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Energy gradient line approach for direct hydraulic calculation in drip irrigation design

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Summary. Direct calculations can be made for all emitter flows along a lateral line and in a submain unit based on an Energy Gradient Line (EGL) approach. Errors caused by the EGL approach were evaluated by a computer simulation. A Revised Energy Gradient Line (REGL) approach, developed using a mean discharge approximation, can reduce the errors and match with the results from a Step-by-Step (SBS) calculation for all emitters in a drip system. The developed equations can be used for computerized design of drip irrigation systems.

The output of a drip irrigation system is represented by all the emitter flows whose uniformity is used to determine application efficiency for irrigation scheduling. The uniformity of a drip irrigation system is affected mainly by hydraulic design, manufacturer's variation, temperature effects and plugging. Among these factors, the hydraulic design can be controlled by the engineers who design the system for a certain specified design criterion.

A drip irrigation design can be made for a single lateral line or for a whole submain unit which contains many laterals. Since each lateral line contains hundreds of emitters, the direct step-by-step calculation would be tedious and impractical. Early research in drip irrigation design was conducted mostly for a single lateral line (Myers and Bucks 1972; Howell and Hiler 1974; Wu and Gitlin 1974). It was only recently (Bralts and Segerlind 1985) that a computer aided system design program was developed for a submain unit.

Computer-aided design techniques have become more popular with the advent of microcomputers. There are computer programs for drip irrigation design using finite element approach (Bralts and Segerlind 1985) and step-by-step calculations (Pitts et al. 1986; Meshker and Warner 1985). A simple approach is presented in this paper using the energy gradient line concept. Simple equation were developed for direct calculation for emitter flows along a lateral line or in a submain unit which can be used for manual hydraulic design, to develop design charts and for computerized design.

Energy relations and design criteria

A drip irrigation system is pressurized piping system which consists of a main line, submain and laterals. The pressure variation in the laterals will affect directly the emitter flows in the drip irrigation system. Considering the velocity head in the total energy relation (Bernoulli's equation) is relatively small for drip irrigation lines, the total energy can be simply expressed by

$$H = z + h \tag{1}$$

where H is the total energy expressed as a height (or head) of water, z is elevation as potential energy and h is pressure head. The change of energy with respect to the length of the lateral, using the x-direction for length, can be expressed as,

$$\frac{dH}{dx} = \frac{dz}{dx} + \frac{dh}{dx} \tag{2}$$

where $\frac{dz}{dx}$ is the slope for the lateral line and is $-S_0$ for downslope situation; $\frac{dH}{dx}$ is energy slow and is $-S_f$. S_f is also termed the energy gradient line which is a straight line for a single pipe flow such as a main line with a constant discharge, and a series of straight lines forming a curve for a lateral line and submain; $\frac{dh}{dx}$ is the pressure variation along the drip line and can be expressed simply by the energy slope and the line slope as,

$$\frac{dh}{dx} = S_0 - S_f. \tag{3}$$

Equation 3 illustrates clearly that if the energy gradient line is known, the pressure variation along the lateral line can be determined by a linear combination of line slope and energy slope. When an operation pressure is given and known, all h-values along the lateral line can be directly calculated. Furthermore, all emitter flows along a lateral line can be calculated by

$$q = k\, h^x \tag{4}$$

where q is emitter flow, k is a coefficient and is constant for a given emitter and x is an emitter exponent of water pressure which shows the characteristics of the emitter; $x=1$ specifies a laminar flow emitter and 0.5 is a turbulent flow emitter. Both k and x are determined from a hydraulic test of a given emitter using various water pressures, h.

The design criterion of drip irrigation is based on the uniformity of emitter flow along a lateral line or in a submain unit. For hydraulic design, the variation of emitter flow is determined based on the pressure variation in the drip system according to the relationship shown by Eq. (4). There are several uniformity parameters which can be used as design criteria. The following is a review of several different uniformity definitions.

Emitter flow variation (q_{var})

Emitter flow variation was defined as (Wu and Gitlin 1974)

$$q_{var}=\frac{q_{max}-q_{min}}{q_{max}} \tag{5}$$

where q_{var} is the emitter flow variation, q_{max} and q_{min} are maximum, and minimum emitter flow respectively along a lateral line or in a submain unit. Similarly, the pressure variation, h_{var} can be expressed as

$$h_{var}=\frac{h_{max}-h_{min}}{h_{max}} \tag{6}$$

where h_{var} is the pressure variation, h_{max} and h_{min} are the maximum and minimum pressure respectively along a lateral line and in a submain unit. The relationship between emitter flow variation q_{var} and pressure variation h_{var} can be expressed as (Wu and Gitlin 1974),

$$q_{var}=1-(1-h_{var})^x . \tag{7}$$

This indicates that the q_{var} can be determined by the maximum and minimum pressure and the emitter exponent x.

Uniformity coefficient (UCC)

The uniformity coefficient of emitter flow is determined using the uniformity coefficient equation developed by Christiansen (Christiansen 1942).

$$\mathrm{UCC}=1-\frac{\overline{\Delta q}}{\bar{q}} . \tag{8}$$

UCC is the Christiansen uniformity coefficient, where $\bar{q}$ is the mean emitter flow and $\overline{\Delta q}$ is the mean deviation of emitter flow.

Statistical uniformity (UCS)

The statistical uniformity used for drip irrigation design was proposed by Bralts (Bralts et al. 1981). It is expressed as

$$\mathrm{UCS}=1-\frac{S_q}{\bar{q}} \tag{9}$$

where UCS is the statistical uniformity coefficient, S_q is the standard deviation of emitter flow. The last term in Eq. (9) is also a uniformity parameter specified as coefficient of variation, CV

$$\mathrm{CV}=\frac{S_q}{\bar{q}} . \tag{10}$$

The coefficient of variation is statistically defined as the standard deviation divided by the mean value.

There is a definite relationship between any two of the above mentioned uniformity parameters used for drip irrigation design (Wu and Irudayaraj 1987). This indicates that the simple design criterion, emitter flow variation, q_{var}, using only the two values of maximum and minimum emitter flow can be used as a design criterion for drip irrigation design.

Energy gradient line (EGL)

The energy gradient line is a curve for a lateral line or submain since the discharge in the line decrease with respect to the length so the friction drop in the upstream sections is more than that of downstream sections. The actual energy gradient line is determined based on a step-by-step calculation from the downstream end for each emitter flow, friction drop in each section, line slope and water pressure of the emitter using the energy relation as shown in Eq. (2). Equation (3) indicates that the water pressure in a lateral line can be calculated directly if the energy gradient line is pre-determined.

Assuming the drip irrigation system is designed for an emitter flow variation less than 10% (or 20%), the shape of energy gradient line can be derived mathematically using constant emitter flows along the lateral line and expressed as (Wu and Gitlin 1975):

$$R_i=1-(1-i)^{m+1} \tag{11}$$

where $R_i=\Delta H_i/\Delta H$ is a friction drop ratio; $\Delta H=$total friction drop at the end of lateral line; $\Delta H_i=$total friction drop at a given length ratio i; $i=l/L$, a ratio of a given length from the inlet l to the total length L; and m is a power coefficient of total discharge in the friction drop equation. When the Hazen-Williams equation is used, m is 1.852; Eq. (11) can be expressed as

$$R_i=1-(1-i)^{2.852} \tag{12}$$

when i, the length ratio as 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 and 1.0, the corresponding R_i can be calculated as 0, 0.26, 0.47, 0.64, 0.77, 0.86, 0.93, 0.99, 0.999 and 1.0. Based on the same assumption that emitter flow is constant, the total friction drop at the end of the lateral line can be determined by (Wu and Gitlin 1975)

$$\Delta H=\frac{K}{2.852}\,\frac{Q^{1.852}}{D^{4.871}}\,L . \tag{13}$$

ΔH is the total friction drop at the end of lateral line, where K is a constant for a given friction coefficient "C" in Hazen-Williams equation for pipe flow with a constant total discharge, Q is the total input discharge at the inlet of the lateral, D is the inside diameter and L is the total length of the lateral. Once the total friction drop ΔH is determined by Eq. (13), the friction drop along the line ΔH_i can be calculated by the R_i-value determined by Eq. (12). Using the operation pressure as the starting point, the energy gradient line can be determined.

Direct calculation of water pressure and emitter flow

Using the energy gradient line approach, the water pressures and emitter flows along the lateral line and in a submain unit can be determined by direct calculation:

Along a lateral line

The water pressure variation along a lateral line can be determined by using the energy gradient line (EGL) approach through direct calculation. It can be calculated by (Wu and Gitlin 1974)

$$h_i = H - \Delta H_i + \Delta H'_i \tag{14}$$

where h_i is the water pressure at any i location along the lateral line, H is the total energy at the inlet and is specified as operating pressure, ΔH_i is the friction drop at i location and $\Delta H'_i$ is the energy gain for downslope situation at the i location. By introducing the R_i ratio into Eq. (14), it becomes

$$\frac{h_i}{H} = 1 - R_i \frac{\Delta H}{H} + R'_i \frac{\Delta H'}{H} \tag{15}$$

where R_i is the friction drop ratio and expressed by Eq. (12), $\Delta H'$ is the total energy gain by downslope at the end of a lateral. $R'_i = \frac{\Delta H'_i}{\Delta H'}$ has the same value of i for uniform slope situations. Equation 15 can be used to calculate water pressure h_i along the lateral line based on the shape of energy gradient line R_i, operating pressure H, total friction drop ΔH and total energy gain by slope $\Delta H'$ at the end of lateral line. The emitter flows along a lateral line can be determined by direct calculation by the equation derived from Eq. (15) as

$$q_i = q_0 \left(1 - R_i \frac{\Delta H}{H} + R'_i \frac{\Delta H'}{H}\right)^x \tag{16}$$

where q_i = emitter flow at a given length ratio i; q_0 = emitter flow at the inlet determined by the operating pressure H.

Equation 16 offers a simple direct calculation of emitter flows based on the energy gradient line approach. It can be used for lateral line design by evaluating the uniformity of emitter flows. Through a computer simulation of all possible combinations of $\Delta H/H$ and $\Delta H'/H$, design charts were developed for drip irrigation lateral design (Wu and Gitlin 1974).

In a submain unit

The emitter flows in a submain unit can also be derived assuming the energy gradient line along a submain using the similar relation as shown in Eq. (11) if the number of outlets along the submain is more than five (Wu and Gitlin 1983).

$$R_j = 1 - (1 - j)^{m+1} \tag{17}$$

where j is a length ratio along the submain specifies the location of laterals along the submain; $R_j = \Delta H_{sj}/\Delta H_s$ is a friction drop ratio along the submain; ΔH_s is the total friction drop at the end of a submain and ΔH_{sj} is the total friction drop at a given length ratio j along a submain. The emitter flows along any lateral line connecting the submain at a length ratio j can be expressed similarly to Eq. (16) as,

$$q_{ij} = q_{0j} \left(1 - R_i \frac{\Delta H_j}{h_{j(s)}} + R'_i \frac{\Delta H'}{h_{j(s)}}\right)^x \tag{18}$$

where q_{ij} is the emitter flow of the jth lateral at ith location of the lateral, q_{0j} is the 1st emitter flow of the jth lateral, ΔH_j is the total friction drop at the end of the jth lateral, $h_{j(s)}$ is the pressure head at the inlet of jth lateral, and $\Delta H'$ is the energy gain at the end of the lateral by a uniform downslope situation. A general equation for all emitter flows in a submain unit can be derived as (Wu and Irudayaraj 1989):

$$q_{ij} = q_{00} \left[\left(1 - R_j \frac{\Delta H_s}{H} + R'_j \frac{\Delta H^s_{\prime}}{H}\right) - R_i \frac{\Delta H_0}{H} \cdot \left(1 - R_j \frac{\Delta H_s}{H} + R'_j \frac{\Delta H'_s}{H}\right)^{m/2} + R'_i \frac{\Delta H'}{H}\right]^x \tag{19}$$

where q_{00} is the emitter flow resulted from the operating pressure H and is considered as the flow from the first emitter of the first lateral line; ΔH_0 is the total friction drop at the end of the first lateral, $\Delta H'_s$ is the total energy gain by the downslope situation of a submain and R'_j is the energy gain ratio along the submain with respect to the length ratio j caused by downslope. In Eq. (19), ΔH_s is determined by the total discharge Q_0 for a submain unit and the ΔH_0 is determined by the total discharge for the first lateral line, $\frac{nQ_0}{N}$. N and n are the total number of emitters in a submain unit and along a lateral line respectively. Equation 19 can be used to calculated directly all emitter flows within a submain unit. It can be programmed for computerized designs of drip irrigation systems.

Error assessments

The Equations derived above offer a direct calculation of all emitter flows along a lateral line and in a submain unit respectively. But the solution is only an approximation since the energy gradient line (EGL) is determined by assuming all emitter flows are constant. Two types of errors are caused by this simple energy gradient line ap-

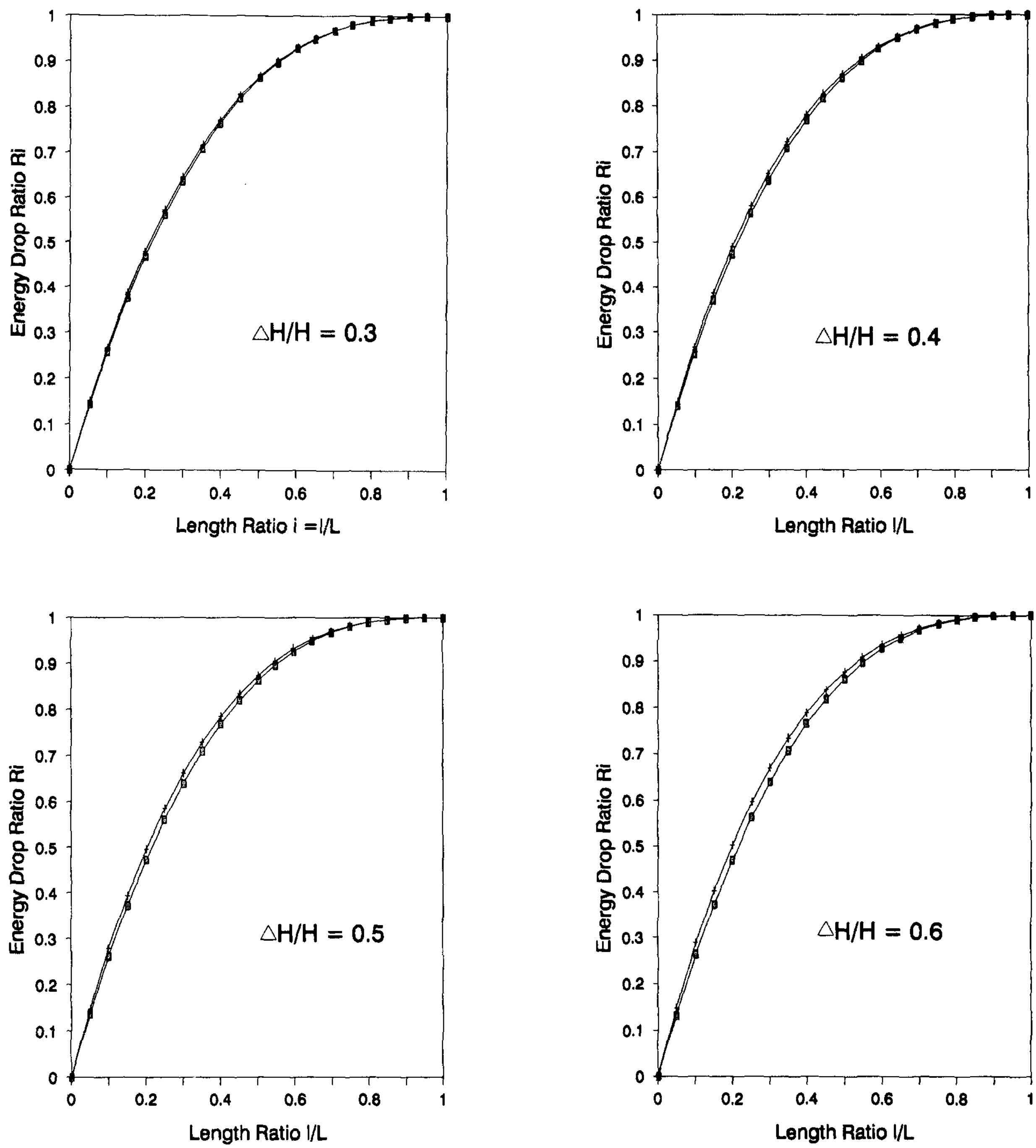

Fig. 1. Energy Gradient Lines determined by EGL approach and SBS calculation for $\Delta H/H = 0.3$, 0.4, 0.5, and 0.6; $x = 0.5$. ▫ EGL + SBS

proach; one is associated with the shape of energy gradient line and the other is the total friction drop at the end of the line. Evaluation of the errors were conducted as shown as follows:

The shape of energy gradient line

A computer program was developed to simulate different flow conditions in a horizontal lateral line which included nine total friction drop ratios ($\Delta H/H = 0.1$, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9), ten emitter exponent values ($x = 0.1$, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0) with a fixed operating pressure, and lateral line size. Energy gradient lines were determined for each combination of the above simulated conditions using the step-by-step (SBS) calculation and the energy gradient line (EGL) approach. Comparisons were made for the energy gradient lines determined by the two methods. Results showed that only the total friction drop ratio $\Delta H/H$ affects the shape of energy gradient line. The comparisons of energy gradient lines determined by step-by-step (SBS) calculation and the energy gradient line (EGL) approach for different $\Delta H/H$ were presented in Fig. 1, $\Delta H/H = 0.3$, 0.4, 0.5 and 0.6.

It is clear from Fig. 1 that the two energy gradient lines determined from the step-by-step (SBS) calculation and energy gradient line (EGL) approach are almost the same for the cases in which $\Delta H/H = 0.3$. There is only a slight difference in the shape of energy gradient lines for the situation that $\Delta H/H = 0.4$. The shape of energy gradient line determined by the energy gradient line (EGL) approach showed distinct differences from the true energy gradient line determined using the step-by-step (SBS) calculation for the total friction drop ratio $\Delta H/H = 0.5$, and 0.6. The criteria of hydraulic design is usually set as 10% and 20% emitter flow variation which is equivalent to about 20% to 40% pressure variation respectively for turbulent flow emitter with an x-value as 0.5 as given by Eq. (7). It can be seen from Fig. 1 that the shape of energy gradient line determined by Eq. (11) can be used for drip irrigation design as long as the emitter flow variation is less than 20%.

The total friction drop, ΔH

The total friction drop, ΔH determined by Eq. (13) will also create errors since the emitter flow is not constant. When the drip system is designed for an emitter flow variation of 10% or 20%, there will be errors up to $\pm 9\%$ and $\pm 18\%$ in the determined ΔH depending on the slope situations respectively. These errors are simply estimates using a revised total discharge as 0.95 Q or 1.05 Q and 0.9 Q or 1.1 Q for emitter flow variations of 10% and 20% respectively in the Eq. (13). This estimation provides a range of possible errors which might occur when using the simple energy gradient line approach in the design of a lateral or a submain unit.

The above results indicate that the errors are mainly caused by the determination of total friction ΔH. The significance of these errors on the design were evaluated by a computer simulation for a lateral line with fixed size and operating pressure. The simulation was conducted for different emitters with six different emitter exponent x-values, ranging from 0.1 to 1, five downslope situations from 1% to 5%, two emitter spacings 0.5 m and 1 m and for two design criteria, 20% and 40% pressure variation (h_{var}). A total of 120 lateral line designs were simulated. Each lateral line was designed by a step-by-step (SBS) calculation and the energy gradient line (EGL) approach. The emitter flow variation, q_{var}, was calculated by using the energy gradient line approach based on a 20% and 40% pressure variation, h_{var}. The emitter flow variation, q_{var}, for the step-by-step calculation was determined using the same length designed by the EGL approach and using 0.5 as the emitter exponent, x.

The simulation results showed the design made by the energy gradient line (EGL) approach actually over-estimated the variation as shown in Table 1 and 2. The error caused by the over-estimation changes with respect to the type of emitters used in the design; the larger the x value the larger the error will be. When using a turbulent flow emitter with an x-value of 0.5, and designing a system for an h_{var} of 20%, the EGL approach showed that the q_{var} is about 10% while the SBS calculated q_{var} is 9%; the EGL approach causes a 1% error in the calculation of the emitter flow variation as shown in Table 1. Table 2 is prepared for a lateral line designed by Energy Gradient Line (EGL) approach for an h_{var} of 40%. When a turbulent flow emitter with an x-value of 0.5 is used, the EGL approach showed a q_{var} of about 22% while the SBS calculated q_{var} was 16%; a difference of about 6%.

Table 1. Comparison of uniformity parameter for a lateral line design by energy gradient line (RGL) approach, step-by-step (SBS) and revised energy gradient line (REGL) (EGL design criterion, $h_{var} = 20\%$)

Uniformity parameter (%)	x-value					
	0.1	0.3	0.5	0.7	0.9	1.0
q_{var} (EGL)	2.20	6.45	10.46	14.32	18.00	19.62
q_{var} (SBS)	2.15	6.08	9.22	11.68	13.56	14.25
q_{var} (REGL)	2.16	6.14	9.37	11.97	14.04	14.80

Table 2. Comparison of uniformity parameter for a lateral line design by energy gradient line (EGL) approach, step-by-step (SBS) and revised energy gradient line (REGL) (EGL design criterion, $h_{var} = 40\%$)

Uniformity parameter (%)	x-value					
	0.1	0.3	0.5	0.7	0.9	1.0
q_{var} (EGL)	4.97	14.15	22.39	29.77	36.37	39.52
q_{var} (EBS)	4.60	11.63	16.11	19.09	21.41	22.60
q_{var} (REGL)	4.65	11.92	16.71	19.95	22.50	23.82

Table 1 also showed that when using an emitter exponent of 0.5 and an h_{var} design criterion of 20% in the EGL design, the difference between the Energy Gradient Line approach and step-by-step calculations is insignificant and can be neglected. For this case, the Energy Gradient Line approach can be used for drip irrigation design. But in other cases, when h_{var} is 20% and the emitter exponent is larger than 0.5, or the design criterion, h_{var} is 40% and for all x values, the errors caused by the Energy Gradient Line approach as shown in Table 1 and 2 cannot be overlooked.

A mean discharge approximation

Since the error produced by the Energy Gradient Line (EGL) approach are caused mainly by the total discharge used to calculate the total friction drop ΔH in Eq. (13), the actual discharge which is the summation of all emitter flows should be the total discharge used for determining the total friction drop ΔH. The actual total discharge can be calculated by the overall mean emitter flow and the total number of emitters. The mean emitter flow can be determined by the mean pressure along a lateral line or in a submain unit when the coefficient of variation of pressure head is less than 20% (Anyoji and Wu 1987) and can be expressed as,

$$\bar{q} = k\,\bar{h}^{x} \tag{20}$$

where k is a proportionality factor and x is an emitter exponent coefficient. Both k and x are constant for a given emitter. The mean water pressure along a lateral line can be determined by (Anyoji and Wu 1987),

$$\bar{h}=H-\frac{m+1}{m+2}\Delta H+\frac{1}{2}\Delta H' \quad (21)$$

where $\bar{h}$ is the average pressure head along the lateral line, and the other terms are defined previously in Eq. (1) and (16). The total discharge which represents the summation of all emitter flows can be estimated as,

$$Q=n\,\bar{q} \quad (22)$$

where Q is the total discharge and n is the total number of emitters along the lateral line. The ratio of Q, determined by Eq. (22), and the total discharge determined by the operating pressure can be expressed by

$$\frac{Q}{n q_0}=\left(\frac{\bar{h}}{H}\right)^x \quad (23)$$

where q_0 is the emitter flow corresponding to the operating pressure H and the total discharge determined by the operating pressure, Q_0 is $n q_0$. Substituting Eq. (21) into Eq. (23) and replacing Q_0 for $n q_0$, yields

$$\frac{Q}{Q_0}=\left(1-\frac{m+1}{m+2}\frac{\Delta H}{H}+\frac{1}{2}\frac{\Delta H'}{H}\right)^x. \quad (24)$$

The total friction drop ΔH in Eq. (24) should be determined by the total discharge Q expressed at the right side of the same equation. IF the Hazen-Williams formula is used ($m=1.852$) for calculating ΔH, Eq. (24) becomes

$$\frac{Q}{Q_0}=\left(1-0.7404\,K_1\frac{Q^{1.852}}{D^{4.871}}\frac{L}{H}+\frac{1}{2}\frac{\Delta H'}{H}\right)^x. \quad (25)$$

where K_1 is a coefficient in the Hazen-Williams formula for determining ΔH for a lateral line and is $K/2.852$ from Eq. (13). Equation (25) is implicity and cannot be solved directly. A trial and error method will be used to determine the total discharge Q in Eq. (25).

In the analysis of a submain unit, the mean pressure in the submain unit can be determined by the assumption that the mean pressure is located at a lateral line which is connected at the location of mean submain pressure. The mean pressure in a submain unit can then be expressed as (Anyoji and Wu 1987),

$$\bar{h}=H-\frac{m+1}{m+2}(\Delta H_s+\Delta H_l)+0.5(\Delta H_s'+\Delta H_l') \quad (26)$$

where

$\bar{h}$ = mean emitter pressure in a submain unit
m = exponent coefficient for discharge in Williams-Hazen formula (m = 1.852) used by lateral line and submain
H = operating pressure at the inlet of submain
ΔH_s = total friction drop at the end of submain determined by a total discharge which is $N\bar{q}$; N is total number of emitters in a submain unit and $\bar{q}$ is the mean emitter flow
ΔH_l = total friction drop at the end of the lateral line connecting submain at its mean pressure location, and determined by a total discharge which is $n\bar{q}$; n is the total number of emitters along a lateral line and $\bar{q}$ is the mean emitter flow
$\Delta H_s'$ = total energy gain or loss at the end of submain caused by a uniform slope condition ($-\Delta H_s'$ indicates upslope condition)
$\Delta H_l'$ = total energy gain or loss by uniform downslope at the end of the lateral connecting submain at its mean pressure location ($-\Delta H_l'$ indicates upslope condition).

Applying the relationship shown in Eq. (23) and using a similar derivation to Eq. (25), the ratio of the total discharge and the total discharge determined by the operating pressure can be expressed as,

$$\frac{Q}{Q_0}=\left[1-0.7404\left(K_1\frac{(Q)^{1.852}}{D_s^{4.871}}+K_1\frac{\left(\frac{nQ}{N}\right)^{1.852}}{D_l^{4.871}}\right)+\frac{1}{2}(\Delta H_s'+\Delta H_l')\right]^x \quad (27)$$

where K_1 is constant in Hazen-Williams formula for lateral line and submain; N is total number of emitters in a submain unit; D_s is the submain diameter; D_l is the lateral line diameter; Q is the total discharge and Q_0 is the total discharge determined by the operating pressure; all other terms were defined in previous equations. The total discharge can be determined if all other terms are given and known in Eq. (27). However, the equation cannot be solved directly; a trial and error method is used to determine the total discharge in a submain unit.

Revised energy gradient line (REGL)

The total discharge, Q, determined using Eq. (25) and (27) for a lateral line and submain unit respectively, is the revised total discharge for later line and submain unit design. The revised total discharge for a lateral line will be used to calculated ΔH for Eq. (16). The revised total discharge for a submain unit will be used to calculate ΔH_s and ΔH_0 for Eq. (19). Equations (16) and (19) will provide direct calculation for all emitter flows along a lateral line and a submain unit respectively. The use of revised total discharge in Eq. (16) and (19) is the revised energy gradient line (REGL) approach.

Computer simulations were made to test the revised energy gradient line (REGL) results with that determined by a step-by-step (SBS) calculation. Calculations were also made for the simple energy gradient line (EGL) approach without the revision. Computer simulations were made to design examples for lateral line designs and designs for submain unit. Lateral line slopes ranging from 0 to 5% downslope (uniform) and zero submain slope were programmed in the simulation calculation. The results, showed only for zero and 4% lateral line slopes, are plotted in Fig. 2, 3, 4 and 5. Figure 2 showed the comparison between the emitter pressures calculated by (a) SBS and EGL and (b) SBS and REGL for a lateral line with zero slope. Figure 3 showed the comparison between the emit-

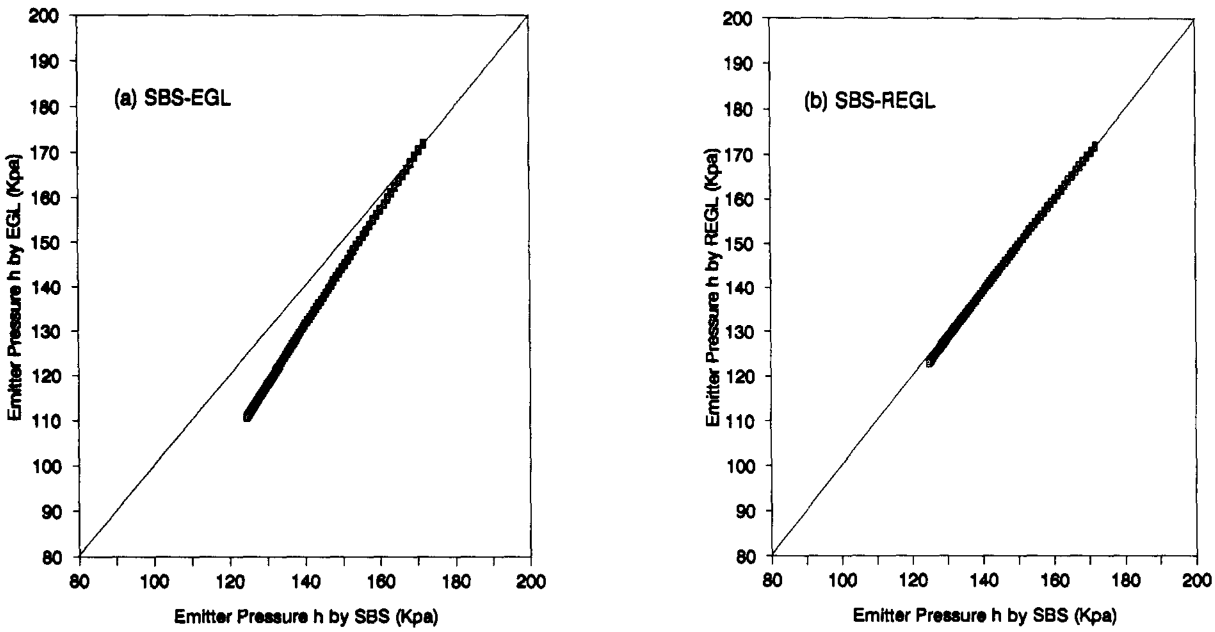

Fig. 2. The comparison among the Emitter Pressures Calculated by SBS, EGL and REGL for a lateral line (lateral slope = 0%)

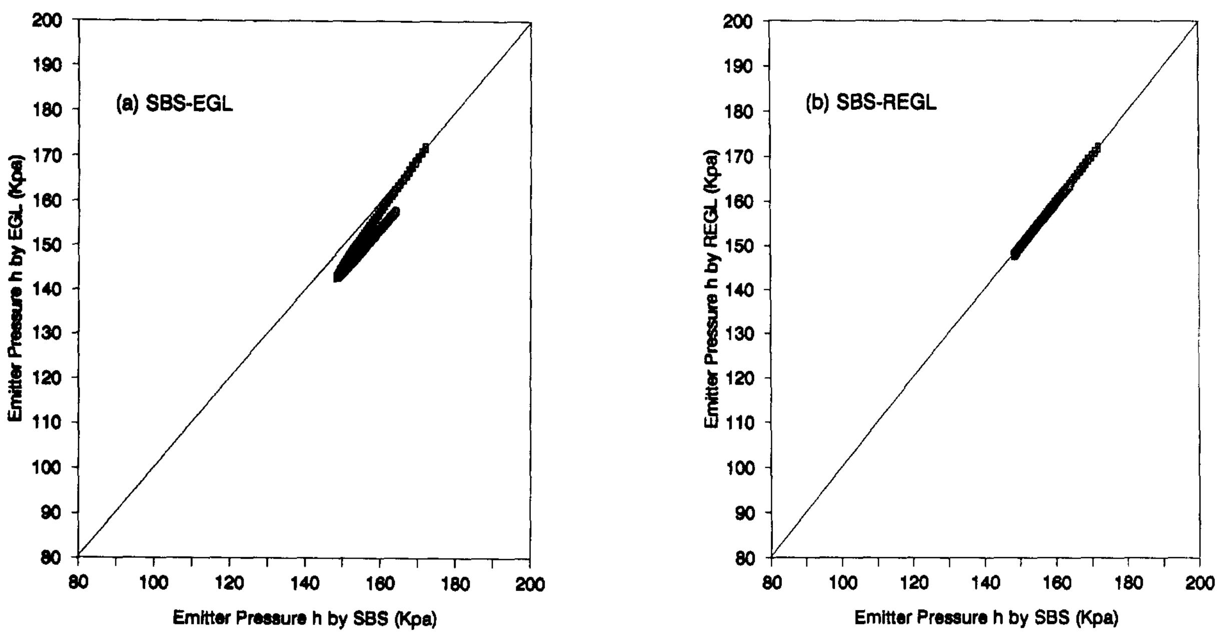

Fig. 3. The comparison among the Emitter Pressures Calculated by SBS, EGL and REGL for a lateral line (lateral slope = 4%)

ter pressures calculated by (a) SBS and EGL and (b) SBS and REGL for a lateral line with 4% downslope situation. Figure 4 showed the comparison between the emitter pressures calculated by (a) SBS and EGL and (b) SBS and REGL for a submain unit with 0 slope for both lateral and submain. Figure 5 showed the comparison between the emitter pressures calculated by (a) SBS and EGL and (b) SBS and REGL for a submain unit with 0 submain slope and 4% uniform downslope for lateral lines.

All data points in Figure 2, 3, 4 and 5 were plotted against a 45° line which indicates no variations between the two parameters evaluated. The improvment achieved by the REGL approach as shown by Fig. 2 b, 3 b, 4 b and 5b, which showed very little variations of water pressures determined by the REGL and SBS can be clearly seen by comparison with the difference between the water pressures calculated by SBS and EGL shown by Fig. 2 a, 3 a, 3 b, 4 a and 5 a. The results shown in Figures 2, 3, 4 and 5 were based on the simulation conditions in which submain slope is zero and lateral line slope is zero or 4% downslope. Future evaluations will include sloped situations for submain in the submain unit analysis. The sloped lateral caused the pressure increase in downstream

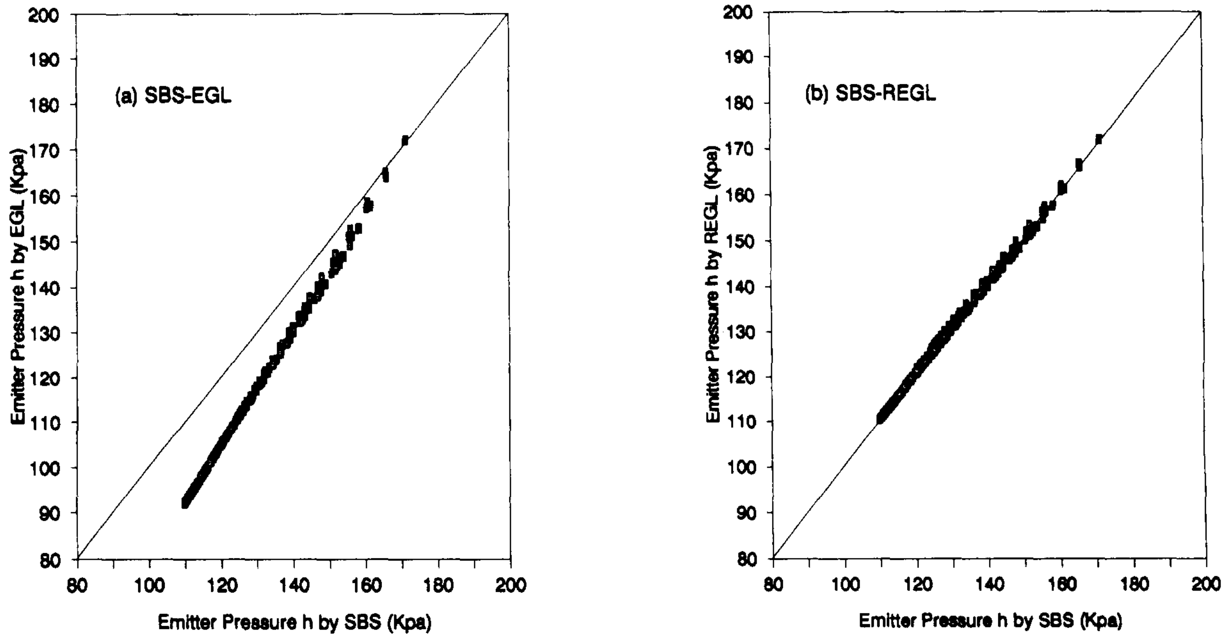

Fig. 4. The comparison among the Emitter Pressures Calculated by SBS, EGL and REGL for a submain unit (submain slope = 0%, lateral slope = 0%)

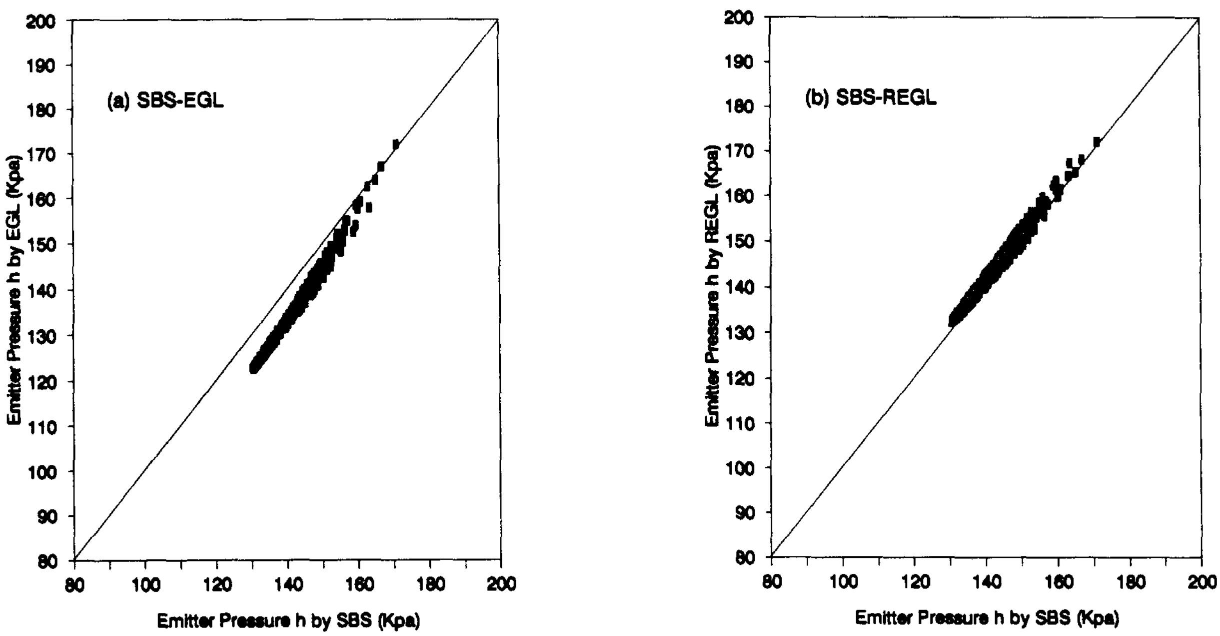

Fig. 5. The comparison among the Emitter Pressures Calculated by SBS, EGL and REGL for a submain unit (submain slope = 0%, lateral slope = 4%)

sections of the lateral line and created better uniformity of emitter flows but irregular shaped curves as shown in Fig. 3a. This situation was damped for a submain unit where many lateral lines were plotted together as shown in Fig. 5a.

Similar computer simulations as presented in Tables 1 and 2 for comparing EGL with SBS was also conducted to show the difference between the SBS and REGL. Tables 1 and 2 shows the simulation results of emitter flow variation q_{var} determined by REGL and SBS for different x values when the design criterion made by EGL design is 20% and 40% pressure variation, h_{var}, respectively. The emitter flow variation calculated by REGL and SBS shows much better agreement than that determined by EGL and SBS. It indicates the errors caused by REGL as practically nil and can be neglected for turbulent emitters for which the x value is 0.5. Even for laminar emitters for which the x value is 1.0, the errors caused by REGL is only about 1%.

Conclusions

1. Direct calculations can be made for emitter flows along a drip irrigation lateral line and a submain unit

using the Energy Gradient Line approach. Simple equations Eq. (16) and (19) were derived for direct calculation. This technique is simple; however, it is subject to certain errors since the energy gradient line is determined by the assumption of constant emitter flow.

2. Based on an analysis of possible errors, it can be concluded that for the turbulent flow emitter and an emitter flow variation equal or less than 10%, the simple Energy Gradient Line (EGL) approach can be used for drip irrigation design. For non-turbulent flow emitters or when the emitter flow variation is larger than 10%; designs can be made by using an adjusted total discharge or Revised Energy Gradient Line (REGL) approach.

3. A mean emitter flow approximation can be used to determine the adjusted total discharge for calculating total friction drop at the end of lateral line and submain and used for direct calculation for emitter flows for the REGL approach.

4. Comparisons of EGL or REGL with a step-by-step (SBS) calculation were made by the uniformity parameter, emitter flow variation, q_{var}. The SBS method calculates each emitter flow from the downstream end step-by-step to upstream points based on energy relations used as the base for comparison. The REGL approach results in less than 1% difference in emitter flow variation compared with SBS design as long as the design is made within 20% emitter flow variation.

5. A computerized drip irrigation design was developed using the derived equations for EGL and REGL approaches for a single lateral line and a submain unit. The computerized design was made for both metric and British units.

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