Gravity-Powered Chemical Dose Controller for Sustainable, Municipal-Scale Drinking Water Treatment

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Abstract

Accurate chemical dosing in water treatment plants is imperative to ensure optimal efficiency of flocculation and disinfection. Design algorithms, calibration techniques, and standardized components are presented for a linear flow orifice meter (LFOM) and a linear chemical dose controller (LCDC). These coupled systems allow water treatment plant operators to easily and reliably set and maintain the desired doses of coagulant and disinfectant. The combined system adjusts the chemical flow rate automatically in response to changes in plant flow rate to maintain the target chemical dose. The LFOM maintains a linear relationship between height of water in the entrance tank and plant flow rate. A lever and float are used to create a direct relationship between the plant flow and chemical flow produced by the LCDC. A linear relationship between head loss and chemical flow in the LCDC is created by using the major head loss through a small diameter tube to control the chemical flow rate. Experimental tests are described that minimize minor losses and verify performance of the LCDC.

Subject headings: coagulation; flow control; flow measurement; municipal water; water treatment plants; control systems;

Introduction

The accurate application of coagulant prior to rapid mix and the addition of disinfectant after filtration are essential to the production of safe, clean drinking water at municipal drinking water treatment facilities. Reliable and easily maintained chemical dosing systems are vital. Many municipal water treatment plant chemical dosing systems rely on electronic supervisory control and data acquisition (SCADA) dose control systems to regulate the addition of coagulant and disinfectant. SCADA control systems are complex and require multiple interdependent technology platforms including sensors, signal convertors, microprocessors,

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software, and variable speed pumps. SCADA-type technology platforms also often rely on proprietary components and require a high level of technical expertise in each platform for maintenance. As a consequence, SCADA dose control systems have many failure modes and a significant number of the ensuing failures can require either replacement of specialized parts or the presence of highly trained technicians. These systems may be appropriate in facilities that have ready access to replacement part suppliers and that have financial capacity to pay the high labor costs for maintenance and technical support. However, SCADA-based water treatment plants perform poorly where replacement parts are not easily obtained and are commonly abandoned in developing countries when critical components malfunction. Simplified chemical dosing systems underpinned by sophisticated designs have been created to promote sustainable operation and are presented in this paper.

Design Constraints for Sustainability:

The AguaClara Program at Cornell University has developed a set of design guidelines for the creation of sustainable water treatment technologies. These guidelines embody lessons learned from years of experience inventing new technologies and taking them to full scale implementation through the program's collaboration with Agua Para el Pueblo in Honduras. The AguaClara drinking water treatment plants represent a new paradigm with a focus on the interaction between the plant operator and the technology. The design guidelines used by the AguaClara program that directly influenced the creation of the chemical dose controller and flow measurement systems described here are as follow:

To be operator-friendly, economical, and resilient, municipal scale water treatment plant designs must...

- be optimized for low cost and high performance.
- be easy to construct using low-precision construction techniques.
- minimize use of moving parts.
- operate without electricity.
- be observable (no sealed reactors) so that the plant operator can receive appropriate feedback for performance of every step of the treatment process.
- operate without requiring numerical calculations.
- use chemical dosages that can be set directly by the operator.
- be maintainable by one person.

A common method of chemical dosing employed in developing countries is the drip feed system consisting of a chemical stock tank with a small orifice through which the chemical exits (WHO, 2011). These systems are unable to maintain a constant chemical feed rate since the chemical flow rate decreases as the liquid level in the chemical stock tank drops. A floating bowl chlorinator is an example of a dosing system that addresses this problem and maintains a constant flow rate by maintaining a constant driving head even as the liquid level varies (Brikke and Bredero, 2003). However, this system and other stand alone chemical flow controllers regulates the chemical flow rate rather than the chemical dose. Chemical flow controllers require the operator to adjust the chemical flow rate when the plant flow rate is changed and that adjustment is generally by trial and error. Chemical flow controllers represent a level of simplicity that functions reliably but delivers less than what a water treatment plant operator needs.

A different solution to the chemical dosing challenge can be obtained given the goals of maximizing reliability, reducing costs, minimizing the use of components that are not available in the local hardware store, and empowering plant operators to maintain and repair the dosing systems. Reliability can be maximized by reducing the number of components and technology platforms. The number of technology platforms can be substantially reduced by using analog kinematics that connect linearized flow measurement to linearized flow control and completely eliminating the dependence on software, digital electronics, chemical pumps, and electricity. Dose controllers that use a minimum number of components can be described as simplicity on the other side of complexity. This type of dosing system requires sophisticated design methods (complexity), however the resulting device is simple to understand and easy to operate and maintain.

The AguaClara plant dose controller that has been implemented in several water treatment plants by the AguaClara program of Agua Para el Pueblo in Honduras has a minimum number of parts and can be easily repaired if a problem is discovered. The dosing system has two main components: (1) a linear flow orifice meter (LFOM) that creates a linear variation between water height and plant flow and (2) a linear chemical dose controller (LCDC) that provides a chemical flow that is directly proportional to plant flow rate. The design, construction, and testing of these components are described below.

Theory and Design

Linear Flow Orifice Meter

The Sutro Weir developed by Victor Sutro in 1915 mimics a Stout weir and creates a linear relationship between height of water and flow rate. A Stout weir is a theoretical flow control device in which weir width is proportional to $1/\sqrt{water\, height}$. It is not physically possible to fabricate such a device because the base would be infinitely wide. The Sutro weir, shown in Figure 1 serves as a practical alternative to the Stout weir. The width of the base, W, and upper portion of Sutro weir, y, as a function of height can be calculated by Equations 1 and 2, respectively.

$$W = \frac{Q_{Max}}{H_{Sutro}^{3/2} C_D \sqrt{3g} \Pi_{Sutro}} \quad (1)$$

$$y = \frac{W}{2}\left[1 - \frac{2}{\pi}\arctan\left(\sqrt{\frac{z_{Sutro}}{s}}\right)\right] \quad (2)$$

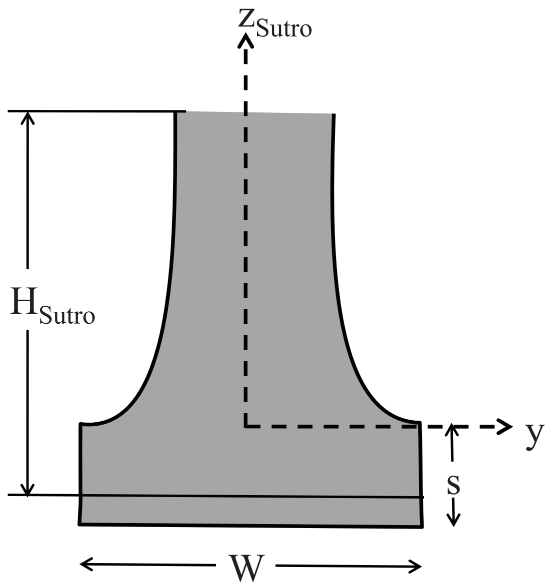

Figure 1: Diagram of the Sutro weir

where W is the width of the rectangular base of the weir, Q_{Max} is the maximum flow through the weir, H_{Sutro} is the total height of the weir measured from $s/3$ above the bottom of the rectangular weir, Π_{Sutro} is $(2s/3)/H_{Sutro}$, C_D is a discharge coefficient, g is acceleration due to gravity, z_{Sutro} is the vertical distance from the start of a curved section, and s is the height of the rectangular base (Thandaveswara, 2012). The theoretical flow through the Sutro weir, Q_{Sutro}, is described by Equation 3.

$$Q_{Sutro} = \frac{W}{2}\left(2C_D\sqrt{2gsh}\right) \tag{3}$$

where h is the vertical height of water measured from $s/3$ above the bottom of the rectangular weir. Equation 3 is only valid when the height of water is above the rectangular portion ($h \geq 2s/3$).

Accurate fabrication of a Sutro weir is somewhat difficult and the Sutro weir has the unfortunate property that the flow rate does not actually go to zero when $h = 0$ because the rectangular opening extends below the datum used for the linear relationship between flow and height. These two disadvantages were addressed in the linear flow orifice meter (LFOM) described in this paper. The LFOM approximates a Sutro weir using a vertical PVC pipe with a pattern of identically sized holes that create a linear relationship between water height and plant flow. The simple construction of the LFOM eliminates the need for skilled labor and uses readily available materials and tools. The LFOM is typically located in the entrance tank of the water treatment plant where water flows through the orifices created by the holes in the vertical pipe on its way to rapid mix and flocculation. The flow through each individual hole, $Q_{Orifice}$, is described by the vertical orifice equation (Equation 4). With correct placement of multiple holes, the overall flow can be rendered linear with respect to height of water in the tank, justifying the designation as a Linear Flow Orifice Meter (LFOM).

$$Q_{Orifice} = \Pi_{vc}\sqrt{2g} \int_{0}^{min(D_{Orifice},h)} D_{Orifice} sin\left[acos\left(\frac{2z}{D_{Orifice}}\right)\right]\sqrt{h-z}dz \tag{4}$$

where Π_{vc} is the cross-sectional area of the constricted flow divided by the area of the orifice caused by the vena contracta for the orifice ($\Pi_{vc} = 0.62$ for all cases), $D_{Orifice}$ is the diameter of the orifice, z is integrated from 0 to the minimum of the orifice diameter and height of water ($min(D_{Orifice}, h)$), and h is the height of water above the bottom of the orifice (Franz and Melching, 1997).

There are many potential approaches to the design of an orifice based linear flow meter. The design presented here uses a vertical PVC pipe of appropriate diameter (based on plant flow as described below), a single standard sized drill bit, a minimum number of holes, and a target water level change that is appropriate to drive the dose controller. The algorithm that creates the LFOM hole pattern compensates for the fact that the orifices are all the same size and that there must be an integer number of rows of orifices and an integer number of orifices in each row. The algorithm steps are as follow:

1. calculate the minimum diameter of the vertical pipe required to maintain supercritical flow at the bottom of the LFOM.
2. calculate the row spacing to allow use of a large orifice size to minimize the number of holes drilled.
3. calculate the orifice size constrained to be a standard drill bit size, smaller than the row spacing.
4. calculate the number of orifices in each row starting at the bottom row.

The LFOM pipe must be large enough in diameter to ensure that the pressure inside the LFOM at the bottom row of orifices is atmospheric and that the flow inside the LFOM is supercritical. Supercritical flow in the LFOM ensures that it is unaffected by changes in downstream water levels. Each orifice jet accelerates downward due to gravity and the jets collide and exchange momentum. The very bottom of the LFOM has the highest flow rate inside the pipe and this flow velocity must be high enough so that the LFOM pipe is not completely full of water. The average vertical velocity of water at the very bottom inside the LFOM can be obtained by applying free fall acceleration to each orifice jet and then applying conservation of momentum in the vertical direction to obtain the average vertical velocity. This analysis can be simplified substantially by using the Stout weir equation to approximate the vertical velocity of the free falling water at the bottom of the LFOM weir (Equation 5). The velocity of water exiting the Stout weir as a function of height when the weir is fully submerged, $h = H_{Stout}$, is:

$$V_{Stout} = \sqrt{2g\left(H_{Stout} - z\right)} \tag{5}$$

The Stout weir equation for the width of the weir as a function of height, z, is:

$$W_{Stout} = \frac{2Q}{H_{Stout}\Pi_{vc}\pi\sqrt{2gz}} \tag{6}$$

where Q is the flow through the Stout weir when the constant water depth is H_{Stout} and Π_{vc} is the vena contracta coefficient, 0.62.

The average velocity of the falling water at the bottom of the Stout weir, $V_{Stout_{z=0}}$, can be obtained by integrating over the depth of the weir to obtain the total momentum in the vertical direction of the falling water when it arrives at the bottom of weir. The average velocity at the bottom of the weir is then obtained by dividing the total momentum by the total mass flux. The water enters the Stout weir with no vertical velocity. The vertical velocity obtained by the time it reaches the bottom of the weir is given by $\sqrt{2gz}$.

$$V_{Stout_{z=0}} = \frac{\int_0^{H_{Stout}} \rho_{Water} V_{Stout} W_{Stout} \Pi_{vc} \sqrt{2gz} dz}{\rho_{Water} Q} \tag{7}$$

where ρ_{Water} is the density of water. Substituting equations 6 and 5 into Equation 7 and simplifying gives:

$$V_{Stout_{z=0}} = \frac{4\sqrt{2gH_{Stout}}}{3\pi} \tag{8}$$

Although the total effective width vs height for an LFOM is slightly different than for the Stout weir, Equation 8 can be used to estimate the vertical velocity of water at the bottom of the LFOM. For an LFOM with $H_{LFOM} = 20\,cm$, $V_{Stout_{z=0}} = 0.841\,m/s$. A wide range of plant flow rates can be accommodated by a maximum height of $20\,cm$ through the LFOM. The cross-sectional area and diameter of the pipe, can then be found by Equations 9 and 10 respectively.

$$A_{LFOM} = \Pi_{Safety} \frac{Q}{V_{Stout_{z=0}}} \tag{9}$$

$$D_{LFOM} = 2\sqrt{\frac{A_{LFOM}}{\pi}} \tag{10}$$

where Π_{Safety} is a safety factor (1.5 used here) that ensures that the velocity at the bottom of the LFOM pipe is more than adequate to ensure that the pipe is not full of water and thus the pressure inside the LFOM is atmospheric. In the design algorithm, the LFOM pipe inner diameter is rounded up to the nearest available pipe size.

Before the surface area of the LFOM can be distributed as a series of orifices, the vertical center-to-center spacing of the rows of orifices, B_{Row} must be found. The design calculation is initialized with two orifices in the top row of orifices (Equation 12); however, this number may subsequently be changed as the algorithm progresses. The width of the top of the Stout weir, $W_{Stout_{z=H_{LFOM}}}$, is used to approximate the average width of the weir corresponding to the top row of orifices in the LFOM.

$$B_{RowMax} W_{Stout_{z=H_{LFOM}}} = 2\frac{\pi D_{Orifice}^2}{4} \tag{11}$$

where B_{RowMax} is the maximum row height and $D_{Orifice}$ is the diameter of the orifices in the LFOM. Since both B_{RowMax} and $D_{Orifice}$ are unknown, the orifice diameter, $D_{Orifice}$, is assumed to equal to the maximum row height allowing Equation 11 to be solved for the maximum row height.

$$B_{RowMax} = \frac{2}{\pi} W_{Stout_{z=H_{LFOM}}} \tag{12}$$

The number of rows of orifices, N_{Rows}, is obtained by dividing the user specified maximum height of the LFOM, H_{LFOM}, by B_{RowMax} and rounding up to the nearest integer with the additional constraint that the total number of rows be between 4 and 10. Linearity between water height and flow is poor when the water level is in the first row of orifices and Equation 4 applies. AguaClara water treatment plants use a minimum of 4 rows to provide a linear response down to 25% of the maximum flow rate. Accuracy increases with the addition of more rows and is quite high with 10 rows. There is no advantage to having more than 10 rows as more rows require drilling more holes but does not greatly improve accuracy.

The next design step is to calculate the orifice diameter. The top row of orifices will contain at least one hole. Thus, the orifice area, $A_{TopOrifice}$, in the top row must be equal to or less than the theoretical stout weir area corresponding to the top row (Equation 13). An estimate of the area of the top row of orifices is obtained by integrating Equation 6.

$$\frac{\pi}{4} D^2_{OrificeMax} = A_{TopOrifice} = \int\limits_{H_{LFOM}-B_{Row}}^{H_{LFOM}} \frac{2Q}{H_{LFOM} \Pi_{vc} \pi \sqrt{2gz}} dz \tag{13}$$

where $D_{OrificeMax}$ is the maximum orifice diameter, Q is the maximum plant rate, g is acceleration due to gravity, and z is the LFOM height over which the equation is integrated.

The diameter of the orifices, $D_{Orifice}$, is constrained to be less than $D_{OrificeMax}$, and also less than B_{Row} and rounded down to the nearest available drill bit size. All orifices in the LFOM design will have this diameter to simplify fabrication. The maximum number of orifices that will physically fit along the circumference of the LFOM pipe, $N_{MaxOrificeperRow}$, is another constraint (Equation 14) that is important for high flow rates. The minimum spacing between orifices needed to maintain the structural integrity of the pipe, $S_{MinSpacing}$, is $5\,mm$.

$$N_{MaxOrificeperRow} = \frac{\pi D_{LFOM}}{D_{Orifice} + S_{MinSpacing}} \tag{14}$$

If the number of orifices required in the bottom row exceeds the maximum number of orifices that fit in the circumference of the pipe then the design must be modified by either increasing the height of the LFOM or by further increasing the diameter of the pipe.

The final step in designing the LFOM is to calculate the number of orifices in each row. Because the flow rate through the LFOM is linearly proportional to the height of water in the entrance tank, the expected flow rate through the LFOM, $Q_{Nsubmerged}$, when $N_{Submerged}$ rows of orifices are submerged is equal to Equation 15.

$$Q_{Nsubmerged} = Q \frac{B_{Row} N_{Submerged}}{H_{LFOM}} \tag{15}$$

With an orifice diameter and an expected flow rate per row, the number of orifices per row, $N_{Orifices}$, can be calculated for each row using Equation 16 starting at the bottom and incrementing $N_{Submerged}$. The vertical orifice equation (Equation 4) is used to find the flow through a single orifice, $Q_{Orifice}$. As the number of orifices in each row is calculated, the

Table 1: Summary of Design Specifications for a Linear Flow Orifice Meter (LFOM)

Input	Value
Q_{Plant}	$10\,L/s$
$Drill\ Bits$	$US\ Standard$
H_{LFOM}	$20\,cm$
$S_{MinSpacing}$	$5\,mm$

Output	Value
B_{Row}	$2\,cm$
D_{LFOM}	$15.2\,cm$ $(6\,in)$
$D_{Orifice}$	$1.9\,cm$ $(0.75\,in)$
$Error_{Max}$	0.34%

flow provided by the lower rows, $Q_{N-1submerged}$, is subtracted from the total expected flow, $Q_{Nsubmerged}$, based on their depth of submergence to obtain flow required through the row of orifices being calculated. The required flow through the row being calculated is divided by the flow per orifice, $Q_{Orifice}$ from (Equation 4), and the result is rounded to the nearest integer to obtain the number of orifices required. Once the LFOM pattern of orifices is drilled, the flow rate that corresponds to the water height at each row of the LFOM pattern can be written on the LFOM pipe itself, allowing the operator to read the flow rate directly, avoiding the need for mathematical calculations.

$$N_{Orifices} = \frac{Q_{Nsubmerged} - Q_{N-1submerged}}{Q_{Orifice}} \tag{16}$$

Table 1 provides an example of the input and output design parameters for an LFOM for a plant with a maximum design flow of $10\,L/s$. Figure 2 shows equivalent designs for the Sutro weir and LFOM with their respective flow profiles. Flow through the LFOM as a function of depth remains linear when orifices are partially full. Custom designs for LFOMs may be obtained at no charge from the AguaClara Design Tool *(aguaclara.cornell.edu/design)*.

Linear Chemical Dose Controller

With the linear relationship between height of water in the entrance tank and plant flow rate provided by the LFOM, the linear chemical dose controller (LCDC) utilizes a float in the entrance tank and a lever to connect the chemical flow rate to plant flow rate. When the plant flow rate increases, the water level in the entrance tank rises proportionally, and the float and lever arm rise as illustrated in Figure 3. A stock tank provides a reservoir of the chemical solution (coagulant or disinfectant) and is connected to a constant head tank. The constant head tank is regulated by a float valve which keeps the chemical depth constant. A small diameter tube, referred to here as the dosing tube, leads from the stock tank to a connector tube and then to a vertical drop tube that delivers the chemical to the chemical injection point. The chemical flow rate is controlled by the length of the dosing tube and the elevation head driving the flow - the vertical distance between the chemical surface in the constant head tank and the outlet of the connector tube where it reaches the vertical drop tube. The vertical drop tube is connected to the lever arm via a slider. The plant operator sets the slider at the desired coagulant dose based upon characteristics of the influent water. A locking mechanism holds the slider in place on the lever arm. The float attached to the lever arm changes elevation in response to plant flow rate changes, thus changing the elevation of the dosing tube outlet, and maintaining a constant chemical dose.

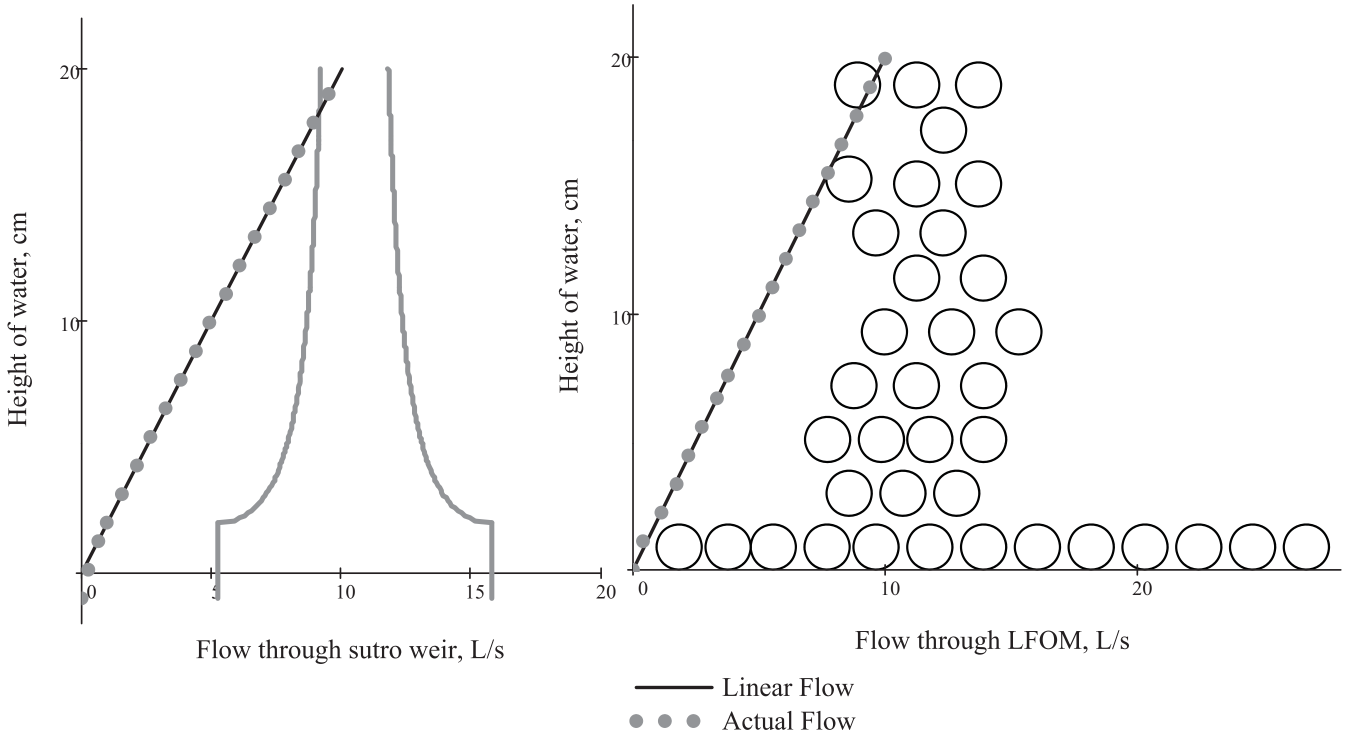

Figure 2: Performance of a) a Sutro weir and b) a LFOM designed to provide a $10\,L/s$ flow over a vertical distance of $20\,cm$. Both images are scaled, with the x-axes representing both $0-20\,L/s$ and $0-20\,cm$. The Sutro weir equation is only valid when the height of water is above the rectangular portion. Therefore, the equation for flow over a rectangular weir, $Q_{Rect} = \frac{2}{3} W C_D \sqrt{2g}\,(H_d + s/3)^{2/3}$, was used to calculate the flow for the Sutro weir when the height of water is less than s. The base of the Sutro weir, W, is $9.76\,cm$, the height of the rectangular portion, s, is $4\,cm$. The orifices in the LFOM are $1.905\,cm$ ($3/4\,in.$) in diameter and the row height, B_{Row}, is $2\,cm$.

The LCDC is a semi-automated dosing system that allows the plant operator to set and maintain a chemical dose over time-varying plant flow rates in a visually-accessible system. Dosing changes are made without requiring calculations.

The LCDC uses major head loss in the dosing tube to regulate chemical flow. The linear relationship between major head loss and the chemical flow rate is given by the Hagen-Poiseuille equation (Equation 17).

$$Q_C = \frac{h_f g \pi D_{Tube}^4}{128 \nu L_{Tube}} \tag{17}$$

where Q_C is the chemical flow rate, h_f is the major head loss, D_{Tube} is the inner diameter of the dosing tube, ν is the kinematic viscosity of the chemical solution, g is the acceleration due to gravity, and L_{Tube} is the length of the small diameter dosing tube. The Hagen-Poiseuille equation assumes that the chemical flow is laminar, viscous and incompressible. The equation also assumes that the flow passes through a straight tube with a constant circular cross-section that is significantly longer than its diameter. Laminar flow in the dosing tube is indicated by a Reynolds number, Re, less than 2100 (discussed below). The assumption that major head loss regulates flow requires that minor losses be minimized. Experiments related to minimization of minor losses are discussed below.

A number of constraints are applied to the design of the LCDC to ensure that the simplest functional solution is chosen. The design algorithm calculates several key parameters for all available dosing tube diameters and chooses the design with the minimum number of tubes and maximum allowable tube length. The algorithm steps are as follows:

1. calculate the maximum flow rate through each available dosing tube diameter that keeps error due to minor losses below 10%.
2. calculate the total chemical flow rate that would be required by the treatment system for the maximum chemical dose and the maximum allowable stock concentration.
3. calculate the number of dosing tubes required if the tubes flow at maximum capacity.
4. calculate the length of dosing tube(s) that correspond to each available tube diameter.
5. select the longest dosing tube that is shorter than the maximum tube length allowable based on geometric constraints.
6. select the dosing tube diameter, flow rate, and stock concentration corresponding to the selected tube length.

For the majority of inputs, limiting the effect of minor losses dictates the design. This constraint is addressed by solving a system of equations where L_{Tube} and the maximum chemical flow rate, $Q_{MaxError}$, are both unknown. Rearranging equation 17 gives the mechanical energy loss due to shear on the tube wall or major head loss:

$$h_f = \frac{128\nu L_{Tube} Q_C}{g\pi D_{Tube}^4} \tag{18}$$

where h_f is the major head loss, which is the lost mechanical energy expressed as a change in elevation. Minor head loss is the mechanical energy loss to deceleration of the fluid caused by changes in the flow geometry and can be calculated by Equation 19.

$$h_e = \frac{8Q_C^2}{g\pi^2 D_{Tube}^4} \sum K \tag{19}$$

where $\sum K$ is the sum of the minor loss coefficients, all of which use the average velocity in the tube as their reference velocity. The total head loss, h_L, is the sum of the major and minor losses.

$$h_L = h_f + h_e \tag{20}$$

The maximum departure from the idealized linear relationship between flow and head loss is equal to the minor loss contribution normalized by the total head loss (Equation 21).

$$\Pi_{LinearError} = \frac{h_e}{h_L} \tag{21}$$

The maximum flow for a dosing tube will produce an error of $\Pi_{LinearError}$, which is limited to 10% in the design algorithm. This maximum allowable flow rate, $Q_{MaxError}$, based on allowable error can be obtained by substituting Equation 19 into Equation 21 and solving for Q_C

$$Q_{MaxError} = \frac{\pi}{4} D_{Tube}^2 \sqrt{\frac{2gh_L \Pi_{LinearError}}{\sum K}} \tag{22}$$

There is a maximum flow rate for each chemical dosing tube diameter. The array of tube diameters is determined by the available tubes and barbed fittings on the market.

The flow through the dosing tube must be laminar and this sets an upper bound on the tubing diameter that can be used. Equation 22 can be solved for the maximum average velocity by dividing by the cross sectional area of the tube.

$$V_{MaxError} = \sqrt{\frac{2gh_L \Pi_{LinearError}}{\sum K}} \tag{23}$$

The laminar flow constraint is met when the Reynolds number, Re, is less than the value representing the transition to turbulence, $Re_{Transition} = 2100$, and prevents the use of large diameter tubes that would also correspond to very long dosing tubes.

$$Re = \frac{V D_{Tube}}{\nu} \tag{24}$$

The maximum tubing diameter, $D_{TubeMax}$ than can be used at the maximum flow rate and still maintain laminar flow is obtained by substituting Equation 23 into Equation 24 and solving for the tubing diameter.

$$D_{TubeMax} = \nu Re_{Transition} \sqrt{\frac{\sum K}{2gh_L \Pi_{LinearError}}} \tag{25}$$

The minimum chemical flow rate required by a water treatment plant, Q_{Min}, given the maximum allowable stock concentration, $C_{StockMax}$, is

$$Q_{Min} = \frac{Q_{Plant} C_{DoseMax}}{C_{StockMax}} \tag{26}$$

where $C_{DoseMax}$ is the maximum required dose in the plant and $C_{StockMax}$ is the maximum allowable stock concentration. The number of tubes required to deliver that flow rate, N_{Tube}, for each available tube diameter is calculated and rounded up to the nearest integer.

$$N_{Tube} = \frac{Q_{Min}}{Q_{MaxError}} \tag{27}$$

Because the design uses a discrete number of tubes and discrete tube diameters, the actual maximum flow through all tubes, Q_C is calculated for each available tube diameter (Equation 28).

$$Q_C = Q_{MaxError} N_{Tube} \tag{28}$$

Table 2: Summary of Design Specifications for a Linear Chemical Dose Controller (LCDC)

Input	Value
Q_{Plant}	$10\,L/s$
$Tube\,Diameters$	$US\,Standard$
h_L	$20\,cm$
$\sum K$	4
$\Pi_{LinearError}$	0.1
$C_{StockMax}$	$400\,g/L$
$C_{DoseMax}$	$60\,mg/L$
$L_{TubeMax}$	$2\,m$

Output	Value
D_{Tube}	$3.175\,mm$ $(1/8\,in)$
L_{Tube}	$1.03\,m$
N_{Tube}	1
Q_C	$2.3\,mL/s$
C_{Stock}	$260\,g/L\,PACl$

This algorithm maximizes the flow through each dosing tube to reduce the required length of the dosing tubes. If lower flow rates were used, the tubing would need to be made longer to achieve the target head loss. The concentration of the chemical stock, C_{Stock}, is calculated for each available tube diameter because of its effect on the chemical viscosity, ν (Equation 29). Variation of coagulant viscosity with concentration was experimentally determined and is discussed below.

$$C_{Stock} = \frac{Q_{Plant} C_{DoseMax}}{Q_C} \tag{29}$$

The tube lengths that correspond to the available tube diameters are based on the relationship between the maximum error and major and total losses by combining Equations 18, 19, 20, 21, and 22 and solving for the tube length.

$$L_{Tube} = (1 - \Pi_{LinearError}) \frac{D_{Tube}^2}{64\nu} \sqrt{\frac{2gh_L \sum K}{\Pi_{LinearError}}} \tag{30}$$

The length of the tube increases with the square of the tubing diameter. This creates a practical upper limit on the tubing diameter that can be used while maintaining a length of tubing that can be accommodated easily in the water treatment plant. The optimal design is chosen by selecting the tube diameter, stock concentration, and chemical flow rate that correspond to the longest tube that does not exceed the maximum length specified by the user.

The parameters noted above are summarized in Table 2 for an example plant with a maximum flow of $10\,L/s$ and are implemented in a design algorithm to select a dosing tube diameter and length, chemical stock tank concentration, and number of dosing tubes. The resulting designs for different plant flow rates are shown in Figure 4. Custom designs for chemical dose controllers may be obtained from the AguaClara Design Tool *(aguaclara.cornell.edu/design)*.

Experimental Methods

Determination of minor head loss coefficient

If the major losses dominate minor losses, the linear relationship between the chemical flow rate and the major head loss described by Equation 17 would be maintained. Minor head losses caused by flow expansions and contractions as well as tube curvature are proportional to the square of the chemical flow rate. The magnitudes of the minor head losses were modeled in tandem with experimental analysis to minimize their sources. The total head loss through the system (h_L) is the sum of the major (h_f) and minor (h_e) head losses. Therefore, the total head loss through the system can be represented as:

$$h_L = \frac{128\nu L_{Tube}}{g\pi D_{Tube}^4} Q_C + \frac{8\sum K}{g\pi^2 D_{Tube}^4} Q_C^2 \tag{31}$$

There are two terms in Equation 31, one with a linear relationship between head loss and chemical flow rate, the other non-linear. The minor head loss coefficient can only be roughly estimated by summing standard values for each change in flow path, but should be experimentally determined. The minor head loss coefficient for the tested tubing configuration was determined from the array of observed flow rate data and total head loss values using Equation 31. Once $\sum K$ is determined for a particular tubing configuration, it can be used to design similar systems for all tube diameters and lengths.

LCDC Prototype Calibration and Testing

LCDC performance tests were conducted in the laboratory using a stationary test stand to simulate changes in plant flow rate. The end of the lever arm that would normally connect to the float was adjusted by inserting a metal pin into holes at specified elevations in the test stand. By setting the driving head directly, deviations from the expected flow rates were attributed to minor losses only. With the slider at the maximum dose, the flow rates through the small diameter dosing tubes and the large diameter connector tubes were measured for tube lengths of $1.32\,m$ to $2.56\,m$ and driving head $0-20\,cm$ in $4\,cm$ increments. At each position, three 60 second flow tests were performed and the mean was compared to the expected flow rates. Field tests must ultimately verify that the the maximum desired coagulant flow rate can be achieved.

Calibration of the LCDC system in the field requires adjusting the length of the chain that connects the float to the lever arm to ensure that the lever arm is horizontal at zero plant flow with the slider at maximum chemical dose. Next, with the lever arm still horizontal, the constant head tank must be raised or lowered so that there is no flow through the dosing tube until the lever arm float is raised. The plant flow should then be set to maximum and the chemical flow rate measured. If the flow rate is different than predicted by the algorithm, the length of the dosing tube(s) should be adjusted to achieve less than 5% error at the maximum chemical flow rate (maximum dose and maximum plant flow rate). Guidelines for calibration suggest starting with a dosing tube 10% longer than calculated by the design algorithm and then shortening it in 2 cm increments until a satisfactory agreement wit the maximum flow is obtained.

Results

Minimizing the Minor Loss Coefficient

Minor losses in the LCDC system cause the flow rate to become increasingly nonlinear with respect to head loss, increasing the errors in dosing. Since minor losses are caused by changes in the flow geometry, several dosing tube configurations were tested to quantify their impact on the sum of the minor loss coefficients (Figure 5).

Tube curvature was found to be a significant source of minor losses. Perfectly straight tubing had the lowest $\sum K$ value (2.74). The highest measured loss coefficient (10.36) was observed when the tubing was allowed to drape freely. The optimal tube configuration that allowed the needed flexibility was obtained by reducing minor losses associated with curved tubing and connectors. The curved tubing was straightened by attaching a weight to the dosing tube at the low point between the constant head tank and the drop tube, which decreased $\sum K$ to 5.79. The connector losses were also significant and the minor loss coefficient present with straightened tubing was reduced to $\sum K = 3.13$ by providing a $0.952\,cm$ $(3/8\,in)$ connector tube. The connector tube decreases the flow velocity and thus reduces the minor losses in the fittings and at the point where the flexible tube connects to the drop tube. The length of the connector tube can be adjusted without affecting the accuracy of the dosing system.

LCDC Performance Testing

A series of flow tests were carried out for a $1.42\,m$ dosing tube with a weight and a $0.952\,cm$ $(3/8\,in)$ inner diameter connector tube as described previously. The results are displayed in Figure 6; also displayed are the flow rates calculated using the Hagen-Poiseuille equation for major losses (Equation 17). By fitting the observed flow rates to the total head loss equation (which includes both major and minor losses) (Equation 31) and using a least squares regression, the minor loss coefficient, $\sum K$, was estimated to be 3.13.

Error caused by slider mass

An additional source of error in dose is caused by movement of the slider along the lever arm. Due to the mass of the slider and drop tube on the slider side of the lever arm, there is a variable moment about the pivot point as the slider is moved, which causes a change in the force acting on the float. The change in height of the float when the slider is moved will cause an error in chemical dose. The error resulting from a change in submergence of the float is directly dependent on the total mass of the slider assembly. The vertical displacement of the float, Δh, as a function of float diameter, D_{Float}, is calculated in Equation 32.

$$\triangle h = \frac{4M_{Slider}}{\pi D_{Float}^2 \rho_{Water}} \tag{32}$$

The lever is leveled at zero plant flow with the slider at maximum chemical dose. Because flow through the dosing tube is linearly proportional to height, the maximum displacement error is $\Delta h / H_{LFOM}$. The maximum allowable error due to changing submergence of the float is given by $\Pi_{FloatError}$, and is set equal to 5% for the calculations presented in this paper. The minimum float diameter that adheres to this constraint, $D_{MinFloat}$, is given by Equation 33.

$$D_{MinFloat} = \sqrt{\frac{4M_{Slider}}{\pi\rho_{Water} \cdot \Pi_{FloatError}h_L}} \tag{33}$$

With a slider assembly mass, M_{Slider}, of $120\,g$, $D_{MinFloat}$ for the experimental prototype was $12.36\,cm$ ($4.86\,in$); a float diameter of $15\,cm$ ($6\,in$) was used. The prototype has a maximum float displacement of $0.658\,cm$. This error is eliminated by calibration at the maximum chemical dose and then grows to 3.3% for smaller chemical dosages. Moving the slider away from the maximum dose position decreases its moment and decreases the dose which counteracts the increased dose due to minor loss error in the mid dose range. The area of the float at the air-water interface can be increased by using a $20\,cm$ ($8\,in$) diameter float to distribute the volume of displaced water over a larger area, and reduce the maximum displacement error to 1.9%. For plant flow rates large enough to warrant multiple dosing tubes or a larger drop tube, the mass of the slider assembly will increase the dosing error, motivating the switch to a larger float diameter.

Coagulant Viscosity

The viscosity of the chemical solution has a considerable impact on the design and performance of the LCDC. Little information is available regarding the viscosity of high concentration coagulant solutions. Therefore, experiments were performed with a Vibro Viscometer to directly measure the kinematic viscosity of alum and PACl solutions with concentrations ranging from $10\,g/L$ to $600\,g/L$ of alum and PACl at $20°C$ (Figure 7). To better mimic coagulants used in water treatment practice, industry grade polyaluminum chloride (PACl), (Amuco, Inc.), and technical grade aluminum sulfate, $Al_2\left(SO_4\right)_3 \cdot 14.3H_2O$, (PTI Process Chemicals) were used as coagulants for all experiments. Each coagulant was diluted with distilled water to make the stock solutions.

Kinematic viscosity must be taken into account when predicting chemical flow rates through the LCDC system. Fits to the experimentally observed relationships were used in the LCDC design algorithms to properly estimate the expected chemical flow through the small diameter dosing tube (Equations 34 and 35).

$$\nu_{Alum} = \nu_{Water}\left(1 + 4.255 \times 10^{-6} C_{Alum}^{2.289}\right) \tag{34}$$

$$\nu_{PACl} = \nu_{Water}\left(1 + 2.383 \times 10^{-5} C_{PACl}^{1.893}\right) \tag{35}$$

where ν_{Water} is the viscosity of water at $20°C$, $1\,mm^2/s$, C_{Alum} is the alum concentration in g/L alum, and C_{PACl} is the PACl concentration in g/L PACl. The curve fits for Alum and PACl have a sample size, N, of 13 and $R^2_{Alum} = 0.99$ and $R^2_{PACl} = 0.97$. The reader is cautioned that these relationships are for industry and technical grade chemicals, and that other suppliers may provide different compositions. Preliminary tests suggested that viscosity did not vary significantly from ν_{Water} for calcium hypochlorite. Accurate viscosity data is required before designing the LCDC for use with other chemicals.

Conclusions

The linear chemical dose controller and linear flow orifice meter work in concert to provide a gravity-powered semi-automated chemical dosing system whose function is explained entirely by basic hydraulics, and can be easily fabricated. Through many tests and prototypes, we have converged on a dosing system design that minimizes deviation from the desired linear relationship. Experiments show that use of straight dosing tube segments and connector tube can minimize minor losses. The additional error in dosing created by the variable moment that the slider assembly causes about the pivot point can be minimized by a large diameter float and small mass slider assembly design. Careful component selection and fabrication can ensure that the system will function properly with any chemical solution for a wide range of chemical and plant flow rates (Appendices A and B). The dosing system is versatile, and was designed with the end-user in mind. The design equations have been incorporated into a design algorithm that takes as input the target plant flow rate and outputs all necessary design specifications (available at *aguaclara.cornell.edu/design*). Variation of stock chemical viscosity is considered in the design calculations. The coupled LCDC and LFOM have been tested in six gravity-powered municipal scale drinking water treatment plants designed by the AguaClara Program at Cornell University and built in Honduras. Operator feedback is positive and the systems continue to perform as designed.

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Appendices

Appendix A: Fabrication and Component Selection

In adherence to the sustainable design constraints stated above, the LCDC should, to the extent possible, be made of locally available materials. Therefore, it is important to define the characteristics of each component that are necessary to good performance vs. those which are incidental. The system components are designated in Figures 3 and 8 and their necessary characteristics are as follow:

- The **constant head tank** should have a wide mouth to allow operator access and a diameter that fits the float valve. It should have a cover to prevent debris from entering the chemical solution and one or more small holes in the cover to ensure atmospheric pressure inside. The through-wall bulkhead fittings that connect the dosing tubes to the constant head tank should be barbed and one size larger than dictated by the diameter of the dosing tube to minimize minor losses due to contractions/expansions. A rubber o-ring prevents leaking at the bulkhead connections.

- The **float valve** in the constant head tank (CHT) is the only component that may not be locally sourced in all countries; it is manufactured by Kerick Valves, Inc. and the size used is set by the diameter of the orifice inside the float valve. The orifice diameter needed for the maximum chemical flow rate can be calculated by the orifice equation ($Q = \Pi_{vc} \frac{\pi}{4} D^2 \sqrt{2gh}$).

- The **dosing tube** must be kept taut by a weight of approximately $20\,g$ to reduce minor losses due to curvature to maintain straight sections of tubing.

- The dosing tube, attaches to a larger ($0.25 - 0.5\,in$) inner diameter **"connector" tube** with a reducing barbed fitting. Experimental results revealed that attaching the connector tube to the drop tubes rather than attaching the dosing tube directly reduced the minor loss coefficient by 46% (See Figure 5). Therefore, the large diameter tube should be used even in plants where additional length is not required. The length of the connector tube is arbitrary and allows the placement of the constant head tank to be more flexible. The connector tube attaches to the drop tube with an NPT-threaded barbed fitting that is also one size larger than the tube diameter.

- The **drop tube** should be transparent to allow the operator to visually confirm chemical flow. The drop tube must be of sufficient length that the bottom of the drop tube is below the lowest water level in the flocculator (zero plant flow). This prevents air from entering the flexible tubing that connects the drop tube to the rapid mix; air in the tubing would create an additional head loss in the flexible tubing which causes intermittent chemical flow to the plant.

- The **lever arm** should be a three foot long aluminum bar, approximately 2 in wide to provide space for the dosing scale below the slider and to prevent the slider from obscuring reading of the dose. The lever arm should be mounted to the side of the entrance tank at the pivot point.

Table 3: Detailed list of components for the LCDC. This listing is for a LCDC designed for a $10\,L/s$ water treatment plant. Depending on the plant capacity, different quantities or sizes may be required.

- The **scale** may be printed on a sticker attached to the lever arm, or stamped directly onto the aluminum lever arm. The scale is to be defined in $\frac{mg}{L}$ of the coagulant or as a percentage of the maximum dose.

- The **slider** should also be aluminum, with one threaded hole for a small screw that acts as a locking mechanism, and another similar screw that holds the drop tube. This connection should be loose, allowing free rotation of the drop tube, which should be vertical at all times. The slider assembly (slider, screws, drop tube, barbed fitting) should be as light as possible because it creates a variable moment about the central pivot that is compensated for by a shift in the height of the float (see *Error caused by mass of the slider* above). To accommodate large flow plants where multiple dosing tubes are needed, a “T”-shaped slider assembly can be used. The “T” is made of the same clear PVC as the drop tubes, and each of the barbed fittings is located along a horizontal bar that adjusts to be level with the ground as the lever arm moves. In the case of multiple tubes, all tubes supply the desired chemical doses simultaneously, allowing the LCDC to dose plants with high flow rates. A counterweight can be used to maintain tension in the chain connecting the float to the lever arm if the variable moment caused by the slider is insufficient (See Figure 8).

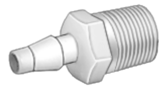
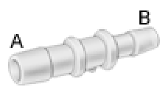
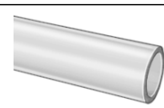
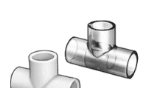
- The **float** should be as wide and short as possible. The float should not touch the bottom of the entrance tank at zero plant flow and should be water tight. The mass of the float should be high compared to the mass of the slider assembly. The float must have a center of gravity that is below the center of buoyancy to provide stability.

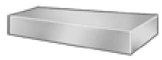
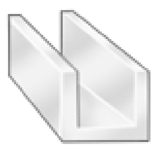
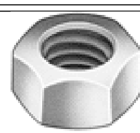
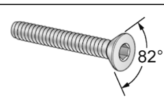
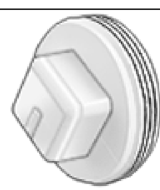
A list of parts used in the LCDC prototype is included in the Supplemental Materials section (Table 3).

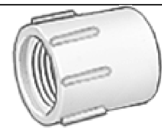
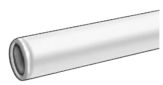
While chemical compatibility between the aluminum and PVC components and coagulant and chlorine solutions will protect the LCDC from degradation over time, occasional maintenance is required. If calcium hypochlorite is used as a disinfectant, calcium carbonate precipitate forms when the chlorine solution comes in contact with atmospheric carbon dioxide, and the upper, open end of the drop tubes are likely to develop significant calcium carbonate precipitate. Periodically, this will need to be removed or dissolved with vinegar so it does not interfere with the chemical flow.

Appendix B: Components List

Part Name	Picture	Description and Explanation

Barbed Fitting for Constant Head Tank		Durable nylon single-barbed tube fitting through-wall adapter for connecting the dosing tube to the CHT.
Barbed Fittings for Drop Tubes		Allows the chemical/coagulant to enter the drop tube from the 0.952 cm (3/8 in) inner diameter connector tube.
Reducing Barbed Fittings		Reducing barbed fitting that goes from 0.317 cm (1/8 in) inner diameter dosing tube to 0.952 cm (3/8 in) inner diameter connector tube.
PVC Drop Tubes		Clear plastic so that plant operator can observe flow. Should be 1.22 cm ($\frac{1}{2}$ in) in diameter to keep as lightweight as possible while ensuring free fall of the chemical solution.
PVC Tubes for Counterweight		A short (5 cm) section of PVC pipe can be used as the optional counterweight.
Large Diameter Connector Tubing		Clear plastic tubing with 0.952 cm (3/8 in) inner diameter to be used as a connector to the drop tube.
Small Diameter Dosing Tubing		Attached to the base of the CHT and the connector tube via a reducing barbed fitting. Clear 0.317 cm (1/8 in) inner diameter. Length specified by the algorithm.
PVC Tee		1.24 cm (1/2 in) PVC tee. Used for a T-shaped slider assembly when the algorithm recommends more than one dosing tube for higher flow systems.
PVC Pipe Cap		Schedule 40 white PVC pipe cap attached to the ends of the "T" and to the bottom of the drop tubes.
Turnbuckle		Connects the float chain to the lever-arm apparatus. Allows for adjustment during calibration.

Constant Head Tank		Translucent plastic jar (2 L), 14.92 *cm* base diameter, 15.88 *cm* height with a hole drilled in the bottom center for the through-wall barbed fitting. The cover prevents contamination of the chemical by particles in the air, but does not make the container air-tight. Small drilled holes can be used to allow air flow.
Lever Arm		Aluminum, 0.914 *m* (3 *ft*) in length, 5 *cm* (2 *in*) in width, and 0.635 *cm* (1/4 *in*) in thickness.
Slider		Corrosion resistant aluminum, u-channel, 0.317 *cm* (1/8 *in*) thick, 1.27 *cm* (1/2 *in*) base, 1.905 *cm* (3/4 *in*) legs, 10.16 *cm* (2 *in*) in length. Attached to the top of the lever arm to vary the coagulant dose.
Aluminum shaft collar		0.952 *cm* (3/8 *in*) bore, 1.905 *cm* (3/4 *in*) outer diameter, 0.952 *cm* (3/8 *in*) width; aluminum shaft collars are secured on either side of each of the lever arms to prevent the lever arms from shifting laterally along the shaft
Hex nut		For use between the drop tube and the slider. Permits the drop tube to swing freely.
Screws		1.27 *cm* (1/2 *in*) 10-32 screws. One for the slider locking mechanism, one to hang the drop tube
Kerick Float Valve		Attached to the side of the constant head tank, and it keeps the water level constant inside the CHT.
Square head plug		15.24 *cm* (6 *in*) PVC threaded square head plug for the top of the float. Water tight but removable to allow weight to be added to the float

PVC cap		15.24 cm (6 in) unthreaded PVC cap for the bottom of the float
Threaded adapter		15.24 cm (6 in) threaded adapter to receive the square head plug and convert to unthreaded pipe
PVC pipe		15.24 cm (6 in) pipe is needed to connect the adapter to the PVC cap. Use no more than is necessary for this purpose.

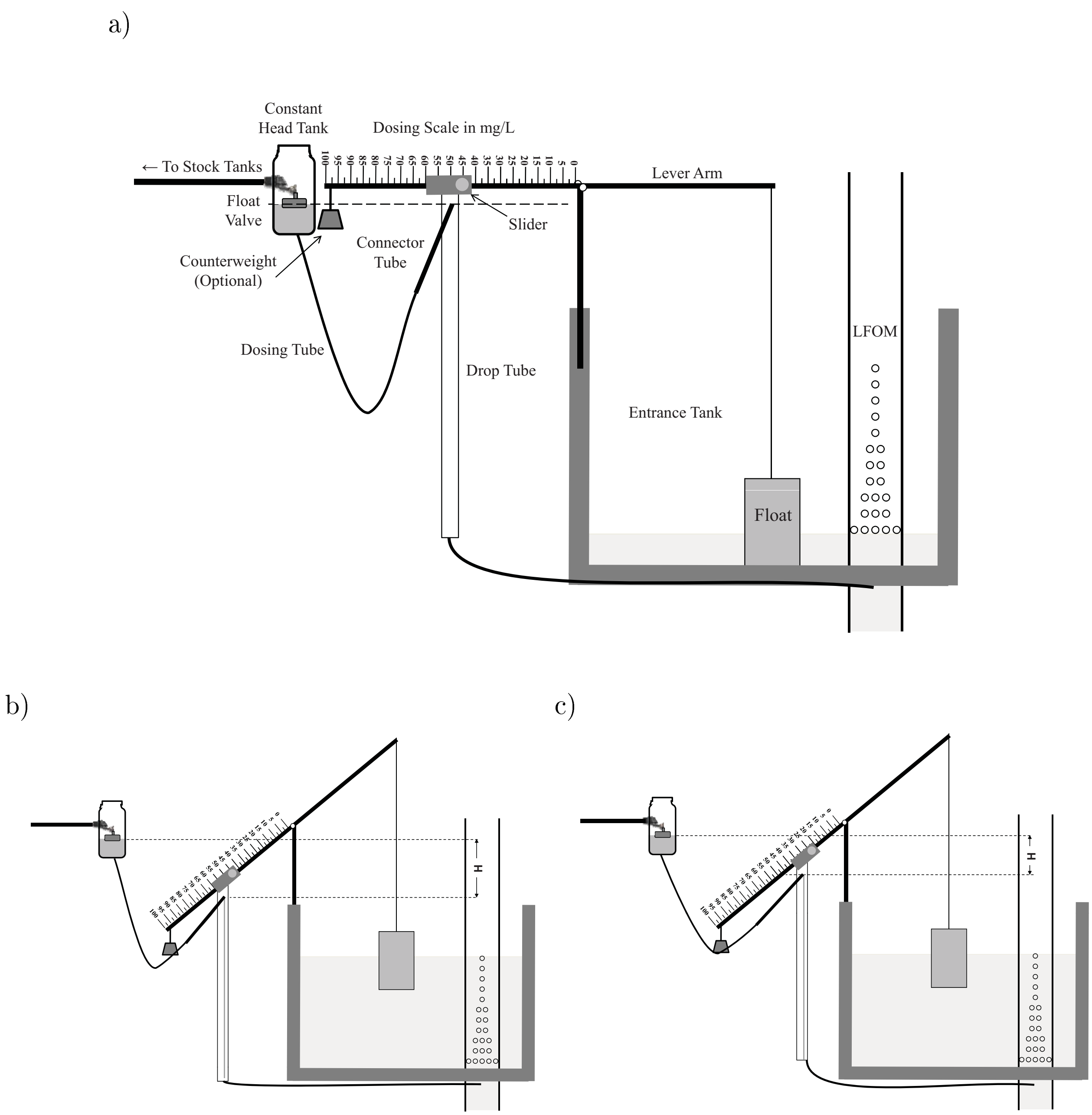


Figure 3: Linear chemical dose controller schematic under conditions of: a) no flow, b) maximum flow, and c) maximum flow with a lower chemical dose.

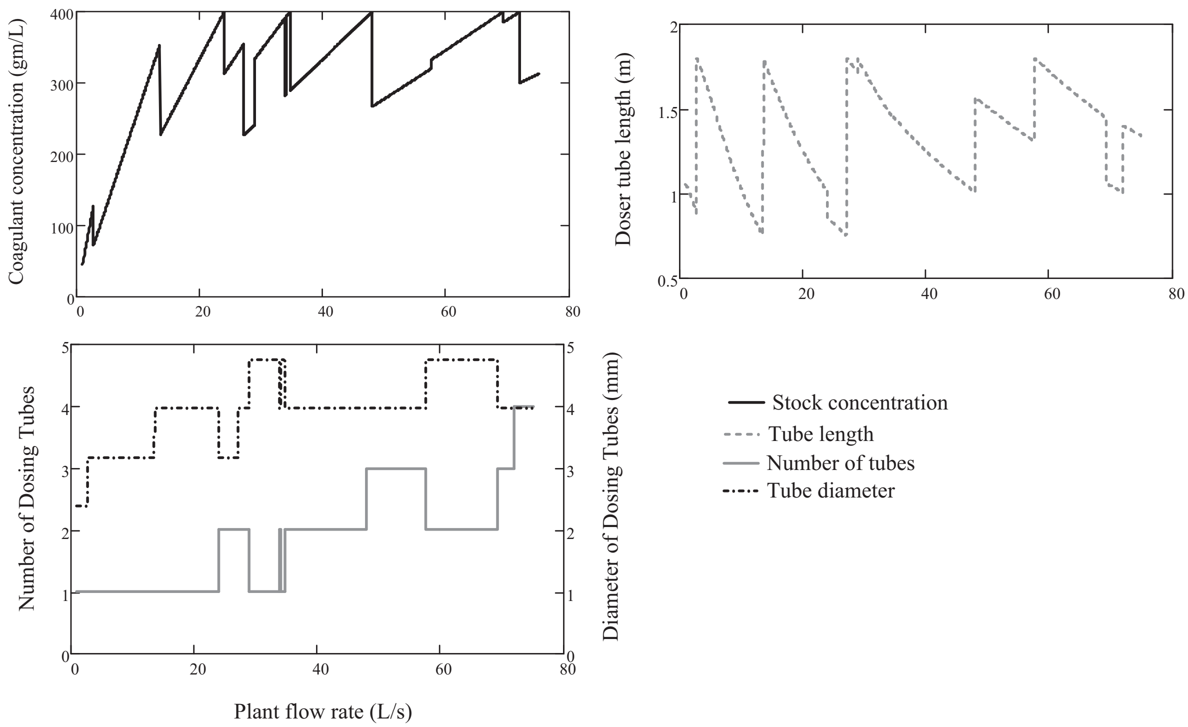


Figure 4: LCDC design algorithm results for plant flow rates $1-75\,L/s$. As the flow rate changes, the dominating constraint may change causing the values given by the algorithm to fluctuate. The discontinuities shown are caused by the discrete sizes of tubing and the requirement of an integer number of tubes. For example at approximately 3 L/s the algorithm changes the specified diameter of the dosing tube from 2.38 mm ($3/32\,inch$) to 3.175 mm ($1/8\,inch$) and the doser tube length and coagulant concentrations must both change to maintain constant dose.

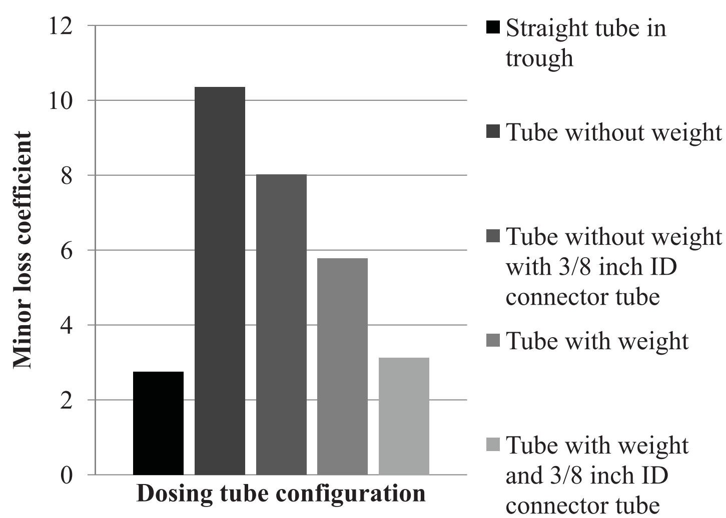


Figure 5: Minor loss coefficients for alternative tubing configurations. Values are an average of three trials for a $1.42\,m$ dosing tube over a range of head losses ($0-20$ cm).

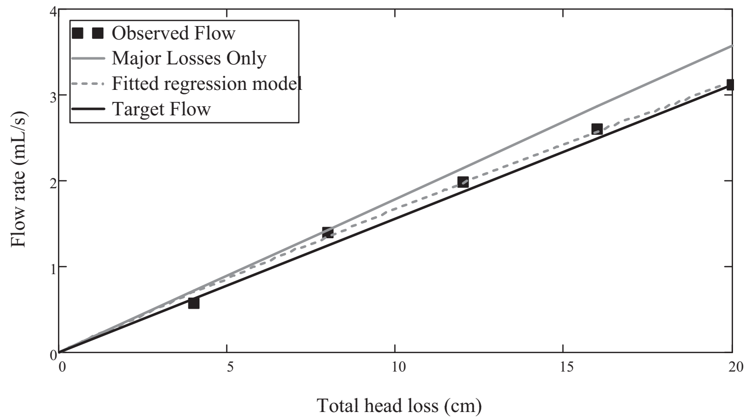


Figure 6: Performance test results from a $0.317\,cm$ $(1/8\,in)$ $1.42\,m$ dosing tube with a weight and a $0.952\,cm$ $(3/8\,in)$ connector tube using tap water with $\nu_{Water} = 1\,mm^2/s$. A least-squares regression used the initial observed flow rates to fit a minor loss coefficient, $\sum K$, of 3.13. Field calibration occurs at zero flow and at maximum flow where the deviation from flow expectations based solely on major losses is greatest. Thus, the calibration procedure compensates for minor loses at the maximum flow. Minor losses cause some deviation from the linear relation between the two calibration points but this error is less than 10%

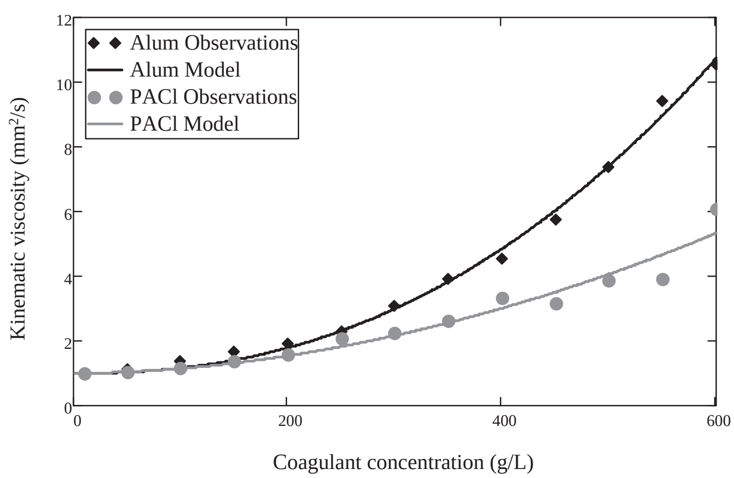


Figure 7: Experimentally determined kinematic viscosities of alum and PACl solutions for use as chemical stock concentrations.

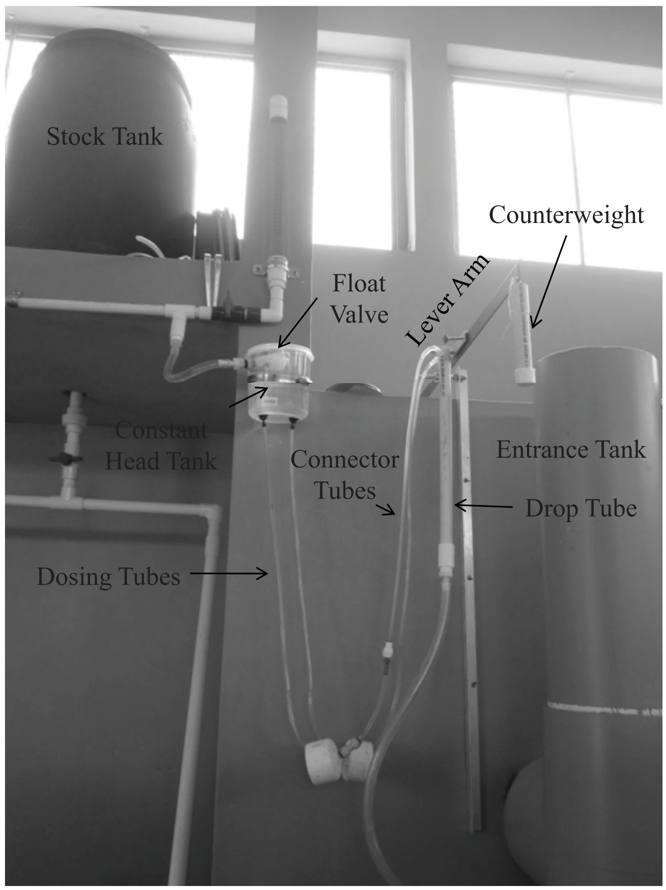


Figure 8: LCDC in operation at the Alauca municipal water treatment plant in Alauca, Honduras. Plant flow rate is $12\,L/s$.