Rotational Scheduling Concept for Opened Hydrants at Improved On-Farm Irrigation Projects in Egypt

Hany G. Radwan

Abstract— Egypt has been suffering from severe water scarcity in recent years. Uneven water distribution, misuse of water resources and inefficient irrigation techniques are some of the major factors playing havoc with water security in the country. Improved on-farm irrigation systems are important projects that have proven effective by reducing irrigation time and increasing the agricultural area, crop production, and irrigation efficiency in addition to other benefits. These projects started at 1989 until now and it concerns with replacing the existing on-farm earth sections of Mesqas and Marwas with most common alternative of buried pipelines system including several hydrants (outlets) at the head of irrigated lands. Due to the existence of several hydrants along the improved pipeline Mesqa and Marwa without specified operating rules, the beneficiaries suffer from uneven water distribution. The main objective of this paper is to present a new concept that can be applied to detect the actual discharge from any opened hydrant along any pressurized pipeline network. This technique is applied for improved on-farm irrigation system in Egypt in case of two and three hydrants are opened at the same time along improved mesqa pipeline. This concept considers the hydraulic design of the improved irrigation system through developing a combined system curve for the opened hydrants in addition to taking the characteristics of the pump curve into consideration. Finally the actual operating condition and the corresponding expected discharge from each opened hydrant can be detected. Then accepted operational scenarios can be detected to satisfy two constraints; first constraint is to achieve equitable water distribution between two and three opened hydrants with allowable difference in the discharge within 20% of the maximum discharge. Second constraint is that the actual pump efficiency was taken into consideration in the selection of accepted scenarios with a minimum actual pump efficiency equals 80% of the maximum pump efficiency. Due to the expected large number of unaccepted operational scenarios, the concept of optimizing the valve closure was used to control the high flows. Irrigation schedule are introduced to detect the corresponding irrigation time for each operational scenario to achieve the total required irrigation water volume per each hydrant. This concept was applied to two case studies at improved on-farm irrigation system at Mahmoudia command area in Egypt with good results. Finally, this paper presents a concept that can be used and can be extended to be used in improved on-farm system in addition to other water distribution network to achieve equitable water distribution between beneficiaries.

Index Terms— Equitable water distribution, Improved irrigation system, On-farm irrigation, Opened hydrants, Rotational scheduling

1 Introduction

Egypt will face water scarcity in the near future due to limited water resources and the increase in water demand [1]. One of the main strategies that the Ministry of Water Resources and Irrigation ($MWRI$) uses is to increase water use efficiency. Irrigation for Agriculture consumes more than 80% from the available water in Egypt [1]. The traditional structure of the distribution systems include successive levels, starting from main feeders (rayah) to main (primary) canals, branch canals (secondary), mesqa (tertiary) and marwa (quaternary field ditches) as shown in Figure 1a [2]. Improved irrigation system at on-farm is taken as an example of integrated water management at the farm level (mesqa and marwa). On-farm system is a private property owned and maintained by beneficiaries (farmers). One of the main problems at on-farm is lower water use efficiency as shown in Figure 1b.

So, improved on-farm irrigation projects came to increase water use efficiency through two main projects; Improved Irrigation Projects (IIP), and Integrated Improved Irrigation and Management Projects ($IIIMP$). IIP is concerned by replacing the existing earthen cross section of mesqa at on-farm level into one alternative between three options; lined section, elevated concrete section, and low pressure pipeline system.

Low pressure pipelines mesqa achieves adequacy and reliability for the farmers in a high performance compared with other two improved alternatives (Improved lined mesqa, and raised concrete mesqa), so farmers satisfy and prefer the option of low pressure pipeline system compared with other options [3]. Low pressure pipeline option concerns with replacing the opened earthen mesqa cross section to buried pipeline system with valve at the head of irrigated lands (at the head of marwa section), see Figure 2. The main objective of the IIP in the old lands is to improve the efficiency of the water use at mesqa level. It also encourages user participation in the operation, maintenance and management of the improved irrigation system [4].

Several positive impacts have been achieved through Improved Irrigation Project (IIP) such as; land saving, increase in crop yield, increase conveyance efficiency, and decrease irrigation time [5-8]. $IIMP$ came as a natural

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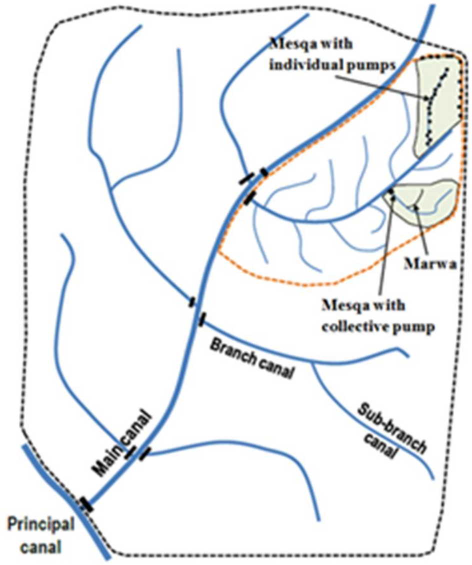
extension for IIP and to complete its success through converting the earthen marwa section to low pressure pipeline system and overcome some environmental aspects.



(a)[2]

(b)

Figure 1: (a) Main water distribution systems in Egypt, (b) existing earth mesqa at on-farm system

(a)

(b)

Figure 2: (a) Existing earthen mesqa at on-farm level, (b) improved pipeline mesqa system at on-farm level

$IIIMP$ is expected to enhance the overall water use efficiency at on-farm level. Improved on-farm irrigation projects started by IIP at 1989 until now. The improved irrigation projects at on-farm level were applied in five selected command areas within five targeted governorates of Kafr El Sheikh and Behera (12,000 feddan) in Lower Egypt and of Qena, Sohag, and Assuit (13,500 feddan) in Upper Egypt, and nowadays the improved system is under the implementation in Minya and Beni-Sueif governorates with about 7,800 feddan. Improved irrigation system at on-farm level consists of three main elements; improved pipeline for mesqa and branch mesqa (if exist) (IIP), improved marwa pipeline ($IIIMP$), and pump station at the mesqa's head as shown in Figure 3.

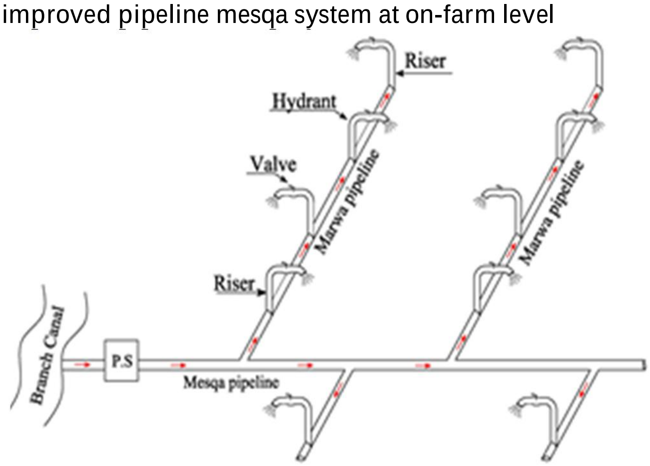


Figure 3: Main elements for total improved irrigation projects at on-farm level in Egypt

After the implementation of improved irrigation projects at on-farm level, there is still one main problem concerning with water shortage at the tail-end of improved mesqa or marwa due to random operation between farmers along the improved system. This problem annoy the farmers except they don't have another opened water source except the nearest agricultural drain to complete their irrigation needs. This problem can destroy the main benefits of improved irrigation projects and let the farmer feel with uncertainty in water availability.

The design concept of improved on-farm irrigation system is based on the calculation of the required mesqa capacity (discharge) for the whole served area and according to a constant released discharge from each valve (hydrant) of 30 l/s, the corresponding number of hydrants (valves) that should be opened at the same time within the served area should be determined. This number of opened hydrants that should be opened at the same time ranges between 1, 2, 3, and four as a maximum which is corresponding to calculated mesqa capacity of $30, 60, 90, and\ 120\ l/s$, respectively. For more than one opened hydrants at the same time, there is a problem of detecting which hydrants should be opened together to achieve equitable water distribution between opened hydrants with maximum difference in the released discharge taking into consideration the characteristics of pump curve. There are two types of scheduling; rotational and on-demand schedule. Rotational scheduling deals with providing water for a specific time to certain farms then it is switched to other farms which are our concept at improved on-farm irrigation system. But on-demand schedule deals with giving farmers complete flexibility in the frequency, rate, and duration for water delivery in accordance to consumptive uses of the plants during its growing periods. On-demand schedule has been covered through several researches in the last decade [9-17]. Concerning the rotational scheduling, a computer spreadsheet model was developed in Jordan to define the pressure problems at a pressurized network in case of selected rotation (operation) [18]. Then program WISCHE (Water Irrigation for SCHEduling) program was developed to provide dynamic planning of the daily irrigation scheduling for certain land area, which is recommended for high class investors in the new lands due to its high cost [19]. Rotational scheduling between two opened hydrants along improved on-farm irrigation system in Egypt has been studied [20]. The required theoretical operational conditions to achieve fairness water distribution between two opened hydrants at improved on-farm system have been studied in three different cases; case of laser leveling, variable water pressure at hydrants, and finally in case of variable land levels [21-23]. Through the previous three case, the concept for fairness water distribution are established based on allowable difference in the discharge between opened hydrants with four limits 5%, 10%, 15%,and 20%. The suggested distance between opened hydrants was detected to achieve the various limits of the discharge differences and the final decision was left to the decision maker. All previous rotational scheduling at on-farm level were studied in case of only two opened hydrants are opened at the same time with maximum mesqa capacity of 60 l/s. But there is high percentage of improved on-farm system with capacity greater than 60 l/s with accepted three opened hydrants at the same time.

The main objective of this paper is to study how to achieve fairness water distribution between beneficiaries in case of three hydrants are allowed to be opened at the same time at improved on-farm system taking into consideration the characteristics of pump curve.

2 Rotational Scheduling Methodology

This section discusses the methodology that is used to achieve the main objective of this paper. The methodology is started by defining the main concept used to design the improved on-farm system, and then discuss the main concept of combined system and pump curves generally in case of one; two and three opened hydrants are opened at the same time. After that all actual operational conditions are detected to define all resulted scenarios for all random operational cases with their corresponding discharges. Then some constraints are defined to achieve fairness water distribution between opened hydrants taking actual pump efficiency into consideration. According to the previous constraints, the accepted operational scenarios are selected. Finally, scheduling for irrigation time corresponding to the random operational scenarios is discussed. Figure 4 illustrates the main procedures used to achieve the main objective of this paper.

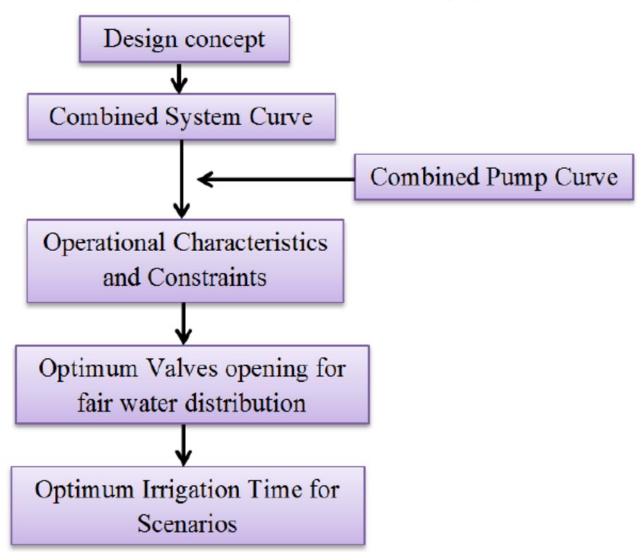


Figure 4: Methodology for rotational scheduling process

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3 DESIGN CONCEPT

The operation of improved on-farm irrigation system starts with withdrawal of water from the nearest branch or secondary canal through intake structure contains of intake pipe and pump sump then to pump station located at the mesqa's head. Then pumps inject water into improved mesqa pipeline then to improved or unimproved marwa and accordingly water is extracting through the existing hydrants.

3.1 Mesqa capacity

The design concept for the improved on-farm irrigation system begins with the calculations of maximum mesqa capacity (discharge) for the served area from (1), and then the detection of the suitable diameters for the improved mesqas and marwas based on maximum design velocity of 1.5 m/s.

$$Q = \frac{4200AW_D}{T} \qquad (1)$$

where $Q, A, W_D, and\ T$ are mesqa capacity ($l/sec.$), total served area ($feddan$), Water duty requirement (mm/d), and Working time per day ($seconds$). The calculated discharge is approximated to multiples of 20 l/sec or 30 l/sec according to the designed hydrant discharge to detect the number of opened hydrants at the same time.

3.2 Pressure head at hydrant

Pressure head at hydrant was derived as follows (see Figure 5) [20, 24].

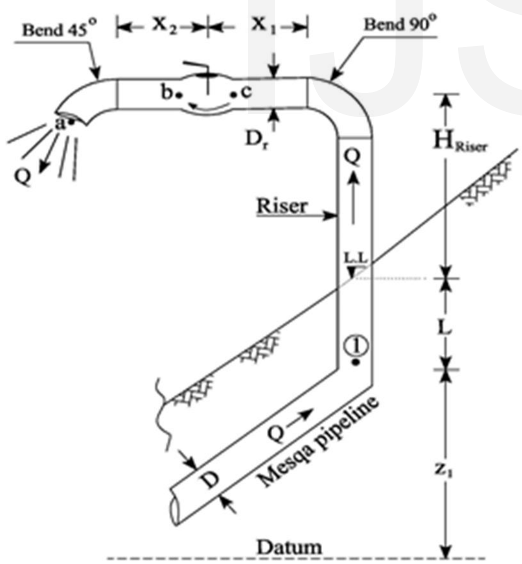

Figure 5: Main elements of hydrant connection

By applying Bernoulli's Equation between points (a, c) and using valve equation to calculate the head losses between the two points (b, c), the following equations are obtained:-

$$Z_C + \frac{P_C}{\gamma} + \frac{V_c^2}{2g} = Z_a + \frac{P_a}{\gamma} + \frac{V_a^2}{2g} + h_{l_{c\to a}}, \qquad (2a)$$

$$V_a = V_b = V_c\,, P_a = 0.0\,, Z_c = Z_b \cong Z_a\,, \qquad (2b)$$

$$\frac{P_c}{\gamma} = h_{l_{c\to a}} = h_{l_{b\to a}} + h_{l_{c\to b}} \qquad (2c)$$

$$h_{l_{b\to a}} = \frac{Q^2}{2gA_r^2}(K_e + K_b) + \left(\frac{10.67Q^{1.852}X_2}{C_H^{1.852}D_r^{4.87}}\right) \qquad (2d)$$

where $P/\gamma\,, Z, V, and\ h_l$ are pressure head (m), elevation head (m), velocity (m/s), and the head losses (m) between two specified points, respectively.

Also $Q, D_r, A_r, C_H, x_2, K_e, and\ K_b$ are hydrant discharge (m^3/s), diameter and inner area of the riser in meter and meter square respectively, coefficient depends on pipe material (taken 150 for PVC), horizontal distance in meter, coefficient of exit and bending (45^o) losses respectively. For the calculation of the head losses between the two points ($b\ and\ c$) ($h_{l_{c\to b}}$), valve equation can be used as follows:-

$$h_{l_{b\to c}} = K_{Valve}\left(\frac{V_b^2}{2g}\right) \qquad (2e)$$

where K_{Valve} is the losses coefficient of butterfly valve depending on the opening ratio. So, the pressure head at point (c) can be calculated as follows:-

$$\frac{P_c}{\gamma} = \frac{Q^2}{2gA_r^2}(K_e + K_b + K_{Valve}) + \left(\frac{10.67Q^{1.852}x_2}{C_H^{1.852}D_r^{4.87}}\right) \qquad (2f)$$

By applying Bernoulli's Equation between points (C, 1):

$$Z_1 + \frac{P_1}{\gamma} + \frac{V_1^2}{2g} = Z_c + \frac{P_c}{\gamma} + \frac{V_c^2}{2g} + h_{l_{1\to c}} \qquad (3a)$$

$$V_c = V_1, (Z_c - Z_1) = H_{Riser} + L, L_t = x_1 + x_2 + H_{Riser} + L \qquad (3b)$$

$$\frac{P_1}{\gamma} = (H_{Riser} + L) + \frac{Q^2}{2gA_r^2}\left(K_e + K_b + K_{90^o} + K_{Valve} + K_{Tee}\right) + \left(\frac{10.67Q^{1.852}L_t}{C_H^{1.852}D_r^{4.87}}\right) \qquad (3c)$$

where $H_{Riser}, L, K_{90}, K_{Tee}, and\ L_t$ are the height of the riser above the land (m), the buried part of the riser under the ground level (m), coefficient of losses due to bending (90^o), coefficient of losses due to tee section between the riser and main mesqa pipeline, and total friction lengths (m), respectively. Then the hydraulic head (H) at point (1) can be as follows:

$$H_1 = \frac{P_1}{\gamma} + Z_1 = (H_{Riser} + L) + \frac{Q^2}{2gA_r^2}(K_{Total}) + \left(\frac{10.67Q^{1.852}L_t}{C_H^{1.852}D_r^{4.87}}\right) + Z_1 \qquad (4a)$$

$$K_{Total} = K_e + K_b + K_{90^o} + K_{Valve} + K_{Tee} \qquad (4b)$$

where , Z_1 is the elevation head of point (1) above a reference datum. Equation ($4a$) can be rewritten as follows:

$$H_1 = L.L + H_{Riser} + \frac{Q^2}{2gA_r^2}(K_{Total}) + \left(\frac{10.67Q^{1.852}L_t}{C_H^{1.852}D_r^{4.87}}\right) \quad (5a)$$

$$Where\ L.L = Z_1 + L \quad (5b)$$

where L.L is the land level at the hydrant location (m). Then the total required head (H_{T_1})at point (1) in meter can be as follows:-

$$H_{T_1} = H_1 + \frac{V^2}{2g} \quad (6a)$$

$$H_{T_1} = L.L + H_{Riser} + \frac{Q^2}{2gA_r^2}(K_{Total} + 1) + \left(\frac{10.67Q^{1.852}L_t}{C_H^{1.852}D_r^{4.87}}\right) \quad (6b)$$

where $V$is the velocity along the reach before studied hydrant. This velocity is assumed to be the velocity at the beginning of the riser (m/s). Equation ($6b$) can be rewritten as follows:-

$$H_{T_1} = L.L + H_{Riser} + \frac{Q^2}{2gA_r^2}(K_{Total}) + \left(\frac{10.67Q^{1.852}L_t}{C_H^{1.852}D_r^{4.87}}\right)$$

$$= L.L + H_{Riser} + (C_1Q^2 + C_2Q^{1.852}) \quad (7a)$$

$$Where\ C_1 = \frac{(K_{Total} + 1)}{2gA_r^2}, C_2 = \frac{10.67Q^{1.852}L_t}{C_H^{1.852}D_r^{4.87}} \quad (7b)$$

Head losses for minor and main losses through mesqa and marwa's reaches are calculated through the critical operating path [25]. Main friction losses (h_f) are calculated using Hazen-William equation as follows [26] (see Figure 6).

$$h_f = \frac{10.67Q^{1.852}L}{C_H^{1.852}D_r^{4.87}} \quad (8)$$

where $h_f, D, L, and\ g$ are friction losses in pipeline (m), diameter of pipeline reach (m), length of pipeline reach (m), and gravity acceleration (m/s^2) respectively.

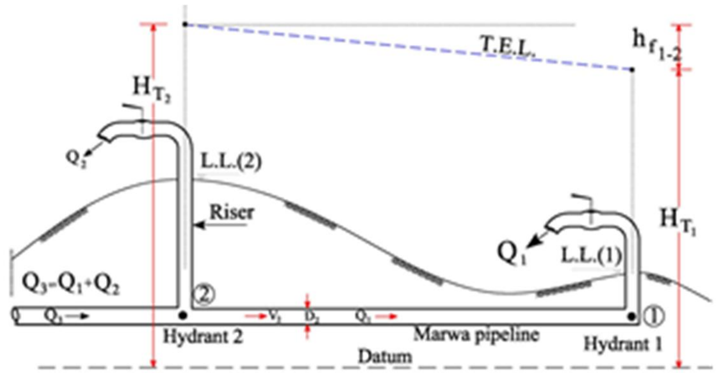

Figure 6: Representation between two hydrants along improved marwa / mesqa pipeline

The relation of the total hydraulic head between any two successive hydrants can be calculated using the following equation (see Figure 6):

$$H_{T_2} = H_{T_1} + h_{f_{1\to2}} \quad (9)$$

Finally, the suitable pump is selected to overcome the total head losses through the critical operating path. Figure 7 illustrates the total energy line through the critical operating path in case of one opened hydrant at improved on-farm irrigation system (last valve is opened).

The total governing equations used to detect the characteristics of the required pump can be summarized as follows [20]:

$$H_{T_6} = H_{T_1} + h_{f_{1\to6}} \quad (10)$$

By applying Bernoulli's equation between points A and 6 ($V_A = P_A = 0.0$):

$$H_P + Z_A + \frac{P_A}{\gamma} + \frac{V_A^2}{2g} = H_{T_6} + h_{l_{A\to6}} \quad (11)$$

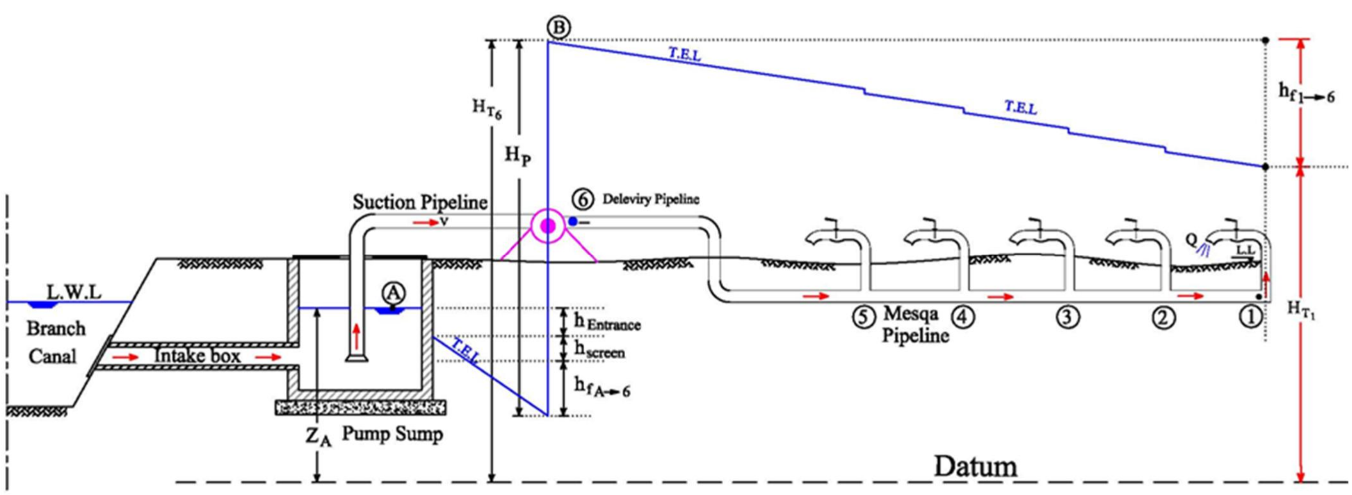

Figure 7: Energy line through the critical operating path-one opened hydrant

$$H_P = \left(H_{T_6} + h_{l_{A\to6}}\right) - Z_A \quad (12)$$

Where $h_{1\ A\to6}$ are head losses (m) between points "A" and "6", pressure head (m), velocity (m/s), and water elevation (m) at point "A" inside the pump sump, and pump head (m) respectively where;

$$h_{l_{A\to6}} = h_{Entrance} + h_{Screen} + h_{f_{A\to6}} + h_{bending} \quad (13a)$$

$$h_{screen} = \frac{1}{2C_d g}\left(\frac{Q^2}{A_e}\right) \quad (13b)$$

$$h_{Entrance} = K_{suction}\left(\frac{Q^2}{2gA^2}\right) \quad (13c)$$

$$K_{suction} = D + \frac{5.6\,Q}{\sqrt{2g}D^{1.5}} - \frac{8Q^2}{g\pi D^{1.5}} \quad (13d)$$

Where $C_d, Q, A_e, A, and\ D$ are discharge coefficient (taken 0.6), discharge at pump suction, and effective opened area for the screen, cross section area and diameter of the suction pipe respectively. The previous design steps have been programmed using Matlab software [27, 28].

4 COMBINED SYSTEM CURVE

Through this section the operational characteristics in case of one hydrant is opened at improved on-farm irrigation system will be discussed. Then the main concept for combined system curve in case of more than one hydrant are opened will be discussed.

4.1 CASE 1: ONE OPENED HYDRANT AT IMPROVED ON-FARM IRRIGATION SYSTEM

One opened hydrant at improved on-farm irrigation system is the simplest case. Through this case the operational condition can be detected by intersecting the system curve for the opened hydrant until reaching the pump with the pump curve. The system curve consists of two main components static head (constant value and independent of flow) and friction head which is a function of the flow rate. For example if hydrant number 1 in Figure 7 is the only opened hydrant, the total system curve for this hydrant at the pump location can be generated through the following stages. First stage concerns with developing the system curve (A) at the opened hydrant itself as shown in Figure 8 as follows:

$$H_{T_1} = L.L_1 + H_{Riser_1} + (C_1^2Q^2 + C_2Q^{1.852})$$

$$H_{T_1} = K + f(Q^2, Q^{1.852}) \quad (14)$$

$$where\ \ K = L.L_1 + H_{Riser_1}$$

Where K is a constant value represents the static head at the opened hydrant, and the component $f\ (Q^2, Q^{1.852})$ represents the dynamic head. Then second stage concerns with converting the generated system curve at the opened hydrant to the pump location (point 6) by adding the friction as in Equation 12. This stage is represented by curve (B) in Figure 8. Third stage concerns with developing the required final system curve in case of hydrant number 1 is opened. This is done through two steps, first the delivery and suction losses from point A to point 6 are added to curve B to get curve (C) which is the first part in equation (12). Then all values on curve (C) will be subtracted by constant value of Z_A (water elevation at pump sump) as illustrated in equation (12) to get the final required final system curve. The actual operational condition and total head at the opened hydrant can be detected as shown in Figure 8.

4.2 CASE 2: MORE THAN ONE OPENED HYDRANT

This section describes the concept for combined system curve in case of more than one opened hydrant is opened. This concept will be illustrated in case of two and three hydrants are opened at the same time on a pipeline system.

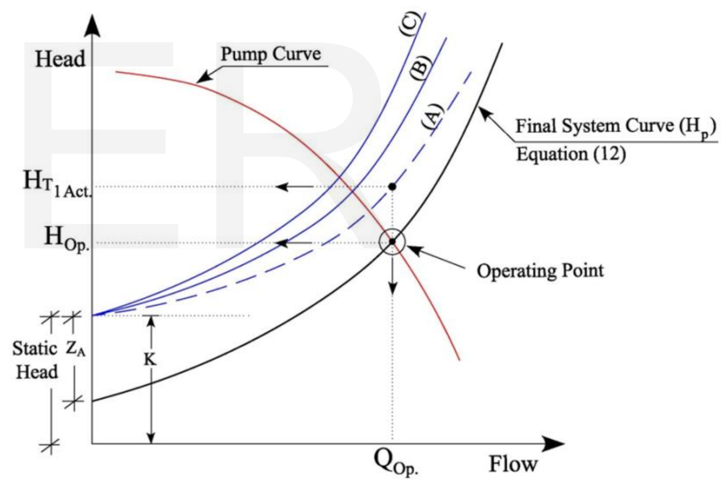

Figure 8: Operational condition for one opened hydrant

4.2.1 CONCEPT OF COMBINED SYSTEM CURVE- TWO OPENED HYDRANTS

This section concerns with the development of combined system curve in case of two hydrants are opened at the same time at improved on-farm irrigation system [29, 30]. For example, assume that hydrant number 1, and 3 in Figure 7 are opened together and it is required to know the actual operational condition for the pump and actual flow from each hydrant. Assume that land level at hydrant number 1 ($L.L_1$) is greater than land level for hydrant number 3($L.L_3$), and height of the risers (H_{Riser}) for the two hydrants are the same. The final combined system curve can be derived as follows (see Figure 9):-

- Create the system curve (required pressure head) at each opened hydrant separately by substituting in equation (14) for each hydrant to get curves "A", "B" as shown in Figure 9. The static head K_1 and K_3 for hydrant number 1 and 3 respectively are different so the starting point for each curve is different.
- Reach the system curve "A" for hydrant number 1 (far opened hydrant) to the location of hydrant number 3 (nearest opened hydrant) by adding the friction losses through the path from hydrant 1 to 3 to get curve "C".
- Now there are two system curves "B, and C" for the same point at hydrant number 3. So, there is a need to create the combined system curve at hydrant number 3 to get curve "D".
- Reach curve "D" to pump location (point 6) by adding the total friction losses from hydrant number 3 to pump location (point 6) to the combined system curve "D" to get curve "E".

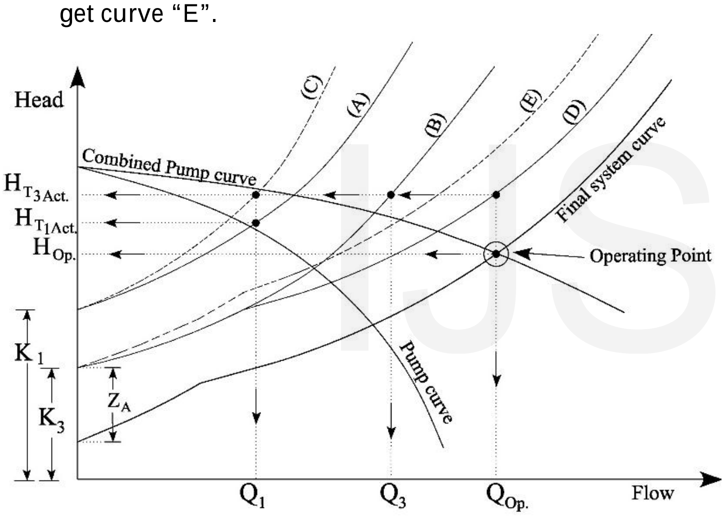

Figure 9: Combined and final system curve for two opened hydrants.

- Add the losses from points A to point 6 (suction losses) to the resulted system curve "E" to get the first term between brackets in equation (12), then subtract the resulted curve from constant value of Z_A (see equation (12)) to get the final system curve (required pump curve).
- The final system curve should be intersected with the combined pump curve (assume two similar pumps) to get the final operation point and therefore the actual discharge and pressure head at every opened hydrant can be detected as shown in Figure 9.

4.2.2 Concept of Combined system curve- three opened hydrants

This section discusses the concept for developing the final combined and system curve and the detection of the actual operational condition in case of three hydrants are opened at the same time. For example, assume that the three hydrants number 1, 3, and 5 in Figure 7 are opened at the same time and it is required to detect the actual operational characteristics at this case. Assume the three hydrants have the same values for the height of the risers (H_{Riser}), and there is a difference in the land level between the three hydrants($L.L_1 > L.L_3 > L.L_5$). The final combined system curve can be derived as follows (see Figure 10):-

- Create the system curve (required pressure head) at each opened hydrant separately by substituting in equation (14) for each hydrant to get curves A, B, and C as shown in Figure 10. The static headK_1, K_3, and K_5 for hydrant number $1, 3, and\ 5$ respectively are different so the starting point for each curve is different.
- Starting from the far opened hydrant to the nearest one, reach the system curve "A" for hydrant number 1 (far opened hydrant) to the location of the next opened hydrant number 3 by adding the friction losses through the path from hydrant number 1 to 3 to get curve "D".
- Now there are two system curves "B, and D" for the same point at hydrant number 3. So, there is a need to create the combined system curve at hydrant number to get curve "E".
- Reach curve "E" to the next opened hydrant number 5 by adding the friction losses through the path from hydrant number 3 to 5 to get curve "F".
- Now there are two system curves "F, and C" for the same point at hydrant number 5. So, there is a need to create the combined system curve at hydrant number 5 to get curve "G".
- Reach curve "G" to pump location (point 6) by adding the total friction losses from hydrant number 5 to pump location (point 6) to the combined system curve "G" to get curve "H".
- Add the losses from points A to point 6 (suction losses) to the resulted system curve "H" to get the first term between brackets in (12), then subtract the resulted curve from constant value of Z_A (see equation (12)) to get the final system curve (required pump curve).
- The final system curve should be intersected with the combined pump curve (assume three similar pumps) to get the final operational point and therefore the actual discharge and pressure head at every opened hydrant can be detected as shown in Figure 10.

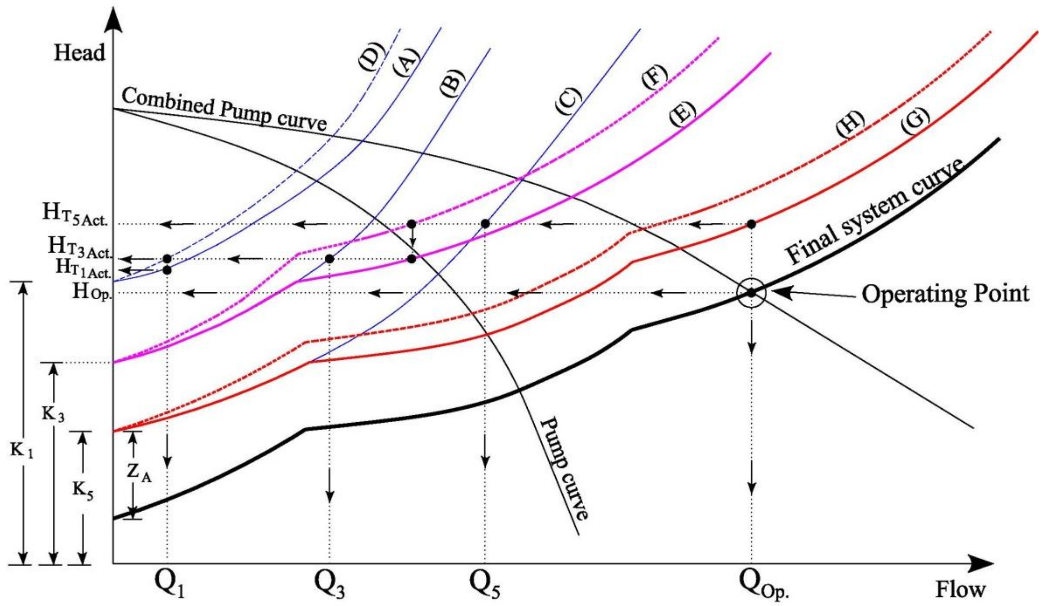

Figure 10: Combined and final system curve for three opened hydrants.

5 Operational Characteristics and Constraints

This section concerns with the calculation of the expected operational scenarios due to random operation of hydrants along improved mesqa pipeline. Also this section discusses the constraints for accepted operational scenarios. For improved on-farm irrigation system and after the selection of the suitable pumps, there are many operational scenarios due to random operation of hydrants. The total random operational scenarios for any number of opened hydrants at the same time along the improved mesqa pipeline can be calculated as follows:-

$$N = C_r^n = \frac{n!}{r!\,(n-r)!} \qquad (15)$$

Where; $N, r, and\ n$ are total random operational scenarios, number of opened hydrants at the same time, and total number of hydrants along the improved mesqa pipeline, respectively. Table 1 illustrates the total random operational scenarios in case of two or three opened hydrants at the same time for different number of hydrants along improved mesqa pipeline.

Table 1: Total random operational scenarios for two / three opened hydrants at the same time.

Number of opened hydrants (r)	Number of hydrants along improved mesqa pipeline (n)							
	1	2	3	4	5	6	7	8
2	-	1	3	6	10	15	21	28
3	-	-	1	4	10	20	35	56

Due to random operation for hydrants along improved mesqa pipeline, it is expected to have unaccepted operational scenarios that don't achieve equity water distribution between opened hydrants. So, the accepted operational scenarios will be selected according to two constraints. First constraint deals with the difference in the actual discharge between opened hydrants which shouldn't exceed 20% (as a maximum accepted difference) of the maximum discharge as follows:

$$\Delta Q = \left(\frac{Q_{Max.} - Q_{Min.}}{Q_{Min.}}\right) \leq 20\% \qquad (16)$$

where; $Q\_Max.\ and\ Q_{Min}$ are the maximum and minimum discharge for the opened hydrants, respectively. The second constraint deals with the actual pump efficiency which shouldn't be less than 80% of the maximum pump efficiency in order to increase the life time of pumps.

6 Optimum Valves opening

There is a probability that the two operational constraints mentioned in item 5 will not be achieved due to random operational scenarios and due to ignoring this issue during the initial design of the network. So, there is another way to control large flows through optimizing the valves closure. By decreasing the opening ratio for the valve, the friction losses will be increased which can be reflected on raising the system curve as shown in Figure 11. Therefore, the operating point will move to the left and the expected discharge will be decreased.

The effect of the change in the friction losses through changing the opening ratio of the valve can be illustrated in Equation 4b with the coefficient losses of the valve (K_{Valve}). The values of the coefficient losses for a series of butterfly valve (2000 mm diameter) with respect to different opening ratios are illustrated in Figure 12. This table describes the flow characteristics of series of butterfly valves from Val-Matic Manufacturing Corporation. These values can be slightly changed according to the valve diameter and the manufacturer. Through the technique of optimizing the valve closure, the discharges from all random opened valves can be controlled to achieve the two mentioned constraints mentioned in item 5. Therefore fair water distribution between any random opened hydrants can be achieved. The application of valve closure can be achieved through an automatic control system using electronic sensors.

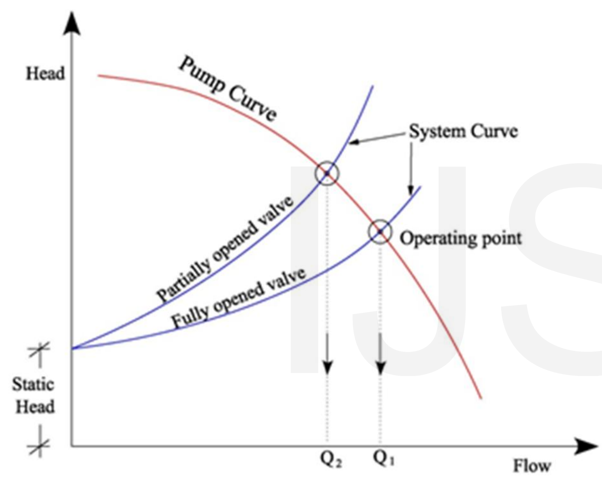

Figure 11: Effect of valve closure on the operational characteristics.

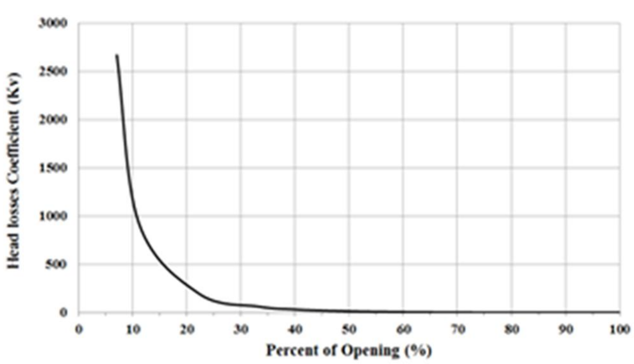

Figure 12: Head losses coefficient for butterfly valve (2000 mm diameter) (Val-Matic Manufacturing Corporation)

7 Optimum Irrigation Time for Scenarios

After ensuring the fair water distribution between opened hydrants, there is a need to discuss the corresponding irrigation time for each operational scenario to achieve the required irrigation water volume. Through detecting the actual discharge for each opened hydrant; the sufficient irrigation water for a specified served area for each opened hydrant will be calculated. The total water volume required for irrigation (V) in liter/hour can be calculated for each hydrant according to the served area per hydrant (A) in feddan and the water duty for Rice (W_D) in mm/day as

$$V = \frac{4200AW_D}{3600} \tag{17}$$

Assuming that there is "n" number of hydrants along the improved mesqa pipeline and k simultaneously hydrants are opened together at specific time (t). Therefore, the number of alternative cases equals $m = C_k^n$. The proposed methodology is to choose n scenarios from the total m scenarios with total alternatives of C_k^m such that the total irrigation time achieved. For example, let us assume that the selected scenarios are $i_1, i_2, i_3, \ldots\ldots, i_n$ and then the total water volume (V) and irrigation time at every hydrant number (a) is given by:

$$V_a = \sum_{j=i_1}^{i_n} t_j Q_{aj} \tag{18}$$

where; Q_{aj} is the discharge of the hydrant "a" at the scenario j, and t_j is the time required ($hr.$) for the scenario j. Similar calculations can be achieved for other hydrants($a_1, a_2, a_3, \ldots a_n$), so the outputs can be arranged in a matrix form (see Equation 19) where the vector of t_{ij} is the unknown. Where A and t are the total served area ($fed.$), and total irrigation time (hours) for the whole served area, respectively. All the previous methodology through developing the combined pump, system curves, selection of accepted operational scenarios, and detection of the suitable irrigation time is coded using Matlab program.

8 Case Studies

Two improved mesqa pipelines at Mahmoudia command area near Edco drain are used as case studies (mesqa 1, and mesqa 2) as shown in Figure 13.The following data can be assumed for the case studies; irrigation time per day is 16 hour, water duty for the cultivated crop is 15.7 mm/day (for Rice). Land level, and height of riser above the land for all hydrants at the two case studies are the same as 4m, 0.3m respectively.

$$V = \begin{bmatrix} V_{a_1} \\ V_{a_2} \\ V_{a_3} \\ \ldots \\ \ldots \\ \ldots \\ V_{a_n} \end{bmatrix} = \begin{bmatrix} Q_{a_1 i_1} & Q_{a_1 i_2} & Q_{a_1 i_3} & \ldots & \ldots & \ldots & Q_{a_1 i_n} \\ Q_{a_2 i_1} & Q_{a_2 i_2} & Q_{a_2 i_3} & \ldots & \ldots & \ldots & Q_{a_2 i_n} \\ Q_{a_3 i_1} & Q_{a_3 i_2} & Q_{a_3 i_3} & \ldots & \ldots & \ldots & Q_{a_3 i_n} \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ Q_{a_n i_1} & Q_{a_n i_2} & Q_{a_n i_3} & \ldots & \ldots & \ldots & Q_{a_n i_n} \end{bmatrix} \begin{bmatrix} t_{i_1} \\ t_{i_2} \\ t_{i_3} \\ \ldots \\ \ldots \\ \ldots \\ t_{i_n} \end{bmatrix} = At \tag{19}$$

The water level inside the pump sump (Z_A) is assumed to be below the land level by 3.0 m. The main components of the total losses coefficients (K_{Total}) in equation (7b) can be detected as follows (K_e = 1.0, K_b = 0.3, K_{90^o} = 0.75, K_{Tee} = 1.8) taking into consideration the value of losses coefficient due to valve (K_{Valve}) is 0.48 for fully opened valve and for other opening ratios refer to Figure 12.

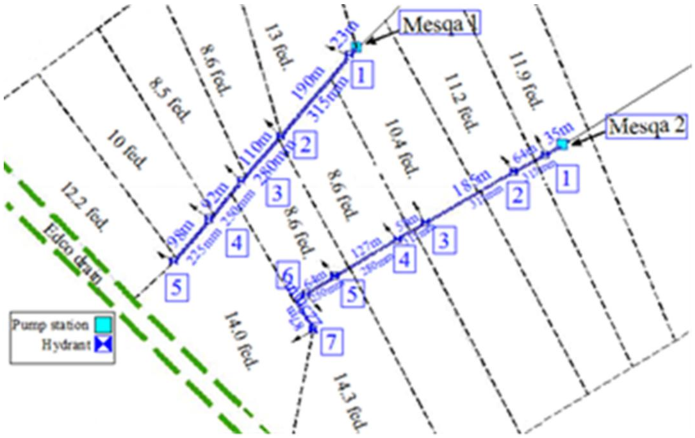

Figure 13: Cases study for improved mesqa 1 and 2 at Mahmoudia command area

Mesqa capacity can be calculated through substituting in equation (1) and by assuming the default design discharge for hydrant of30 l/sec, the total number of hydrants that can be opened at the same time can be detected as illustrated in Table 2. From table 2, the existing number of hydrants per each mesqa is 5 and 7 for mesqa number 1 and 2 respectively. Also from this table, the mesqa capacity for mesqa number 1 and 2 are 59.8 and 90.4 l/s respectively. And due to that the design hydrant discharge is30 l/s, so the number of hydrants that should be opened at the same time for mesqa number 1 and 2 are two and three hydrants respectively. According to Table 1, the total random operational scenarios for mesqa 1 and 2 are 10, and 35 scenario, respectively.

Table 2: Characteristics of two study cases of improved mesqa pipeline

Mesqa number	Served area (fed.)	Number of Hydrants	Mesqa capacity (l/s)	Number of opened hydrants	Number of used pump of type 170ϕ
1	52.3	5	59.8	2	2
2	79	7	90.4	3	3

The default design hydrant discharge is 30 l/s, the expected mesqa capacity is a multiplication of this value, and the required water head for the improved system is between 6 to 10 m. So one suitable pump unit will be selected as a standard one and the total required number of that pump will be detected. The required characteristics of pump (head and discharge) at improved on-farm system can be achieved using ALLWEILER AL-FARID pump charts (pump speed of 1450rpm) through selecting a pump group (100-200). Inside this pump group there are 6 pump types, the selected pump type optimizing the required characteristics is pump 170ϕ with a maximum pump efficiency of 85% corresponding to head of 6 m.

9 Results

The main operational characteristics for the two case studies (mesqa 1 and 2) are detected. Tables 3 and 4 illustrate the characteristics for all expected random operational scenarios for mesqa 1 and 2 respectively where $Q_{op}, H_{op.}, \eta$ are the actual operating pump discharge, head, and efficiency respectively.

From Table 3 it is obvious that all ten random operational scenarios are accepted for the constraint of the drop limit in pump efficiency with allowable minimum pump efficiency of 68% (80% of the maximum of 85%). But only six scenarios (number 1, 3, 5, 6, 9, and 10) are accepted for the constraint of accepted difference in the discharge. From Table 4 it is obvious that all thirty five random operational scenarios are accepted for the constraint of the drop limit in pump efficiency with allowable minimum pump efficiency of 68% (80% of the maximum of 85%). But only six scenarios (number 9, 10, 32, 33, 34, and 35) are accepted for the constraint of accepted difference in the discharge. Due to limited accepted operational scenarios for achieving the two constraints of the discharge and pump efficiency, there is a need to overcome this problem by optimizing the valves opening.

Table 3: Characteristics of the random operational scenarios for mesqa number 1

Scenario Number	No. of first opened hydrant	No. of second opened hydrant	$Q_{op.}$ (L/sec.)	$H_{op.}$ (m)	η (%)	Discharge for first opened hydrant (L/sec.)	Discharge for second opened hydrant (L/sec.)	ΔQ %
1	4	5	62.31	5.32	78.14	34.36	27.95	18.65
2	3	5	65.20	4.97	76.06	37.36	27.83	25.49
3	3	4	65.69	4.88	75.70	34.86	30.82	11.59
4	2	5	67.36	4.68	74.37	39.44	27.92	29.20
5	2	4	68.11	4.61	73.70	37.34	30.76	17.63
6	2	3	68.81	4.57	73.07	35.88	32.93	8.24
7	1	5	70.14	4.39	71.87	41.86	28.28	32.45
8	1	4	70.77	4.31	71.30	39.89	30.88	22.59
9	1	3	70.87	4.24	71.22	38.29	32.58	14.92
10	1	2	71.61	4.21	70.55	37.34	34.27	8.24

A. Optimum Valve Opening

By adjusting the opening ratios of the valves for the unaccepted operational scenarios they can be converted to accepted scenarios. For the operational scenarios of mesqa number 1, there are two opened hydrants and the required changes for the opening ratios of valves will be achieved only to the nearest opened hydrants and the far opened hydrant is fully opened (with opening ratio of 100%) as shown in Table 5. According to Table 5 fair water distribution between all random operational scenarios can be achieved by optimizing the valve opening ratio.

Table 4: Characteristics of the random operational scenarios for mesqa number 2

Scenario Number	No. of first opened hydrant	No. of second opened hydrant	No. of third opened hydrant	$Q_{op.}$ (L/sec.)	$H_{op.}$ (m)	η (%)	Discharge for first opened hydrant (L/sec.)	Discharge for second opened hydrant (L/sec.)	Discharge for third opened hydrant (L/sec.)	ΔQ %
1	5	6	7	83.37	6.00	80.99	34.24	26.92	22.21	35.13
2	4	6	7	88.36	5.67	79.79	40.28	26.35	21.73	46.05
3	4	5	7	89.45	5.60	79.53	37.62	29.24	22.59	39.95
4	4	5	6	89.72	5.58	79.47	36.75	27.68	25.29	31.19
5	3	6	7	89.91	5.57	79.42	41.89	26.32	21.71	48.18
6	3	5	7	90.96	5.50	79.17	39.43	29.07	22.46	43.03
7	3	5	6	91.36	5.47	79.07	38.70	27.52	25.15	35.02
8	3	4	7	92.63	5.37	78.54	35.06	32.42	25.15	28.26
9	3	4	7	93.01	5.35	78.36	33.82	30.90	28.29	16.36
10	3	4	5	93.30	5.32	78.22	33.12	30.04	30.14	9.31
11	2	6	7	94.84	5.20	77.47	46.62	26.43	21.80	53.24
12	2	5	7	95.87	5.12	76.98	44.62	28.92	22.34	49.94
13	2	5	6	96.17	5.10	76.84	44.01	27.26	24.90	43.42
14	2	4	7	97.41	5.00	76.24	41.29	31.61	24.51	40.63
15	2	4	6	97.79	4.97	76.06	40.41	29.96	27.41	32.16
16	2	4	5	98.02	4.95	75.95	39.92	29.00	29.09	27.36
17	2	3	7	97.83	4.97	76.04	40.19	32.45	25.18	37.34
18	2	3	6	98.33	4.93	75.80	39.25	30.85	28.24	28.05
19	2	3	5	98.47	4.92	75.73	38.65	29.86	29.96	22.74
20	2	3	4	98.53	4.91	75.71	38.70	29.92	29.92	22.69
21	1	6	7	96.77	5.05	76.55	48.32	26.55	21.90	54.66
22	1	5	7	97.78	4.97	76.07	46.43	28.97	22.38	51.80
23	1	5	6	98.04	4.95	75.94	45.85	27.28	24.92	45.65
24	1	4	7	99.33	4.85	75.32	43.36	31.52	24.44	43.63
25	1	4	6	99.71	4.82	75.14	42.57	29.84	27.30	35.86
26	1	4	5	99.88	4.81	75.06	42.10	28.84	28.94	31.49
27	1	3	7	99.83	4.81	75.08	42.40	32.34	25.09	40.82
28	1	3	6	100.21	4.78	74.87	41.50	30.66	28.06	32.40
29	1	3	5	100.39	4.77	74.76	40.98	29.66	29.75	27.64
30	1	3	4	100.45	4.76	74.73	41.03	29.71	29.71	27.58
31	1	2	7	101.47	4.68	74.12	38.51	35.41	27.55	28.46
32	1	2	6	102.07	4.63	73.76	37.24	33.83	31.00	16.74
33	1	2	5	102.31	4.61	73.61	36.46	32.87	32.98	9.84
34	1	2	4	102.36	4.60	73.58	36.51	32.93	32.93	9.82
35	1	2	3	102.36	4.60	73.58	36.51	32.93	32.93	9.82

Table 5: Effect of optimum valve opening on the operational scenarios for mesqa number 1

Scenario Number	No. of first opened hydrant	No. of second opened hydrant	Qop. (L/sec.)	$H_{op.}$ (m)	η (%)	Discharge for first opened hydrant (L/sec.)	Discharge for second opened hydrant (L/sec.)	ΔQ %	Optimum valve opening ratio for first opened hydrant (%)
1	4	5	62.31	5.32	78.14	34.36	27.95	18.65	100 (Fully opened)
2	3	5	64.93	5.02	76.25	35.98	28.94	19.55	78
3	3	4	65.69	4.88	75.70	34.86	30.82	11.59	100
4	2	5	66.90	4.79	74.79	37.01	29.88	19.27	73
5	2	4	68.11	4.61	73.70	37.34	30.76	17.63	100
6	2	3	68.81	4.57	73.07	35.88	32.93	8.24	100
7	1	5	68.64	4.53	73.22	38.04	30.60	19.54	70
8	1	4	70.39	4.34	71.65	38.86	31.53	18.86	82
9	1	3	70.87	4.24	71.22	38.29	32.58	14.92	100
10	1	2	71.61	4.21	70.55	37.34	34.27	8.24	100

By following the same technique for optimizing the opening ratios for the valves, fair water distribution between all random operational scenarios for mesqa number 2 as illustrated in Table 6. From this table the changing in the opening ratios is applied only for the nearest opened hydrant and sometimes it is extended to the middle opened hydrant.

Table 6: Effect of optimum valve opening on the operational scenarios for mesqa number 2

Scenario Number	No. of first opened hydrant	No. of second opened hydrant	No. of third opened hydrant	Qop. (L/sec.)	$H_{op.}$ (m)	η (%)	Discharge for first opened hydrant (L/sec.)	Discharge for second opened hydrant (L/sec.)	Discharge for third opened hydrant (L/sec.)	ΔQ %	Optimum valve opening ratio For first opened hyd. (%)	Optimum valve opening ratio For second opened hyd. (%)
1	5	6	7	82.57	6.04	80.95	29.53	29.03	24.00	18.73	67	100
2	4	6	7	85.85	5.83	80.40	30.60	30.23	25.02	18.25	57	100
3	4	5	7	87.37	5.73	80.03	29.10	32.37	25.91	19.95	58	85
4	4	5	6	88.95	5.63	79.65	33.08	29.18	26.68	19.33	71	100
5	3	6	7	86.86	5.77	80.15	31.22	30.44	25.20	19.30	56	100
6	3	5	7	88.61	5.65	79.73	30.53	32.26	25.82	19.96	58	85
7	3	5	6	90.12	5.55	79.37	33.35	29.65	27.12	18.69	67	100
8	3	4	7	91.68	5.45	78.99	30.36	34.02	27.30	19.75	67	85
9	3	4	7	93.01	5.35	78.36	33.82	30.90	28.29	16.36	100	100
10	3	4	5	93.30	5.32	78.22	33.12	30.04	30.14	9.31	100	100
11	2	6	7	89.95	5.56	79.41	32.44	31.46	26.06	19.67	52	100
12	2	5	7	91.53	5.46	79.03	31.01	33.60	26.92	19.86	52	85
13	2	5	6	93.48	5.31	78.13	34.82	30.63	28.03	19.52	60	100
14	2	4	7	95.07	5.18	77.37	32.68	34.61	27.79	19.71	60	85
15	2	4	6	96.79	5.05	76.54	35.99	31.74	29.06	19.26	70	100
16	2	4	5	97.44	5.00	76.23	37.22	30.06	30.16	19.24	75	100
17	2	3	7	96.03	5.11	76.91	33.09	34.90	28.03	19.69	63	85
18	2	3	6	97.59	4.99	76.15	36.21	32.04	29.34	18.98	74	100
19	2	3	5	98.28	4.93	75.82	37.73	30.23	30.32	19.89	84	100
20	2	3	4	98.34	4.93	75.80	37.78	30.28	30.28	19.83	84	100
21	1	6	7	91.02	5.49	79.16	32.74	31.87	26.41	19.35	51	100
22	1	5	7	92.61	5.38	78.55	31.43	33.96	27.22	19.84	51	85
23	1	5	6	94.77	5.21	77.51	35.41	31.00	28.36	19.91	58	100
24	1	4	7	96.41	5.08	76.72	33.47	34.90	28.03	19.69	58	85
25	1	4	6	98.15	4.94	75.89	36.63	32.11	29.40	19.74	67	100
26	1	4	5	98.87	4.89	75.54	37.90	30.44	30.53	19.69	71	100
27	1	3	7	97.03	5.03	76.43	32.67	35.68	28.68	19.64	58	85
28	1	3	6	99.09	4.87	75.44	36.93	32.44	29.71	19.54	71	100
29	1	3	5	99.82	4.81	75.09	38.22	30.75	30.85	19.55	75	100
30	1	3	4	99.76	4.82	75.11	38.22	30.77	30.77	19.49	75	100
31	1	2	7	100.69	4.74	74.59	35.52	36.12	29.04	19.61	73	85
32	1	2	6	102.07	4.63	73.76	37.24	33.83	31.00	16.74	100	100
33	1	2	5	102.31	4.61	73.61	36.46	32.87	32.98	9.84	100	100
34	1	2	4	102.36	4.60	73.58	36.51	32.93	32.93	9.82	100	100
35	1	2	3	102.36	4.60	73.58	36.51	32.93	32.93	9.82	100	100

B. Irrigation time

With respect to the corresponding irrigation time, there is a need to discuss all operational combinations to achieve the required irrigation volume for each hydrant. The total water volume (V) for mesqa number 1 per hydrant number 1 to 5 is 238.13, 157.51, 155.68, 183.18, and 223.44 m^3, respectively. The same water volume for mesqa number 2 per hydrant number 1 to 7 is 217.98, 205.15, 190.51, 157.52, 157.51, 261.90, and 256.43 m^3, respectively.

The total operational alternatives (combinations) for mesqa 1 and 2 to satisfy the required irrigation water volume for each hydrant are 252, and 6,724,520 alternatives (combinations), respectively. Here one of all these alternatives (combinations) is selected for mesqa number 1 and 2 which achieve minimum total irrigation time for the whole served area. Table 7 illustrates the selected operational alternative (combination) for mesqa number 1 to achieve minimum total irrigation time of 14.10 $hour/day$. The selected operational combination for mesqa number 1 contains the operational scenarios number 2, 4, 6, 8, and 9 with their actual discharge illustrated in Table 5. Each operational scenario will be operated separately for a specified time then the other one until the last scenario. Table 8 illustrates the characteristics for the selected alternative (combination) for mesqa number 2 to achieve the minimum total irrigation time of 15.43 $hour/day$.

Table 7: Selected alternative (Combination) for minimum total irrigation time at mesqa number 1

Scenario no.	Irrigation time (hr.)	Q_1 (L/sec.)	Q_2 (L/sec.)	Q_3 (L/sec.)	Q_4 (L/sec.)	Q_5 (L/sec.)
2	3.70	0.00	0.00	35.98	0.00	28.94
4	3.90	0.00	37.01	0.00	0.00	29.88
6	0.37	0.00	35.88	32.93	0.00	0.00
8	5.81	38.86	0.00	0.00	31.53	0.00
9	0.32	38.29	0.00	32.58	0.00	0.00
Total	14.10 hr.	V= 238.13 m^3	V=157.51 m^3	V=155.68 m^3	V=183.18 m^3	V=223.44 m^3

Table 8: Selected alternative (Combination) for minimum total irrigation time at mesqa number 2

Scenario no.	Irrigation time (hr.)	Q_1 (L/sec.)	Q_2 (L/sec.)	Q_3 (L/sec.)	Q_4 (L/sec.)	Q_5 (L/sec.)	Q_6 (L/sec.)	Q_7 (L/sec.)
7	2.23	0.00	0.00	33.35	0.00	29.65	27.12	0.00
8	0.64	0.00	0.00	30.36	34.02	0.00	0.00	27.30
11	2.90	0.00	32.44	0.00	0.00	0.00	31.46	26.06
12	2.72	0.00	31.01	0.00	0.00	33.60	0.00	26.92
15	0.74	0.00	35.99	0.00	31.74	0.00	29.06	0.00
24	3.22	33.47	0.00	0.00	34.90	0.00	0.00	28.03
28	2.98	36.93	0.00	32.44	0.00	0.00	29.71	0.00
Total	15.43 hr.	V= 217.98 m^3	V= 205.15 m^3	V= 190.51 m^3	V= 157.52 m^3	V= 157.51 m^3	V= 261.90 m^3	V= 256.43 m^3

10 Conclusions

This paper discussed the general concept technique to detect the actual water discharge from two and three opened hydrants along pipeline system taking into consideration the combined system and pump curves. The technique was applied with good results to improve the operational conditions for on-farm irrigation system in Egypt. The accepted operational scenarios were detected to achieve equitable water distribution with adapted difference limit in the discharge between opened hydrants not more than 20%. In addition to maintain high pump efficiency with limit not less than 80% of the maximum pump efficiency.

The concept of optimum valve closure was applied to achieve fairness water distribution between all random operational scenarios. Then irrigation time schedule are discussed to provide the required irrigation water volume at each hydrant. Finally, the presented techniqure in this paper can be used generally in any pressurized network in order to achieve equitable water distribution between any opened valves.

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