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Performance of Water Delivery by Direct Pumping System at Farm Level: Case Study of Abu-Gabal Tertiary Canal, Egypt

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ABSTRACT - The Ministry of Water Resources and Irrigation (MWRI) initiated a national program to improve the existing irrigation system of agricultural lands in the Nile River Delta during the past five decades. The program implemented a series of interventions in the irrigation delivery system. Eventually, electric pumps are used to directly supply irrigation water (direct pumping system) instead of using an open stand tank. The main objective of this paper is to evaluate the direct pumping system for an irrigation improvement project in the El-Baslaqoun command area, Abu-Gabal Tertiary Canal (at farm level canal), as a model example in the Kafr El-Dawar area, Egypt. The results of water delivery performance reveal that efficiency, equity, and dependability were evaluated as “poor” according to the performance standards. Using MATLAB code, different scenarios were explored to improve water delivery performance. It is found that when the riser diameter is mostly modified to be four inches for all valves, the system not only delivers an adequate amount of water required to crops without excess flow but also gives a fair share of water among farmers.

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1. Introduction

Water shortage is expanding around the world due to climate change and population growth. Around 70% of the freshwater worldwide is utilized within the agriculture sector, of which irrigation water could be a major component [1]. Irrigation water is lost due to water transport, using inefficient irrigation systems, and ineffective water allocation between farmers. Allocation mechanisms not only determine the social distribution of water among farmers but also have a reflective impact on the conservation and efficient utilization of water resources [2]. Globally, many researchers studied the effect of water delivery allocation between farmers and the resulting performance. A study carried out in a Spanish irrigation district found that not only is equitable distribution impossible, but also that more than 50% of supplied water is lost due to mismanagement of agricultural water distribution networks [12]. Additionally, a study conducted in four agricultural regions in Ethiopia found that improper development, damage of irrigation structures, and the development of irrigation infrastructure without proper management program improvements have resulted in low agricultural water, which was followed by extreme inequity in water distribution [3]. In Egypt, since the 1970s, MWRI launched many programs to improve the irrigation water efficiency, such as the Egypt Water Use and Management Project (EWUP) and the Regional Irrigation Improvement Program (RIIP) in 1989 [5]. Then, a series of irrigation improvement projects were achieved; the first phase of the irrigation improvement project (IIP1) was implemented from 1996 to 2007, and the second phase of the irrigation improvement project IIP from 2007 to 2009 [6]. Egypt is evolving a sustainable agricultural development strategy to encourage environmentally (Allam, 2002) [5].

Friendly practices among farmers, such as crop rotation and water management [12]. Eventually, the Integrated Irrigation Improvement and Management Project (IIIMP) started in 2009 as a successor of the IIP projects with an integrated improvement package that tackles irrigation and drainage improvement. The project replaces the individual pumps and open stand tank with a direct pumping system that is installed at the head of each Tertiary Canal. Teaima et al. (2013) studied the feasibility of using the direct pumping system and concluded that it can be used without any risk where reasonable cost reduction is remarked [7].

Moreover, El-Gafy & El-Bably (2016) carried out a comparative study among three categories of on-farm irrigation direct pumps (non-improved diesel pumps, improved diesel pumps, and improved electrical pumps) in three regions (El-Nakhla, Hamed Minisy, and Nekla canals) at El-Behera governorate in Egypt [4]. The study revealed that the improved electrical pumps, followed by the improved diesel pumps, produce less CO_2 emissions. In general, the electrical pumps are more environmentally, economically, and socially efficient than the diesel pumps. However, there is no solid conclusion that evaluates the farmers' practices using the direct pumping system.

Therefore, the main objective of this study is to evaluate direct pumping systems in the El-Baslaqoun command area, as a case study to understand the farmers' practices in their farms. The set of performance indicators proposed by Molden & Gates (1990) (adequacy, efficiency, equity, and dependability) is used in this evaluation. Moreover, a MATLAB mathematical model is developed for further understanding the hydraulic behavior of the system to propose reasonable modifications to the system [8].

2. The study area

Abu-Gabal Tertiary Canal is located in the El-Baslaqoun command area, Kafr El-Dawar district, El-Beheira governorate, Egypt. **Figure 1** shows the El-Mahmoudia Main Canal, which is considered the major source of irrigation water for this area. El-Baslaqoun Canal is located at km 42.245 on the left of El-Mahmoudia Canal, as illustrated in **Figure 1**. El-Baslaqoun BranchCcanal head regulators are opened according to the rotation schedule. In the summer season, the two-turn rotation system consists of 4 days on / 6 days off. While in the winter, the three–turn rotation system consists of 5 days on/10 days off [9]. Branch Canal head regulators are generally equipped with control gates, and regulation of water deliveries is achieved by adjusting gates to maintain target downstream water levels.

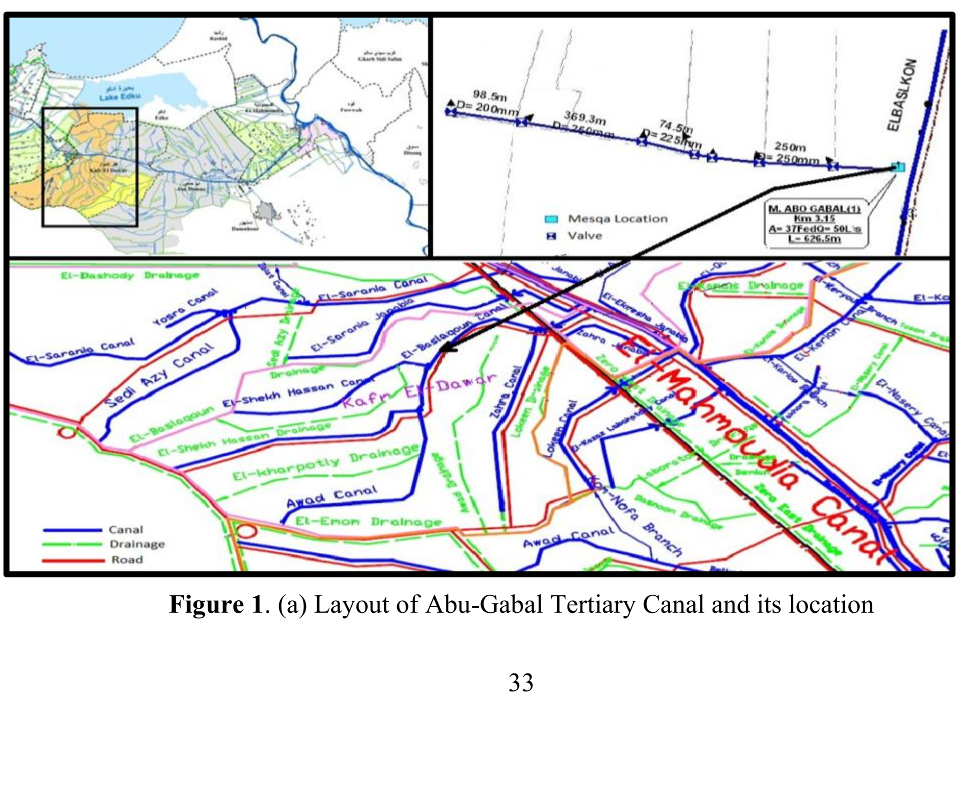

Figure 1. (a) Layout of Abu-Gabal Tertiary Canal and its location

In the El-Baslaqoun command area, the direct pumping system was applied at four Tertiary Canals (El-Basounye, Armsh, Abu-Gabal, and Frank), which receive water from the El-Baslaqoun Branch canal. **Figure 1** shows the Abu-Gabal tertiary canal, which is located on the right-hand side of the canal at km 3.15. The pump station consists of two small single-stage end-suction centrifugal pumps with the characteristics shown in **Table 1**. Pumps are connected directly to a PVC pipeline system with 200 mm and 250 mm in diameter. The pipeline has 7 outlets (butterfly valve) at intervals along its length, allowing water to be discharged into the open channel to serve a command area of 39 acres [10].

Table 1. Basic data of selected Tertiary Canals in the El-Baslaqoun command area, (WMRI, 2015)

Tertiary Canal	Pump (1)			Pump (2)			Area served (Acre)	Number of valves	Pipeline Diameter (mm)
	Q (l/s)	Power (hp)	Head (m)	Q (l/s)	Power (hp)	Head (m)			
El-Basyone	30	7.5	10.5	30	7.5	10.5	54	9	200 / 250
Frank	30	10	13	30	10	13	48	9	200 / 250
Armsh	20	5.5	10.5	20	5.5	10.5	34	4	200
Abu-Gabal	30	10.5	13	20	7.5	13	39	7	200 / 225

3. MATERIALS AND METHODS

3.1 Determination of performance indicators

Successful irrigation water delivery systems are important to achieve the objectives of delivering the accurate amount of water to farmers. Therefore, the four performance indices that were developed by Molden and Gate (1990) were used to assess the distribution system performance (Adequacy (PA), efficiency (PF), dependability (PD), and equity (PE), **Equations 1 to 4**. The values of these indicators are classified as "good", "fair", or "poor" according to performance standards. **Table 2** illustrates the performance standards of PA, PF, PE, and PD.

$$\mathrm{PA} = \frac{1}{\mathrm{T}} \sum_{\mathrm{i=1}}^{\mathrm{n}} a_i \frac{\mathrm{Q_{Di,t}}}{\mathrm{Q_{Ri,t}}} \quad (1)$$

$$\mathrm{PF} = \frac{1}{\mathrm{T}} \sum_{\mathrm{i=1}}^{\mathrm{n}} a_i \frac{\mathrm{Q_{Ri,t}}}{\mathrm{Q_{Di,t}}} \quad (2)$$

$$\mathrm{PE} = \frac{1}{\mathrm{T}} \sum_{\mathrm{t=1}}^{\mathrm{T}} \mathrm{CV_R} \left(\frac{\mathrm{Q_{Di,t}}}{\mathrm{Q_{Ri,t}}}\right) \quad (3)$$

$$PD = \frac{1}{R} \sum_{i=1}^{n} a_i . CV_T \left(\frac{Q_{Di,t}}{Q_{Ri,t}}\right) \quad (4)$$

where $Q_{Di,t}$ and $Q_{Ri,t}$ are the amount of water delivered and required in sub-region i with area a_i during a certain time (t). n is the number of sub-regions in the irrigation system, T is the time period, and R is the total irrigated area.

Table 2: Evaluation criteria for each indicator (Molden & Gates, 1990)

Performance Indicators	Good	Fair	Poor
PA	0.90 - 1.00	0.80 - 0.89	<0.8
PF	0.85 - 1.00	0.70 - 0.84	<0.7
PD	0.00 - 0.10	0.11 - 0.20	>0.2
PE	0.00 - 0.10	0.11 - 0.25	>0.25

3.2.Mathematical modeling

A mathematical model developed by MATLAB code is used to simulate the Abu-Gabal Tertiary Canal, as well as to further investigate the actual hydraulic behavior of the system. All elements of the irrigation network (Tertiary Canal) that are applied in this model are described in the form of nodes and reaches. Nodes contain the connection points between agricultural land and the Tertiary Canal, while reaches represent each pipeline connecting any two nodes. **Figure 2** shows a schematic sketch for the direct pumping system components, i.e., the sump, Pumps, delivery pipeline, and valves. The model is a successive iterative method to solve energy and conservation equations, **Equations 5 to 8**, to calculate the opened valves' discharge.

$$Qpipe_n = Qpipe_{n-1} - Q_{valve} \quad (5)$$

$$TEL = Z + \frac{Q_{valve}^2}{2g\,A^2} + h_v + \text{h} \quad (6)$$

$$TEL_{A1} = (H_P + WL) - (h_{suction} + k_{inlet} * \frac{v2}{2g}) \quad (7)$$

$$TEL_n = TEL_{n-1} - h_f \quad (8)$$

Head losses through reaches is the main friction losses through pipelines (h_f) **Equation 9**, which is calculated from Hazen-William equation:

$$Pipe\ friction\ (h_f) = 10.667 * L * \left(\frac{Q_{pipe}}{CHw}\right)^{1.852} * \left(\frac{1}{D}\right)^{4.872} \quad (9)$$

Losses at outlets are divided into two types **Equations 10, and 11**. The first type is the head losses at the outlet, which is calculated from the orifice **Equation 11**:

$$Outlet\ losses\ (h) = \frac{8\,Q_{valve}^2}{(\pi\ D_{riser}^2\ cd)^2\ g} \quad (10)$$

Second losses are Head losses due to the riser (hv) [11]:

$$Riser\ losses\ (h_v) = k_v * \frac{Q_{valve}^2}{2g\,A^2} \quad (11)$$

Where Z is the elevation of valves above a reference, TEL is the total energy level, Q_{valve} is the discharge at each valve (m^3/sec.) that it depends on the indicator vector (0, 1), i.e, (on, off), and Q_{pipe} is the discharge inside the main pipe. k_{inlet} is the minor losses coefficient, which expresses any obstacles in the suction side and can be used as a calibration factor, WL is the water level at the sump, and Pump head (H_P) can be calculated in the model through an equation that is obtained by fitting the equivalent pump curve of two pumps in parallel. h_f is the friction head losses, L is the reach pipe length, D is the diameter of the inside pipe, D_{riser} is the inner diameter of the riser (m), Cd is the discharge coefficient (Cd = 0.6), and CHW is the Hazen-Williams coefficient, which is taken to be 150 for PVC. K_v is the minor losses coefficient at outlets due to Tee 90 °, sharp edge, Bend 90 ° short radius, Butterfly valve, Bend 45 ° short radius, and Exit losses.

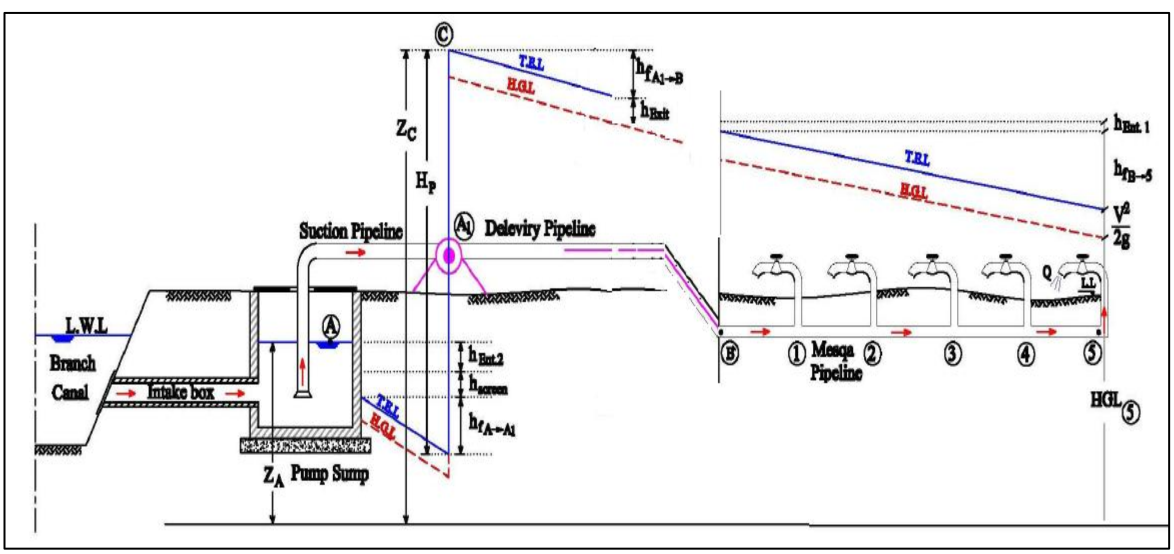

Figure 2: General sketch to illustrate the total energy line and the hydraulic grade line of the direct pumping system.

The model is calibrated by tuning the minor loss coefficient. **Figure 3** represents a comparison between measured and simulated results (riser flow rate and total head) for different operation cases for Abu-Gabal Tertiary Canal. The developed model is successfully calibrated using field data. Coefficient of determination between total head simulated and measured (R^2) in the first and second cases is equal to 0.83 and 0.95, respectively.

(a)

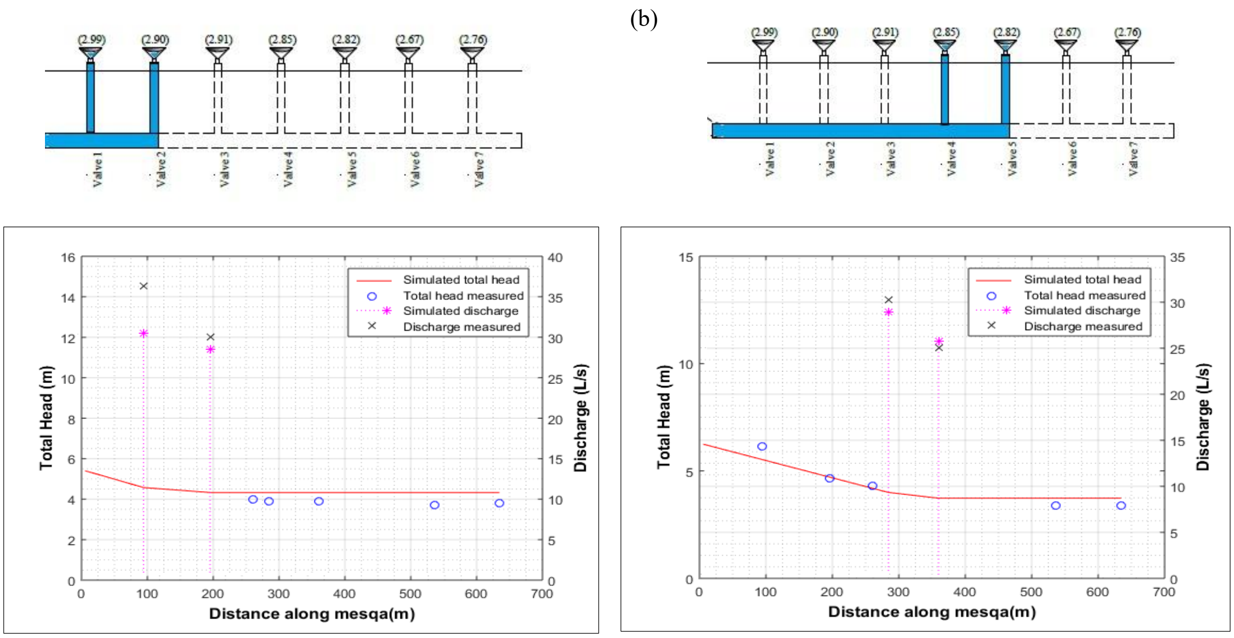

Figure 3: (a) model calibration Case 1 – (valves 1 & 2 opened) and (b) Case 2 – (valves 4 & 5 opened)

3.3.Questionnaires

Some questionnaires were collected to investigate the advantages and disadvantages of the new system as perceived by users, farmers, and operators. These questionnaires have also revealed the role of Water User Associations (WUAs) in monitoring the system. **Figure 4** illustrates the advantages and disadvantages of the direct pumping system according to the opinion of the operators and farmers, where:

- 100% of farmers noticed a reduction in irrigation cost (maintenance and operation) and a saving in agricultural land.
- 88% of farmers mentioned the reduction of irrigation time and cooperation between farmers.
- 75% of farmers noticed the availability of water at the end of the Tertiary Canal and a reduction of losses.
- 100% of farmers irrigate at night because of land preparation for planting rice and the high temperature, which negatively affects the pump. Also, the same percentage of farmers agreed to apply the direct pump system to save the time that was taken in a period of filling the tank.
- 88% of farmers noticed that the system suffered from problems in the electric parts of the direct pumping system. These problems negatively affected the hydraulic behavior of pumps when these problems were not fixed suitably, and that caused the accumulation of problems over time.
- 75% of farmers mentioned a recurring problem with cutting off the electricity. They were waiting for the additional diesel pumps from the improvement directorates because none of the Tertiary Canal users thought of collecting money and purchasing such pumps.
- 20% of farmers suffered from the leakage of valves.
- There were no experts to repair pumps and farmers had to repair their pumps manually which negatively affects the pump performance and the system gradually changed from a designed system to a random system, 100% of the farmers mentioned that.

4. RESULTS AND DISCUSSIONS

4.1. Evaluation of the water delivery of the system

According to performance standards, PA, PF, PE, and PD in Abu-Gabal Tertiary Canal are computed to be 0.97, 0.66, 0.31, and 0.4, respectively. All indicators show "poor" performance except PA, which shows "good" performance. It is indicated that the amount of water delivered by the Tertiary Canals was considered enough but above the required amount, which causes a drop in the value of PF. Moreover, it reveals the randomness and inequality of water distribution of the water supply between farmers. The fundamental objective of any irrigation system is to control water in such a way that it increases agricultural production. The previous results of water delivery performance for the direct pumping system reveal almost "poor" performance. In addition, the system suffered from problems according to questionnaires. Therefore, the mathematical model is applied to further investigate the problem and propose a proper solution to improve the Tertiary canal system performance.

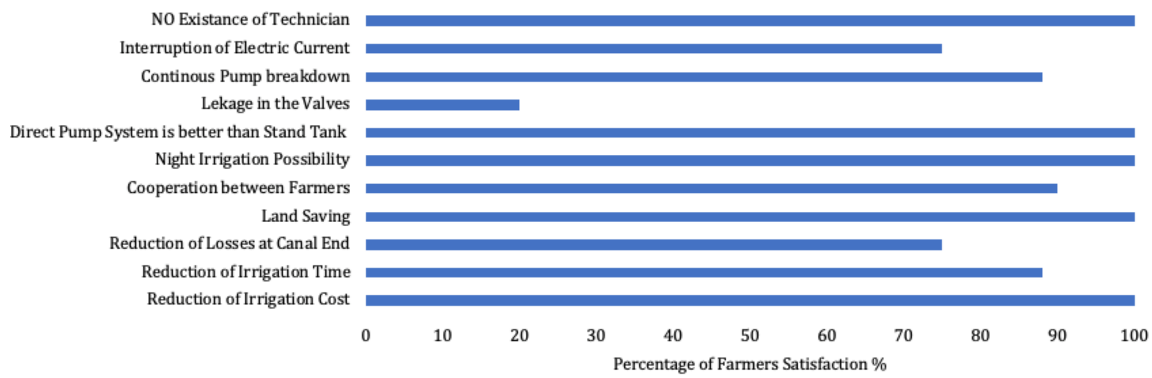

Figure 4: Survey results illustrate the percentage of farmers' satisfaction and the system challenges

4.2. Suggested scenarios for Abu-Gabal Tertiary Canal

Table 3 presents modifications that suggest a different rotational system between farmers and changing riser diameter for all valves to improve water delivery performance at Abu-Gabal tertiary canal as follows:

- The existing scenario presents the original case with a rotational system between valves (2, 2, 2, 1) for four stations of operation, and valve riser diameters are 6 inches.
- The first scenario changes the rotational system to open the first three valves at the same time instead of two valves for three stations of operation (3, 2, 2), and valve riser diameters are 6 inches.
- The second scenario modifies the riser diameter at all valves to be 5 inches.
- The third scenario modifies the riser diameter at all valves to be 4 inches.

The calibrated model is used to predict the resulting discharges at different open valves according to the rotational system. These results are listed in **Table 4,** while **Table 5** shows the resulting values of PA, PF, PE, and PD for different scenarios. It is remarked that performance indicator values are significantly improved while using the suggested scenarios. Using the second and third scenarios gives a fair share of water among farmers compared to the first scenario, where PE is 0.24, 0.19, and 0.18 in the first, second, and third scenarios, respectively. Regarding the efficiency and adequacy indicator, PF reached 0.85, 0.77, and 0.83 while PA changed to 0.91, 0.96, and 0.94 in the first, second, and third scenarios, respectively. Therefore, the modified system delivers the proper amount of water required for crops without excess flow, which promotes conditions of waterlogging and salinity that conserve water resources. A system that achieves almost steady conditions and uniformity of actual supply over crop water requirement is considered dependable. Therefore, variations in the capacity of these scenarios in this canal raised the value of PD and couldn't be improved, where PD is reported to be almost 0.37 in all scenarios. When the riser diameter is modified to be 5 or 4 inches for all valves, the system not only delivers the target amount of water required to crops without excess flow but also gives a fair share of water among farmers. Therefore, we can choose the third scenario to decrease the construction cost. But we should maintain the pumps and the valves regularly so as not to affect the operating system. Regarding the rotational system, the original case with a rotational system between valves (2, 2, 2, 1) for four stations of operation is the best to deliver a fair amount of water to all valves along the Teriary Canal. On the other hand, the rotational system can't be modified to be (3, 2, 2) for three stations of operation, as the flow in valves 2 and 3 is decreased compared with other valves. Consequently, a fair share of water among farmers couldn't be achieved.

Table 3. Suggested scenarios for Abu-Gabal Tertiary Canal

Suggested Scenario	Existing	First scenario	Second scenario	Third scenario
Rotational scheduling	(2,2,2,1)	(3,2,2)	(2,2,2,1)	(2,2,2,1)
Riser diameter for all valves	6 inches	6 inches	5 inches	4 inches

Table 4. Resulted in discharges L/s in each valve for Abu-Gabal Tertiary Canal

Valve	Existing Scenario	First Scenario	Second Scenario	Third Scenario
(1)	30.5	25.1	28.9	25.8
(2)	28.6	19.8	28	25.5
(3)	28.4	18.3	27.3	24.7
(4)	28.4	28.9	27.4	24.8
(5)	29.9	25.7	27.5	24.3
(6)	24.3	28.1	24.7	23.2
(7)	35.9	22.8	33.6	28.8

Table 5: Water delivery performance values of Abu-Gabal Tertiary Canal for the suggested scenarios

Performance Indicator	Existing Scenario (2,2,2,1) 6 inches	First Scenario (3,2,2) 6 inches	Second Scenario (2,2,2,1) 5 inches	Third Scenario (2,2,2,1) 4 inches
PA	0.97	0.91	0.96	0.94
PF	0.66	0.85	0.77	0.83
PE	0.40	0.24	0.19	0.18
PD	0.31	0.37	0.37	0.37

5. CONCLUSION

Water delivery by direct pumping system in Kafr El-Dawar area is assessed using performance indicators that were proposed by (Molden and Gate, 1990). PA, PF, PE, and PD in Abu-Gabal Tertiary Canal are computed to be 0.97, 0.66, 0.31, and 0.4, respectively. All indicators show "poor" performance except PA, which shows "good" performance. It is indicated that the amount of water delivered by the system to Tertiary Canals was considered enough but above the required amount, which causes a drop of value PF. Moreover, it reveals the randomness and inequality of water distribution of the water supply between farmers. Based on field surveys, 88% of farmers noticed that the system is suffering from electromechanical problems and lack of maintenance. These problems negatively affected the hydraulic behavior of the pumps when these problems were not fixed suitably. Moreover, a mathematical model is developed to simulate the direct pumping system and calibrated with field data. The comparison between predicted and measured results is satisfactory, and it is used to generate operation scenarios. To achieve high water delivery performance, valves' diameter should be mostly modified to be 4 inches for all valves. The expected theoretical water saving by applying this modification ranges from 8-20% per acre.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author(s).

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