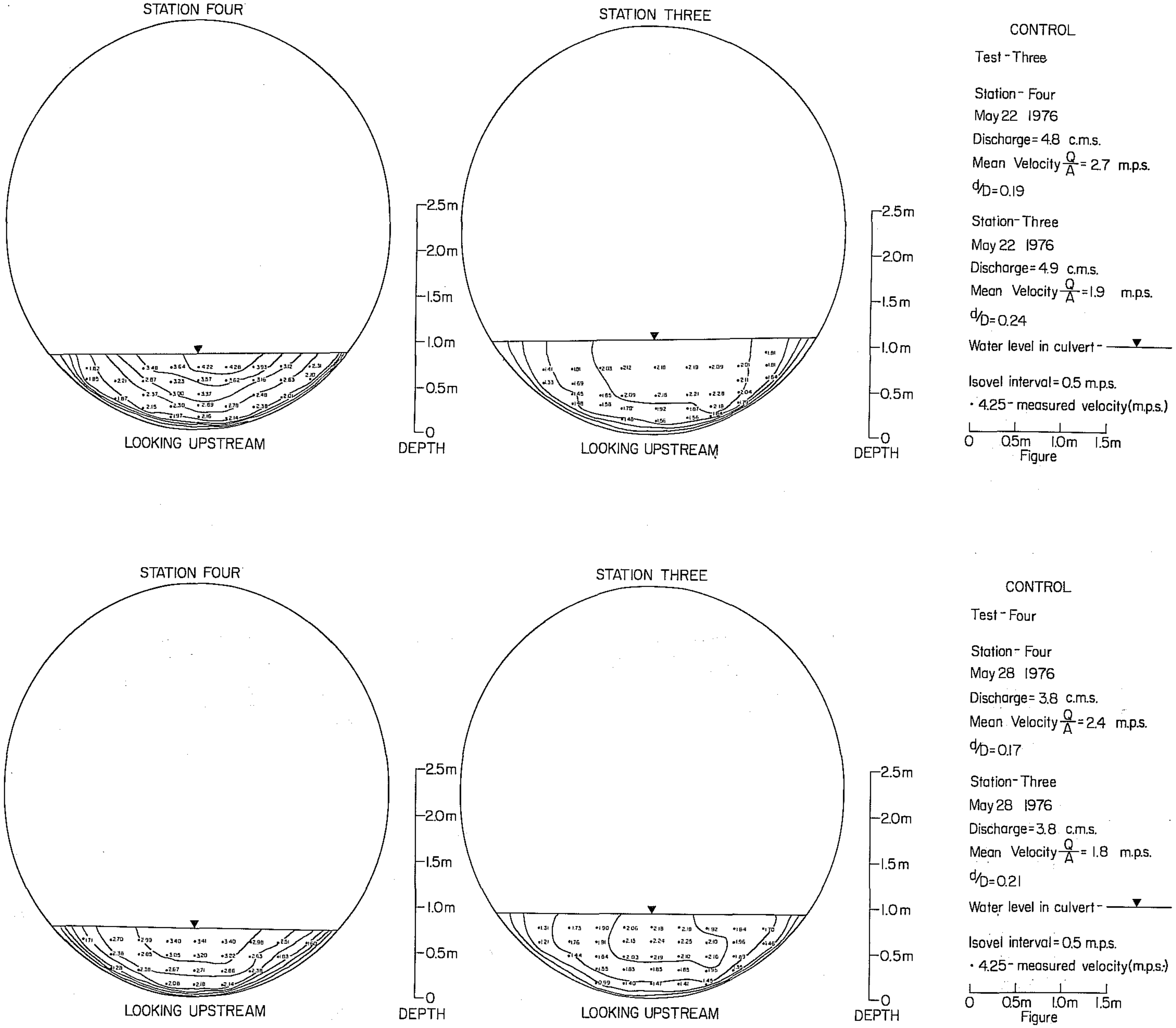
Station - Three
May 16 1976
Discharge = 7.6 c.m.s.
Mean Velocity $\frac{Q}{A}$ = 2.1 m.p.s.
$d/D = 0.33$

Water level in culvert - ▼

Isovel interval = 0.5 m.p.s.
• 4.25 - measured velocity (m.p.s.)

0 0.5m 1.0m 1.5m
Figure

Fig. A4.1. Culvert velocity distribution.



CONTROL

Test - Three

Station - Four
May 22 1976
Discharge = 4.8 c.m.s.
Mean Velocity $\frac{Q}{A}$ = 2.7 m.p.s.
d/D = 0.19

Station - Three
May 22 1976
Discharge = 4.9 c.m.s.
Mean Velocity $\frac{Q}{A}$ = 1.9 m.p.s.
d/D = 0.24

Water level in culvert - ▼

Isovel interval = 0.5 m.p.s.
· 4.25 - measured velocity (m.p.s.)

0 0.5m 1.0m 1.5m
Figure

CONTROL

Test - Four

Station - Four
May 28 1976
Discharge = 3.8 c.m.s.
Mean Velocity $\frac{Q}{A}$ = 2.4 m.p.s.
d/D = 0.17

Station - Three
May 28 1976
Discharge = 3.8 c.m.s.
Mean Velocity $\frac{Q}{A}$ = 1.8 m.p.s.
d/D = 0.21

Water level in culvert - ▼

Isovel interval = 0.5 m.p.s.
· 4.25 - measured velocity (m.p.s.)

0 0.5m 1.0m 1.5m
Figure

Fig. A4.2. Culvert velocity distribution.

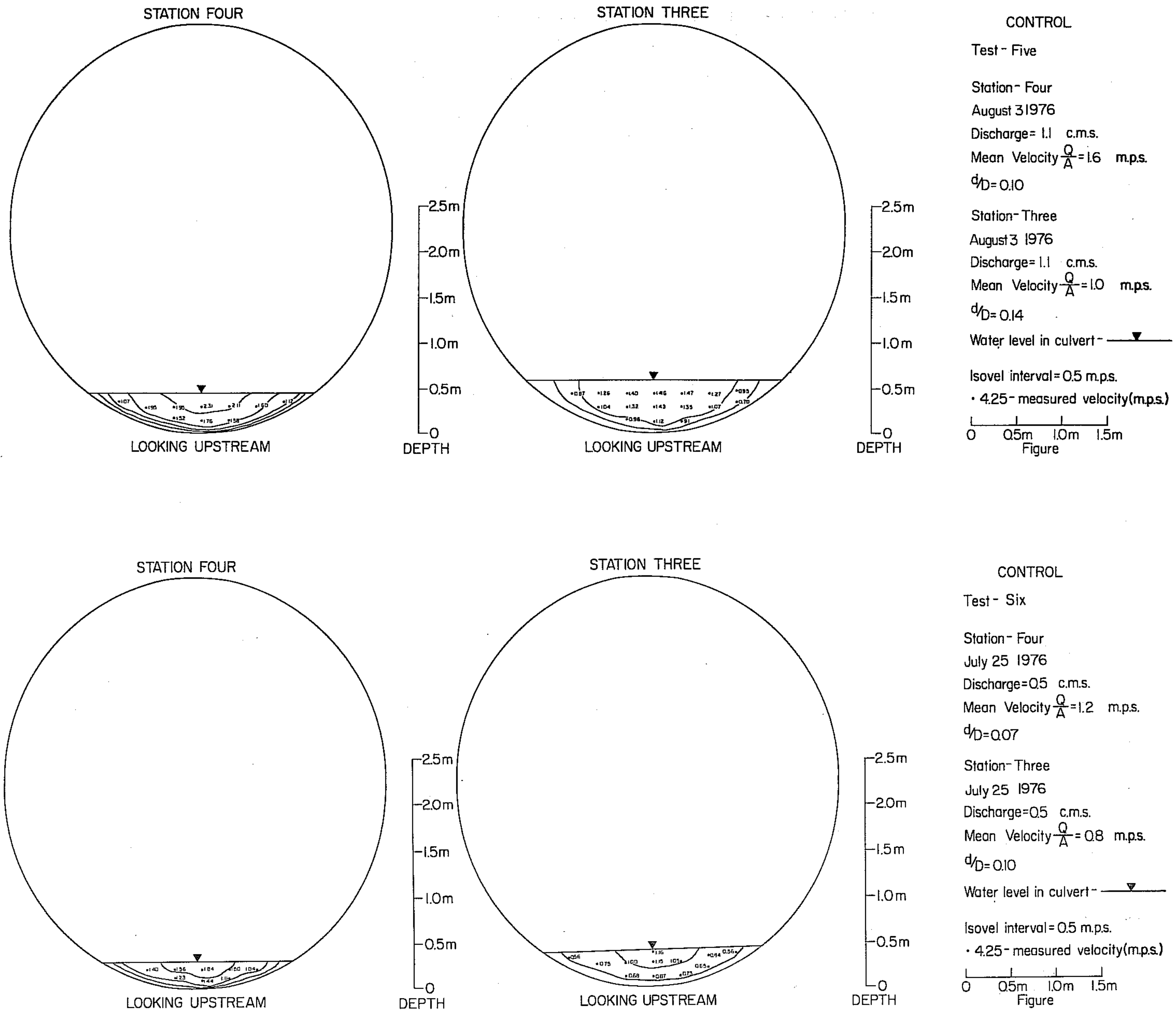
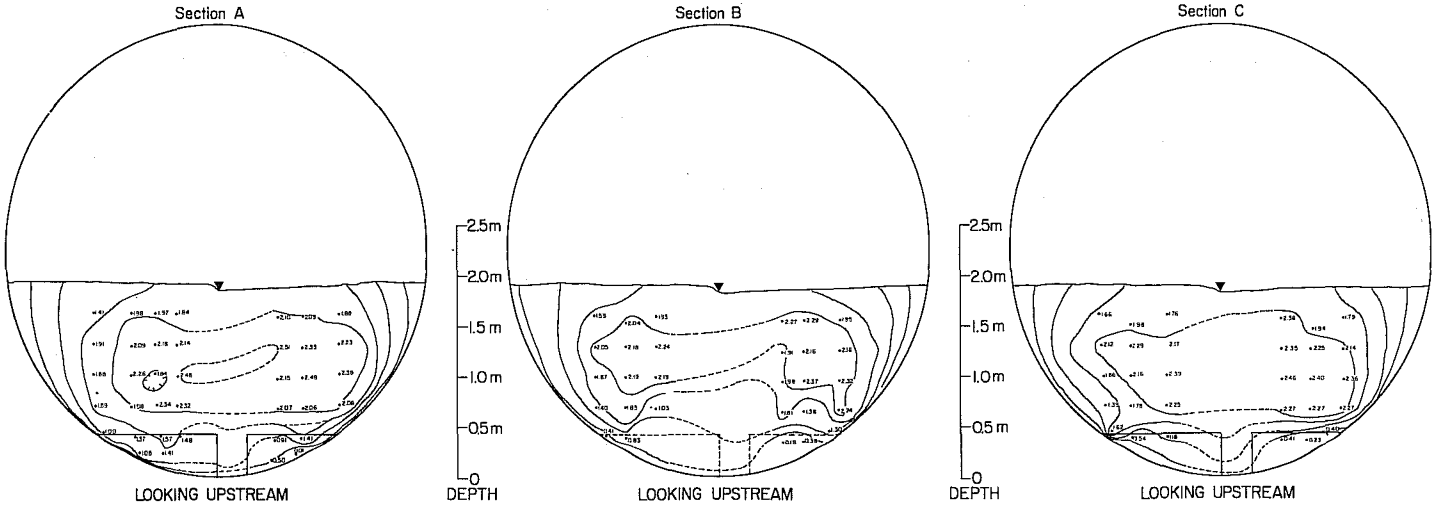


Fig. A4.3. Culvert velocity distribution.



OFFSETS

Station-Five

Test-One

May 7 1976

Discharge= 11.9 c.m.s.

Mean Velocity $\frac{Q}{A}$= 2.1 m.p.s.

$^d/_D$= 0.42

Water level in culvert- ▼

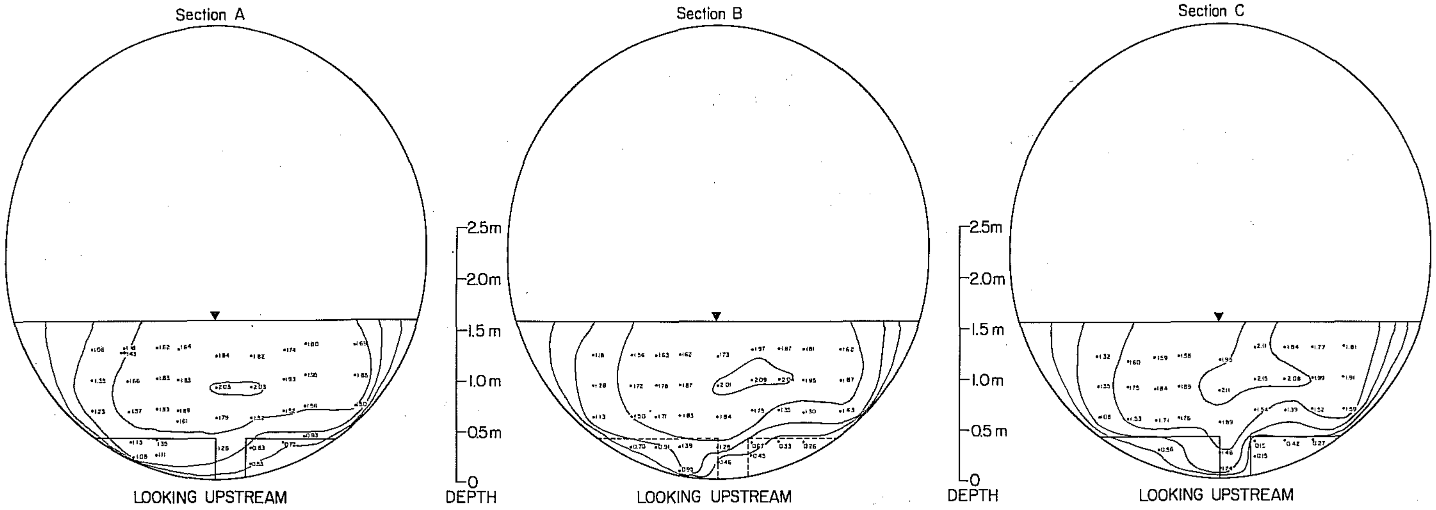
Isovel interval = 0.5 m.p.s.

• 4.25 measured velocity (m.p.s.)

→ 4.25 velocity parallel to long baffle

0 0.5m 1.0m 1.5m

Figure



OFFSETS

Station-Five

Test-Two

May 15 1976

Discharge= 6.2 c.m.s.

Mean Velocity $\frac{Q}{A}$= 1.4 m.p.s.

$^d/_D$= 0.34

Water level in culvert- ▼

Isovel interval = 0.5 m.p.s.

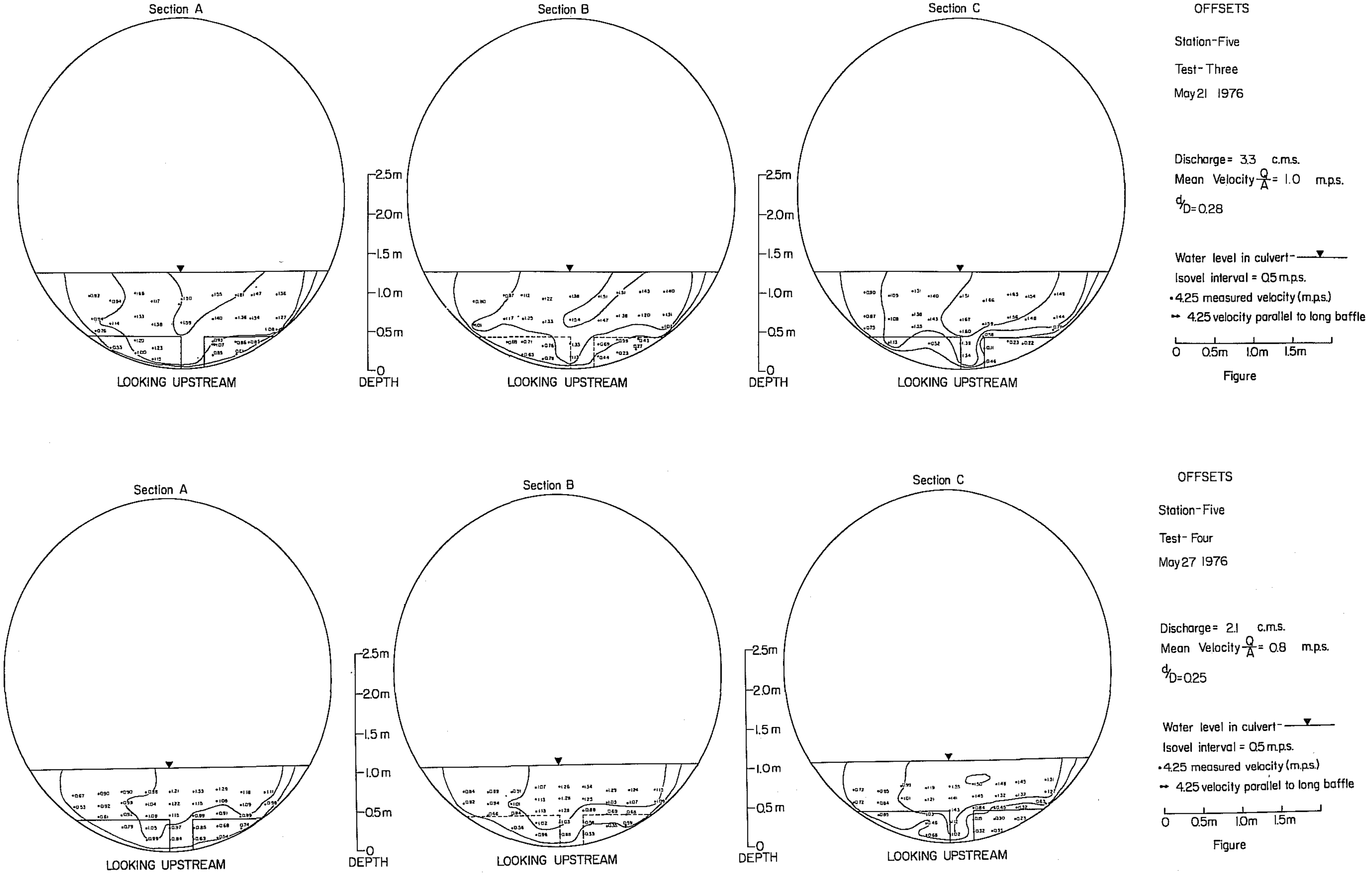
• 4.25 measured velocity (m.p.s.)

→ 4.25 velocity parallel to long baffle

0 0.5m 1.0m 1.5m

Figure

Fig. A4.4. Culvert velocity distribution.



OFFSETS

Station-Five

Test-Three

May21 1976

Discharge= 3.3 c.m.s.

Mean Velocity $\frac{Q}{A}$= 1.0 m.p.s.

d/D=0.28

Water level in culvert-▼

Isovel interval = 0.5 m.p.s.

•4.25 measured velocity (m.p.s.)

→ 4.25 velocity parallel to long baffle

OFFSETS

Station-Five

Test-Four

May27 1976

Discharge= 2.1 c.m.s.

Mean Velocity $\frac{Q}{A}$= 0.8 m.p.s.

d/D=0.25

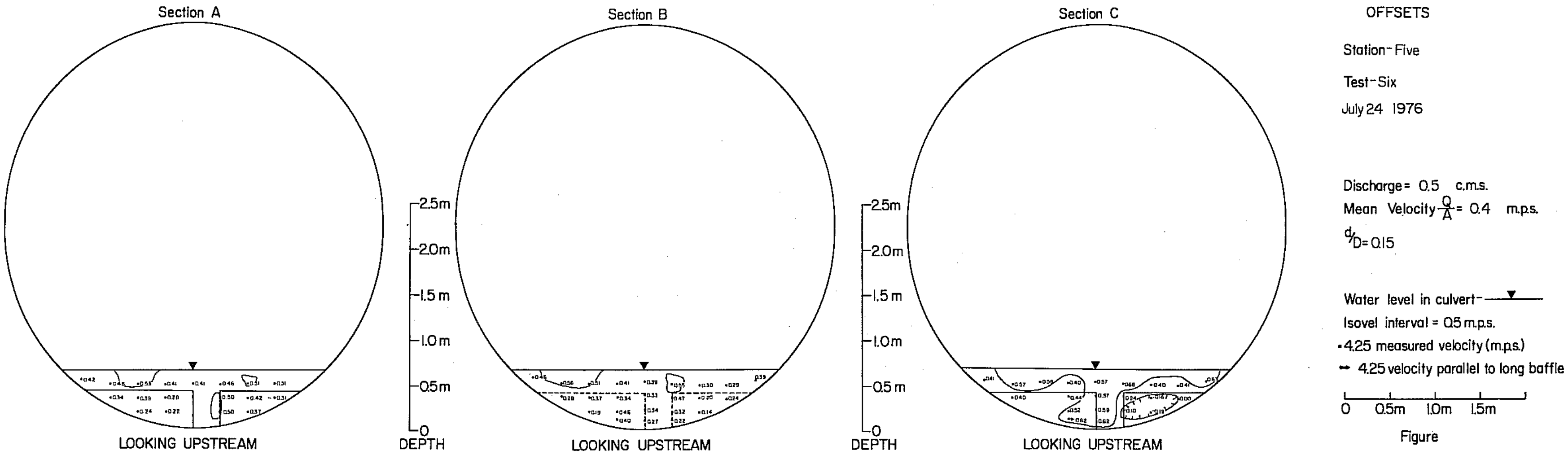
Water level in culvert-▼

Isovel interval = 0.5 m.p.s.

•4.25 measured velocity (m.p.s.)

→ 4.25 velocity parallel to long baffle

Fig. A4.5. Culvert velocity distribution.



OFFSETS

Station-Five

Test-Six

July 24 1976

Discharge = 0.5 c.m.s.

Mean Velocity $\frac{Q}{A}$ = 0.4 m.p.s.

d/D = 0.15

Water level in culvert- ▼

Isovel interval = 0.5 m.p.s.

•4.25 measured velocity (m.p.s.)

→ 4.25 velocity parallel to long baffle

Fig. A4.6. Culvert velocity distribution.

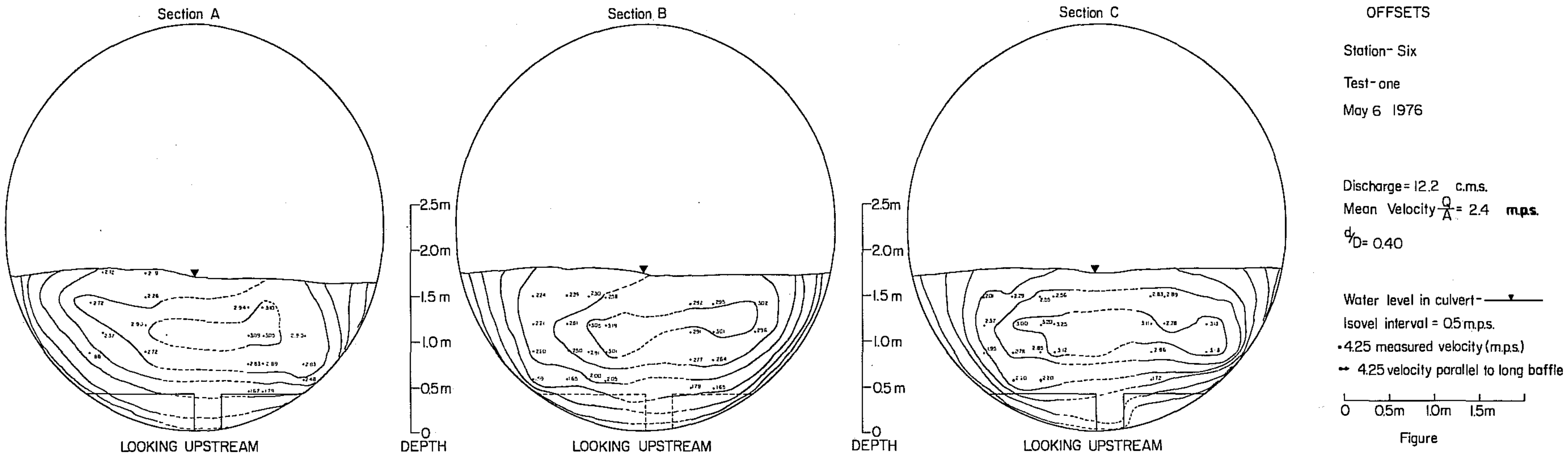
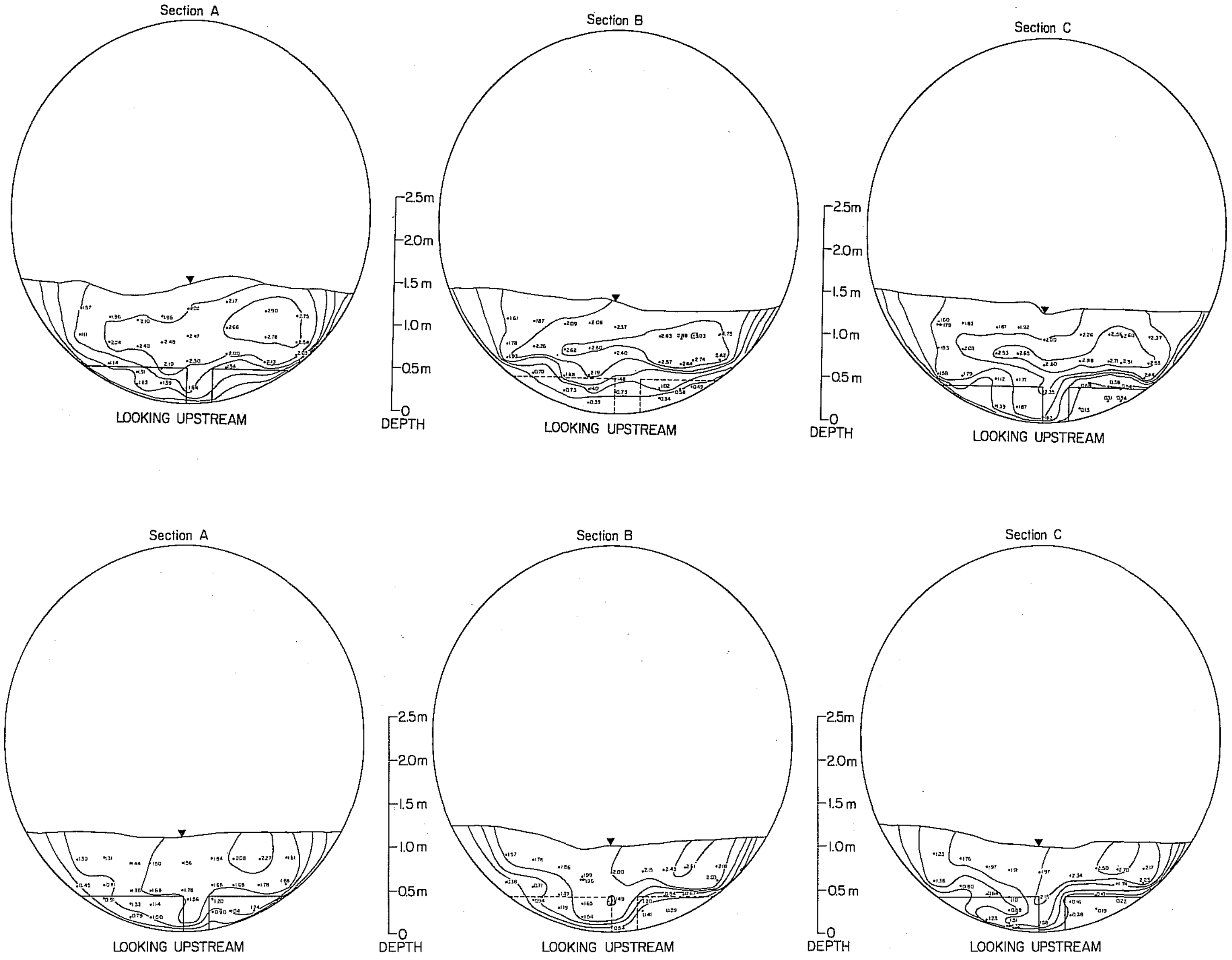


Fig. A4.7. Culvert velocity distribution.



OFFSETS

Station- Six

Test- Two

May 14 1976

Discharge = 6.9 c.m.s.

Mean Velocity $\frac{Q}{A}$ = 2.0 m.p.s.

d/D = 0.30

Water level in culvert - ▼

Isovel interval = 0.5 m.p.s.

• 4.25 measured velocity (m.p.s.)

↔ 4.25 velocity parallel to long baffle

0 0.5m 1.0m 1.5m

Figure

OFFSETS

Station- Six

Test- Three

May 20 1976

Discharge = 3.8 c.m.s.

Mean Velocity $\frac{Q}{A}$ = 1.4 m.p.s.

d/D = 0.25

Water level in culvert - ▼

Isovel interval = 0.5 m.p.s.

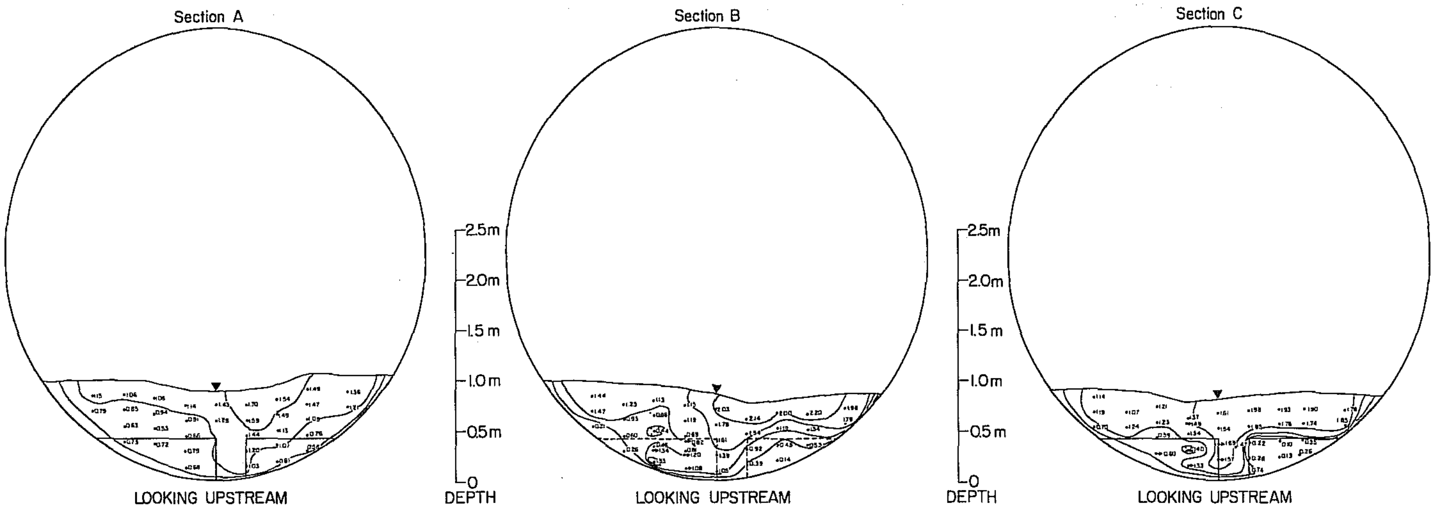
• 4.25 measured velocity (m.p.s.)

↔ 4.25 velocity parallel to long baffle

0 0.5m 1.0m 1.5m

Figure

Fig. A4.8. Culvert velocity distribution.



OFFSETS

Station-Six

Test-Four

May27 1976

Discharge = 2.3 c.m.s.

Mean Velocity $\frac{Q}{A}$ = 1.1 m.p.s.

d/D = 0.20

Water level in culvert-▼

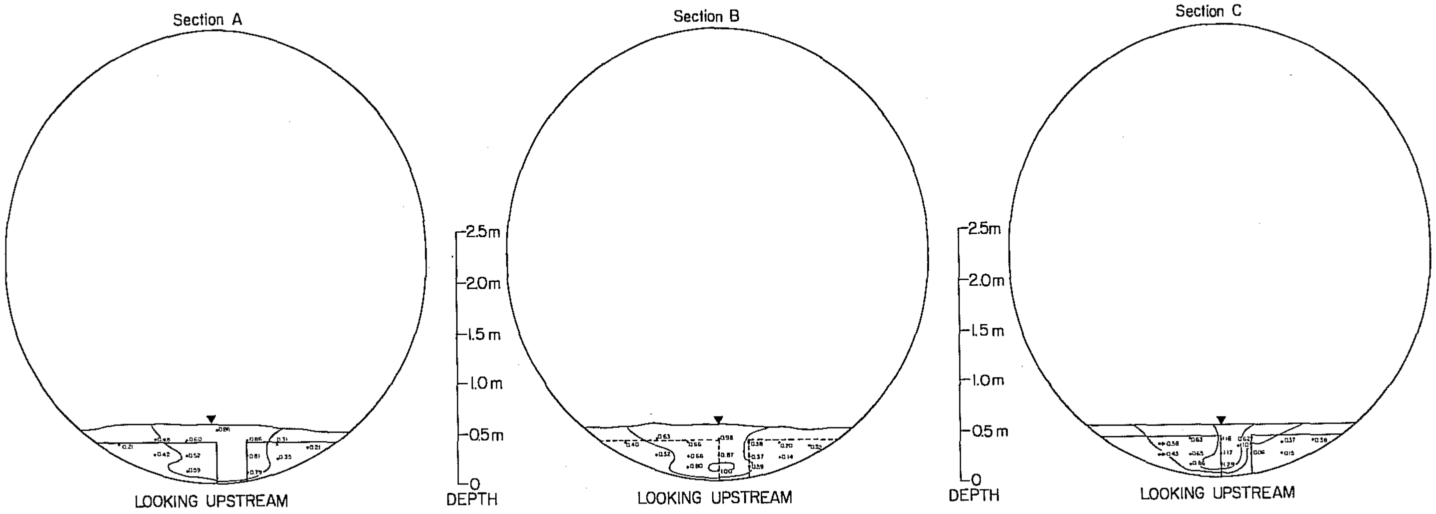
Isovel interval = 0.5 m.p.s.

•4.25 measured velocity (m.p.s.)

→ 4.25 velocity parallel to long baffle

0 0.5m 1.0m 1.5m

Figure



OFFSETS

Station-Six

Test-Six

July24 1976

Discharge = 0.50 c.m.s.

Mean Velocity $\frac{Q}{A}$ = 0.5 m.p.s.

d/D = 0.12

Water level in culvert-▼

Isovel interval = 0.5 m.p.s.

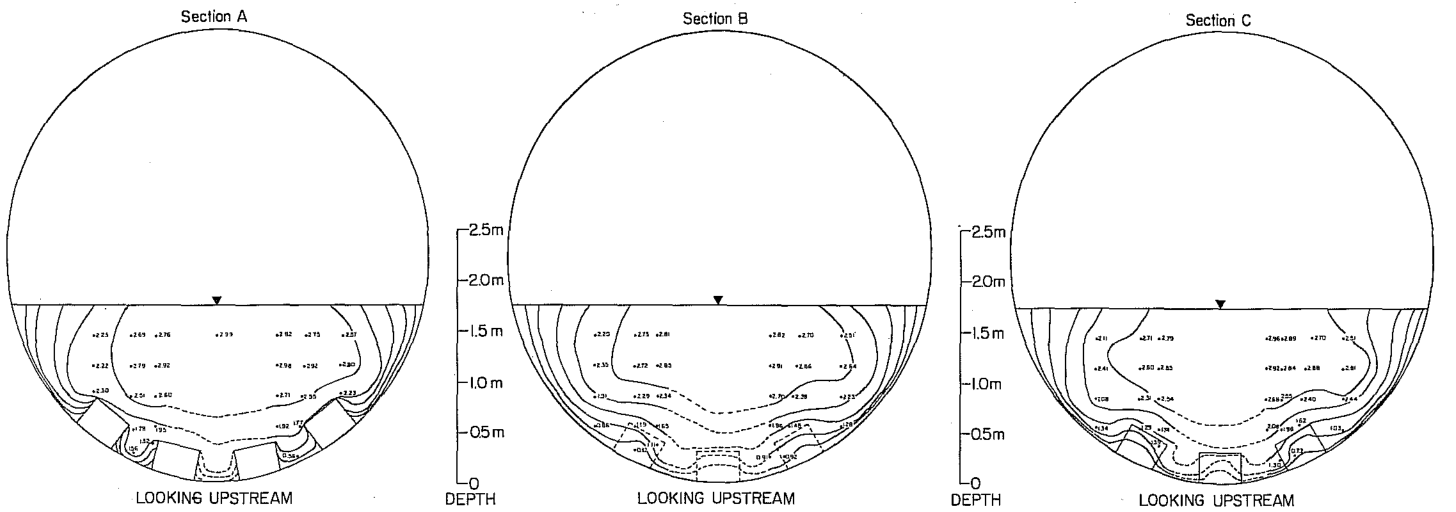
•4.25 measured velocity (m.p.s.)

→ 4.25 velocity parallel to long baffle

0 0.5m 1.0m 1.5m

Figure

Fig. A4.9. Culvert velocity distribution.



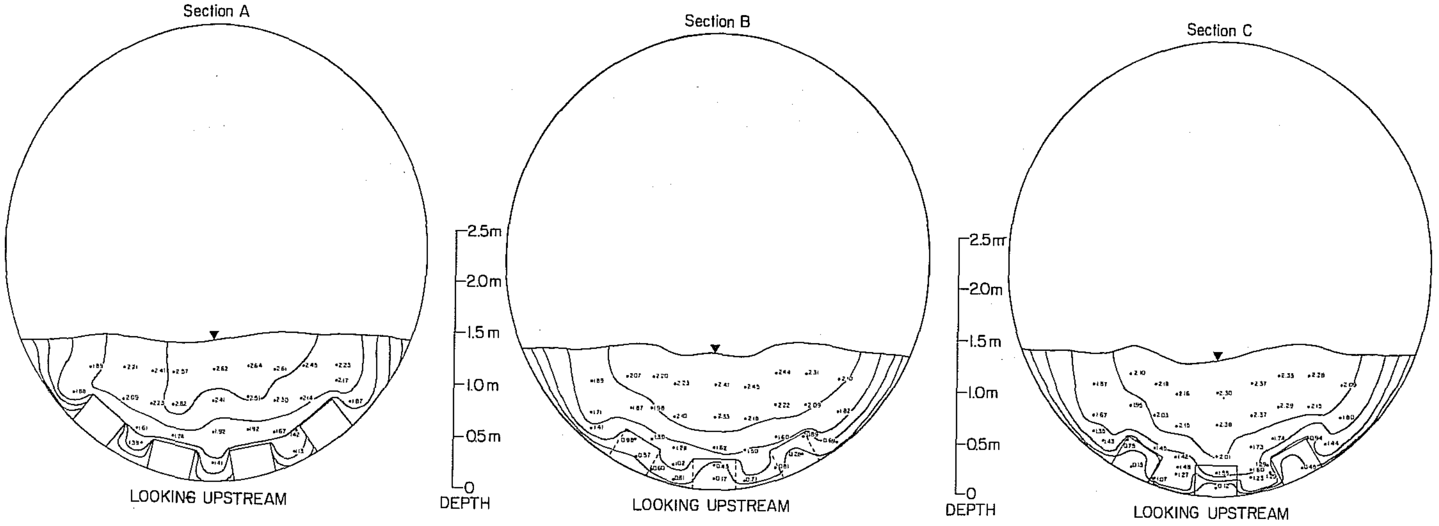
SPOILERS

Station-One

Test-One
May 10 1976

Discharge = 12.3 c.m.s.
Mean Velocity $\frac{Q}{A}$ = 2.3 m.p.s.
d/D = 0.41

Water level in culvert - ▼
Isovel interval = 0.5 mps
• 4.25 measured velocity (m.p.s.)
0 0.5m 1.0m 1.5m
Figure



SPOILERS

Station-One

Test-Two
May 17 1976

Discharge = 6.5 c.m.s.
Mean Velocity $\frac{Q}{A}$ = 1.7 m.p.s.
d/D = 0.32

Water level in culvert - ▼
Isovel interval = 0.5 mps
• 4.25 measured velocity (m.p.s.)
0 0.5m 1.0m 1.5m
Figure

Fig. A4.10. Culvert velocity distribution.

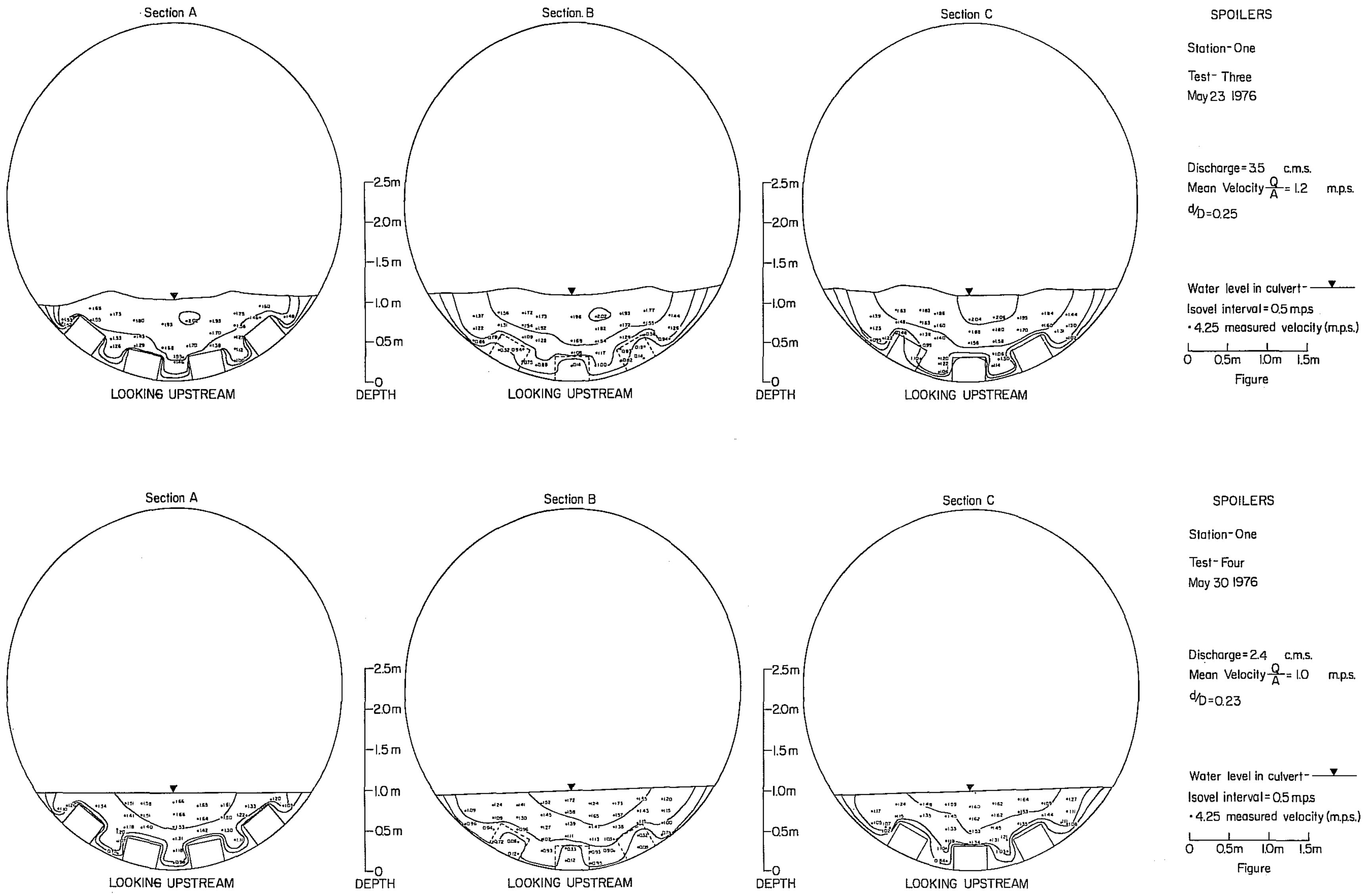


Fig. A4.11. Culvert velocity distribution.

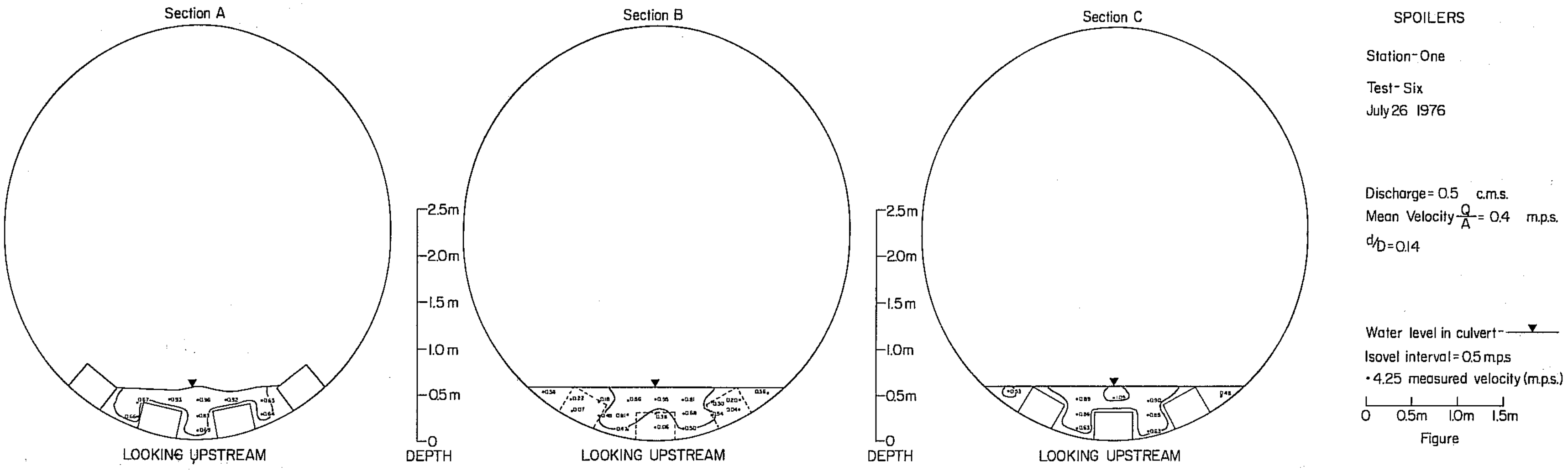


Fig. A4.12. Culvert velocity distribution.

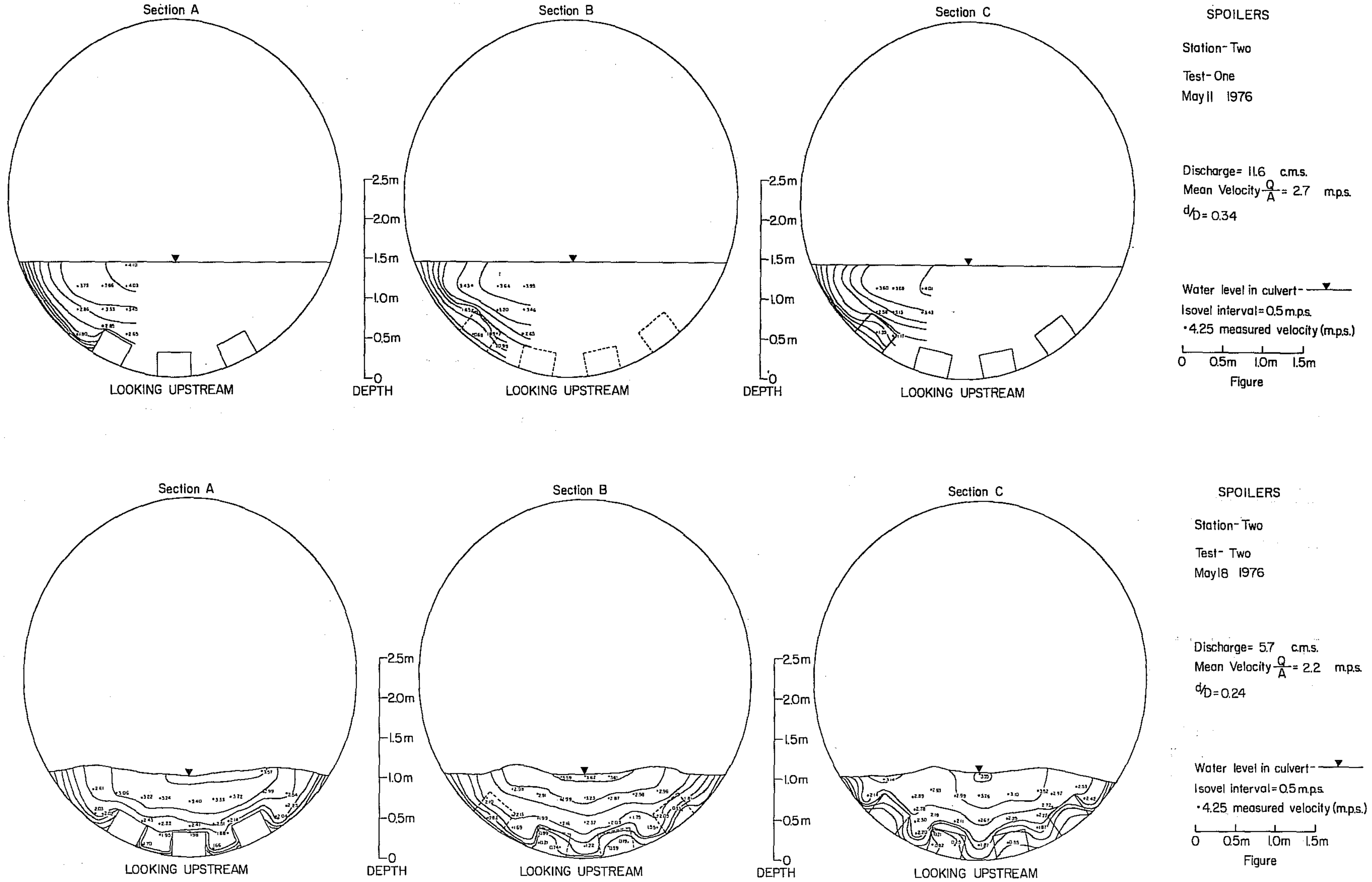


Fig. A4.13. Culvert velocity distribution.

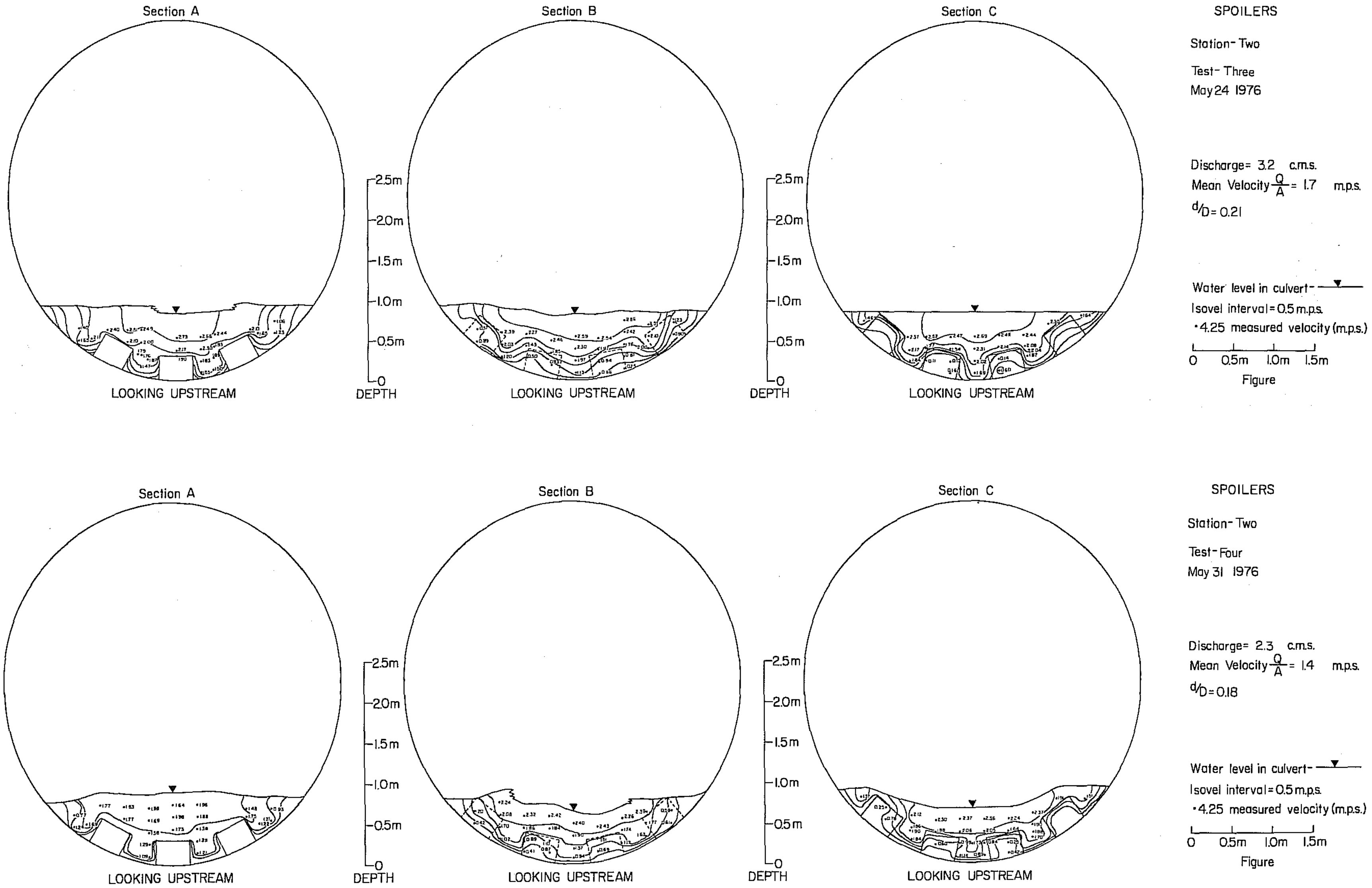


Fig. A4.14. Culvert vleocity distribution.

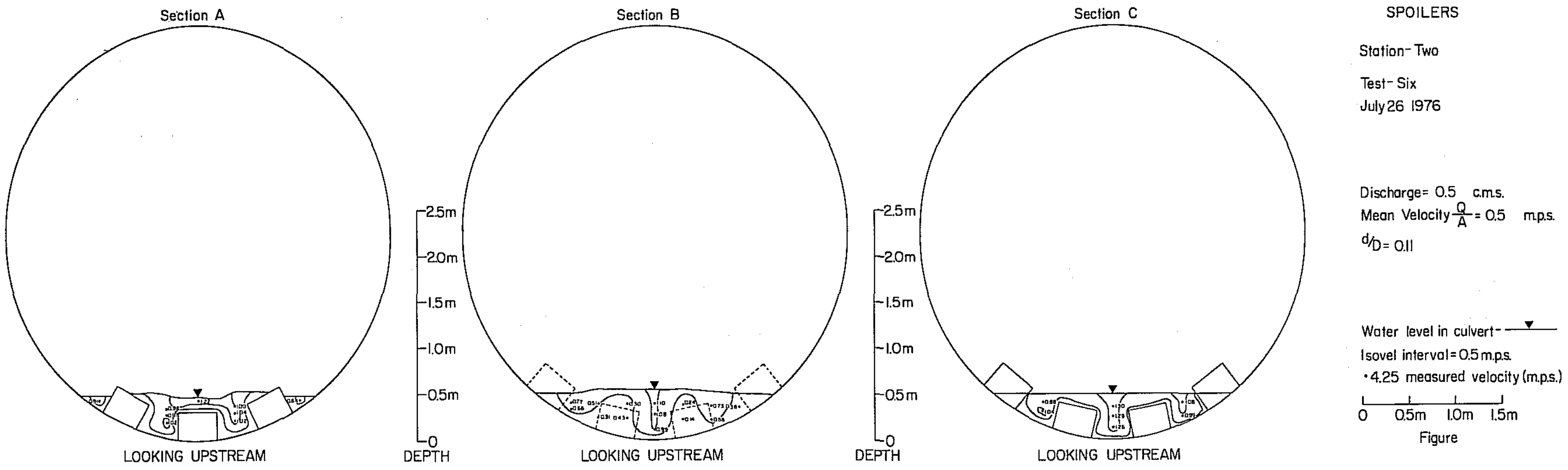


Fig. A4.15. Culvert velocity distribution.

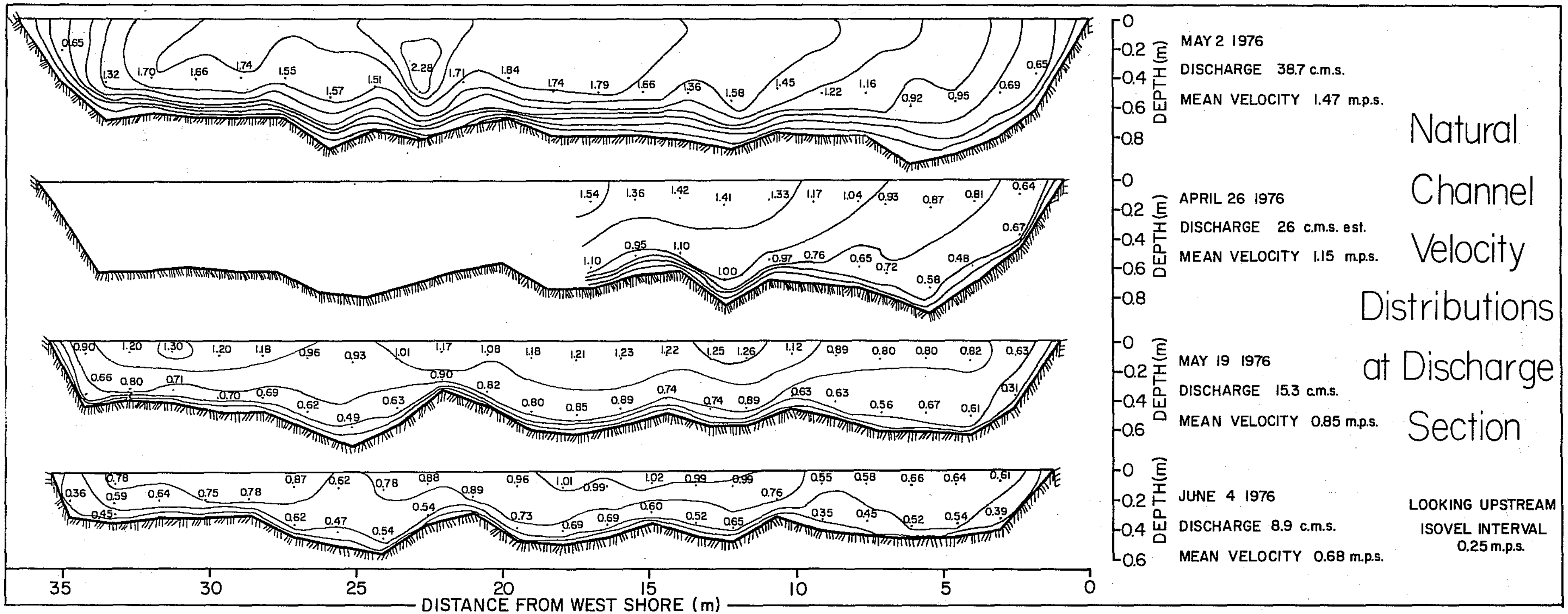


Fig. A4.16. Natural channel velocity distribution.

APPENDIX 5. DESCRIPTION OF WATER SURFACE CHARACTERISTICS FOR FLOW WITH BAFFLES.

Test Number	Offsets	Spoilers
1	- discharge 12.1 cms (427 cfs) - first standing wave on west side at 12th baffle set, breaking waves continue on west side until 5th baffle set. - wave parallel to flow on the centreline between 4th and 5th baffle sets, boiling east side water hit west side, waves caused decreased size and shape of standing waves. - outlet water level in middle lower than along edges.	- discharge 12.0 cms (425 cfs) - water surface undulated in upper section. - waves in the lower section appeared just upstream of the rows of spoilers. - wave pattern poorly defined in the extreme lower section.
2	- discharge 6.6 cms (233 cfs) - water surface in upper section undulated. - waves along west side increased in size breaking between the 2nd and 5th rows. - waves broke above short baffles, subcritical depth extended about 1.4 m (4.6 ft) downstream. - waves level east side about 0.3 m (1 ft) higher than at centreline. - Auxiliary short baffle did not create noticeable disturbance.	- discharge 6.1 cms (215 cfs) - first waves in upper section form beneath upstream crown. - end baffles caused humps in middle section resulting in 'V' shaped waves across the flow. - flow over end baffles in rows of three baffles was supercritical in lower section. - jumps formed downstream of them.
3	- discharge 3.6 cms (127 cfs) - two waves between short baffles presented in upper section. - primary crest occurred between baffles, secondary crest occurred above baffles. - standing waves about 0.4 m (1.3 ft) high broke 1.0 m (3.3 ft) downstream of the short baffles in the lower section. - these waves were the largest at this discharge.	- discharge 3.4 cms (120 cfs) - end baffles formed humps and then troughs which extended to the upstream edge of the next row, where waves were formed. - well-defined lines of standing waves were present between the rows in the middle section. - in the lower section these regular rows of waves broke up into more turbulent crests and troughs. - the rows of waves moved upstream as flow decreased. - 1st row of baffles had leeward velocities extending 0.6 m (2 ft) downstream of the concrete lip. - jet velocities above the end baffles swept down and cut out the leeward velocities behind them.
4	- discharge 2.2 cms (78 cfs) - waves along west side formed further upstream than before. - east side boiling flow extended one-third of distance across culvert.	- discharge 2.4 cms (85 cfs) - upper section had choppy surface. - supercritical flow depth occurred over the 12th row baffles.

APPENDIX 5. (Cont'd.).

Test Number	Offsets	Spoilers
4	- standing waves in lower section formed 1.5 m (5 ft) upstream of the short baffles. - small standing wave was created by the auxiliary short baffle, water depth behind this baffle was considerably less than on the east side.	- breaking waves were present downstream of the 11th row of baffles. - flow in the lower section was similar to test three. - location of the rows of standing waves was not in place with the rows of baffles.
6	- discharge 0.5 cms (18 cfs) - water surface was smooth along both sides in the upper and middle sections. - small waves were created by both the short and long baffles. - head loss at each baffle set increased downstream. - the auxiliary short baffle created a shallow back eddy which extended downstream of the concrete lip.	- discharge 0.5 cms (18 cfs) - upper section surface was smooth. - first waves appeared at 14th row. - the middle baffles created small 'V' shaped areas of supercritical flow which broke into subcritical flow downstream of the baffle rows. - the waves formed were very small.

APPENDIX 6. GLOSSARY

A	cross-sectional area of flow
A_c	cross-sectional area of flow at critical depth
B	top width of flow cross-section
B_c	top width at critical flow
C	Chezy's coefficient
D	diameter of culvert
d	depth of water
d_n	normal depth
d_c	critical depth
Fr	Froude number
F	jet Froude number
f	Darcy-Weisbach's friction coefficient
g	acceleration of gravity
h	baffle height
n	Manning's roughness coefficient
n_p	Manning's n for the plain culvert
n_t	Manning's for the baffled culvert
P	Wetted Perimeter
p	denotes conditions for plain pipe
Q	discharge
R	hydraulic radius
S	water surface slope
S_o	channel bottom slope
S_f	frictional slope
s	second
t	denotes conditions with baffles
V	velocity (average)
V_j	jet velocity
cms or c.m.s.	m^3/s
mps or m.p.s.	m/s
α	kinetic energy coefficient
Δd	change in depth
Δx	change in longitudinal distance
δ	relative depth (d/D)
δ_n	normal relative depth
δ_c	critical relative depth
ζ	a constant dependant on units used only
θ	angle
λ	baffle relative height (h/D)
λ_a	ratio: A/D^2
λ_b	ratio: B/D
λ_p	ratio: P/D
λ_r	ratio: R/D
ξ	the constant $8g/\zeta^2$