MEMORANDUM

TO: Carina Chan
FROM: Jim Ji
DATE: December 07, 2021
SUBJECT: Preliminary Design for the UW Bypass Channel Culvert Crossing Replacement

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1.0 Introduction

Waterloo Engineering Ltd. has been sanctioned to provide a design for the replacement of the culverts for the bypass channel of Columbia Lake. The bypass channel was excavated in 2005 as phase 1 of the restoration of Columbia Lake. The replacements of the culvert crossing mark the beginning of phase 2 of the project.

1.1 Site Location

The site of the project will be at one of the four main locations at the University of Waterloo. Columbia Lake is situated withing the UW Environmental Reserve, which next to the North Campus (research facilities). A map of the 4 features is shown below (**Figure 1**).



Figure 1 University of Waterloo Campus Master Plan 2009

The lake is in between the, yet to be developed, Northwest Campus and the North Campus. This man-made lake is used to control floods, is used as a reserve for aquatic life and is a site used for research purposes as well.

1.2 Background

The man-made Columbia Lake was originally designed to provide relief and control over floods for the University of Waterloo and downtown Waterloo as well as for recreational purposes, in 1967. As time went on the overall health of the lake declined, bearing poor conditions for aquatic life. This was due to a rising in water temperature, as well as a build up of sediments.

It was determined that the water from Columbia Lake was carrying significant amounts of phosphorus into Laurel Lake. A dam was constructed, but it negatively affected the aquatic life as blockade, preventing aquatic movement.

A remodelling project was authorized in 2004, to improve the overall quality of the water in the lake. The improvements were delayed until 2005. The lake was drained, and different depths were created to create different habitat zones and vegetation was added to improve aquatic life. Forebays were created at the north of the lake. These were created to keep sediments from entering the lake as they are accumulated in the forebays. To reduce further erosion from the wind, artificial beach flats were put in on the east shores of the lakes. In phase one, a temporary trapezoidal bypass channel was created to improve the flow of water in the lake, to increase the diversity in fish and to allow them to move more freely. After this, the project was lacking in budget and the project was not progressed any further.

1.3 Project Motivation

The bypass channel was originally supposed to be a temporary solution to improve the flow of water and fish. However, the bypass channel has remained for fifteen years. Many issues have been called to attention. Firstly, the upstream channel and the existing culverts are oversized and undersized, respectfully. The first tasks of phase 2 are to replace the two culverts. Secondly, the bypass channel has a build up of sediments, preventing any vegetation growth. Thirdly, since the culverts are undersized, they do not act as an adequate passageway for fish. Finally, since the gravel roadway is so low, the freeboard is much lower as well. This can cause a problem because this system would not hold if a large storm were to occur.

1.4 Stakeholders

The stakeholders of this project have made it known that the design of the culvert replacements should improve the flow of water, sediments, and aquatic life. The design should also allow for the roadways width to remain the same or to be increased and for the impacts of constructions to reduced towards the environment. The stakeholders of the project include:

i. the University of Waterloo (UW)
ii. the Grand River Conservation Authority (GRCA)
iii. the City of Waterloo
iv. the Regional Municipality of Waterloo

v. the Ministry of the Environment and Climate Change (MOECC)

1.5 Purpose/Scope of Report

The motivation behind this report is to introduce the project and establish the objectives, the constraints, and the criteria behind the design of the culverts. It also formally presents the different design options and the final recommended design. The final recommended design was based off the following:

i. a topographic map of the present culvert crossing
ii. an analysis of the different design options for the culvert replacement
iii. a decision for the suitable design option
iv. the recommended sizing for the recommended culvert design, following the constraints

2.0 Existing Culvert Crossing

2.1 Site Description

The site of the project is a section of private land, owned by the University of Waterloo. It is adjacent to the North campus. There are many structures here, including the B.E.G. Hut (Building Engineering Group) and greenhouses, used for research and experimentation, and the U.W. weather station, which tracks the weather conditions on the campus.

The following image is a drone image of the project site from Google Earth. The Bypass channel can be seen at the top of the site and the U.W. weather station can be seen to the left, followed by the B.E.G. hut and the greenhouses to the right, in **Figure 2**.



Figure 2 The project site facing south.

The site has unmaintained gravel roads with no curb. The road is used to reach the U.W. weather station, the private lands, and the other structures on the site. It is also used recreationally for the general public. The site is open for walking, fishing, picnicking, etc.

A great build up of sediments was found at the time of the site visit, as water levels were lowered. The culverts were also a location of sediment build up. The banks were determined to be stable and are not in danger due to erosion. Site visits were made at a later time, where the water levels were normal. It was determined that there were large amounts of suspended sediments upstream from the existing culverts. It was also determined that there was no movement of water in the bypass channel.

2.2 Site Survey

A site survey was carried out using a GPS instrument, on September 21, 2021. The surveyors collected around 1400 data points. Tree inventory and the linear features of the B.E.G Hut, the greenhouses, the gravel roads, and the lane were established during this survey. The invert elevations of the culverts were also recorded. From the 1400 data points, the eight points included in **Figure 3** represent the data of a cross-section of the bypass channel. This cross-section upstream from the current culverts.

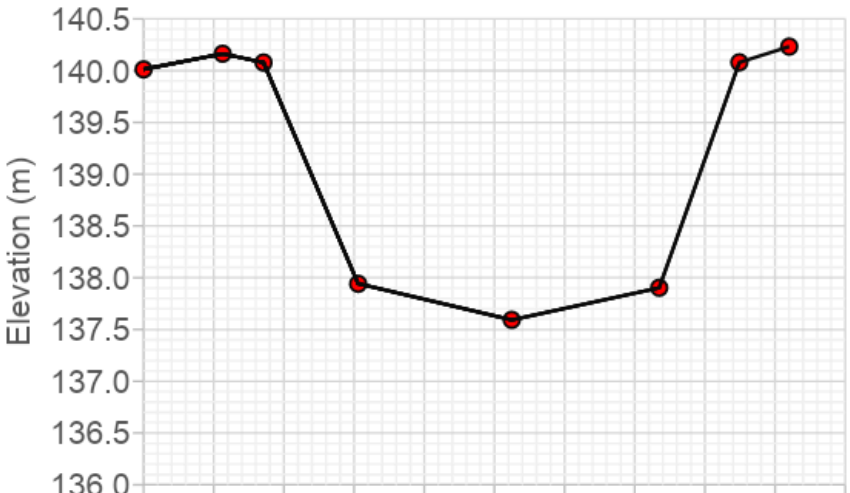


Figure 3 Data points of cross-section of bypass channel

This information can be seen on the topographic map of the current culverts and crossing, as shown on **Drawing T-1**. The northing, easting, chainage, and elevations of each point was recorded during the survey.

2.3 Description of Existing CSP Crossing

The existing culverts are considered CSP culvert barrels. These types of culverts are lower in price in comparison to the other options. It is not demanding to install these types of culverts, they are manufactured off-site, and are transported onto site.

The existing culvert connects the water from the bypass channel into Columbia Lake. The gravel road is laid on top of the crossing and provides access to the U.W. weather station and to the private sections of turf.

The two existing culverts are shown under the bypass crossing as shown in **Figure 4**.



Figure 4 End of bypass channel with culverts under gravel road crossing

As shown in **Figure 4**, the existing culverts are very undersized in comparison to the bypass channel as they only account for approximately 5% of the width of the bypass channel. This is does not promote

an adequate flow of water and does not favour the movement of aquatic life. Since the depth cover of the culverts is less than 0.5 m, there is very limited freeboard. If a flood were to occur, it would surmount the crossing and it is probable that it would sustain damage as well.

The technical specifications of the existing culverts are presented in **Table 1**.

Table 1. Summary of Existing Culvert

Hydraulic Parameter	
Number of Barrels	2
Culvert Diameter (m)	0.90
Barrel Length (m)	15.36
Barrel Slope (%)	0.90%
Top of Road Elevation	138.82
Downstream Invert Elevation	137.27

From the values presented above, it can be seen that the freeload of this crossing is very limited as the difference between the elevation of the top of the road and the elevation of the invert is only a meter and a half. Taking the in consideration that the diameter of the culver is 0.9 meters, there is not much room in the case of flood conditions. It can also be seen that culvert diameters too small. Culvert diameters of 0.9 meters is not enough to promote aquatic life and leads to a build up of sediments.

3.0 Assessment of Design Alternatives

3.1 Design Objectives

The stakeholders of the project have identified five objectives for the design of the culvert replacement. These objectives were determined to ensure the improvement of the waterway and to certify the sustainability of the water system.

1. To enhance the hydraulic conveyance of the waterway. Low hydraulic conveyance is observed with the current culverts, leading in a build up of sediments. It needs improvement for a better distribution of sediment across the lake.
2. The roadway needs to be widened to allow for longer culverts.
3. Natural processes for sediment transportation need to be developed to ensure better water flow as sediment build up can clog the culverts and to prevent a decrease in water depth in areas with heavy sediment deposition.
4. Favorable conditions need to be brought up for aquatic passage as the existing culverts are too small to promote aquatic movement. This can cause the biodiversity of the lake to decline.
5. Impacts to the environment need to be reduced throughout the construction progress as to not disturb the natural reserve adjacent to the project site.

3.2 Conceptual Alternatives

Five different courses of action were determined to help identify the right option for the culvert replacement. The alternatives are listed below with advantages and disadvantages.

1. The first option to this project was no action done. Under this alternative, no changes were to be done to do current culvert crossing. This course of action was eliminated as the state of the current culverts do not fulfill the design objectives and project goals. It is used as a basis for comparison to the other options.
2. The second option is replacement in kind. This course of action would be relatively cheap as the culverts are CSP culverts, which are cheaper and easier to install. However, this course of action would not be needed as the current culverts are still in good condition. Further, it would not fulfill the design objectives as it would not resolve the issues with sediment build up and fish passage due to low conveyance. This course of action was removed from consideration.
3. The third course of action is to install multiple culverts along side the existing two. This alternative would increase the site's conveyance. However, it does not satisfy the remaining objectives as the culverts would be the same size as the existing two. It would not address the issue of sediment build up in the culverts and still would not promote the movement of the aquatic life. This course of action was removed from consideration.
4. Bottomless culverts were put into consideration as they are great for waterflow and are favorable for simulating streams. They also promote aquatic movement. The downside of these culverts is that they need to be designed with established and firm bases so that the culvert and the crossing are supported and do not crumble. Flood conditions and high velocities of water could destroy the footing, leading to the crumbling of the crossing.
5. The final alternative is embedded or buried culverts. The opening of the culvert is installed under the bed of the stream. Natural substrate is added into the culvert bottom to continue the stream bed and to maintain the flow of the water. The advantage to this alternative is that it promotes the movement of the wildlife and will have a better basis compared to bottomless culverts. This will ensure that it will last longer and be better at handling flood conditions.

From all the conceptual alternatives. The bottomless culverts and embedded culverts can be said to be best possible courses of action to this project as they fulfill the design objectives. Further evaluation of the options is done to determine the best course of action.

3.3 Assessment Criteria

To reach an agreement on the best possible course of action, assessment criteria was determined to assess every design option. All criteria taken into account are listed below.

1. The primary assessment of the design options is evaluated on how well it fulfills the design objectives. This is the most important criteria as meeting design objectives will mean the fulfilling of the project goals, outlined by the stakeholders of the project.

2. The design alternatives are assessed based on their sustainability. They are assessed by how much they increase conveyance, how they are installed, how well it promotes the movement of aquatic life and how effectively the sediments are transported. The sustainability, in terms of maintenance and the durability of the culverts and the crossing must also be considered.
3. The environmental impacts of the construction process of the culvert replacement and the turning circle are assessed to see which alternatives is best suited for this project. Design options that do not negatively affect the surrounding environment of the reserve, adjacent to the project site, will be more desirable.
4. Design alternatives must be cost effective to be able to be taken into consideration for the project. When comparing design options, the most sustainable and cost-effective solution is going to be picked.

3.4 Decision Matrix

The analysis of the criteria of each design alternative is done visually through a decision matrix. Each design option is compared to one another to determine the best design for the project. They are all assigned a ranking of "Low", "Moderate" or "High" as seen in **Table 2**.

Table 2. Decision Matrix

Alternative	Achieves All Design Objectives	Suitable for Site	Minimizing Environmental Impacts	Cost Effectiveness	Recommended for Conceptual Design
No Action	No	Low	High	High	No
Replacement In Kind	No	Low	High	High	No
Multiple Culverts	No	Moderate	Moderate	Low	No
Bottomless Culvert	Yes	Moderate	Moderate	Moderate	Yes
Embedded Culvert	Yes	High	High	Moderate	Yes

From the decision matrix, it can be seen that the first three design options are not suitable for this project. They do not fulfill the design objectives and are taken out of consideration. However, they were the more cost-effective options. Replacement in kind had a high-cost effectiveness due to the fact that it would be CSP culverts that are cheaper and easier to install in comparison to embedded culverts that require extra digging and the addition of natural substrate to the inside of the culverts.

3.5 Recommended Alternative

The two viable design options are the bottomless culvert or the embedded culvert.

The bottomless culvert needs extra designing and construction to establish adequate footing and base to support the culvert and gravel road crossing. To add on, the base needs to be built in beneath the streambed. These extra steps will extend the time it takes to complete the construction, which in turn, will increase the budget. Even with proper footing, concerns of the base failing are still present.

Due to these facts, an embedded/buried culvert has been established to be the recommended option to this project as it satisfies the design objectives.

i. The streambed will be lay flush at a continuous elevation, improving water flow.
ii. The velocity of water will be cutdown down the culvert.
iii. Hydraulic conveyance will be improved.
iv. Reducing sediment build up upstream of the culverts and within the culverts as well.
v. Will promote healthy aquatic passage, increasing the biodiversity of the lake.

To conclude **Chapter 3**, an embedded culvert will be recommended to the stakeholders as the optimal design option to fulfill the design objectives.

4.0 Recommended Replacement Crossing

4.1 Recommended Culvert Replacement

The design option, for the replacement crossing, that was chosen is the embedded culvert. This design and all of its features will be formally presented in this chapter.

An elementary diagram of an embedded culvert design is shown in **Figure 5**.

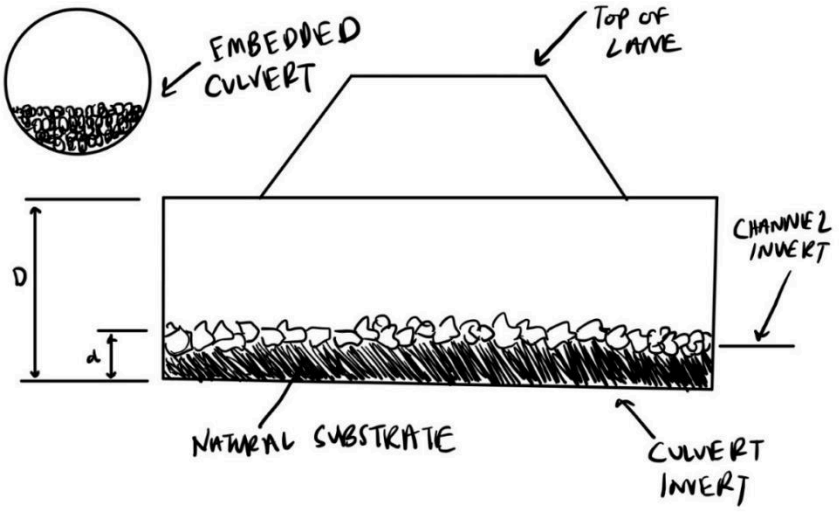


Figure 5 Embedded/Buried Culvert

For the type of barrel used for the embedded culvert replacement design, a CSP culvert barrel was chosen for the project. Seven reasons as to why this type of barrel is used is presented below:

i. CSP culvert barrels are frequently used for embedded culverts are they work very well for this purpose.
ii. Local manufacturers produce a large variety of CSP barrel sizes.
iii. The installation of CSP culverts is fast and less challenging to install compared to the other culvert options. They also do not have a large impact on the waterway and the environment around the site.
iv. CSP barrels are very cost-effective in comparison to other design options. They will cost a lower amount to purchase and transport to the site.

v. CSP culverts require minimal maintenance, long term.
vi. CSP culverts are very durable and will be able to last a very long time.
vii. The specified cover agrees with level of the proposed crossing.

Embedded culverts are installed at an elevation beneath the streambed where ten to fifty percent of the culvert opening is underground. Natural substrate is added into the culvert so that the elevation of natural substrate aligns with the elevation of the streambed. This allows for roughness to be created, along with natural habitats for wildlife. It will also help promote aquatic passage as fish can move more freely down the culvert.

4.2 Design Criteria

Design criteria has been put into place to ensure that the proposed culvert and the replacement crossing are long-lasting and do not fail under harsh conditions. The following criteria must be satisfied by the design. Criteria is based off local and provincial culvert design customs.

The criteria involve design discharge and the freeboard, which is the distance between the water level and crossing above. Two criteria were established for the design of the replacement project to follow.

i. A return period design flow for the project must be minimum of 10 years.
ii. The minimum allowed freeboard for this design is 300mm.

The design must adhere to these two criteria, set by agencies. Failure to do so will result in the design not being approved.

4.3 Design Constraints

The design has four constraints that have been established. The design must satisfy these conditions in order to function properly and to adequately fulfill the design objectives.

The four constraints are listed as follows.

i. The embedment ratio is the ratio between the depth of embedment and the diameter of the culvert. The site must have an embedment ratio greater than 30% as established by local agencies.

ii. A geotechnical evaluation was done on the site. It has been determined that erosion is probable downstream of the culverts. To prevent this a maximum velocity of 2 m/s has been recommended. The stakeholders of the project have concurred on this constraint (Chan, 2020).
iii. Laurel Creek has had a hydraulic study done on it. From this study, a tailwater elevation was determined. As tailwater effects culvert and the water that flows through it. It is considered a constraint as it must follow the first criteria (Babra, 2019).

iv. The elevation of the embankment has become a constraint as the Grand River Conservation Authority (G.R.C.A.) has raised their concerns. An increase in the elevation of the embankment can lead to the rising of water levels upstream during a flood. Therefore, a maximum embankment elevation has been imposed onto the project by the G.R.C.A.

Outside agencies and companies have imposed constraints on specific characteristics of the project. For the design to work and be sustainable and for the project to continue on, these constraints must be followed.

4.4 Preliminary Design

There are many characteristics that affect the flow of water through the culverts. These include the conditions of the inlet and outlet and the physical properties of the culvert barrel, such as size, slope, roughness, and slope. Using this information, the behavior of the water through the culverts can be determined.

Since the culvert has a roughness, the water that passes through it will experience a loss in energy due to friction and other sources. The energy loss all together will result in a difference of elevations between the tailwater and the headwater, where the elevation of the headwater will always be higher. This is illustrated in **Figure 6**, as well the flow of the water being defined at four points on the channel invert.

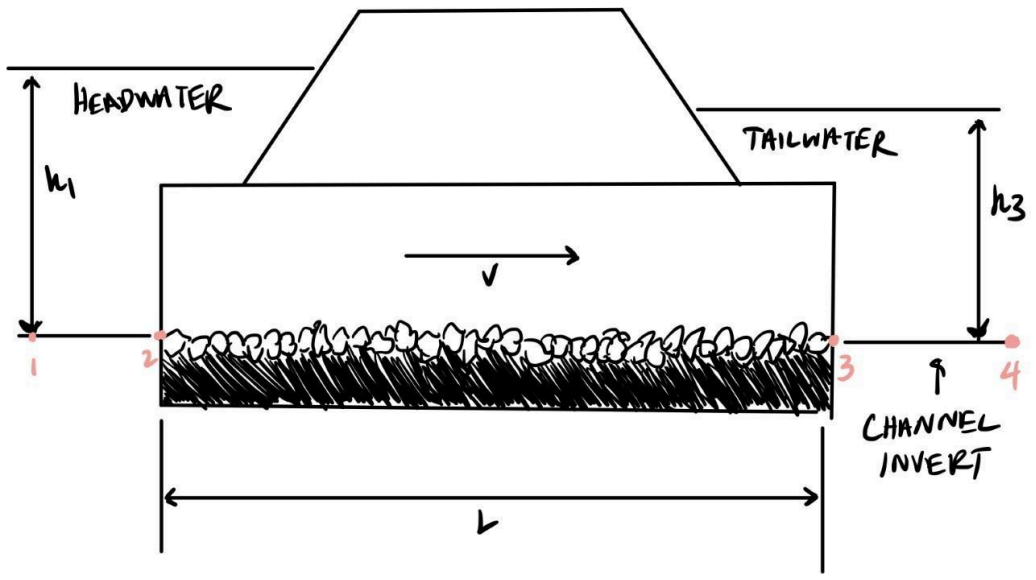


Figure 6

Energy components at headwater and tailwater

From the rearrangement of the Bernoulli's Equation (Chow, 1950), which balances energy values for the headwater and tailwater, the elevation of the water levels with respect to the channel invert can be found, as shown in **Equation 1**.

$$h_1 = h_3 + \frac{V^2}{2gC^2} + \frac{LQ^2}{k\hat{}2}$$

This equation can be used to determine the headwater and tailwater elevations, both important values for this project. The tailwater elevation for this project was determined from the hydraulic study done at Laurel Creek. It also is important due to the fact that it is affected by the 10-year return period design flow.

The final recommended replacement culvert has been determined after analysing the data to ensure all constraints and criteria are satisfied. Further, a cost analysis has been done with every radius size of barrels to determine the cheapest culvert design. The data is summarized in **Table 3.**

Table 3. Performance of Recommended Culvert Replacement

Design Discharge (m3/s)	11.0
Number of Culvert Barrels	2
Culvert Diameter (mm)	2.400
Embedment depth (m)	0.816
Channel Invert Elevation	137.268
Culvert Invert Elevation	136.452
Culver Obvert Elevation	138.852
Top of Road Elevation	140.568
Headwater Elevation	139.391
Tailwater Elevation	139.018
Velocity Through Culvert (m/s)	1.736
Freeboard (m)	1.177
Depth of Cover	1.716
Total Mass (kg)	7896

Two 2.400 mm diameter CSP culverts was determined to be the most cost-effective size, while satisfying every constraint and criteria. The length of the culvert is 28 m. As mentioned before, the tailwater elevation of 139.018 was predetermined during the hydraulic study (Babra, 2019)

The replacement design has a reported embedment ratio of 34%, which satisfies the required minimum of 30% for embedment ration. The velocity through each culvert is a reported 1.736 m/s. The velocity restraint is fulfilled as it is less than the maximum velocity of 2 m/s per culvert. The tailwater elevation corresponds to the criteria as it will withstand the return period. Finally, the new elevation of the roadway does not exceed the maximum value provided by the modelling of the G.R.C.A.

All physical characteristics of the replacement culvert ensures that both barrels and the replacement crossing will withstand a heavy flow of water once every ten years. The new design has a freeboard of

1.177 m, which satisfies the criteria of needing a freeboard greater than 0.3 m. Since all the criteria and constraints are fulfilled by the design, this design was recommended.

To summarize and finalize the recommended culvert and crossing design, **Figure 7** is shown with all the key features of the culvert crossing.

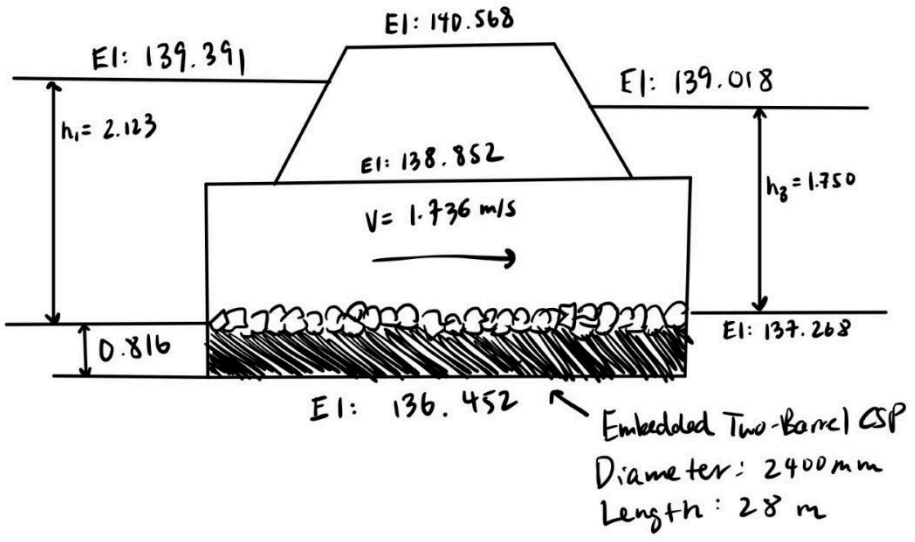


Figure 7 Summary of the replacement culvert design

To conclude the report, the recommended culvert replacement design is suitable for this project as has better water flow, meaning an improved conveyance. The embedded design is also better suited for the passage of aquatic life. Furthermore, this design improves the transportation of sediments, has moderate environmental impacts, and fulfills all design constraints. To view the topographic map of the recommended culvert design, refer to **Drawing T-2**.

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Civil Engineering

Encl:
Drawing T-1: Topographic Plan
Drawing T-2: Proposed Culvert Replacement and Turning Circle

Reference List

Chow, Ven Te (1959), Open Channel Hydraulics, McGraw Hill Book Company, New York.

Babra Engineering Ltd. (2019), Laurel Creek Channel Restoration Study, Prepared for the City of Waterloo.

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Appendix A: Site Photographs



Figure A1: Columbia Lake Bypass Channel



Figure A2: Twin existing culverts with bypass sediment buildup



Figure A3: Sediment buildup within existing culvert



Figure A4: Existing culvert and crossing leading to U.W. weather station

Appendix B: EXCEL workbook with CSP culvert design sizes and features

Project: Bypass Channel Replacement Culvert						
Purpose: Preliminary Sizing of Embedded CSP						
Date: November 2021						
DESIGN PARAMETERS						
Surveyed Channel Invert Elevation (Shot 328)	137.268					
Proposed Embankment Elevation	140.568					
Design Discharge (m3/s)	11.00					
Tailwater Surface Elevation	139.018					
Tailwater Depth, h3 (m)	1.750					
Embedment Ratio, d/D (m)	0.340					
Culvert Length (m)	28					
Discharge Coefficient, C	0.920					
COMMERCIAL CULVERT PROPERTIES						
Culvert Diameter (m)	1.600	1.800	2.000	2.200	2.400	2.700
Handling Mass (kg/m)	95	106	118	129	141	159
CULVERT ELEVATIONS						
Culvert Radius, r (m)	0.8000	0.9000	1.0000	1.1000	1.2000	1.3500
Embedment Depth (m)	0.544	0.612	0.680	0.748	0.816	0.918
Culvert Invert Elevation (m)	136.724	136.656	136.588	136.520	136.452	136.350
Culvert Obvert Elevation (m)	138.324	138.456	138.588	138.720	138.852	139.050
Depth of Cover (m)	2.244	2.112	1.980	1.848	1.716	1.518
GEOMETRIC PROPERTIES (EMBEDDED CULVERT)						
Theta	1.245	1.245	1.245	1.245	1.245	1.245
Area of Flow (m2)	1.408	1.782	2.200	2.662	3.168	4.009
P (m)	3.034	3.414	3.793	4.172	4.552	5.121
T (m)	1.516	1.705	1.895	2.084	2.274	2.558
Hydraulic Radius (m)	0.309	0.348	0.387	0.425	0.464	0.522
COMPOSITE ROUGHNESS						
n1 (Substrate)	0.035	0.035	0.035	0.035	0.035	0.035
n2 (CSP Wall)	0.025	0.025	0.025	0.025	0.025	0.025
Composite Roughness, n	0.029	0.029	0.029	0.029	0.029	0.029
CULVERT HYDRAULICS						
Number of Culvert Barrels	4	4	3	3	2	2
Discharge in Each Culvert (m^3/s)	2.750	2.750	3.667	3.667	5.500	5.500
Conveyance, K	22.577	30.909	40.935	52.781	66.566	91.129
Frictional Loss (m)	0.415	0.222	0.225	0.135	0.191	0.102
Velocity Through Culvert (m/s)	1.953	1.543	1.667	1.378	1.736	1.372
Headwater Depth, h1 (m)	2.395	2.115	2.142	1.999	2.123	1.965
Headwater Elevation (m)	139.663	139.383	139.410	139.267	139.391	139.233
Freeboard (m)	0.905	1.185	1.158	1.301	1.177	1.335
TOTAL MASS						
Mass per Barrel (kg)	2660	2968	3304	3612	3948	4452
Project Mass (kg)	10640	11872	9912	10836	7896	8904