A Theory Based Approach to the Design of Rainwater Harvesting Tanks with Subsurface Dripline Emitters

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Abstract

Rainwater harvesting tanks are a useful tool in conserving water and mitigating the impact of smaller rain events on City of Austin stormwater infrastructure. These tanks, when combined with a subsurface dripline emitter (denoted here a rainwater harvesting system), provide a passive, low maintenance method of releasing the collected water back into the environment in a more measured manner. Releasing the stored water too fast into the subsurface may result in saturated conditions and ponding at the ground surface over the emitters, thereby causing nuisance problems. Inhibiting the release of stored water, on the other hand, results in insufficient tank capacity for the next rain event. Therefore, determining tank sizing and emitter spacing that will balance the two objectives of sufficient tank capacity without creating nuisance problems on the ground surface is key to maximizing the design of a functional rainwater harvesting system.

This report provides design criteria and design calculations established to maximize rainwater capture without over saturating soils. Research and first principles guide the development of the design criteria and calculations, which is laid out here. Specifically, this report describes the basis for a 12 inch emitter depth and 12 inch emitter spacing, as well as the derivation for calculating the drawdown time. These design criteria and calculations will also address most of the soil types present in Austin, Texas. This theory-based approach generally matches data collected from a functioning rainwater harvesting system at the Zaragoza Recreation Center. However, further experimentation with various soil types and tank configurations are needed to quantify the uncertainty in the model.

Introduction

As the growth in Austin's population continues and urbanization and impervious cover within the city increases, water quality runoff becomes more degraded impacting receiving water bodies and restricting the filtration of stormwater into the soil. Furthermore, impacts from climatic events become more apparent in longer droughts and flashier floods exacerbating the stress on stormwater infrastructure and water supply resources. Thus, water management is becoming a more important issue for city governance. Concerns for water management include addressing the inefficiencies in infrastructure leakage, attending to polluted streams, and strategically reducing consumptive water use. Rainwater harvesting has the potential to engage in all of these issues.

A passive rainwater harvesting system for the purposes of this analysis consists of a rainwater harvesting tank whose outlet is a subsurface dripline emitter. This dripline emitter is a ½" pipe with $^{1}/_{8}$" perforations along the pipe at set increments. The size of the perforations are key to conserving water for irrigation with the tank detaining rain water and reducing the impacts from short flashy floods, thereby reducing pollution of the receiving stream and moderating impacts on storm water infrastructure. This can be an especially cost effective means of water conservation for buildings with large areal footprints, as it mitigates the need for potable water irrigation, reduces drainage utility fees, and can provide the added benefit of improved water quality for the receiving stream.

Implementing such a system, however, requires finding the appropriate trade-off between discharging the tank in time to have sufficient capacity available for the next rain event and suppressing the discharge in a manner to prevent its expression on the ground surface (i.e. "surfacing"). This paper applies theoretical calculations in the aid of the design and requirements for a rainwater harvesting system. This theory incorporates the trade-off mentioned by:

1. first requiring a minimum depth and spacing for dripline emitters to reduce the risk of surfacing based on a set of models/equations; and
2. applying the theory to design an appropriate tank capacity, hydrostatic pressure, soil properties, and the number of emitters along a dripline to maintain the time required to empty the tank within 120 hours (a City of Austin Environmental Criteria Manual requirement).

In meeting these requirements, it is anticipated that nuisance conditions (surfacing and insufficient tank capacity) from rainwater harvesting will be minimized and can assist in suitably managing water for any property owner.

Background

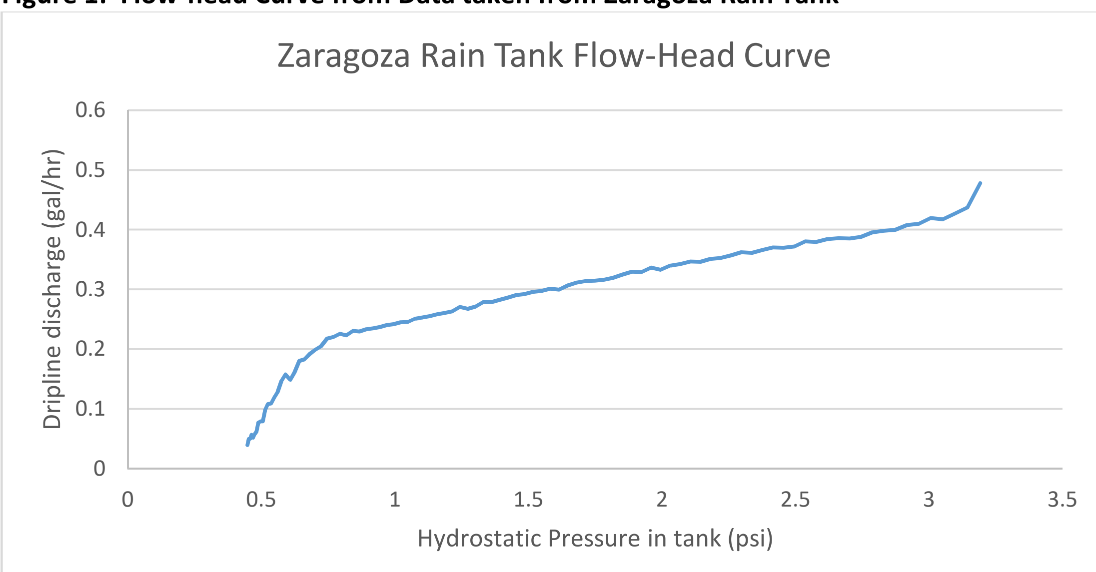
Over the past decade, the City of Austin has installed a variety of rain tanks on various public properties but has yet to do it with resolve. Many of the City-owned rain tanks appear to have no regular use of the water collected. Moreover, some of the rain tanks have been sitting full for a long time. One possible reason for this reluctance in utilizing rain tanks is that there is no cost-effective, low maintenance solution to discharging its effluent. Typically, rain tanks discharge onto a gravel-filled trench or to large drain fields. However, this can create undue costs in the form of labor and idle capital. A passive rain harvesting system was installed as a pilot to test whether a passive rainwater harvesting system at Zaragoza Recreation Center can be utilized for any soil type. This pilot system is anticipated to provide a cost-effective alternative to the gravel-filled trench and can potentially be used as a gauge for future rainwater harvesting systems. This passive system uses a drip line (GEOFLOW 2016) originally designed for land application of treated effluent. Emitter testing by the manufacturer only include emitter flow rates between 10 and 45 psi (Table 1). However, the release of the harvested water from the storage tank into the subsurface is meant to be passive and relies solely on the hydrostatic pressure (i.e. hydraulic head) in the tank. Given a 7 ft high rainwater harvesting tank, this generates a hydrostatic pressures of around 3 psi or less. No reliable flow-head curve is known for such low pressures.

Table 1. Flow rate versus pressure of GEOFLOW CLASSIC WASTEWATER dripline.
http://www.geoflow.com/wastewater/w_pdfs/classic.pdf

Pressure	Head	Flow Rate
10 psi	23.10 ft.	.81 gph
15 psi	34.65 ft.	1.00 gph
20 psi	46.20 ft.	1.16 gph
25 psi	57.75 ft.	1.31 gph
30 psi	69.30 ft.	1.44 gph
35 psi	80.85 ft.	1.57 gph
40 psi	92.40 ft.	1.68 gph
45 psi	103.95 ft.	1.80 gph

Preliminary measurements collected at the test site depict the hydrostatic pressure in the tank (in pounds/in^2) to the dripline discharge (in gal/hr) for the one observed rain event (Figure 1).

Figure 1: Flow-head Curve from Data taken from Zaragoza Rain Tank



However, this pilot does not have replication across different soil types to enable extension of the results to a broader scale. Therefore, additional work is required to verify that such a system will work under any soil type. A unified framework is needed to quantify the effluent release under any soil type and any tank size and hydrostatic pressure. This report aims to provide this framework and design criteria that will enable users to install these systems without excessive calculations or experiments. In developing design criteria for this report, data from this experiment will be examined with respect to the equations.

Theory

This section consists of two parts. The first part describes the theory used to set the minimum depth of the dripline emitter to prevent surfacing given a range of soil properties and the discharges expected from a passive rainwater harvesting system. The second part examines the implications of this theory as it relates to the computations needed to calculate the time to empty the rainwater tank (i.e. the drawdown time).

Design Calculation to Determine the Minimum Depth

The theory describing subsurface flow was first formulated by Richards (1931) and is commonly referred to as Richards' equation. However, this formulation, when applied to continuous point sources (such as dripline emitters), provides an indefinitely large soil water pressure adjacent to the emitter. Such a large soil water pressure implies that the soil water will follow Laplace's equation for flow in saturated media rather than flow in unsaturated media. This is problematic when calculating the soil water pressure since finding the *free-surface boundary condition*[1] surrounding the saturated zone turns to questions of whether the solution is *well-posed*[2]. J. R. Philip (1992) addressed this question and developed a sound framework from which others were to analyze flow from continuous point sources in unsaturated media. This work was expanded upon by Shani et al (1996), Warwick and Shani (1996), and Revol (1997). This work was used as the theoretical justification of the design calculations herein, and provide a manner to determine the free-surface boundary condition, which is necessary in order to find the locus in space that partitions the subsurface porous media into saturated media (defined by positive gage pressure in the soil water) and unsaturated media (defined by negative gage pressure in the soil water).

To find the minimum depth and spacing required to mitigate surfacing, one must ensure that the saturated sphere emanating from the dripline emitters will not cross the ground surface. To meet this requirement, the free-surface boundary condition is assumed to be at steady state and is defined as the locus of zero gage pressure in the soil water. Furthermore, it was assumed that the extent of the locus was spherical. If that locus crosses the ground surface, then additional depth is required, otherwise saturation is confined to the subsurface. Four equations (or models) were used to determine the locus of zero gage pressure, each presented in order of increasing complexity. If the models approach a solution, then this provides confidence that the models have some validity[3]. Each model assumes that the locus forms a cylindrical shape (in the case of the simpler models) or a spherical shape (in the case of the more complex model) and is at steady state. The first assumption suggests that the free-surface boundary condition can be characterized by a radius. That last assumption implies that the evolution of free-surface boundary condition has ceased.

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[1] A free-surface boundary condition is a mathematical term referring to the type of boundary condition in differential equations. Conventional problems in differential equations consist of boundary conditions fixed in space. For problems where the boundary conditions are within the model domain and are unknown, such as those involving flow through unsaturated media, a free-surface boundary condition is needed.

[2]There are three attributes to well-posed problems. They preclude that the solution: exists, is unique, and is continuously dependent on the data. The final attribute implies that small fluctuations in the input do not produce large fluctuations in the output.

[3] Once it is confirmed that the models approach a solution, the user can choose which model will best serve the needs of the problem

The first two models describe a cylindrical wetted surface area developed from dripline flow released at the surface. These models were mostly used to compute an upper limit for the wetted radius. The last two models compute a wetted sphere from subsurface discharge, and is considered to be more accurate for the purpose of this paper. From this wetted sphere, a minimum depth and emitter spacing can be established.

Surface Models

Two surface models were developed to validate the appropriateness of the subsurface models. The first model was a preliminary calculation where the discharge from the emitter was assumed to travel down vertically at the same rate as the soil's saturated hydraulic conductivity. Thus, the wetted area of emitter was computed by:

$$r_o = \sqrt{\frac{Q}{K_{sat} \cdot \pi}} \tag{1}$$

In Equation 1, r_o is the radius of wetted surface area (inches), Q is the discharge from the emitter (inches^3/hr), and K_{sat} is the saturated hydraulic conductivity (inches/hr).

A second model was utilized based on Revol (1997). This model again assumes percolation from a surface dripline emitter and represents the radius, r_o, in inches of a wetted area on the surface.

$$r_o = \frac{-2\phi + (4\phi^2 Q \pi K_{sat})^{1/2}}{\pi K_{sat}} \tag{2}$$

The parameters in the model are the same except for the Kirchoff potential, ϕ, which is defined as:

$$\phi = \int_{-\infty}^{0} K_{sat} e^{\alpha\psi}\, d\psi \tag{3}$$

This model improves upon the first model by accounting for the unsaturated nature of the soil. This can be seen with the inclusion of the air entry pressure, α (inches^{-1}) and unsaturated soil water pressure, ψ (inches), in the Kirchoff potential. The integral goes from negative infinity to 0 to reflect the fact that soil water pressure is at negative gage pressure under unsaturated conditions and at positive gage pressure for saturated conditions.

Subsurface Models

The first two models presented above are simple equations incorporating multiple assumptions. Some of these assumptions oversimplify the impacts of the dripline emitters on the surrounding media as proposed by this paper. Thus, to account for these complexities, two other models were included. These models draw directly upon the work on subsurface flow from dripline emitters by Shani et al. (1996) and Warwick (2003).

Warwick proposed the following model to account for the subsurface nature of the continuous point source.

$$\psi = \frac{Q\alpha}{8\pi(0.5\alpha^2 {r_0}^2)} e^{0.5(\alpha r_0 - \alpha^2 {r_0}^2)} \tag{4}$$

For Equation 4, the parameters are the same as Equation 2. However, one must iterate to a solution where the user inputs a radius of saturated sphere, r_o (inches), to try to find zero gage pressure, ψ, in the soil water.

In the final model, Shani et al. (1996) calculate a radius (in) corresponding to some positive soil water pressure emanating from the dripline emitter, ψ_s (inches). To find the radius of the free-surface boundary condition (i.e. zero gage pressure in the soil water), simply input zero gage pressure into ψ_s in Equation 5:

$$r_o = \frac{2Q\alpha}{8\pi K_{sat}(\alpha\psi_s+1)+\alpha^2 Q} \quad (5)$$

The calculations for the four radii presented in this section will form the basis of our model selection, which will, in turn, provide an estimate of the required dripline emitter spacing and depth. An evaluation of these models will be discussed in the Results section.

Calculations to Estimate Drawdown Time

Warwick and Shani (1996) expanded upon their model to find the radius of a saturated sphere around a dripline emitter and developed a method by which one can derive the flow rate of water from subsurface dripline emitters. Their method takes into account the positive soil water pressure, ψ_s, emanating from the dripline emitter, which also pushes back on the flow from the dripline emitter. Once this actual dripline emitter flow rate is known, the drawdown time can be calculated. First, Warwick and Shani note that the actual dripline emitter flow rate, Q, is always less than the flow rate from the tank, Q_o, without any soil back pressure.

$$Q = Q_o\left(\frac{\psi_l-\psi_s}{\psi_l}\right) \quad (6)$$

This equation describes this by scaling Q_o down based on the percent difference between the pressure in the dripline, ψ_l, and the soil water pressure pushing back, ψ_s. The pressure in the dripline, ψ_l, is always larger than the soil water pressure ψ_s; otherwise, water would be entering the dripline. The pressure in the dripline, ψ_l, can be ascertained by either manufacturer's specifications or field tests of the tank without the presence of soil water pressure.

To calculate the soil water pressure, ψ_s, the right hand side of Equation 6 is substituted into Equation 5, and solved for ψ_s. Equation 7 presents the result of this substitution.

$$\frac{\psi_s}{\psi_l} = \left[(\lambda\cdot\frac{Q_o}{r_o K_{sat}} - \frac{1}{\alpha})\cdot\frac{1}{\psi_l}\right] / \left[1+\lambda\cdot\frac{Q_o}{r_o K_{sat}}\cdot\frac{1}{\psi_l}\right] \quad (7)$$

The parameters for this equation are similar to the ones used previously, and λ is the dimensionless parameter where:

$$\lambda = \frac{2-\alpha\cdot r_o}{8\pi} \quad (8)$$

Inserting Equations 7 and 8 into Equation 6 produces an estimate of the actual flow rate from the dripline emitters. Note that the flow rate, Q, is dependent on pressure in the dripline, which for the rainwater harvesting system described here is dependent on the hydrostatic pressure (i.e. head) in the tank. To calculate the drawdown time one must consider that, as the water in the tank is discharged, the head in the tank is lowered reducing the discharge flow rate from the emitter. This dependency is required to calculate the total drawdown time as the actual flow rate is dependent on the head in the tank and the head in the tank is determined by the actual flow rate that has been discharged into the soil.

One way to derive the total drawdown time for a tank, is to partition the head in the tank into discrete intervals (say 1 inch intervals). For each interval of head, calculate the associated actual flow rate from Equations 6 and 7. Then, divide the volume in the tank for that interval (in^3/in) by its associated actual flow rate (in^3/hr) to get the drawdown time for that interval (hr/in). Once this is completed for every interval of head in the tank, sum the drawdown times for each interval to arrive at the total drawdown time (hr). Repeat this for smaller intervals until the total drawdown time converges at a number to reach a solution.

Another way to do this is analytically. That is, an integral performs the same algorithm as above, but with less computations needed and for more general cases. To calculate the total drawdown time, the integral of the reciprocal of the flow rate, Q, is needed over the span of head in the tank[4] multiplied by the cross-sectional area of the tank, A_T. Mathematically, this is:

$$DDT = \int_{\psi_1}^{\psi_2} \frac{A_T}{Q(\psi_l, K_s)}\, d\psi_l \qquad (9)$$

Combining Equations 5, 6, 7, 8, and 9, the total drawdown time over a beginning and ending head in a tank (ψ_2 and ψ_1, respectively) is equal to:

$$DDT = A_T \int_{\psi_1}^{\psi_2} \left\{\frac{1}{Q_o} - \left[1 + \lambda \cdot \frac{Q_o}{r_o K_s} \cdot \frac{1}{\psi_l}\right] / \left[Q_o\left(\lambda \cdot \frac{Q_o}{r_o K_s} - \frac{1}{\alpha}\right) \cdot \frac{1}{\psi_l}\right]\right\} d\psi_l \qquad (10)$$

Or, simplifying

$$DDT = A_T \int_{\psi_1}^{\psi_2} \left\{\frac{1}{Q_o} - \frac{\psi_l}{Q_o\left(\lambda \cdot \frac{Q_o}{r_o K_s} - \frac{1}{\alpha}\right)} - \frac{\lambda \cdot \frac{Q_o}{r_o K_s}}{Q_o\left(\lambda \cdot \frac{Q_o}{r_o K_s} - \frac{1}{\alpha}\right)}\right\} d\psi_l \qquad (11)$$

Evaluating the integral over the beginning and ending head:

$$DDT = A_T \left[\frac{\psi_l}{Q_o} - \frac{{\psi_l}^2}{2 \cdot Q_o\left(\lambda \cdot \frac{Q_o}{r_o K_s} - \frac{1}{\alpha}\right)} - \frac{\psi_l \cdot \lambda \cdot \frac{Q_o}{r_o K_s}}{Q_o\left(\lambda \cdot \frac{Q_o}{r_o K_s} - \frac{1}{\alpha}\right)}\right]\Bigg|_{\psi_1}^{\psi_2} \qquad (12)$$

This results in a drawdown time for any tank size, under any soil conditions, and under any flow rate from the tank. Note, though, that this works only for the parameters that are constant. In this situation, the flow rate, Q_o, in the dripline is not constant. Rather, as discussed above, the flow rate is a function of the pressure head in the tank. This additional complexity will be taken up in the Results section.

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[4]We are essentially performing the same algorithm: dividing the volume of the tank by the flow rate and then summing over the height of the tank.

Results

Design Calculation to Determine the Minimum Depth

Equations 1, 2, 4, and 5, were used to determine the range of potential depths and spacing of the dripline emitters under different soil types. It was assumed that a maximum flow rate, Q_o, of 115.51 in^3/hr would be applied to the equations. This assumption was based on the maximum flow measured from a 7 ft high rainwater harvesting tank at the Zaragoza Recreation Center, in Austin, Texas. From this, it was presumed that the maximum flow rate would produce the maximum radius of wetted area. The other variables in the model pertain to soil properties. Table 1 below shows the soil properties for the various soils used in the equations.

Table 2: Parameter Values used in the models (Equations 1, 2, 4, 5)

	Clay	Clay Loam	Loam	Sandy Loam	Sand
K_s, saturated hydraulic conductivity (in/hr)	0.08	0.19	0.41	1.74	11.7
α, air entry pressure (in^{-1})	0.15	0.18	0.33	0.57	0.75

The results of the models can be seen in Table 2 below.

Table 3: Results of Wetted Radii (inches) from the Four Models to determine Minimum Depth and Spacing

		Clay	Clay Loam	Loam	Sandy Loam	Sand
Surface Models	Equation 1	21.4	19.2	9.5	4.6	1.8
	Equation 2	17.7	10.9	7.7	3.6	1.1
Sub-surface Models	Equation 4	9.3	6.6	4.2	2.2	0.9
	Equation 5	7.5	4.9	3.3	1.6	0.5

From Table 2, the surface models estimate larger wetted radii than the sub-surface models. This is predictable since the sub-surface models assume that the point source is surrounded by unsaturated media, thereby slowing the expansion of a wetted sphere. However, the surface models are helpful in that they validate the magnitude of the results of the sub-surface models. Similarly, within the sub-surface models, Equation 5 approximates a smaller wetted radius than Equation 4 because it incorporates the buildup of soil water pressure around the dripline emitter, which slows down the expansion of the wetter sphere.

<u>Recommendation for Dripline Spacing and Minimum Depth</u>

For the purposes of this report either Equation 4 or 5 appears to provide a reasonable estimate of a radius of a wetter sphere surrounding a dripline emitter. Thus, for dripline emitters with a maximum flow rate from the tank of 115.5 in^3/hr, we are recommending that the dripline emitter can be buried at a minimum depth of 12 inches without causing surfacing. We are also recommending that dripline emitter spacing be no less than 12 inches apart. This would afford sufficient spacing under most soils with the exception of soils with a saturated hydraulic conductivity of around 0.08 in/hr. However, even in this case, any nuisance from surfacing would be mitigated by the 12 in minimum depth. Thus, this spacing would appear adequate.

Calculations to Estimate Drawdown Time

In order to determine the total drawdown time (Equation 12), several approximations were necessary. First, a function relating actual flow rate, Q_o, and the head in the tank, ψ_l, was developed. For a pressurized system, these two variables would be independent, but in keeping with the passive nature of this system, the actual flow rate (i.e. the flow rate measured from the dripline emitter) is dependent on the head in the tank. To find the relationship between actual flow rate, Q_o, and the head in the tank, ψ_l, these two variables were measured at different head elevations as rainwater was emptied from a tank. The result was the following regression curve:

$$Q_o = 0.1368 \ln(\psi_l) - 0.2034 \tag{13}$$

Furthermore, the air entry pressure parameter, α, is a function of soil texture, and thus, was linked to the saturated hydraulic conductivity, K_S, as follows:

$$\alpha = 4.818 \ln(K_s) + 18.249 \tag{14}$$

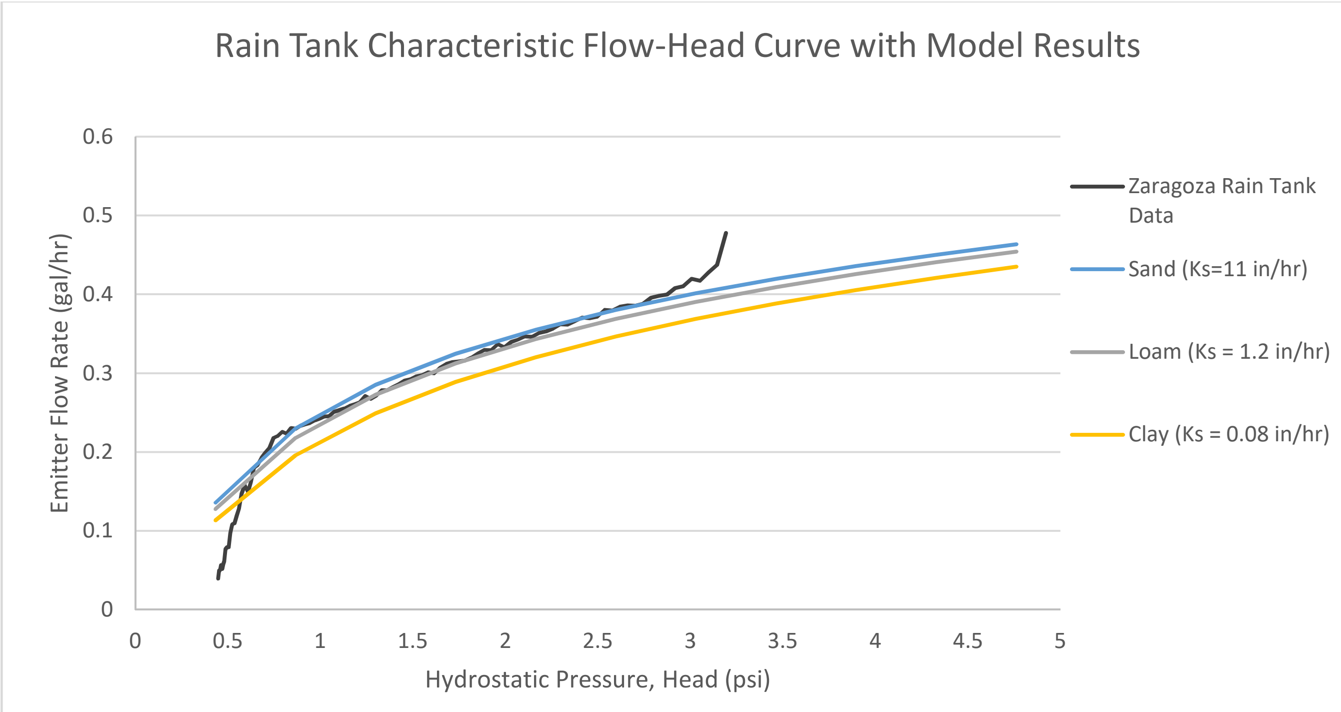
These regression equations should be substituted into Equation 11; however, solving the integral for this would be unwieldy. Instead, for simplicity, the regression equations were substituted into Equation 12 for three soil textures; sand with a K_s of 11 in/hr, loam with a K_s of 1.2 in/hr, and clay with a K_s of 0.08 in/hr. For each soil texture, the functional form of draw down time was developed. That is, an expression of drawdown time as a function of head in tank was developed for the three soils. The coefficients for each of the three expressions were then regressed along the saturated hydraulic conductivities of the soil, to give an additional level of regression. The resulting regressions provided the following equation, which relates the beginning and ending head of the tank (ψ_2 and ψ_1, respectively in inches), the cross-sectional area of the tank (A_T, in inches squared), the number of emitters (N_E, based on a 12" spacing) and the saturated conductivity of the soil (K_S, in inches/hour) to the total drawdown time:

$$DDT = A_T\left[0.000111\left({\psi_2}^2 - {\psi_1}^2\right) + 0.0396(\psi_2 - \psi_1) - 0.001264 \cdot \ln(K_s) \cdot (\psi_2 - \psi_1)\right]/N_E \tag{15}$$

<u>Model Validation</u>

To validate the model, data was taken from the rain tank at Zaragoza Recreation Center. The head in the tank, ψ, was plotted against the actual flow rate discharging from the dripline emitter, Q_o. This was compared against the results from the model (Equation 5 and 6) for three soil textures: sand, loam, and clay. Figure 1 shows the plot, which indicates that the model agrees fairly well with the data collected, and points to the practicality of these models and the theory behind them.

Figure 2: Flow-head Curve from Data taken from Zaragoza Rain Tank superimposed with the results from Equation 15



Next Steps

Equations 5 and 15 can be used to design a passive rainwater harvesting tank, which can be used to calculate the wetted sphere emanating from a dripline emitter and an approximate drawdown time, respectively. From this, we estimate that a depth of 12 inches with emitters at 12 inch spacing is sufficient to avoid surfacing. Equation 15 can be used by designers to size tanks and emitter line lengths to ensure that the tank will empty within 120 hours. However, these equations are approximations. A rough validation of the model was performed using data from a rainwater harvesting system at Zaragoza Recreation Center. The next step in the process would be to perform a more rigorous validation of the models and quantify the uncertainty in the models by conducting an experimental design of the tank system under different heads and soil textures (i.e. saturated hydraulic conductivities). Validation of the models could be as simple as checking for surfacing after the release of water from the tank or as involved as pressure transducers buried in the subsurface around the dripline emitters. For validation of the drawdown time model, a level detecting device could be used to compare the height in elevation in the tank (i.e. head) to that predicted by the model.

Validation of the models could also be used to quantify some of all of the following sources of uncertainty:

1. Uncertainty in model – There are several potential factors unaccounted for in the model that may influence the results. A consistent pattern of deviation in the data from the model across all soil textures and tank sizes could alert decision makers to uncertainty in the model.

2. Uncertainty in model parameters (specifically, the uncertainty in the estimate of wetted radius) – The equation used to develop draw down time relies on an estimate of the wetted radius to calculate the actual flow rate, Q_o. If data on the wetted radius in future experiments are consistent with theory, but the measurements of draw down time are inconsistent, then this could point to flaws in the estimation of a wetted radius in draw down time.

3. Uncertainty in tank properties (specifically, the uncertainty in the regression of flow rate as a function of head) – Equations 13 and 14 were regressions of data taken from a rain tank at the Zaragoza Recreation Center. The number of data points used to fit this data (n=3) and whether these regressions apply to rain tanks at large is an open question. A large scatter in the data forming the flow-head curve in conjunction with a smaller scatter of data in the soil moisture measurements for emitters across all sites might point to issues with these regressions.

4. Uncertainty in soil properties — There may be heterogeneity in the soil properties that may also produce substantial deviation. A large scatter in data from both the flow-head curve as well as soil moisture measurements could point to the need for better soil property measurements.

5. Uncertainty in regressions – Equation 15 was produced by regressing three equations (which themselves have uncertainty). Whether these regressions apply to the rainwater harvesting systems at large is an open question. Large variations in the flow-head curves in rainwater harvesting tanks other than the Zaragoza Recreation Center rainwater tank could point to insufficiently characterized regressions.

These forensic evaluations are just a sample of possible assessments from future experimental designs. Furthermore, the models herein point towards a method of understanding any future data collected from a rainwater harvesting system, which will ultimately provide a way to address soil and tank properties in one equation that can provide users with a simple way to estimate the wetted sphere and draw down time from these systems.

References

Philip, J. R., 1992. What happens near a quasi-linear point source?. Water resources research 28.1, 47-52.

Richards, L.A., 1931. Capillary conduction of liquids in porous mediums. Physics 1, 318–333.

Shani, U., et al. 1996. Soil-limiting flow from subsurface emitters. I: Pressure measurements. Journal of irrigation and drainage engineering 122.5, 291-295.

Warrick, A. W., and U. Shani. 1996. Soil-limiting flow from subsurface emitters. II: Effect on uniformity. Journal of irrigation and drainage engineering 122.5, 296-300.

Warrick, Arthur W. *Soil water dynamics*. Oxford University Press, 2003.