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Plate 3. *Vertical headwall. The rounding of the headwall so that it gradually meets the banks reduces entrance velocity changes and improves fish passage.*

Plate 4. *Bevelled culvert inlet. This type of inlet reduces entrance contraction considerably and therefore is less of a problem for fish exiting the culvert. Fish passage in this culvert could have been further improved by using more stones over the culvert end, especially in the lower part of the headwall.*

8.4 Gradient

As discussed in Section 7.1, fish passage within the culvert is controlled by the water velocities and availability of resting areas. Water velocities are highly dependent on the gradient of the culvert; limits of slope ranging from 0% to 5% are proposed in the literature to maximise fish passage. However, the most sensible criterion is proposed by Clay (1995) who recommends that gradients be as close to, and certainly no more than, that of the stream above and below the culvert. Steeper gradients increase barrel velocities, which in turn can lead to scouring below the outlet, creating vertical barriers for upstream migrating fish.

8.5 Surface roughness

Once culvert diameter and slope are set, increasing the roughness coefficient of the culvert floor and wall is the only way of reducing water velocities. As part of this study, we compared the distances that inanga were able to swim through a 0.48 m diameter pipe with Alberta fish weirs, spoiler baffles and corrugations. The Alberta fish weirs (see Section 9.2.1(iv) and Figure 16) were 65 mm high weirs, with a 105 mm by 30 mm deep slot, placed every 0.29 m along the culvert pipe. The spoilers baffles (see Section 9.2.1(vi) and Figure 18) were 43 mm high, 57 mm wide, and 103 mm long, with one end angled and the other square. These spoilers were placed in rows that were 0.173 m apart and alternately comprised 2 and 3 spoilers. The corrugated culvert was a Polyflo™ culvert 0.45 m in diameter with rectangular corrugations about 100 mm long.

According to Rajaratnam et al. (1991) the effect of weirs and baffles is to increase water depth by a factor of 1 to 3 depending on the design, with a corresponding decrease in velocity. In the tests carried out during our study, this reduction in velocity increased the distance that inanga were able to swim up a culvert set at about 4° slope, by a factor of 2.5 to 3 (Figure 9). The Polyflo™ corrugated culvert was the most effective at increasing the passage distance, with small and large inanga travelling a median distance of around 4 metres, compared to a median distance travelled in a smooth culvert of around 1 metre (Figure 9).

For climbing species, observations have shown that elvers, common bullies and koaro can climb roughened pipes at angles of 45–50° when provided with just a trickle of water (Mitchell and Boubée 1989; Mitchell 1993).

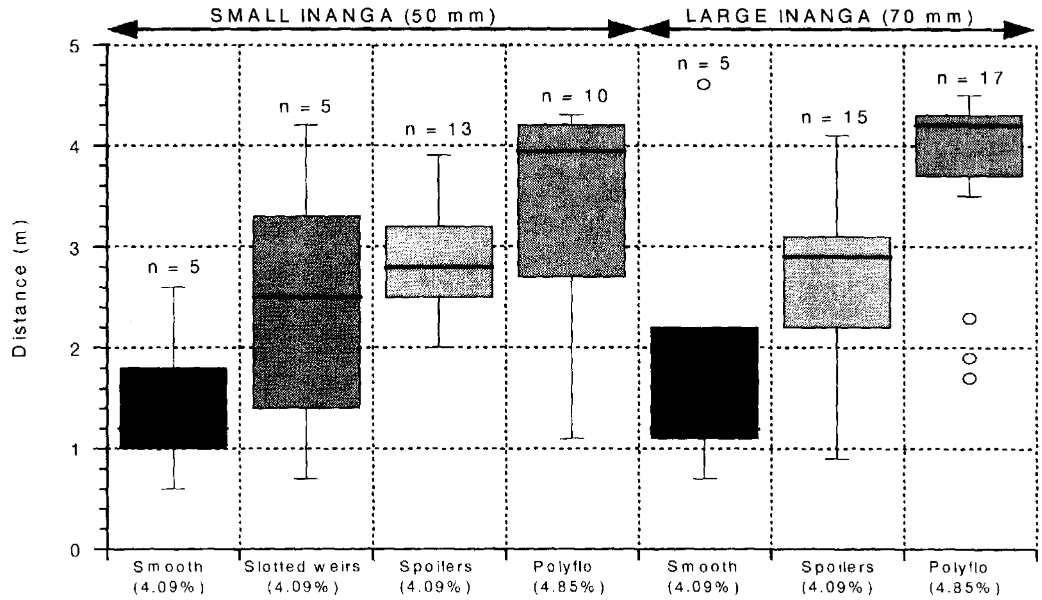

Figure 9. *Comparison of maximum distance swum upstream by inanga (50 and 70 mm) in different culvert types. Culvert types used for testing include: a smooth steel culvert (red), a culvert fitted with slotted weirs (blue) and one with spoilers (green), and a polyflo*TM *corrugated culvert (orange). Gradients are 4.09% and 4.85% respectively. Box plots give the median, displayed as a solid line within the box; the top and bottom.* of *the box mark the 25°k and 75% limits; the lines extending from the box mark the minimum and maximum; and the circles represent the outliers.*

8.6 Alignment

To prevent scouring at the inlet or outlet, culverts should be aligned with the existing channel in a straight or near straight section (Baker and Votapka 1990: see Figure 10). Cutting off meanders or changing the direction of flow to suit culvert placement can increase turbulence, velocity and erosion, which in turn can lower the water levels at the culvert outlet and create a barrier to fish passage. Where the ideal alignment is not possible, suitable streambed and bank protection works need to be undertaken, such as the use of riprap (Plate 5) and/or planting of protective vegetation.

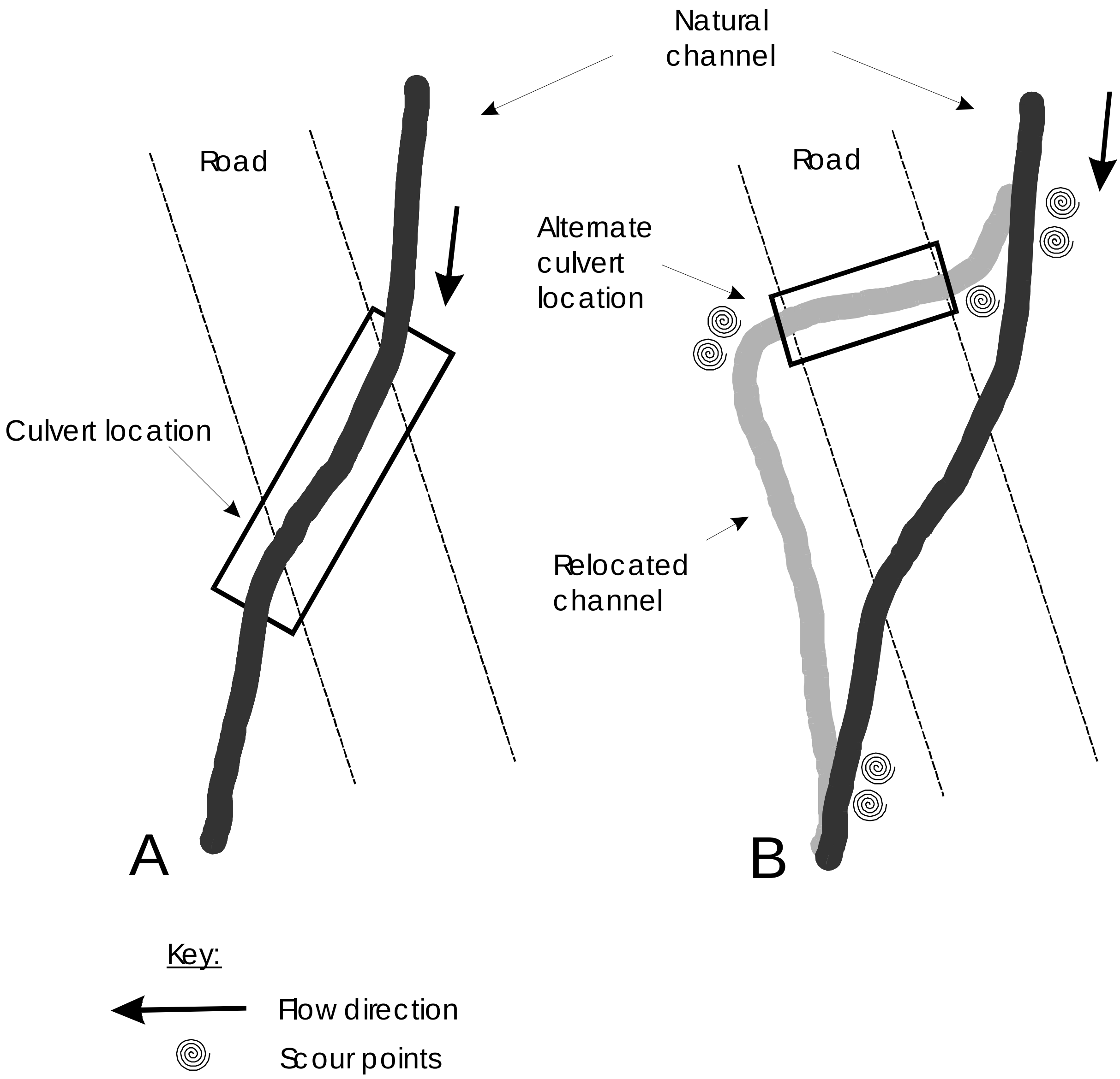

Figure 10. *Culvert alignment.* ***A****, aligned with existing stream;* ***B****, realigned to reduce culvert length. Maintaining stream alignment is the preferred option; however, fish passage can be maintained as long as the realigned stream does not result in a significant reduction of channel length (with corresponding loss of energy dissipation capacity) and the scour points are protected.*

Plate 5. *Use of riprap to protect streambed and streambank at the outlet.*

8.7 Multiple barrels

Generally, one large culvert is better than several smaller ones, as debris blockage is less likely and velocities will be lower. Where the chance of blockage by debris is low, multiple barrels may be quite successful, especially where one or several are placed lower than the others to accommodate low discharges (Plate 6, Figure 11). Dane (1978a and 1978b) suggests placing such barrels 0.3 metres below one another. Stacked barrels (Plate 7) may be useful in catchments where water levels vary markedly (Metsker 1970). Smaller multiple barrels may also fit better in a low fill than a single larger one, thus avoiding the need to increase the elevation of the road, but again these are more likely to become blocked with debris.

Plate 6. *Multiple-barrel installation.*

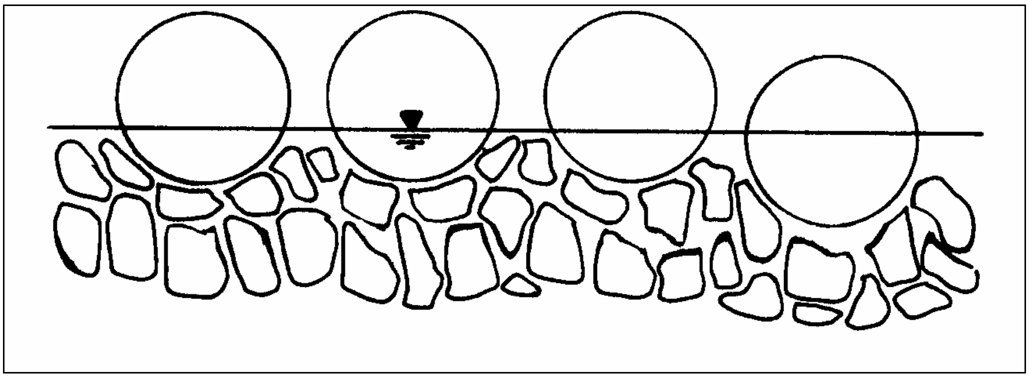

Figure 11. *A multiple-barrel installation, with one barrel lowered to allow fish passage during low flows.*

Plate 7. *Stacked barrels to accommodate varying levels of flow.*

All barrels should be able to collectively accommodate the culvert design discharge. As outlined in WORKS (1988), this flow may be divided equally between identical barrels but where the barrels differ in size, construction or elevation, trials may be needed to produce a configuration which will accommodate the desired total.

In multi-barrel configurations, fish passage need not be provided by all barrels (Evans and Johnston 1974; Dane 1978a and 1978b; Baker and Votapka 1990). Only the lower ones or, where they all are at the same elevation, those deemed most likely to be selected by fish, need to be designed to permit passage (for indigenous species these will probably be the ones nearest the banks). However, fish do not always choose the expected culvert (Baker and Votapka 1990) and retrofitting flow dissipaters in all of the barrels may be required if monitoring has shown the structure to be defective.

8.8 Darkness

The effect of light, or the lack of it, on fish migration remains an area of debate. For example, Kay and Lewis (1970) found that in four culverts between 183 and 229 metres long, darkness seemed to have little effect on fish passage. However, Dane (1978a) commented that these observations were not based on the success rate of passage, but merely on the fact that some fish were able to negotiate the culverts. He also reports that some studies have found passage times to be higher in darkened flumes compared to lit flumes, with the opposite occurring in fishways. Mallen-Cooper et al. (1995) however found that daylight had a strong effect on the upstream movements of fish. They found that adult bony herring, immature smelt and immature silver perch only moved upstream during daylight hours.

Fish use both visual and tactile (e.g. lateral line senses) clues for orientation and movement. Laminar flow in flumes and culverts may thus reduce the fish’s ability to detect and interpret currents in the dark, causing them to move more hesitantly. In fishways, fish may be better at sensing currents than seeing illuminated obstacles. Ensuring that flows in culverts are not laminar is therefore likely to be an effective way of assisting upstream passage.

The passage from light to dark and dark to light conditions upon entering and leaving culverts may inhibit migration, or cause fish to pause to acclimate to the new conditions. This may lengthen the time fish remain in the culvert, increasing fatigue and reducing passage. Shading of culvert inlets and outlets with trees, or awnings where culverts are particularly wide, may be a solution if this is a concern. However, Watts (1974) considered that the light contrast was usually minimal and therefore unlikely to be a major inhibiting factor. Light contrast would not be an issue during nocturnal migration or when waters are highly turbid.

Dane (1978a) concluded that darkness inside culverts was not a major determinant in controlling migration and should only be accounted for in design as a safety factor. Nevertheless, this aspect has not been tested in New Zealand as little is known about the movement of indigenous species. Elvers tend to migrate only at night, so passage in dark culverts is not an issue for them. Furthermore, although McDowall and Eldon (1980) found that whitebait did not, as a rule, migrate at night, a healthy population of banded kokopu has been found above a 300 m culvert on the Coromandel Peninsula (D. West, DOC, Hamilton, pers. comm.). For this species therefore, darkness did not form a migration barrier. Accordingly, until studies have shown conclusively that light does affect passage, including skylights or lighting ports in the design of long culverts is not necessary. However, to maximise the amount of light reaching the centre of long culverts, we recommend that all culverts be installed in a straight line.

9 ANCILLARY STRUCTURES

In addition to the basic design and placement of the culvert, consideration must be given to the effect of any ancillary structures such as aprons, baffles and weirs, on fish passage.

9.1 Concrete aprons

Horizontal, smooth concrete aprons (Plate 2) are often used to disperse flows and prevent the culvert outlet from being undermined. Where large swimming species such as trout and salmon are present, aprons should not be used as the spreading of water can result in depths too shallow for fish to negotiate. Aprons also often end in a vertical drop that becomes a barrier to fish passage at low discharges. These vertical drops are sometimes created at construction but are typically the result of scouring of the bed downstream. The culvert must therefore be designed to allow passage of the target species and the bed must be well armoured to prevent subsequent scouring. Where erosion could cause problems, flow control rock weirs (Section 9.4) will need to be constructed.

While aprons may not be always suitable for swimming species, even small ones like inanga and smelt, they could be a useful way of allowing passage for indigenous New Zealand climbing species such as elvers, banded kokopu and koaro. Properly designed, they would also be of use in correcting existing overhanging culverts, and could be used where engineering restrictions do not allow culverts to be built with inverts below the stream level. Where possible, rocks should be incorporated into the apron to break the flow and the apron should be concave, or at least placed at an angle, to concentrate flows at low discharges. Most importantly, the junction with the culvert should be rounded to ensure passage of climbing species into the culvert. These features are discussed further in Section 9.4.

9.2 Baffles

Baffles have often been installed in culverts to facilitate fish passage by providing resting areas and/or a continuous channel of low velocity water. Some designs may significantly reduce the hydraulic efficiency of the culvert, as the aim of baffles is to slow water velocities (McKinley and Webb 1956). However, reductions in large culverts that are designed for flood flows may be quite small (Baker and Votapka 1990). Baffles may also increase the likelihood of debris completely blocking the culvert. Installation and maintenance of baffles may be difficult and expensive, and care must be taken to match the design life of the baffle system to that of the culvert (Baker and Votapka 1990).

Generally, baffles should be considered the last option in new culverts, with a larger culvert or a lower gradient a better method of reducing velocities. In existing culverts, or where the stream gradient is steep, inserting baffles, spoilers or rocks along the floor of the culvert may be the only available and effective option.

To minimise maintenance problems Metsker (1970), and Baker and Votapka (1990) suggested that baffles should only be installed in large-diameter culverts with a clear width of at least 1.2 m (e.g. if the baffles are 0.3 m high, the culvert needs to be at least 1.5 m in diameter). In structures with flat bottoms, especially those greater than 1.8 m diameter, it is recommended that the culvert be divided in two with a separator wall and only one side baffled (Metsker 1970; Evans and Johnston 1974) (Figure 12). The separator wall should be three times the height of the baffles and low discharges directed through the baffled side (this could be achieved by having the baffled side of the culvert lower that the clear one). Otherwise, baffles may cover the entire width of the culvert.

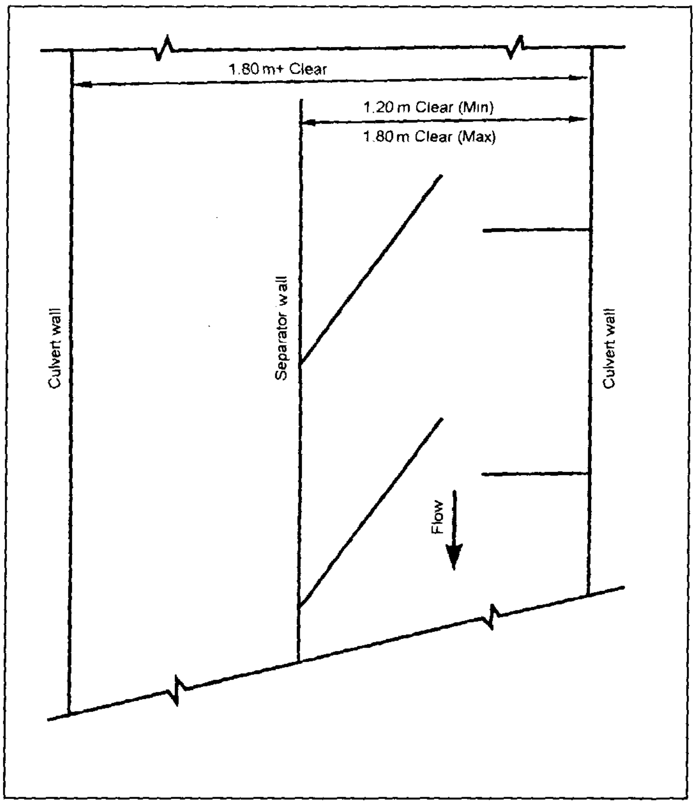

Figure 12. *Plan view of a box culvert divided by a separator wall, with baffling on one side only. For dimensions refer to Figure 13 (redrawn with permission from Baker and Votapka 1990).*

9.2.1 Commonly used baffle designs

In this section we describe some of the more commonly used baffle designs. Except where specifically mentioned, the suitability of the structures for indigenous species has not been determined and we recommend that field trials be undertaken if installation is contemplated. For most designs, Rajaratnam et al. (1988, 1989a, 1989b, 1990, 1991) and Rajaratnam and Katapodis (1990) have developed relationships between discharge, flow depth, culvert slope, culvert diameter and velocity.

i) Offset baffles

Used widely in Canada and the western United States, the paired baffles in this design are short and perpendicular to the culvert wall on one side but long and at 30° angles on the other (Figure 13).

Specific design dimensions have been developed for the optimal baffle length, height and spacing combinations to give the most desirable conditions of flow, velocity, water depth and resistance to maximise upstream passage of large salmonids (Rajaratnam et al. 1988). Bates (1992) recommends the slot width and baffle spacing should be altered depending on debris size and bed material, to prevent blockage and filling.

Offset baffles are difficult and expensive to install in corrugated culverts because the angled baffle in each pair crosses several corrugations. The original designers (McKinley and Webb 1956) found offset baffles to be largely self-cleaning. Bates (1992) suggests offset baffles are best used at culvert slopes of 2.5–5.0%, with the perpendicular baffle being shortened or removed at lower slopes.

ii) Slotted weir baffles

Slotted weir baffles are baffles perpendicular to the flow with a central slot (Figure 14). This design is as effective at reducing velocities and increasing water depth as offset baffles of similar dimensions, but has the advantage of being much easier to install in both new and existing culverts (Rajaratnam et al. 1989b).

iii) Weir baffles

Weir baffles are small weirs installed in the culvert invert, perpendicular to the flow (Figure 15). Rajaratnam and Katopodis (1990) suggested weir baffles are less expensive to build than slotted weir baffles and are just as effective at reducing velocities and increasing water depth. Essentially, they create a pool and weir fishway and, although sediment deposition may occur during low discharges, this material is usually removed during floods.

Bates (1992) recommended that weir baffles should only be installed in culverts of 1.0% slope or less, and that their most appropriate use is to retain bed material. This ability to retain bed material could assist passage of our small indigenous species but, as discussed in Section 9.2.2, we found that the end of the baffles needed to be rounded to allow passage of smelt and inanga.

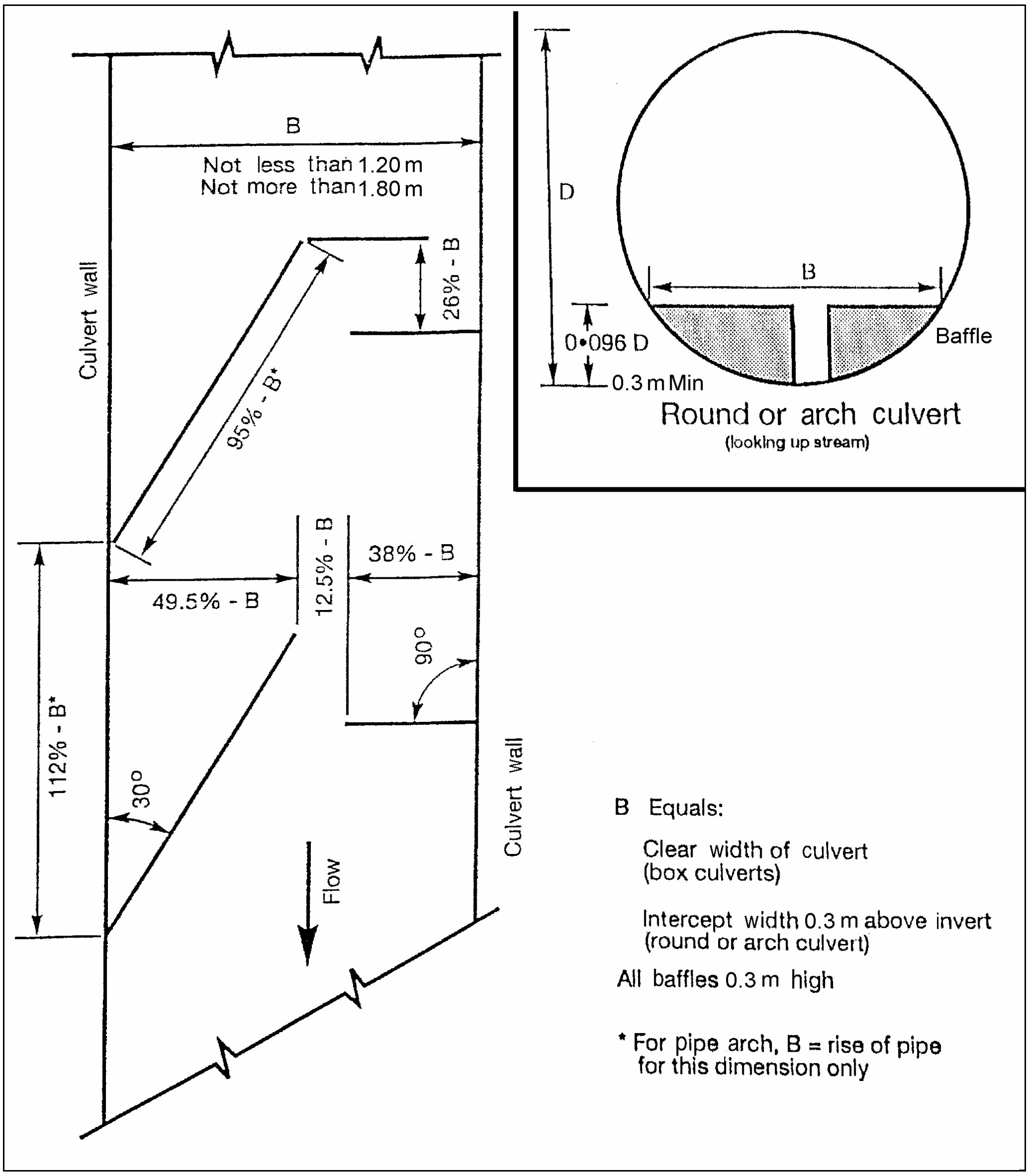

Figure 13. *Plan view (left) and cross-section (top right) of offset baffles. Dimensions and angles shown give the best performance (redrawn with permission from Baker and Votapka 1990).*

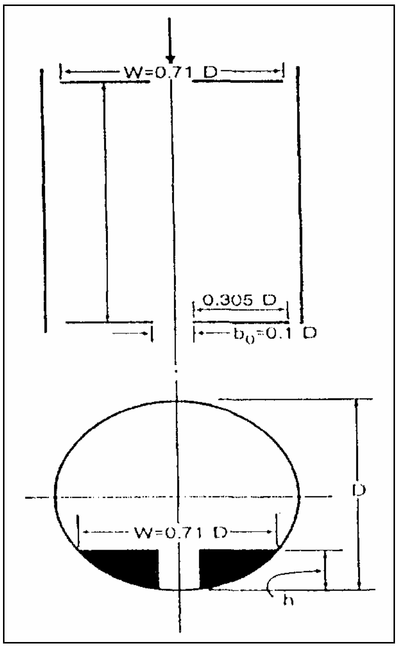

Figure 14. *Plan view (top) and cross-section (bottom) of slotted weir baffles. For the best design from Rajaratnam et al. (1989b); h = 0.1D or 0.15D at a spacing of 0.6D (where D = culvert diameter). b_o = width of the slot (redrawn with permission from Rajaratnam et al. 1991).*

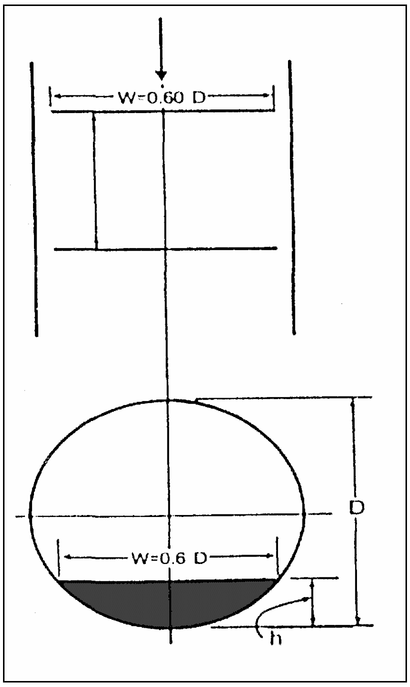

Figure 15. *Plan view (top) and cross-section (bottom) of weir baffles. For the best designs from Rajaratnam and Katopodis (1990); h = 0.1D or 0.15D at a spacing of 0.6D (where D = culvert diameter) (redrawn with permission from Rajaratnam et al. 1991). The edges must be rounded to ease passage of indigenous New Zealand species (see Section 9.2.2).*

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