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CEE 4550 – Design Team Final Report
LFOM Code Revisions and High-Flow Entrance Tank

Part 1: LFOM Code Revisions

Problem Definition

In an AguaClara plant, the linear flow orifice meter (LFOM) establishes a linear relationship between the height of water in the entrance tank and overall plant flow rate. This is accomplished by mimicking the stout weir, a theoretical flow control device in which discharge is precisely linearly proportional to head in the upstream region. Such a relationship is theoretically possible if the weir height were proportional to $1/\sqrt{height}$; however, it is not physically possible to fabricate a device like this because the base would need to be infinitely wide.

Because of this, flow control and measurement devices instead use a modified version of the stout equation, which approximates linear flow by:

$$W(z) = \frac{\alpha}{\sqrt{z}} = \alpha \cdot \text{basicW}(z).$$

In this 2d equation, W is the weir width, and z is the height. Alpha is a constant of proportionality.

Because it would be difficult to integrate an actual weir into the entrance tank, we replicate a weir by drilling a pattern of orifices into a piece of PVC pipe – this is called the LFOM. Fewer orifices are included at the top of the pipe; this simulates the narrowing of the stout weir which occurs with increasing height. An AutoCAD rendering of a typical AguaClara LFOM pipe is shown below:

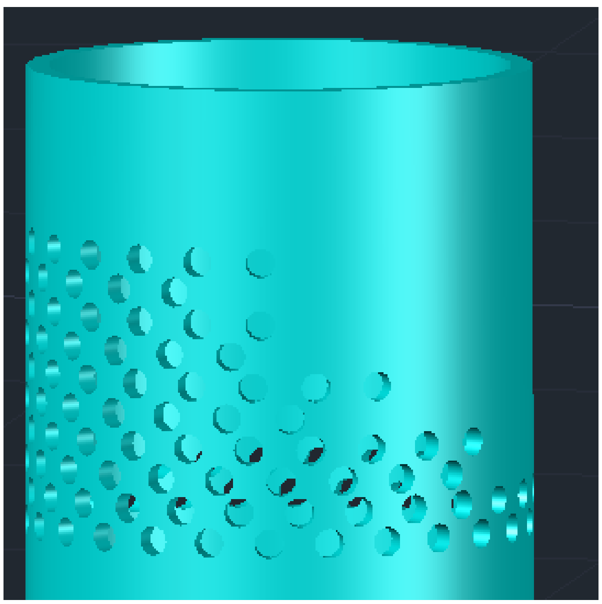


Figure 1A: Illustration of a typical AguaClara LFOM pipe. We see here that the number of holes (orifices) per row decreases with height, and that all orifices are oriented vertically.

Prior to updating the code, a functional LFOM design file was in place and it, for the most part, effectively designed the AguaClara LFOM; however, the old design file did not accurately report flow in certain situations (to be explained below) and was somewhat difficult to understand for someone not familiar with the design algorithm.

The reason why the old LFOM file inaccurately reported flow at certain locations was that it assumed the horizontal orifice equation:

$$Q.Orifice = \pi.VenaContractaOrifice * A\sqrt{2 * g * H}$$

could be used to estimate flow through a vertical orifice. In this equation, Π.VenaContractaOrifice is the ratio of the vena contracta to the orifice area, A is the orifice cross-sectional area, g is the acceleration due to gravity, and H is the height of water above the orifice. As can be seen, this equation expects a constant level of head among all the water flowing through the orifice:

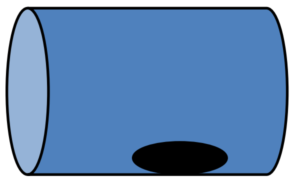


Figure 1B: Typical situation in which the horizontal orifice equation would be used to measure flow

If the water level is sufficiently far above the top of the orifice, this approximation is valid and the horizontal orifice equation will accurately measure flow through an LFOM orifice, because the height difference between the top of the water column and the top of the orifice is much greater than the height difference between the top of the orifice and the bottom of the orifice. However, if the orifice is partially filled or just barely submerged, the vertical orifice equation should be used. The following graph illustrates the situation for a vertical orifice with a 10-cm diameter:

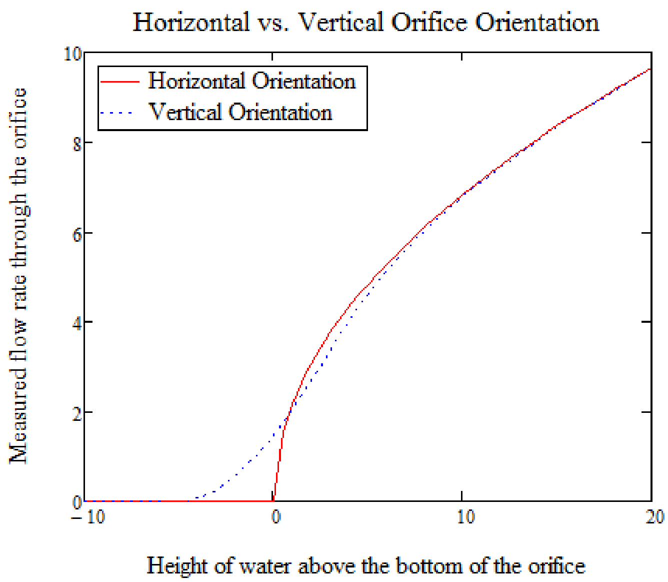


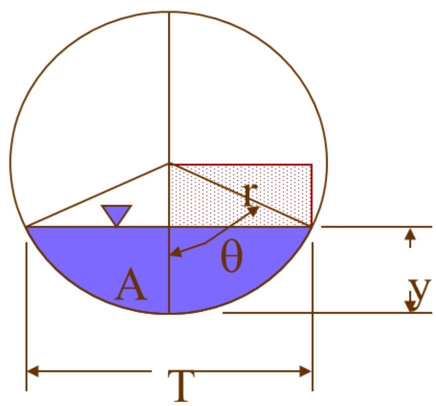
Figure 1C: Performance of the horizontal vs. vertical orifice equation across a 10-cm diameter orifice. This shows that once water reaches the top of the orifice, there is only a negligible difference in performance between the two equations.

In order to ensure that flow is predicted accurately regardless of where the water level falls on the LFOM, the appropriate vertical orifice equation to use is:

$$Q_f(h_u) = C(h_u)\sqrt{2g}\int_0^{\min(D,h_u)} T(z)\sqrt{(h_u - z)}\,dz \qquad (4\text{-}32)$$

http://il.water.usgs.gov/proj/feq/fequtl98.i2h/4_7aupdate.html

This is the equation that measures flow in the new LFOM design file. In it, h_u is the height of water above the bottom of the orifice, z is a reference height (integration variable), C(h_u) is a coefficient of discharge, which we have taken to be approximately 0.62 [=Pi.VenaContractaOrifice], and T(z) is the “width” (horizontal extent) of water in the orifice. In our code, z ranges from 0 to the smaller of D and h_u, allowing us to account for both partially filled and completely submerged orifices. T(z) is defined as sin(cos^-1((D/2-z)/(D/2)), as shown on the diagram below:



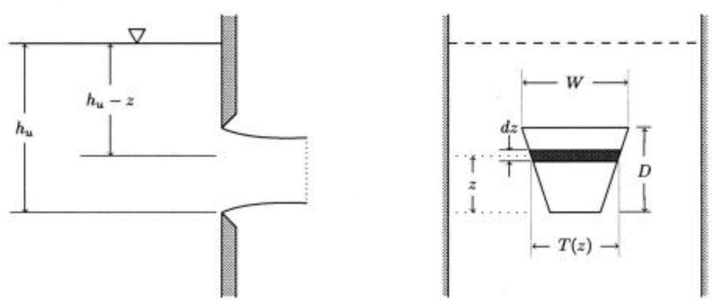


Figure 4-11: Key Values for Computing Orifice Flow

Figure 1D: Illustration of key variables for flow through a partially filled orifice
First image courtesy of Dr. Monroe Weber-Shirk, second courtesy of the USGS

Additionally, as discussed briefly above, the code was completely reorganized in an effort to make the design algorithm more easily understandable for those unfamiliar with the code. This involved adding more documentation and changing variable names so that they are both more descriptive and in better alignment with AguaClara conventions.

Documented Progress

First, we added a new vertical orifice equation to *FluidsFunctions.xmcd*. This equation, Q.orificeV, is as follows:

$$Q_{orificeV}(D, h, Pi_{VenaContractaOrifice}) := \left| \begin{array}{l} Q \leftarrow Pi_{VenaContractaOrifice} \cdot \sqrt{2g} \cdot \displaystyle\int_{\frac{-D}{2}}^{\min\left(\frac{D}{2}, h\right)} D \cdot \sin\left(\operatorname{acos}\left(\frac{z}{\frac{D}{2}}\right)\right) \cdot \sqrt{h - z}\, dz \ \text{ if } h > \frac{-D}{2} \\ Q \leftarrow 0 \frac{L}{s} \ \text{ otherwise} \\ \text{return } Q \end{array} \right.$$

For cases where the water level is at or above the bottom of the orifice, this equation reports flow as determined by the vertical orifice equation described above. If the water level is below the bottom of the orifice, no flow is reported. Note that because h and z are independent of one another, this equation will work if the water level is above the top of the vertical orifice in question. The old (horizontal) orifice equation was kept as Q.orifice, because several plant elements contain horizontal orifices. Additionally, the high-flow entrance tank will contain a flow orifice meter with horizontal, rather than vertical, orifices. For this device, the horizontal orifice equation will be needed.

Then, we placed a call to the revised orifice equation into the LFOM code, as follows:

$$Orientation_{Orifices} := \left| \begin{array}{l} orientation \leftarrow 1 \ \text{ if } Q_{Plant} \le 100 \frac{L}{s} \\ orientation \leftarrow 0 \ \text{ otherwise} \\ \text{return } orientation \end{array} \right.$$

$$Q_{LfomOrifice}(Row_{In}, Row_{Out}) := \left| \begin{array}{l} Q \leftarrow Q_{orifice}\left(D_{LfomOrifices}, h_{LfomOrifice}(Row_{In}, Row_{Out}), Pi_{VenaContractaOrifice}\right) \ \text{ if } Orientation_{Orifices} = 0 \\ Q \leftarrow Q_{orificeV}\left(D_{LfomOrifices}, h_{LfomOrifice}(Row_{In}, Row_{Out}), Pi_{VenaContractaOrifice}\right) \ \text{ if } Orientation_{Orifices} = 1 \\ \text{return } Q \end{array} \right.$$

Orientation.Orifices is the variable which determines whether the horizontal or vertical orifice equation should be called by the LFOM design file. One will correspond with vertical orifices and zero with horizontal orifices. Current research and design testing indicates that the LFOM will cease to provide a linear relationship between flow and water level when overall plant flow rate exceeds 100 liters per second; this cutoff has thus been programmed into our code.

Next, we went through the entire LFOM code, breaking it up into distinct sections and explaining each of the design algorithms used.

Finally, we tested the two algorithms in one of the homework assignments given to Dr. Weber-Shirk's CEE 4540 class in fall 2011. The setup of that assignment allowed us to test the efficacy of the new and old algorithms along the entire vertical extent (20 cm) of the LFOM pipe. As shown below, both algorithms return exactly linear flow at certain locations; however, the algorithm using the vertical orifice equation experiences significantly less deviation from linear flow.

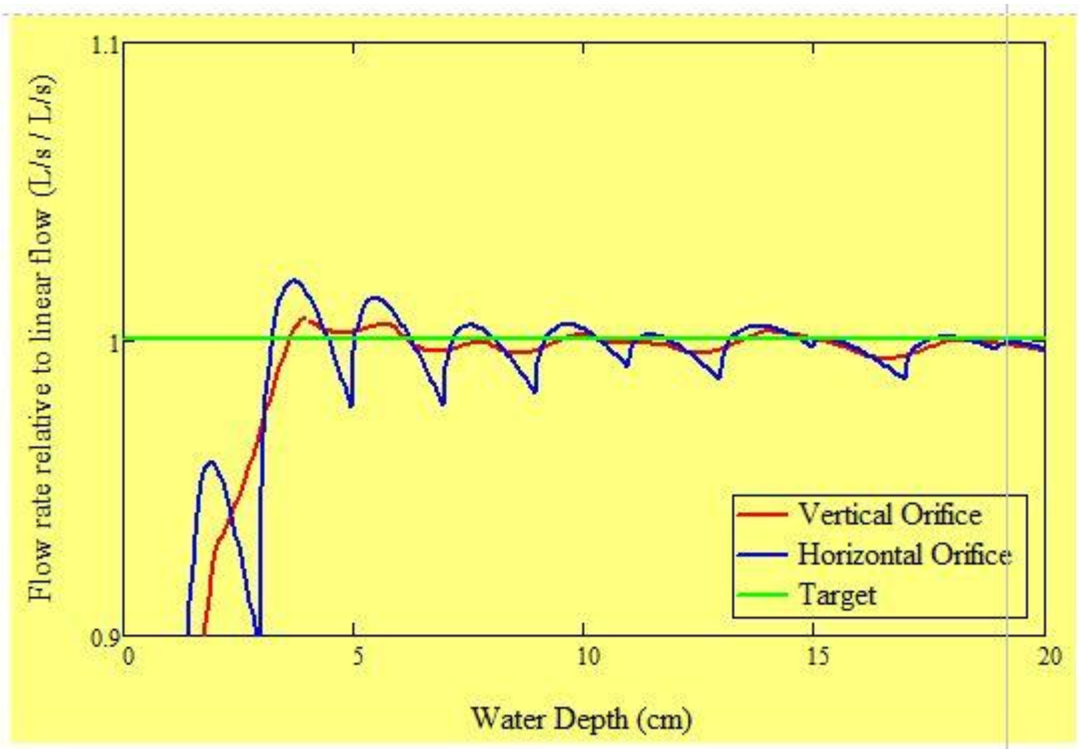


Figure 1E: Performance of the new vs. old LFOM design algorithms

Part 2: High-Flow Entrance Tank Design

Problem Definition

The entrance tank is an essential feature of any AguaClara plant, and one which has evolved rapidly over the past few years as new research has been conducted. A general picture of the plant, taken from the AguaClara wiki, is provided below:

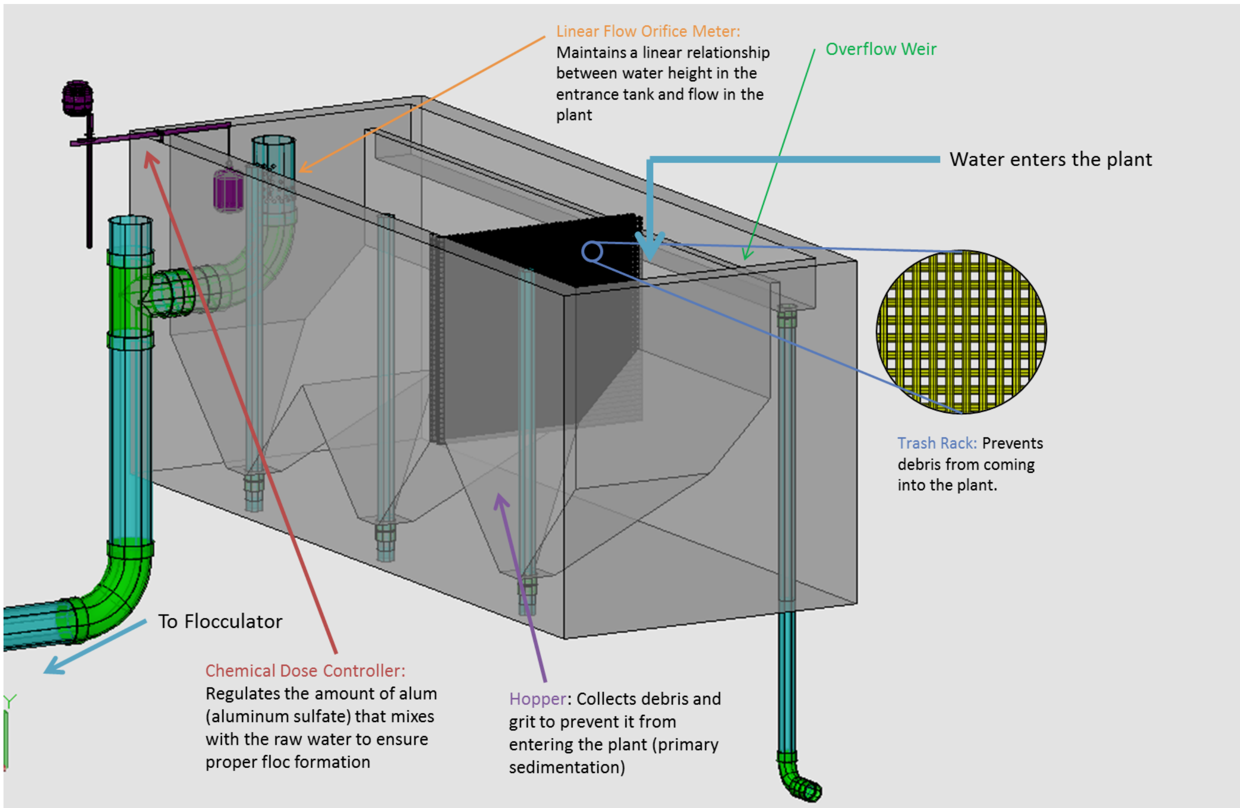


Figure 2A: General overview of an AguaClara treatment plant

The entrance tank serves two main purposes:

1. Grit chamber- particularly after storm events, raw surface water can contain large pieces of debris, which would damage plant elements and reduce plant output if they were allowed to pass through uninterrupted. Because the entrance tank is so large, it acts like a conventional, horizontal-flow sedimentation tank, and large objects are forced out of suspension. They settle into the hoppers (pyramidal basins pictured above), and are eventually removed from the plant. The trash rack provides additional protection against large pieces of debris.
2. Flow controller – if too much water is forced through the plant, key processes like chemical dosing, flocculation and sedimentation may proceed slowly or may not be as effective. The overflow weir avoids such a scenario by redirecting excess raw water back to the source.

Additionally, the LFOM measures the water level in the entrance tank and converts this to an overall plant flow rate. This information is then “sent” to the chemical dose controller, where an appropriate amount of coagulant is added to the raw water. Thus, it may be argued that another function of the entrance tank is to measure flow through the plant.

Transition to high-flow plants

AguaClara has, thus far, been very successful in providing sustainable water treatment facilities to medium-sized communities because plant elements do not change very much if the overall plant flow rate is between 6 and 70 liters per second. However, one of the program's main goals is to provide treatment for larger communities, which may require plant flow rates in excess of 70 L/s. The city of Gracias, Honduras, for example, has already put in a request for a 150 L/s plant. At such high flow rates, plant element designs need to change in order to avoid using excess materials and possibly providing inadequate treatment. The entrance tank is no exception to this rule.

Detailed design algorithm for high-flow entrance tanks

In general, we would like to achieve the maximum degree of primary sedimentation possible while minimizing the use of concrete and other construction materials. At large plant flow rates, two main obstacles prevent us from achieving this goal with the current design algorithm:

1. Plant geometry- the current design algorithm matches the length of the entrance tank with the length of the sedimentation tank. Because many more sedimentation tanks will be utilized in high-flow plants, the overall sedimentation tank length will not change very much, so the entrance tank will not get much longer; however, in order to achieve the required capture velocity, the current design algorithm calls for a much wider tank with much more concrete required to achieve the necessary hopper slope. We are proposing the use of "double hoppers", in which each hopper would have two drains and two milder slopes, meeting at a submerged horizontal ledge in the middle of the section. This setup is shown below in plan view (note that the chemical storage tanks would be located above the entrance tank shown in this image and the sedimentation would be located to the left), and would result in considerably less concrete being poured:

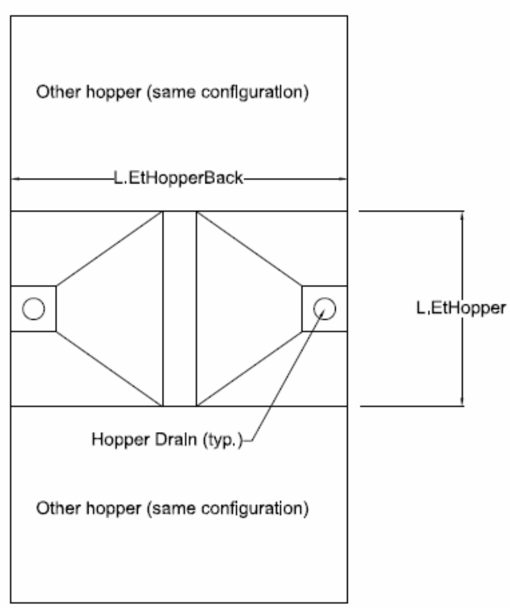


Figure 2B: Plan view of proposed "double hopper" design

2. Flow orifice meter – the current LFOM uses vertical orifices and resides in the far corner of the entrance tank. For flow rates above ~70 L/s, the LFOM ceases to provide a linear relationship between plant flow rate and water height in the entrance tank; thus, we propose switching to a horizontal flow orifice meter design, which makes uses of Georg Fischer Piping System's metering ball valve in calculating plant flow rate. The horizontal manifold pipe called for in this design will have fewer, larger orifices. Additionally, there will, by design, be a nonlinear relationship between water level in the entrance tank and discharge through the manifold pipe. Because of this change in flow orifice meter design, we must make sure that the orifices on top of the manifold pipe are covered whenever there is flow through the plant. If this does not occur, the LFOM will report zero flow (via the horizontal orifice equation described above) and no coagulant will be dosed, even if there is still water flowing through the plant. An elevation view of our proposed flow orifice meter design (including the aforementioned "double hopper") is shown below:

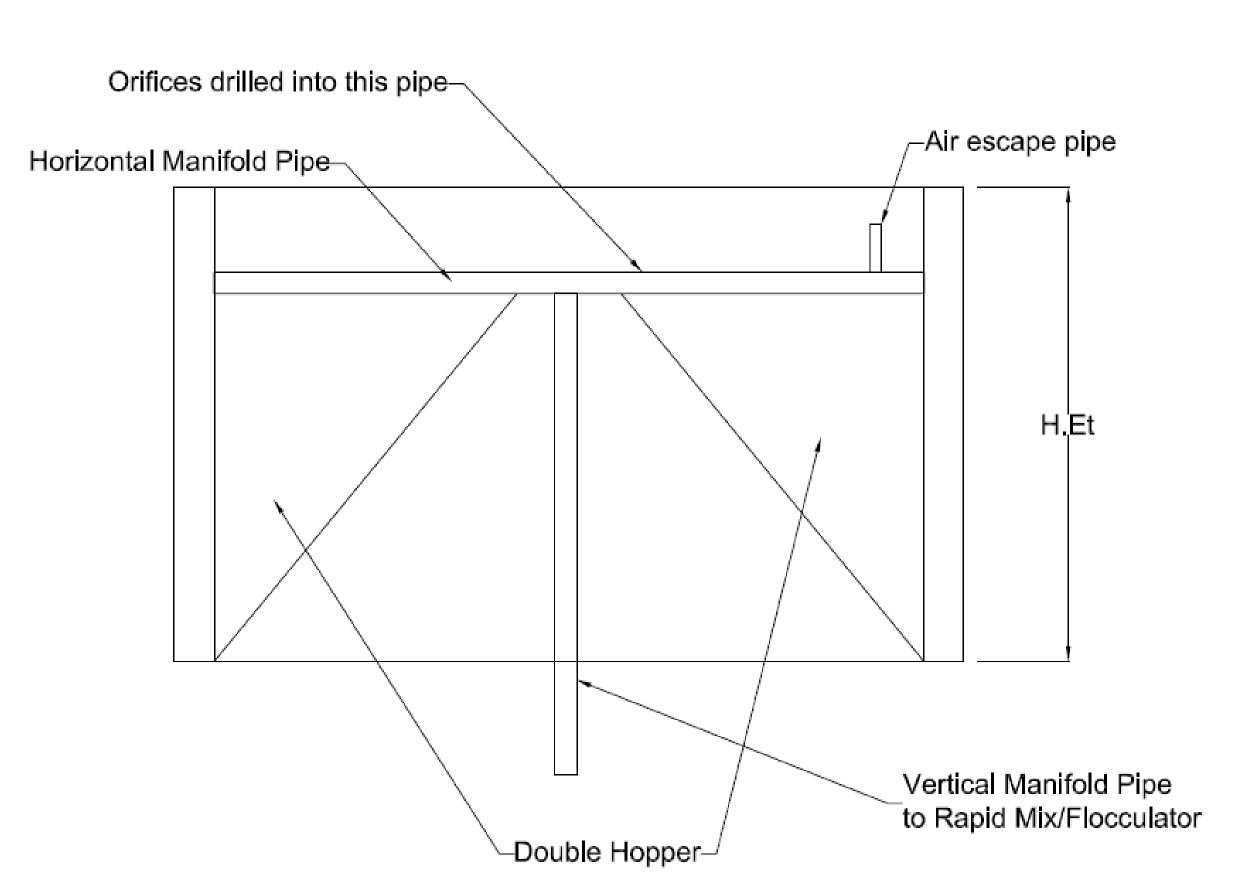


Figure 2C: Elevation view of proposed entrance tank hopper, with nonlinear flow orifice meter

Documented progress
Because we only began work on this task a few weeks ago, much of the work conducted to date has involved testing the current entrance tank design algorithm at high plant flow rates and researching designs which would alleviate the issues discussed above. Some preliminary coding has been done, but it will need to be expanded upon greatly by future members of the design team.

The images below show AutoCAD renderings of the entrance tank being constructed at the AguaClara plant in San Nicolas (32 L/s) as well as a high-flow (150 L/s) entrance tank designed with the current algorithm. We can see that the high-flow tank is much wider and taller than the 32 L/s tank, meaning that much more concrete would need to be used during construction.

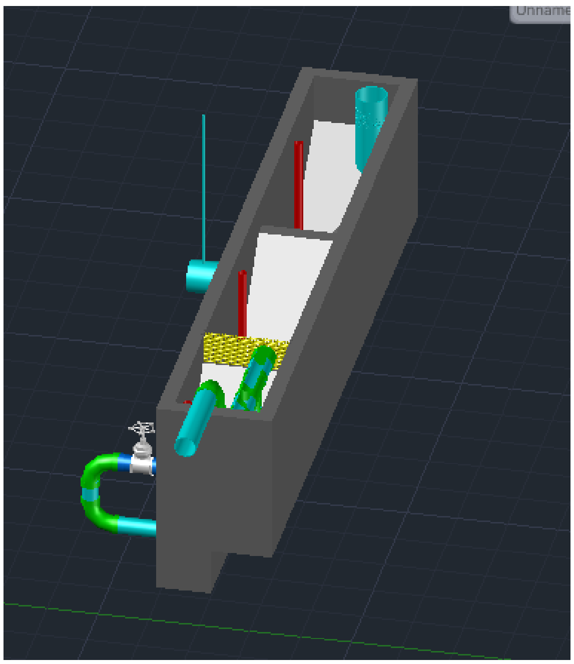


Figure 2D: Entrance tank being constructed at the San Nicolas AguaClara plant

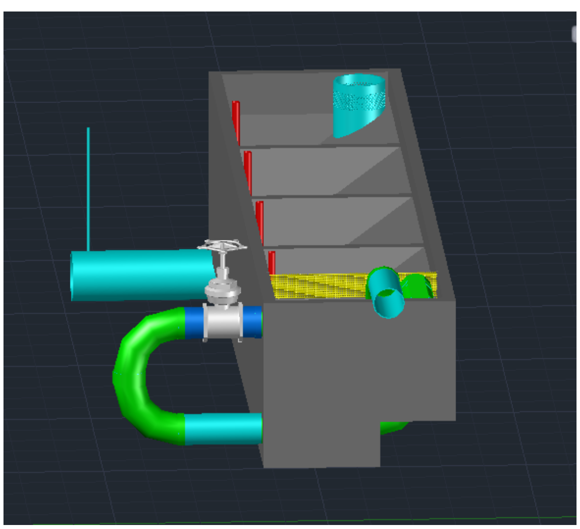


Figure 2E: Proposed 150 L/s entrance tank

As discussed above, we proposed a design in which each hopper in a high-flow entrance tank would be a “double-hopper”, meaning that two, shorter slopes beginning at either side of the hopper would rise up to a platform in the middle of the hopper. Because the slopes would be shorter, less concrete would need to be used; however, an additional drain would be required on the far side of the entrance tank, and thus an additional walkway would need to be constructed for operator drain accessibility. The following preliminary code was written to accomplish this task:

For large entrance tanks (>100 L/s), we will use a double-hopper design, as shown below.
Set thickness of "middle ledge" equal to thickness of hopper ledge (T.EtHopperLedge) + 10 cm
Leave 0.25*HW.Et of water above the "middle ledge". We assume that because water is still free to flow over the middle ledge, capture velocity calculations will not be affected.

$$L_{EtHopperL} := L_{EtHopper} = 2.227m$$

$$L_{EtHopperR} := L_{EtHopperL} = 2.227m$$

$$L_{EtHopperBackL} := \frac{L_{EtHopperBack}}{2} - \frac{T_{EtHopperLedge} + 10cm}{2} = 0.76m$$

$$L_{EtHopperBackR} := L_{EtHopperBackL} = 0.76m$$

$$H_{EtHopperMiddleLedge} := 0.65\,HW_{Et} = 0.788m$$

An.EtSlope does not change

$$An_{EtHopperBackSlope} := \operatorname{atan}\left(\frac{H_{EtHopperMiddleLedge}}{L_{EtHopperBackR}}\right) = 46.038deg$$

Future members of the design team will need to create AutoCAD drawing code for these files and test to see whether the middle ledge height allows enough water to pass between the two hoppers. If too little water passes through, the dimensions calculated based on capture velocity will no longer be valid. Time permitting, it would also be beneficial to carry out a bench-scale laboratory test of this new setup to reaffirm our design assumptions.

We are in the process of preparing preliminary code for the horizontal flow orifice meter. This will also need to be tested extensively, and the current LFOM will need to be replaced with our proposed horizontal manifold in the AutoCAD drawings. When ready, the latest code will be uploaded to the AguaClara wiki.

During the initial design phase, we discovered the potential issue of head loss coupling between the flocculator and the entrance tank. This is one of the reasons why failure occurred at the early Agalteca plant. Water was not given an opportunity to free fall between the entrance tank and the flocculator; thus, when excessive head built up in the flocculator, the entrance tank backed up as well, and the flow orifice meter measured a false, exceedingly high plant flow rate. In order to avoid this issue in high-flow plants, we proposed the addition of an air escape pipe, as shown in figure 2C and repeated below. This pipe would be secured into a flow orifice meter orifice in the same manner as the diffuser tubes are secured into the sedimentation tank inlet manifold.

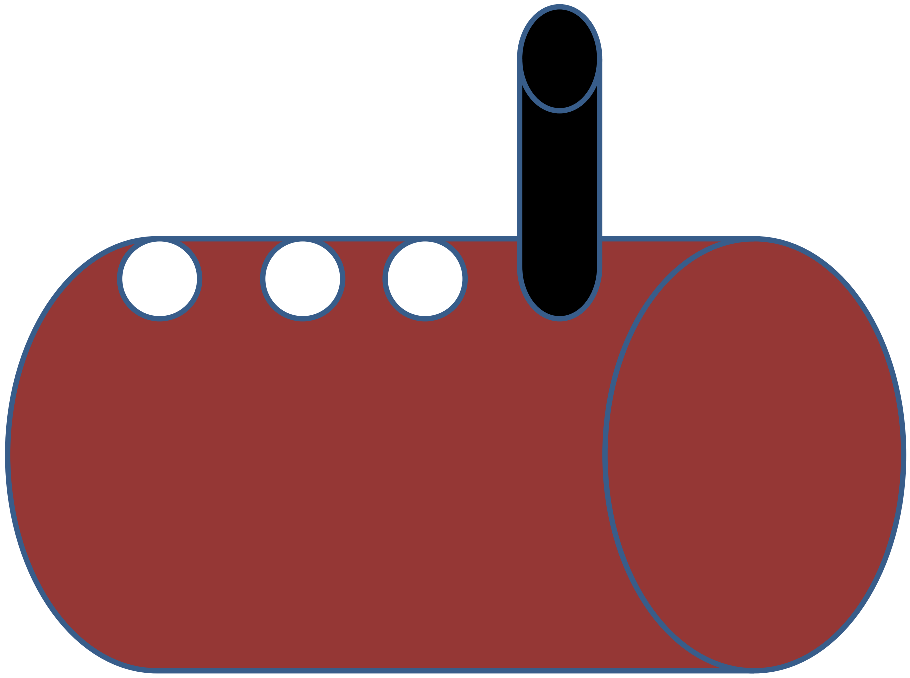


Figure 2F: Illustration of flow orifice meter for high-flow plants. The black cylinder represents an air release tube, which would prevent water from backing up into the flow orifice meter from the flocculator.