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A Model Study of the Hydraulics Related to Fish Passage Through Backwatered Culverts

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Abstract: Due to the relatively low velocities of flow thought to be required for successful fish passage, stream crossing designs often require larger-sized culverts than is otherwise needed for flow passage, which results in correspondingly increased construction costs. In Canada, the design criteria for fish passage through culverts are specified in terms of the mean flow velocity. However, these criteria do not account for a fish's natural ability to seek out low velocity regions within the flow field. Studies have shown that the velocity distribution that exists within a culvert may provide for sufficient area of low velocity flow near to the boundaries for fish passage purposes. Moreover, if the invert of the culvert is embedded below the bed level of the stream or the culvert is operating under a backwater condition, the flow area for a given discharge is increased, which results in a corresponding decrease in the mean velocity of flow. The work described in this paper includes the initial findings from a model study that focuses on the impact of culvert embedment and backwater with respect to fish passage. This initial work examined only the effect of backwater on the velocity distribution within a non-embedded culvert. The flow depth and velocity distribution were measured at several locations along the length of a corrugated steel culvert using an acoustic Doppler velocimeter. The hydraulic conditions were varied between tests by changing the flow rate and the backwater condition. The culvert was set at a 0.72% slope and the invert was placed at the channel bed elevation. The hydraulic data were analyzed to identify the mean velocity of the flow, the evolution of flow development along the culvert length, and the area of flow within a culvert cross section that had velocities less than the mean velocity.

1. Introduction

In Western Canada, there are many stream crossings, and culverts are the most popular stream crossing structure because of their lower comparable cost to other alternatives (Katopodis 1992). In the past, culvert design focused primarily on the size of barrel required to pass a high flow event of a given exceedance probability (Gregory *et al.* 2004). However, with the growing concern of aquatic habitat degradation and blockage to fish migration, culverts must now be designed to satisfy two objectives: (1) to safely convey water from one side of a roadway embankment to the other, and (2) to maintain successful movement of fish within the stream.

Culverts designed for fish passage are relatively expensive to install, largely due to the design criteria thought to be required for successful fish passage. The current criteria generally focus on the water depth and velocity ranges that are felt to be necessary for fish passage under both high and low flow conditions. There are several accepted alternatives for modifying a standard culvert design to satisfy current fish passage requirements, which include increasing the culvert size, changing the culvert type, depressing the culvert invert, installing baffles or weirs, or using a stream simulation approach. The most common alternative is to increase the size of the culvert and to install rock material or baffles along the invert, which also increases the cost of the installation. The rock material is used to simulate the stream bed and velocity profiles of a natural stream, whereas the baffles are used to provide hydraulic obstructions at regular intervals that dissipate energy, increase overall effective roughness, create turbulent flow, and provide potential resting zones for fish (Alberta Transportation 2001). Baffles and weirs are economical for remedying existing culverts; however, they create an artificial environment, reduce culvert conveyance capacity, and require frequent maintenance and routine inspection. Using a stream simulation design is a more recent method for satisfying fish passage requirements. This method focuses on sizing and installing culverts to avoid constricting the stream or river channel. Where culverts can be installed with the same slope as the natural streambed, non-constricting culverts will normally provide water depths, velocities, bottom substrates and channel characteristics that are comparable to the natural stream (House *et al*. 2005). Well-designed culverts can maintain the continuity of stream bottom and hydraulic conditions, thereby facilitating passage for most aquatic organisms utilizing the stream. This design method also increases the cost of culvert installations due to the large spans generally required to avoid constricting the stream channel.

The requirement to design for fish passage through culverts is relatively recent; therefore, the knowledge on methods and techniques for facilitating fish passage is not complete and requires further research to improve the economics and environmental aspects of culvert design. For example, in Canada, the design criteria for fish passage through culverts are specified in terms of the mean flow velocity. However, these criteria do not account for a fish's natural ability to seek out low velocity regions within the flow field. Studies have shown that the velocity distribution that exists within a culvert may provide for sufficient area of low velocity flow near the boundaries for fish passage purposes (Behlke *et al*. 1991; Lang *et al*. 2004). For example, Ead *et al*. (2000) conducted a laboratory study of the velocity field in turbulent open-channel flow in a circular corrugated pipe and found that the velocities were relatively small near the boundaries of the pipes, thereby indicating the possibility that the low-velocity regions may be used for fish passage. Thus, there is question as to whether the mean velocity is an appropriate and proper criterion for assessing a fish's ability to traverse through a culvert. Furthermore, if the culvert is embedded, which means that the invert is placed below the bed level of the stream, then the flow area for a given discharge is increased and the mean velocity of the flow is decreased, provided that the culvert is flowing partially full. This condition could also occur for a culvert operating under a backwater condition, either occurring naturally or forced.

Because of the increasing costs of current methods of culvert installation due to fish passage requirements, Saskatchewan Highways and Transportation (SHT) is promoting the use of embedded culverts, which are thought to improve the hydraulic conditions for fish passage without significantly increasing installation costs. However, for this approach to be accepted by the Department of Fisheries and Oceans (DFO), there must be clear evidence that it provides for effective fish passage. This research program is directed at improving the understanding of the hydraulics of embedded culverts which, if successful from SHT's point of view, will provide the evidence that DFO requires. The work is being undertaken as a model study in a laboratory environment because a larger array of hydraulic and geometric conditions can be studied than is possible in a field setting. This results presented in this paper are focused solely on the effect of backwater on the velocity distribution within a non-embedded culvert.

2. Experimental Program

The culvert model studies reported herein were conducted in the Hydrotechnical Laboratory at the University of Saskatchewan. A Froude model was used for the study. Based on water surface profile calculations, available pump capacity, and flume dimensions, a 500 mm diameter, 8.0 m long circular annular corrugated steel culvert was placed at a 0.72% slope in a 1.21 m wide, 0.61 m deep and 20 m long rectangular flume having a recirculating flow system. The flow was subcritical for all test conditions. The annular culvert had standard 13 mm x 68 mm corrugations. An annular culvert was used to avoid the scale effect associated with a small-scale helical pipe and to properly represent the corrugation alignment most often found in large diameter culverts. Using a small-scale culvert with helical corrugations would have caused an asymmetrical transverse water surface profile due to the spiralling of the flow. From tests conducted in the laboratory, the Manning's n value of the model culvert was found to be 0.024, which is in agreement with commonly published values. To permit access to the flow within the culvert barrel for depth and velocity measurements, access holes were cut into the crown at 15 locations along the length of the culvert as shown in Figure 1. The holes were numbered 1 through 15, with 1 being the hole closest to the inlet.

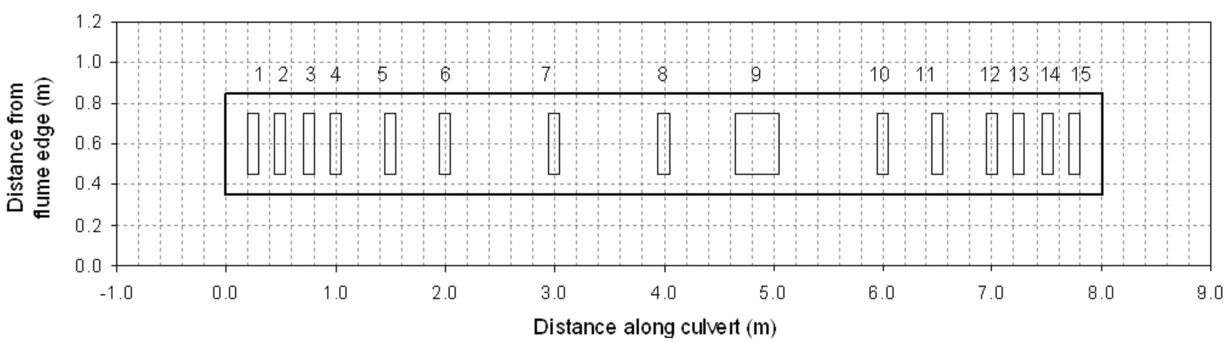

Figure 1. Plan view of culvert showing location and size of culvert access holes.

The flow rate was measured using the magnetic flow meter installed in the supply line. The water depths and temperature were measured using a point gauge and thermometer, respectively. Velocity measurements were taken using a down-looking 3D Sontek Micro Acoustic Doppler Velocimeter (ADV). This ADV probe has the ability to measure three dimensional velocities at a sampling rate of up to 25 Hz. Each point measurement was sampled for 10 minutes to ensure there were enough samples to obtain accurate average velocity and turbulence intensity values. The sampling volume (approximately 0.3 cm^3) in which the ADV makes velocity measurements is located 5 cm from the acoustic transmitter; therefore, the ADV is incapable of taking measurements at or within 5 cm of the water surface. The ADV was mounted on an apparatus that has the ability to rotate within a cross section of the culvert. This entire apparatus was positioned on a trolley that could traverse the length of the flume. The ADV was then positioned automatically using a LabVIEW program that controlled the ADV apparatus. Figure 2 shows photographs of this apparatus.

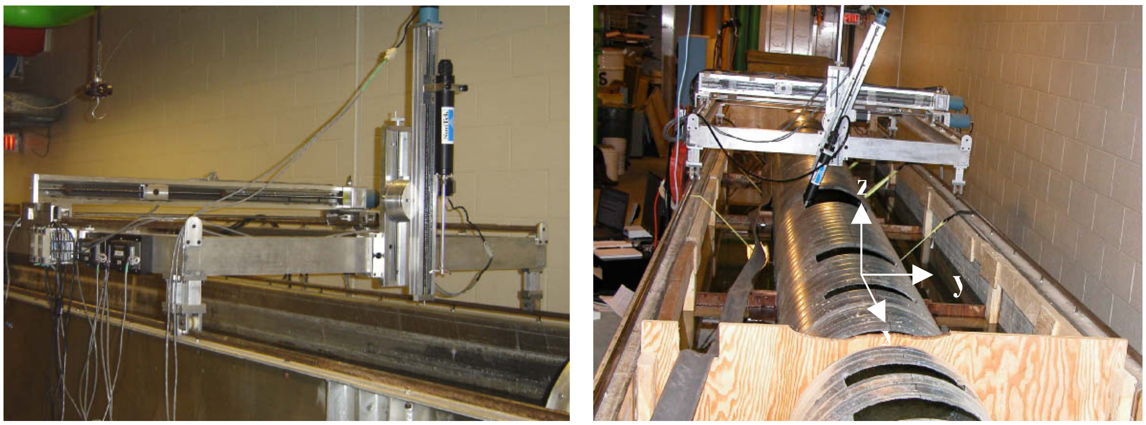

Figure 2. Apparatus for ADV movement.

Preliminary data collection was carried out to confirm model performance, to provide an understanding of the conditions being tested, and to become familiar with the ADV and the experimental apparatus. Once initial testing was complete, cross sectional velocity data were collected for the flow conditions and locations outlined in Table 1. The letters and numbers used for the naming of each full cross section measurement were chosen to provide information regarding each measurement. For example, the first two numbers represent the discharge, while the following letter and number(s) represent the hole in which the measurements were taken. If there was a backwater condition, the name ended with TW1 or TW2 indicating that the flow was set at tailwater condition 1 (which was 4.4 cm above normal depth) or tailwater condition 2 (which was 6.4 cm above normal depth), respectively. With the exception of the four backwater tests, the tailwater depth was set to normal depth, Y_n. The culvert was placed at bed elevation for all test conditions reported in this paper. Experiments with several degrees of embedment are not yet complete; those results will be presented in a future paper.

Table 1. Test matrix of flow conditions reported herein.

Cross section	Discharge (L/s)	Test hole number	Distance from inlet (m)	Slope (%)	Embedment (cm)	Tailwater depth (cm)
50H2	50	2	0.5	0.72	0.00	Y_n of 18.4
50H8	50	8	4.0	0.72	0.00	Y_n of 18.4
50H14	50	14	7.5	0.72	0.00	Y_n of 18.4
50H14TW1	50	14	7.5	0.72	0.00	22.8
50H14TW2	50	14	7.5	0.72	0.00	24.8

70H2	70	2	0.5	0.72	0.00	Y_n of 22.1
70H8	70	8	4.0	0.72	0.00	Y_n of 22.1
70H14	70	14	7.5	0.72	0.00	Y_n of 22.1
70H14TW1	70	14	7.5	0.72	0.00	26.5
70H14TW2	70	14	7.5	0.72	0.00	28.5

For each discharge condition, a water surface profile was obtained throughout the length of the culvert. Also, centerline vertical velocity profiles were collected for five locations along the length of the culvert: 0.25, 1.0, 2.0, 3.0, and 5.0 m from the inlet (i.e. holes 1, 4, 6, 7 and 9). These five profiles were in addition to the three centerline vertical velocity profiles obtain during the three full cross section measurements taken at 0.5 m, 4.0 m and 7.5 m from the inlet (i.e. holes 2, 8 and 14).

3. Results

The water surface profiles within the model culvert for discharges of 50 and 70 L/s are shown plotted versus elevation from the flume floor in Figure 3. For these measurements, the tailwater was set to normal depth. As expected, there is a slight decrease in surface water elevation at the inlet where the water is accelerating.

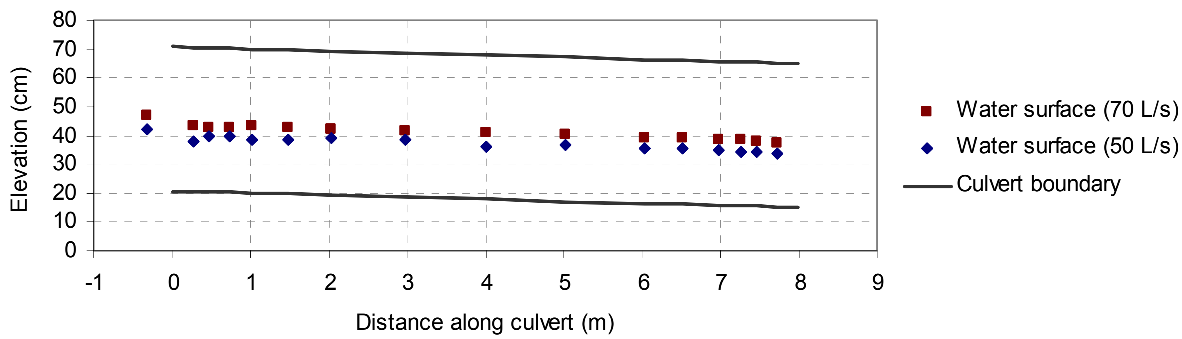

Figure 3. Water surface profiles for discharges of 50 L/s and 70 L/s.

For the backwater test conditions, water surface profiles through the culvert were computed using the direct step method and the experimentally-determined value of Manning's n of 0.024. It was determined that the backwater profile extended 5.5 m and 8.0 m upstream for tailwater conditions 1 (which was 4.4 cm above the water surface for normal depth) and tailwater condition 2 (which was 6.4 cm above the water surface for normal depth), respectively.

For each discharge condition, centerline vertical velocity profiles in the streamwise direction were measured at eight locations along the length of the culvert: 0.25 m, 0.5 m, 1.0 m, 2.0 m, 3.0 m, 4.0 m, 5.0 m and 7.5 m (i.e. holes 1, 2, 4, 6, 7, 8, 9 and 14). Figure 4 shows the profiles overlaying each other for discharges of 50 and 70 L/s. In the figures, V_x is the streamwise velocity.

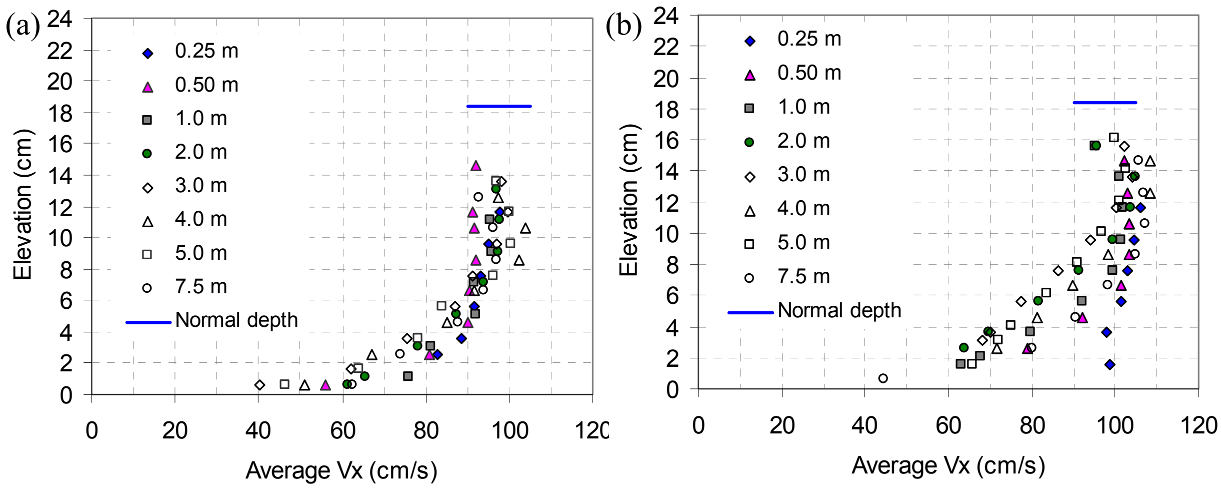

Figure 4. Centerline vertical velocity profiles for (a) 50 L/s and (b) 70 L/s.

The water depths, Y_o, mean velocities, V_{mean}, maximum velocities, V_{max}, and the maximum turbulence intensities, I_{max}, for each cross section are listed in Table 2. V_{mean} was calculated by dividing the measured discharge by the flow area determined from the measured depth of flow. The turbulence intensities were calculated by dividing the root mean square of the velocity fluctuations by V_{mean}. As expected, the mean velocities and turbulence intensities of the cross sections measured under tailwater conditions 1 and 2 are lower than those measured at normal depth.

Table 2. Water depths, mean velocities and turbulence intensities, and maximum velocities and turbulence intensities measured for each cross sectional measurement.

Cross section	Y_o (cm)	V_{mean} (cm/s)	V_{max} (cm/s)	I_{mean}	I_{max}
50H2	19.5	70.9	92.4	0.22	0.88
50H8	18.6	75.5	104.0	0.31	0.83
50H14	19.1	72.3	97.0	0.25	0.67
50H14TW1	22.8	57.2	78.2	0.20	0.52
50H14TW2	24.8	51.3	69.4	0.17	0.36
70H2	23.4	77.5	104.2	0.21	0.73
70H8	22.6	81.3	108.4	0.23	0.40
70H14	22.8	80.3	107.1	0.23	0.37
70H14TW1	27.6	66.0	88.9	0.21	0.72
70H14TW2	28.9	59.6	79.9	0.19	0.47

The percentage of the flow area with velocities less than V_{mean} for each cross section is outlined in Table 3. Here, V_{mean} corresponds to the normal depth condition so that all comparisons are made to the same base value. As shown by the results in Table 3, when the tailwater was set at normal depth, approximately one-third of the flow area had streamwise velocities, V_x, less than V_{mean}. However, the percentage of flow area less than V_{mean} increased significantly when a backwater condition occurred. For example, increasing the tailwater depth by 6.4 cm (which was approximately one-third of the normal depth) caused the velocities within the flow area to be 100% less than V_{mean}. The results in Table 3 also show that there is a small percentage of flow area within a cross section that is less than $0.75V_{mean}$ and virtually no flow area less than $0.5V_{mean}$.

Table 3. Area of each cross section with respect to V_{mean}.

Cross section	Flow area (m^2)	Area < V_{mean}	Area < $0.75V_{mean}$	Area < $0.5V_{mean}$
50H2	0.071	32.1%	14.6%	5.68%
50H8	0.066	43.7%	15.6%	0.17%
50H14	0.069	37.0%	6.6%	0.00%
50H14TW1	0.087	77.6%	27.2%	0.00%
50H14TW2	0.097	100%	41.3%	0.66%
70H2	0.090	19.0%	5.58%	1.68%
70H8	0.086	34.6%	4.65%	0.00%
70H14	0.087	31.1%	2.28%	0.00%
70H14TW1	0.106	64.3%	22.0%	1.05%
70H14TW2	0.117	100%	34.4%	0.77%

Figures 5 and 6 show contour plots of the streamwise velocity, V_x, non-dimensionalized using V_{mean} for the two backwater conditions as measured at hole 14 near the culvert outlet. The dark shaded area represents the area within the cross section that has velocities greater than the mean velocity, while the light shaded area represents velocities less than the mean velocity. The dots on the figures represent the measurement locations. As shown in Figures 5(a) and 6(a), the velocities are as great at 1.3 times the mean velocity for cross sections measured with the tailwater depth equal to the normal depth. .

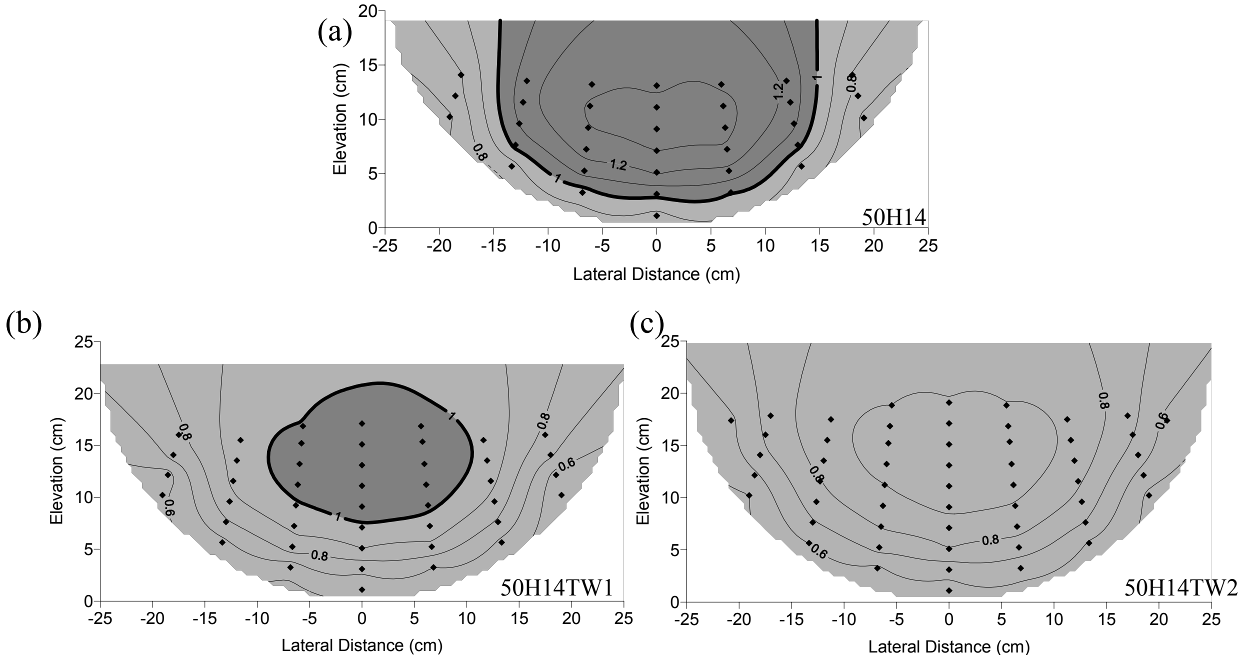

Figure 5. Distribution of Vx non-dimensionalized with respect to V_{mean} at hole 14 for a discharge of 50 L/s and: (a) tailwater depth set at normal depth, (b) tailwater depth set at 4.4 cm above normal depth, and (c) tailwater set at 6.4 cm above normal depth.

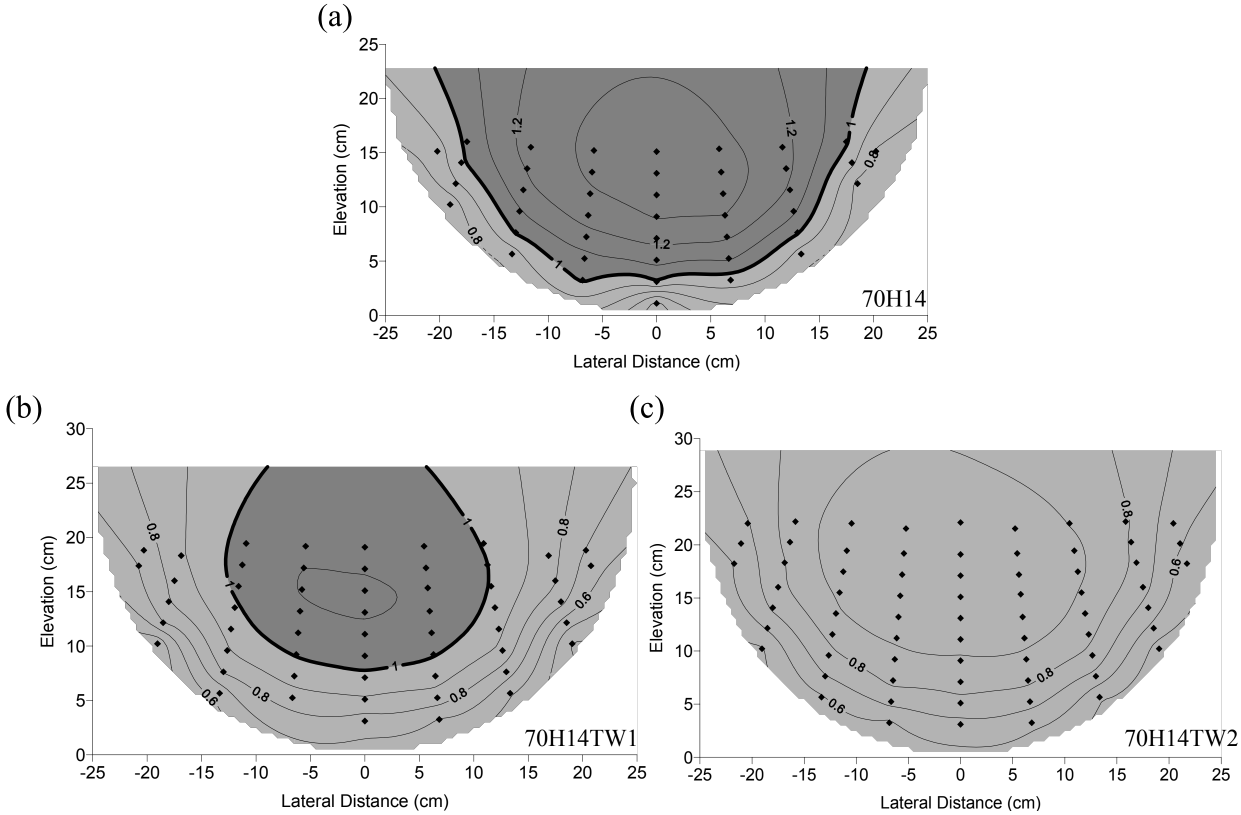

Figure 6. Distribution of Vx non-dimensionalized with respect to V_{mean} at hole 14 for a discharge of 70 L/s and: (a) tailwater depth set at normal depth, (b) tailwater depth set at 4.4 cm above normal depth, and (c) tailwater set at 6.4 cm above normal depth.

The streamwise velocity contour plots for each cross section were used to perform a volume and area integration in order to determine a discharge and mean velocity value, respectively. Comparisons of the measured and computed values are shown in Table 4. The integrated discharge values are, on average, 7% higher than the measured discharge values, while the integrated velocity values are, on average, 8% higher than the measured velocity values. The differences could be because of the lack of ADV measurements made within the top 5 cm of the water surface, thereby requiring that the velocities in that region be estimated. Overall, the comparison is reasonable.

Table 4. Comparison of the measured discharge and mean velocity data to the values found by integrating the contours plots.

Cross Section	Q (L/s) measured	Q (L/s) integrated	Q % Diff.	V_{mean} (cm/s) measured	V_{mean} (cm/s) integrated	V_{mean} % Diff.
50H2	50.1	52.2	4.1	70.9	74.1	4.4
50H8	50.1	50.8	1.4	75.5	77	2.0
50H14	50.1	53.1	5.8	72.3	77.5	6.9
50H14TW1	50.1	54.3	8.0	57.2	62.6	9.0
50H14TW2	50.1	53.9	7.3	51.3	55.6	8.0

70H2	70.0	80.2	13.6	77.5	89.3	14.1
70H8	70.0	76.0	8.2	81.3	88.7	8.7
70H14	70.0	77.2	9.8	80.3	88.9	10.2
70H14TW1	70.0	74.3	6.0	66.0	71.8	8.4
70H14TW2	70.0	74.0	5.6	59.6	64.4	7.7

Recently, it is has been suggested that turbulence intensities within a culvert barrel may influence a fish's swimming performance and/or choice in swimming location (Cotel et al. 2006; Lupandin 2005). To this end, an initial attempt at studying the turbulence intensities was made within the model culvert barrel. The distributions of the magnitude of the turbulence intensities, I_{mag}, are plotted in Figure 7. The contour plots on the left side are for a discharge of 50 L/s, while those on the right side are for a discharge of 70 L/s. The top plots (i.e. Figures 7(a) and 7(b)) where taken at hole 2, the middle plots (i.e. Figures 7(c) and 7(d)) where taken at hole 8, and the bottom plots (i.e. Figures 7(e) and 7(f)) were taken at hole 14. In both cases, the tailwater depth was set to the normal depth of flow. Of course, as with the velocity data presented earlier, it is important to appreciate that the ADV is incapable of taking measurements within 5 cm of the water surface; therefore, caution should be exercised when comparing the top 5 cm of these contour plots. It is also to be noted that, at this juncture, there is some uncertainty as to how the turbulence intensities would change with the physical dimensions of the problem (i.e., potential scale effect).

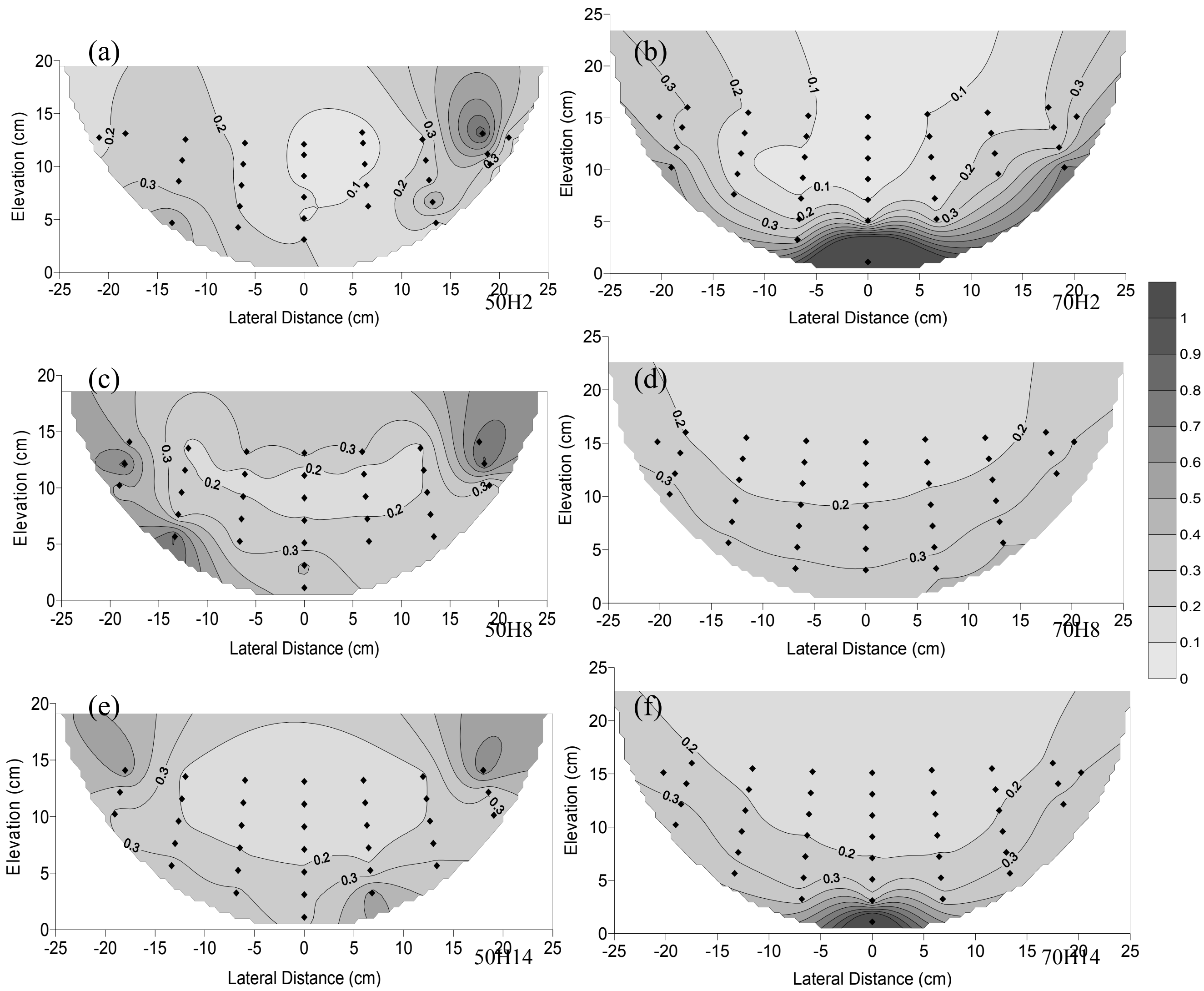

Figure 7. Distribution of I_{mag} for (a) 50 L/s at hole 2, (b) 70 L/s at hole 2, (c) 50L/s at hole 8, (d) 70 L/s at hole 8, (e) 50 L/s at hole 14, and (f) 70 L/s at hole 14.

In general, these plots show that the highest turbulence intensities occur near to the boundaries of the culvert. Also, as shown in Figures 7(a) and 7(b), the minimum I_{mag} is 0.1, which occurs near to the culvert inlet. The minimum I_{mag} occurring in the other four plots is 0.2. As the results show, especially in Figures 7(d), 7(e) and 7(f), the majority of the cross section area contains turbulence intensities of 0.1 to 0.3. These contour plots also appear to have a few inconsistencies. Firstly, the plots for discharges of 50 L/s appear to have specific, circular regions that contain the highest I_{mag}, but the plots for discharges of 70 L/s show only a gradual increase in I_{mag} as toward the culvert boundary. Secondly, it appears that the maximum I_{mag} occurs near to the water surface for a discharge of 50 L/s, but near to the culvert invert for a discharge of 70 L/s. Lastly, in each of Figures 7(b) and 7(f), there is a concentrated area of high turbulence intensity near to the culvert invert, which does not occur in any of the other plots. The reasons for these inconsistencies are uncertain at this time.

4. Conclusions

The velocity and turbulence intensity distributions were studied in a model culvert for different backwater and discharge conditions. Specifically, the area within a cross section was studied in order to determine the area potentially available for fish passage. For conditions in which the tailwater depth was equal to normal depth, approximately one-third of the flow area had a velocity that was less than the mean flow velocity. Creating a backwater condition significantly increased the amount of area that contained velocities less than the mean velocity. For the conditions studied, increasing the tailwater depth by approximately one third of the normal depth caused the entire flow area near the outlet to be less than the mean flow velocity. The turbulence intensities were higher near the culvert boundaries. The majority of the flow area has intensities between 0.1 and 0.3. There were several inconsistencies found when comparing the turbulence intensity contour plots, and the reasons for the inconsistencies are uncertain at this time.

6. Acknowledgements

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