TECHNICAL NOTE:

SIMPLIFIED EQUATIONS TO ESTIMATE FLUSHLINE DIAMETER FOR SUBSURFACE DRIP IRRIGATION SYSTEMS

F. R. Lamm, J. Puig-Bargués

ABSTRACT. *A formulation of the Hazen-Williams equation is typically used to determine the diameter of the common flushline that is often used at the distal end of subsurface drip irrigation systems to aid in joint flushing of a group of driplines. Although this method is accurate, its usage is not intuitive and can be confusing since designers must only consider the portion of flows reaching the flushline. Earlier alternative methods provided simple flushline diameter guidelines related to the cross-sectional areas of the flushline and the driplines contributing flow to it. Improvements to these alternative guidelines and their accuracy with respect to the full Hazen-Williams formulation are reported here in both SI and English units to aid in their usage. The improved equations are accurate and tend to self-regulate their accuracy over the range of typical SDI system design parameters. The authors recommend that these equations be used in concert with the full Hazen-Williams formulation for improved quality assurance in flushline design for SDI systems.*

Keywords. *Hazen-Williams equation, Irrigation design, Microirrigation, SDI, Subsurface drip irrigation.*

Maintenance is very important in ensuring the longevity of subsurface drip irrigation (SDI) systems. Typically, microirrigation systems are designed to provide filtration of particles to approximately one-tenth the size of the smallest emitter passageway (Nakayama et al., 2007), and microirrigation filtration systems usually do not remove the silt and clay particles and bacteria. Over time, these contaminants settle out and accumulate or conglomerate in the dripline and need to be periodically flushed from the SDI system. In many instances, the assurance that adequate SDI flushing velocities can be obtained throughout the system will be the controlling factor (Burt and Styles, 1999) in the SDI system design (e.g., sizing of irrigation zones, pipelines, driplines, and emitter flowrates). The flushing requirement and associated components add considerable complexity and cost to the SDI system, but they are integral to a successful system. SDI systems that are used for closely spaced row crops typically are designed with a flushline (i.e., manifold pipeline) installed at the distal end of the zone that allows for jointly flushing of a group of driplines (figs. 1 and 2). Although the flushline allows for more convenient flushing of driplines, it does not increase the effectiveness of flushing. Hydraulically, it is more effective to flush a single dripline; as a result, flushlines are not typically used on the more widely spaced and greater-value perennial vine and tree crops.

ASABE recommends a minimum flushing velocity of 0.3 m s^{-1} for microirrigation systems (ASABE, 2014). However, recommended flushing velocities for SDI systems ranging from 0.3 to 0.6 m s^{-1} (Burt and Styles, 1999) can be found in the literature; in some states, the USDA-NRCS may require values greater than 0.3 m s^{-1} in their approval of SDI designs. There is some practical rationale for a greater flushing velocity for SDI that perhaps, consequently, could result in improved overall flushing of larger particles when coarser filters are used (Hills and Brenes, 2001; Nakayama et al., 2007). Additionally, flushing velocity may need to be increased to 0.5 to 0.6 m s^{-1} to avoid settling and deposition when larger-diameter driplines are used (Koegelenberg, 1998; Puig-Bargués and Lamm, 2013). Many of these SDI systems are used for multiple years, and system longevity is very important in determining SDI economic feasibility, especially for lesser-value crops. The required flushing velocity should be maintained in all segments of the SDI system, but there are system locations where this guideline cannot be followed, such as the farthest point from the flush valve in a flushline, where only a single dripline is contributing flow. As a result, the primary focus on flushing velocity is for the driplines because the emitters are subject to clogging (Lamm and Camp, 2007).

Flushlines should be installed on a level or near-level grade to prevent irregular system flow characteristics, such as backflow into driplines at a lower slope positions, during the normal irrigation or flushing processes. Likewise, une-

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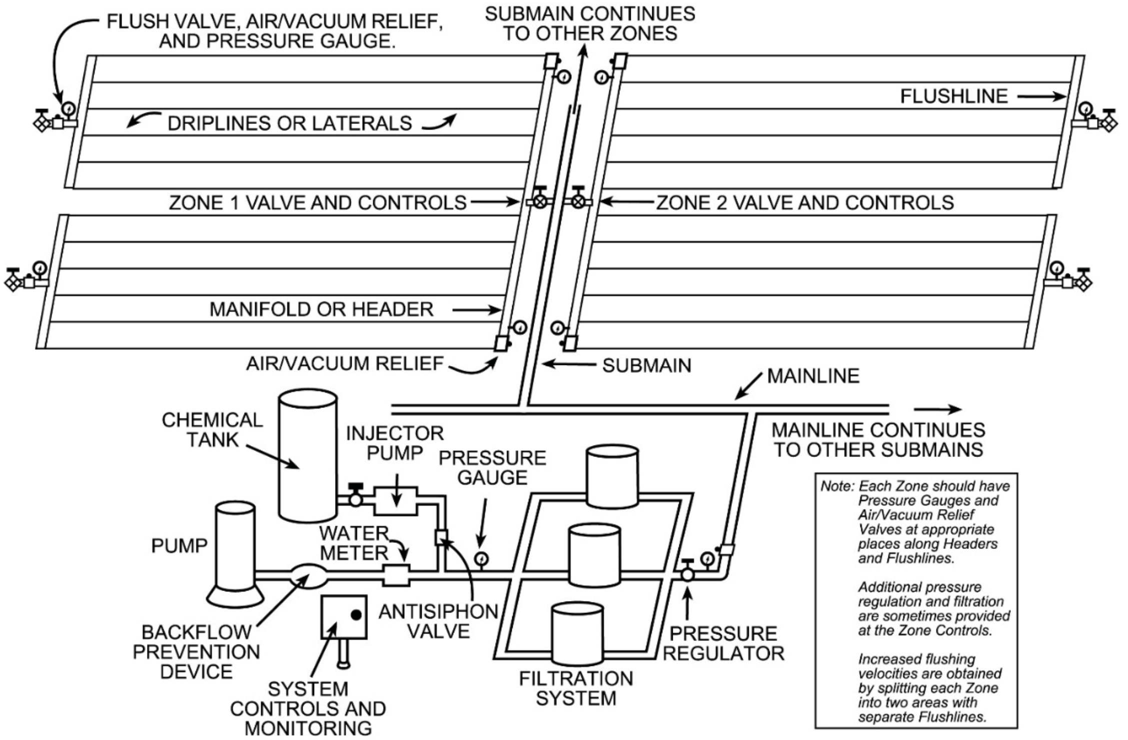

Figure 1. Schematic of an SDI system (after Lamm and Camp, 2007).

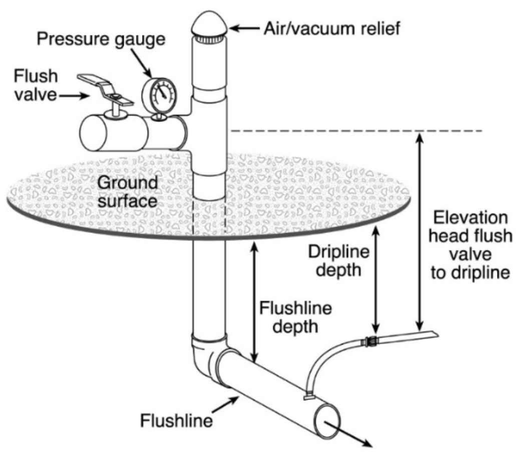

Figure 2. Typical flush valve assembly located at one end of flushline. Multiple driplines would be connected to the flushline (after Lamm and Camp, 2007).

qual dripline lengths that are connected to a common flushline will result in spatial flow variation (Lamm and Camp, 2007). Shorter flushlines are often required on irregular-shaped fields to minimize the total amount of flow variation during both normal operation and flushing. The total allowable downstream dripline pressure must account for friction losses in the dripline due to increased flow during flushing and the friction losses in the dripline connection to the flushline, in the flushline valve assembly, and within the flushline itself. The total downstream dripline pressure during flushing should be as low as economically and operationally practical, typically less than 10 to 15 kPa (Lamm and Camp, 2007), and typical flushline friction losses should be 5 kPa or less.

A common and accurate method to calculate the flushline diameter (D_f, mm) for level-grade flushlines is a rearrangement of the Hazen-Williams equation that includes the multiple outlet factor:

$$D_f = \left[FL_f \left(\frac{1}{h_f}\right)\left(1.212\times10^{10}\right)\left(\frac{Q_f}{C}\right)^{1.852}\right]^{0.2053} \tag{1}$$

where F is the multiple outlet factor, L_f is the length of the flushline section (m), h_f is the friction loss for a level-grade flushline (m), Q_f is the cumulative flowrate in (L s^{-1}) for all driplines flowing into that section of the flushline at a specified flushing velocity, and C is the friction coefficient (varying from 143 to 150 for smooth plastic pipe for typical flushline sizes, with a C value of 146 fitting the vast majority of flushline sizes, i.e., 38 to 127 mm inside diameter). The multiple outlet factor can be assumed to be 0.36 for most long flushlines or can be determined from tabular values available in most irrigation design textbooks (e.g., Burt and Styles, 1999; Keller and Bliesner, 2000; Lamm et al., 2007).

Although equation 1 is accurate and not exceedingly complex, it lacks intuitiveness and its usage can be confusing since it only uses the portion of the total flowrate that exits the ends of the driplines (i.e., flowrate attributable to emitter discharge is not considered in this portion of the design). More intuitive D_f estimation methods exist which state that the cross-sectional area of the flushline is related to the cumulative cross-sectional area of all the flow-contributing driplines (Marais, 2001; Lamm and Camp, 2007). A D_f of one pipe diameter size larger than the equivalent diameter for the total cumulative cross-sectional area of the driplines connected to it was recommended by Marais (2001) without stating any additional constraints or design assumptions. A less conservative recommendation by Lamm and Camp (2007) indicated that a flushline cross-sectional area of 25% or more of the cumulative cross-sectional area of the driplines is typically acceptable for a 0.3 m s^{-1} dripline flushing velocity, which will maintain flushline frictional losses at 5 kPa or less. They indicated that this sizing guideline is adequate for dripline diameters of 16 to 35 mm and typical dripline spacings. Through algebraic simplification, the recommendation of Lamm and Camp (2007) can be expressed as:

$$D_f = 0.5 D_d \sqrt{N_d} \tag{2}$$

where D_f is rounded up to the next available pipe size, D_d is the dripline diameter in similar length units to D_f, and N_d is the number of driplines contributing to the flushline valve exit. For tee-branched flushlines, N_d represents only the driplines on the left or right flushline section. Anecdotal reports from industry indicate that most current designs are avoiding tee-branched flushlines to help ensure adequate flushing.

Equation 2 is an empirical guideline that Lamm and Camp (2007) point out is adequate for many typical design scenarios. They suggest that it can be used for initial D_f estimates, with the more formal Hazen-Williams equation then being used to determine the actual friction loss within the selected flushline. Likewise, irrigation designers using equation 1 can use equation 2 as a rough check on their calculations of D_f. The usefulness of equation 2 might be extended by refining estimates of any coefficient and factor exponents and by including other important design factors that might affect calculation of D_f, such as flushing velocity, dripline spacing, and the allowable friction loss within the dripline. Mathematically, the efforts can be expressed as determining:

$$D_f = f\left(D_d, N_d, V_f, S_d, h_f\right) \tag{3}$$

where D_f is a function of dripline diameter (D_d), the number of contributing driplines (N_d), the required flushing velocity (V_f), the spacing of the driplines (S_d), and the allowable friction loss within the flushline (h_f). This technical note discusses the refactorization of equation 1 to a form similar to equation 3, examines further simplifications that are appropriate in many design scenarios, and through revision of the coefficient and exponents improves the accuracy of an equation similar to the Lamm-Camp guideline expressed in equation 2.

Algebraic Manipulation and Pipe Sizing

For easier understanding of the relationship of the Hazen-Williams formulation to the functional relationship expressed in equation 3, equation 1 was first expanded to:

$$D_f = F^{0.2053} L_f^{0.2053} h_f^{-0.2053} \left(1.212\times10^{10}\right)^{0.2053} \times Q_f^{(1.852\cdot0.2053)} C^{(-1.852\cdot0.2053)} \tag{4}$$

and then further rearranged to:

$$D_f = 117.5285 F^{0.2053} C^{-0.3802} L_f^{0.2053} \times h_f^{-0.2053} Q_f^{0.3802} \tag{5}$$

to group the conversion coefficient with the F and C terms, which can be considered for practical terms as constants for these calculations. As stated earlier, F is 0.36 and C is 146 for most PVC flushlines, so equation 5 becomes:

$$D_f = \left(1.477\times10^{9}\right) L_f^{0.2053} h_f^{-0.2053} Q_f^{0.3802} \tag{6}$$

It can be recognized that:

$$L_f = \left(N_d - 1\right) S_d \tag{7}$$

with L_f and S_d in similar length units. Equation 7 recognizes that the flushline can end at the first and last driplines, but for simplicity of overall calculations of D_f:

$$L_f \approx N_d S_d \tag{8}$$

It also can be recognized that:

$$Q_f = V_f N_d \left(\frac{\pi}{4000} D_d^{\,2}\right) \tag{9}$$

With substitution of equations 8 and 9 into equation 6 and simplification:

$$D_f \approx 0.9455 D_d^{0.7604} N_d^{0.5855} V_f^{0.3802} \times S_d^{0.2053} h_f^{-0.2053} \tag{10}$$

which would be a complete and approximate functionally equivalent form (eq. 3) of the Hazen-Williams formulation (eq. 1) for calculation of the flushline diameter (D_f) in mm, with V_f in m s^{-1}, S_d in m, and h_f in m.

As indicated earlier, the allowable friction loss (h_f) is typically maintained at 0.51 m (5 kPa) or less, so equation 10 can be simplified to:

$$D_f \approx 1.09 D_d^{0.76} N_d^{0.586} V_f^{0.38} S_d^{0.21} \tag{11}$$

Further assuming a dripline spacing (S_d) of 1.5 m, which is typical for many row crop applications, equation 11 reduces to:

$$D_f \approx 1.18 D_d^{0.76} N_d^{0.586} V_f^{0.38} \tag{12}$$

Further assuming a required flushing velocity (V_f) of 0.3 m s^{-1}, per the recommendations of ASABE Standard EP-405 (ASABE, 2014), equation 12 reduces to:

$$D_f \approx 0.75 D_d^{0.76} N_d^{0.586} \tag{13}$$

Equation 13 would be a more accurate estimation procedure for the Lamm-Camp guideline expressed in equation 2 but is only valid for D_f and D_d in mm since the exponent on D_d is no longer a value of 1. Equivalent equations for equations 10 through 13 in both SI and English units are summarized in table 1.

Table 1. Simplified equations to determine flushline diameters for SDI systems as compared to a full Hazen-Williams formulation.

Factors Used	Equation		Units[a]	Comments
D_d, N_d, V_f, S_d, and h_f	$D_f \approx 0.95 D_d^{0.76} N_d^{0.586} V_f^{0.38} S_d^{0.21} h_f^{-0.21}$	(10a)	SI	Approximately equivalent form of the
	$D_f \approx 0.28 D_d^{0.76} N_d^{0.586} V_f^{0.38} S_d^{0.21} h_f^{-0.21}$	(10b)	English	Hazen-Williams equation (eq. 1).
D_d, N_d, V_f, and S_d	$D_f \approx 1.09 D_d^{0.76} N_d^{0.586} V_f^{0.38} S_d^{0.21}$	(11a)	SI	Additional improvement for widely spaced
	$D_f \approx 0.25 D_d^{0.76} N_d^{0.586} V_f^{0.38} S_d^{0.21}$	(11b)	English	driplines, i.e., 3 m (10 ft) or greater.
D_d, N_d, and V_f	$D_f \approx 1.18 D_d^{0.76} N_d^{0.586} V_f^{0.38}$	(12a)	SI	Useful when V_f exceeds 0.30 m s^{-1} (1 ft s^{-1}),
	$D_f \approx 0.35 D_d^{0.76} N_d^{0.586} V_f^{0.38}$	(12b)	English	as may be required in some designs.
D_d and N_d	$D_f \approx 0.75 D_d^{0.76} N_d^{0.586}$	(13a)	SI	Reasonably accurate for typical dripline
	$D_f \approx 0.35 D_d^{0.76} N_d^{0.586}$	(13b)	English	spacings when V_f is 0.3 m s^{-1} (1 ft s^{-1}).

[a] Flushline diameter (D_f), dripline diameter (D_d), and dripline spacing should be expressed in mm (SI) or inches (English), S_d should be expressed in m (SI) or feet (English), flushing velocity (V_f) should be expressed in m s^{-1} (SI) or ft s^{-1} (English), and h_f should be expressed in m (SI) or feet (English).

Table 2. Internal diameters for SDR 26 PVC plastic pipe (Class 160 psi, 1.1 MPa).

Nominal Pipe Size		Actual Internal Diameter	
(mm)	(in.)	(mm)	(in.)
32	1.25	38.91	1.532
38	1.5	44.55	1.754
51	2	55.70	2.193
64	2.5	67.44	2.655
76	3	82.04	3.230
102	4	105.51	4.154
127	5	130.43	5.135
152	6	155.32	6.115
203	8	202.21	7.961
254	10	252.07	9.924
305	12	298.96	11.770

Whenever the calculated flushline internal diameter (D_f) exceeds the actual internal diameter for a commercially available pipe size, the next largest pipe size should be selected. Nominal pipe size selection for the graphical comparisons used internal diameters for SDR 26 (Class 160 psi) PVC pipe (table 2). The selection of SDR 26 pipe for the analysis does not affect the coefficients or exponents for the fitted equations, so other classes of PVC pipe could have been selected as well.

Results and Discussion

Accuracy of Original Lamm-Camp Guideline Equation

The flushline diameter guideline (eq. 2) provided by Lamm and Camp (2007) works reasonably well for typical length flushlines (≈100 m) that also have typical dripline diameter (22.2 mm) and spacing between driplines (e.g., 1.5 m) for a flushing velocity of 0.30 m s^{-1} (fig. 3). However, the accuracy decreases considerably as the design parameters change from these typical values (figs. 3 to 6). This is particularly the case for longer flushlines with their increased number of contributing driplines (N_d) and for changes in flushing velocity (fig. 4) or the allowable friction loss within the flushline (fig. 6).

Improvements to Original Lamm-Camp Guideline Equation

As stated earlier, equation 13 represents an improvement to the original Lamm-Camp guideline (eq. 2) for flushline diameter sizing (fig. 7 as compared to fig. 3). The improved

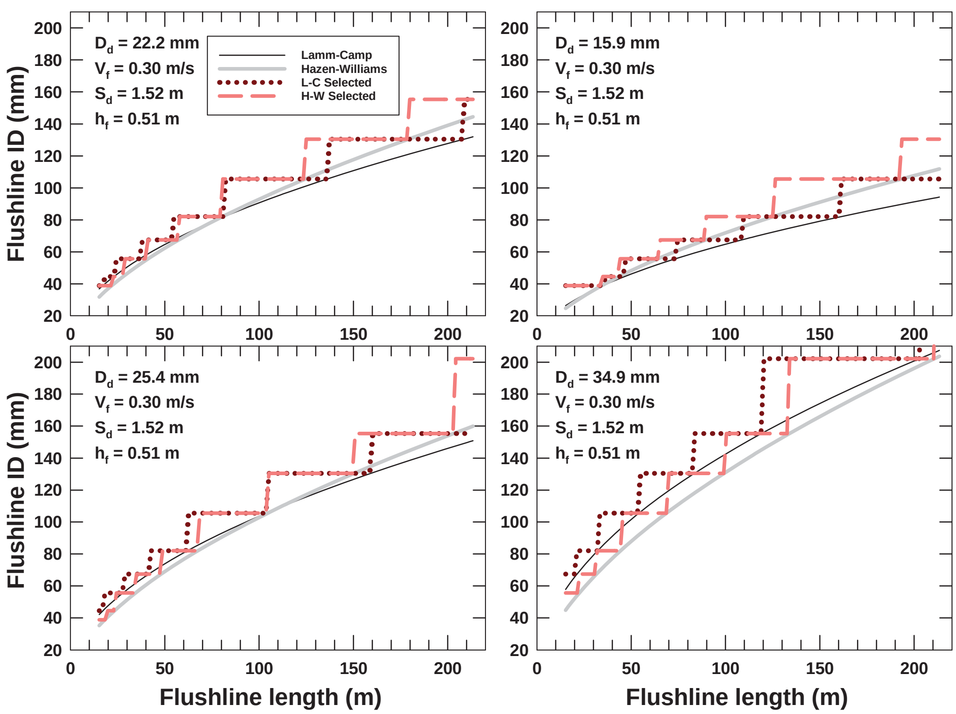

Figure 3. Relationship of flushline internal diameter to flushline length as affected by dripline diameter, assuming a dripline spacing of 1.52 m, flushing velocity of 0.30 m s^{-1}, and allowable friction head loss within the flushline of 0.51 m. The smooth curves represent results from the Lamm-Camp guideline (Lamm and Camp, 2007) (eq. 2) and the more accurate Hazen-Williams formulation (eq. 1), while the step functions represent the appropriately selected commercial PVC plastic pipe size (SDR 26, table 2) for the two calculation methods.

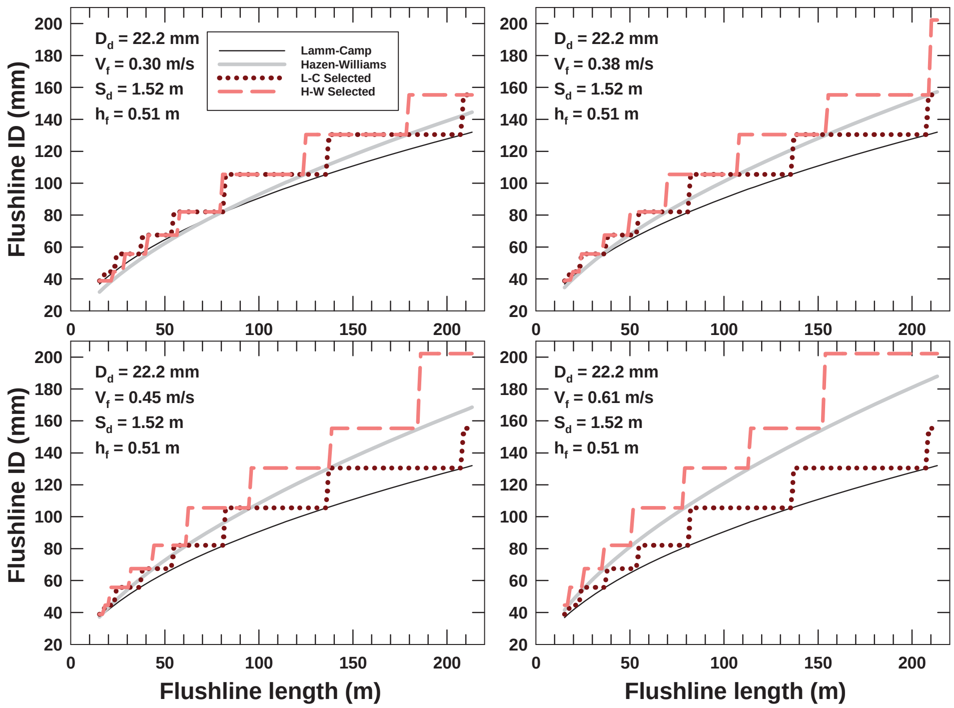

Figure 4. Relationship of flushline internal diameter to flushline length as affected by flushing velocity, assuming a dripline diameter of 22.2 mm, dripline spacing of 1.52 m, and allowable friction head loss within the flushline of 0.51 m. The smooth curves represent results from the Lamm-Camp guideline (Lamm and Camp, 2007) (eq. 2) and the more accurate Hazen-Williams formulation (eq. 1), while the step functions represent the appropriately selected commercial PVC plastic pipe size (SDR 26, table 2) for the two calculation methods.

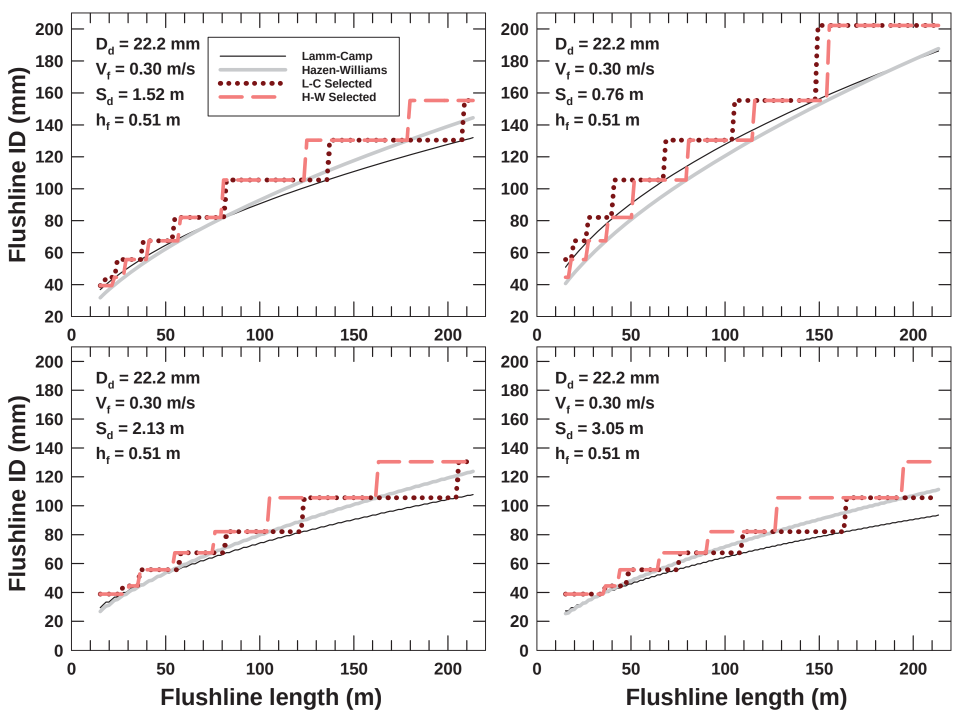

Figure 5. Relationship of flushline internal diameter to flushline length as affected by dripline spacing, assuming a dripline diameter of 22.2 mm, a flushing velocity of 0.30 m s^{-1}, and allowable friction loss within the flushline of 5 kPa (0.51 m). The smooth curves represent results from the Lamm-Camp guideline (Lamm and Camp, 2007) (eq. 2) and the more accurate Hazen-Williams formulation (eq. 1), while the step functions represent the appropriately selected commercial PVC plastic pipe size (SDR 26, table 2) for the two calculation methods.

equation no longer has inaccuracies for longer flushlines (i.e., increased N_d) and larger diameter driplines, which are sometimes used for lesser-value commodity crops to decrease SDI system costs.

As stated earlier, the required flushing velocity (V_f) often varies by designer preference and/or government cost-sharing requirements, with values as great as 0.61 m s^{-1} sometimes being used. There is a marked accuracy improvement

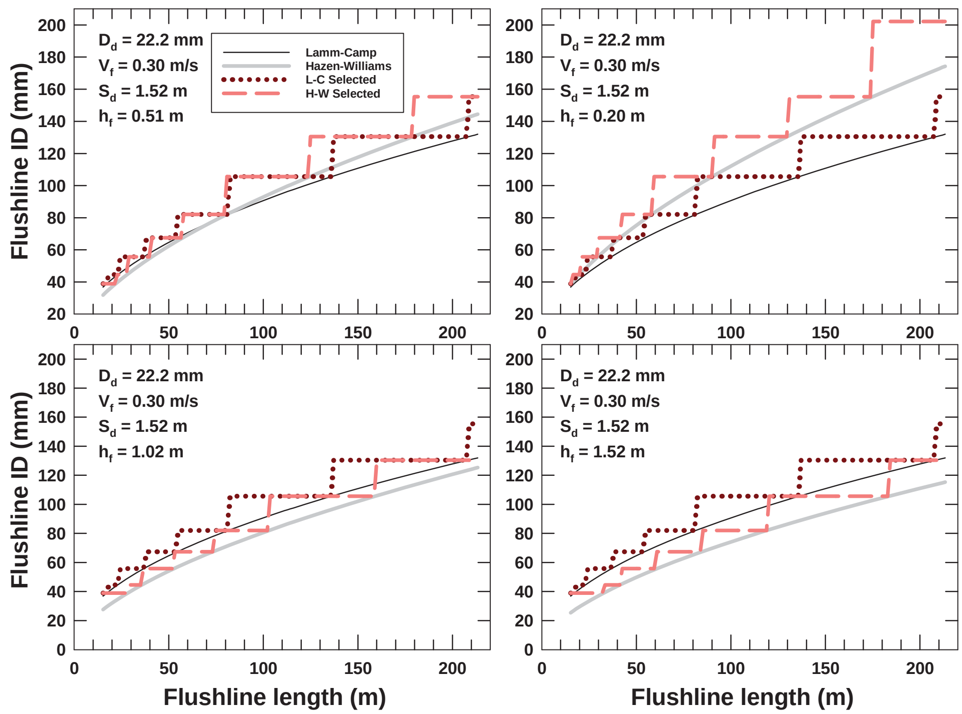

Figure 6. Relationship of flushline internal diameter to flushline length as affected by allowable friction head loss within the flushline, assuming a dripline diameter of 22.2 mm, dripline spacing of 1.52 m, and flushing velocity of 0.30 m s^{-1}. The smooth curves represent results from the Lamm-Camp guideline (Lamm and Camp, 2007) (eq. 2) and the more accurate Hazen-Williams formulation (eq. 1), while the step functions represent the appropriately selected commercial PVC plastic pipe size (SDR 26, table 2) for the two calculation methods.

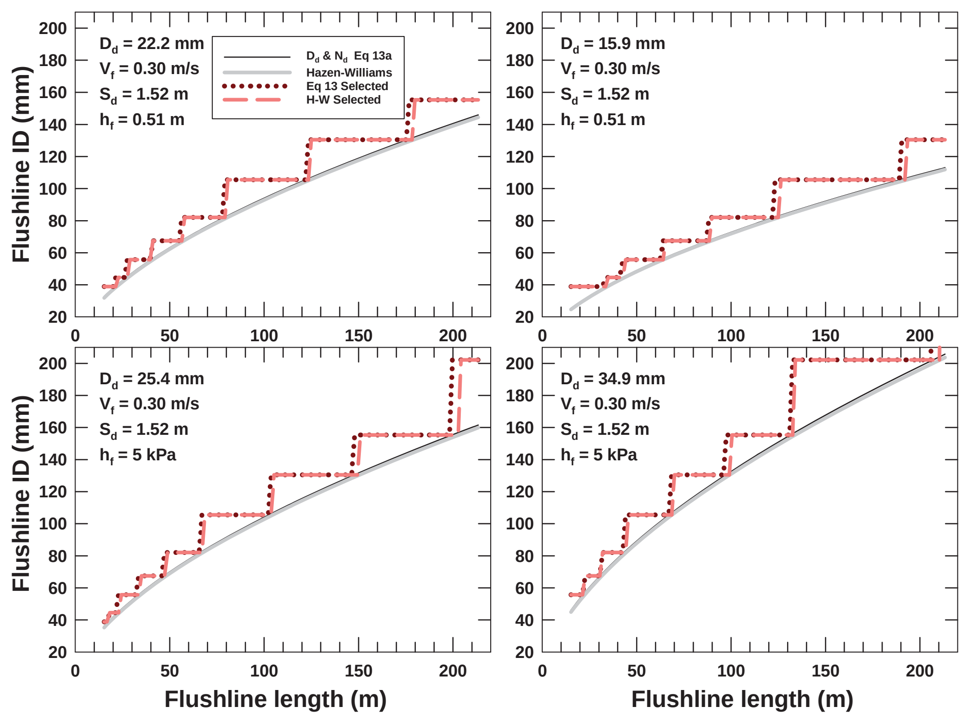

Figure 7. Relationship of flushline internal diameter to flushline length as affected by dripline diameter, assuming a dripline spacing 1.52 m, flushing velocity of 0.30 m s^{-1}, and allowable friction head loss within the flushline of 0.51 m (5 kPa). The nearly coincident gray and black curves compare results from equation 13a in table 1 and the full Hazen-Williams formulation (eq. 1), while the nearly coincident step functions represent the appropriately selected commercial PVC plastic pipe size (SDR 26, table 2) for the two calculation methods.

with the addition of flushing velocity to the calculation of flushline diameter (eq. 12a in table 1) when V_f varies from 0.30 m s^{-1} (fig. 8). The improved equation no longer has inaccuracies for longer flushlines (i.e., increased N_d) and for V_f greater than 0.3 m s^{-1}, and it does not add much complexity to the previously discussed equation 13a.

Although a dripline spacing (S_d) of 1.52 m is common for many SDI systems, it can vary with the crops being grown

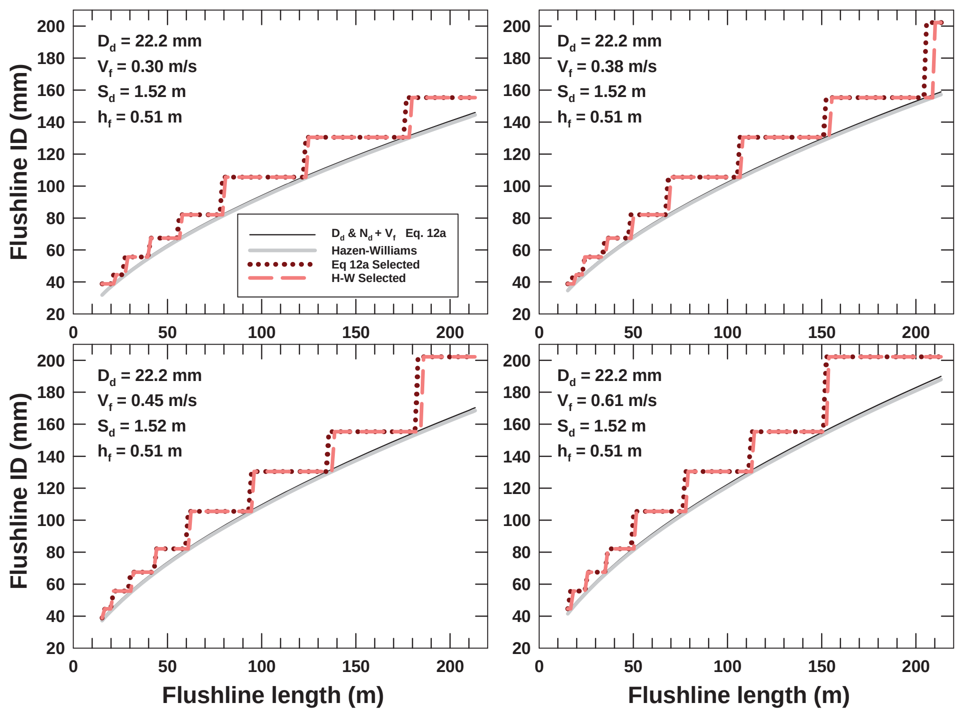

Figure 8. Relationship of flushline internal diameter to flushline length as affected by dripline flushing velocity, assuming a dripline diameter of 22.2 mm, dripline spacing of 1.52 m, and allowable friction head loss within the flushline of 0.51 m. The nearly coincident gray and black curves compare results from equation 12a in table 1 and the full Hazen-Williams formulation (eq. 1), while the nearly coincident step functions represent the appropriately selected commercial PVC plastic pipe size (SDR 26, table 2) for the two calculation methods.

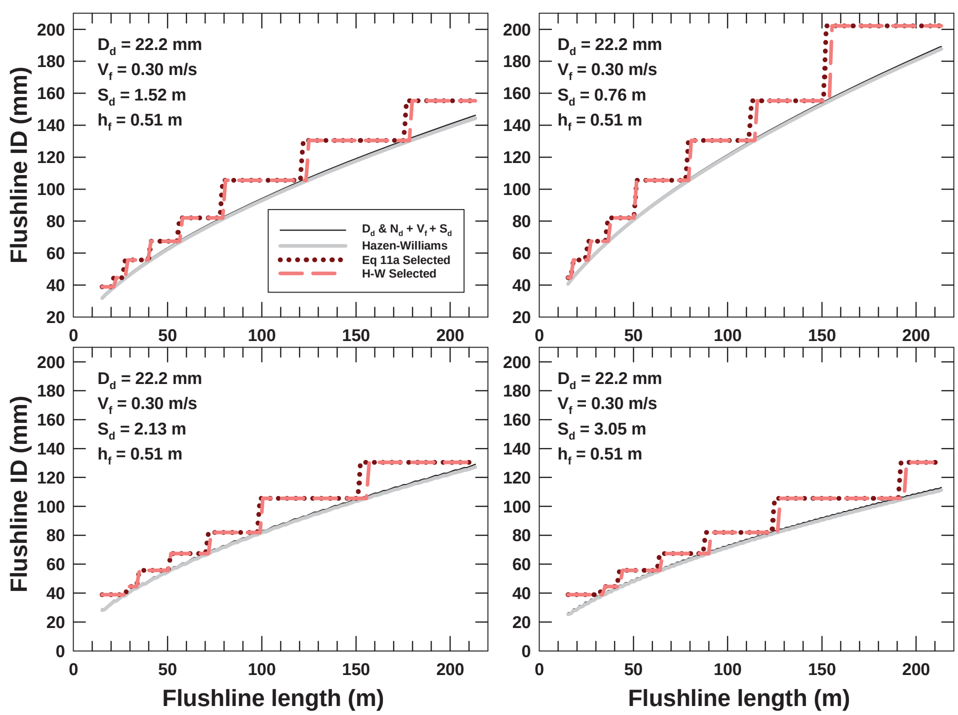

Figure 9. Relationship of flushline internal diameter to flushline length as affected by dripline spacing, assuming a dripline diameter of 22.2 mm, dripline flushing velocity of 0.3 m s^{-1}, and allowable friction head loss within the flushline of 0.51 m. The nearly coincident gray and black curves compare results from equation 11a in table 1 and the full Hazen-Williams formulation (eq. 1), while the nearly coincident step functions represent the appropriately selected commercial PVC plastic pipe size (SDR 26, table 2) for the two calculation methods.

and regional cultural practices. Although the improvements are not as marked as was the case for the inclusion of flushing velocity (V_f), the addition of S_d to the determination of flushline diameter (eq. 11a.) would be desirable when S_d varies considerably from 1.52 m (fig. 9).

The allowable friction head loss within the flushline (h_f) should typically be set at 0.51 m (5 kPa) or less, which is reasonable considering that the total backpressure on the driplines during flushing should be less than 10 to 15 kPa (Lamm and Camp, 2007). Given this practical design limitation, there is less value in adding h_f to the determination, but for completeness it would be equation 10a in table 1, which as stated earlier is approximately functionally equivalent to the full Hazen-Williams formulation (eq. 1).

Appropriate Use of the Improved Equations and Their Self-Regulation of Accuracy

The authors believe that the most appropriate use of the improved flushline diameter (D_f) estimation equations (eqs. 11a through 13b in table 1) would be in concert with subsequent use of the full Hazen-Williams formulation (eqs. 1 or 10a). The appropriate equation in table 1, with its selection based on the most readily available design information or the variances from typical designs, would first be used to calculate the required D_f and then rounded up to the next commercially available pipe size. Subsequently, the Hazen-Williams equation could be used as a check of the D_f calculation. Likewise, the preceding estimate (i.e., the equation in table 1) can be helpful in ensuring that the correct design parameters were used in the Hazen-Williams formulation (e.g., the aforementioned inclusion of only flushing flows at the ends of driplines). After these calculation checks, the actual friction loss within a level-grade flushline (h_f) for the commercial pipe size can be determined by rearrangement of equation 1 and/or rearrangement of equation 10a or 10b.

There are many practical design aspects that tend to self-regulate the accuracy of the estimates provided by the improved equations in table 1. There are a limited number of available dripline diameters (D_d), and the most popular size in commercial use is 22.2 m (0.875 in.) for which the initial equation improvements were made. A dripline internal diameter of 22.2 mm (0.875 in.) was chosen as the initial D_d value because it accounts for 70% to 85% of current commercial SDI use in the U.S. according to anecdotal reports from industry obtained by the authors in early 2015. The number of contributing driplines (N_d) is often limited by the available system flowrate for flushing, or the practical flushline length [$L_f = (N_d - 1) \times S_d$] may be limited by changes in field shape or slope. Additionally, abrupt changes in pipe size and initial cost will likely limit the overall L_f. The required flushing velocity (V_f) typically does not fall outside the range of 0.30 to 0.61 m s^{-1}, so even ignoring the V_f improvement (eq. 12a or 12b) and just using equation 13a or 13b could underestimate the pipe diameter by only one size for a 100 m flushline at a 0.61 m s^{-1} flushing velocity. This undersizing would show up in the design process with an h_f exceeding 0.51 m (5 kPa) and could be corrected at that point. Dripline spacings also tend to self-regulate the accuracy of the equations, as the use of a common flushline is rare for widely spaced crops such as perennial vine and tree crops. As indicated earlier, there cannot be much variance from the selected allowable friction loss within the flushline ($h_f \leq 0.51$ m or 5 kPa), so ignoring it in the selected estimation equation does not greatly change the results.

Summary and Conclusions

Simple empirical equations with different numbers of required parameters were developed to determine SDI flushline diameter from design parameters that are readily available near the beginning of the design process. The authors suggest that the appropriately selected equation developed here (table 1) can be used in concert with the Hazen-Williams calculation of flushline diameter for design quality assurance. Although the equations developed are approximations of the full Hazen-Williams calculation, they tend to self-regulate their accuracy over the range of practical design limitations.

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