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Research Article
Hydraulic Performance Analysis of Flexible Gated Pipe Irrigation Technique Using GPIMOD Model

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Abstract

Background and Objective: Gated pipe is a technique to develop and maximize the irrigation efficiency of surface irrigation. This study focused on hydraulic performance analysis of flexible gated pipe irrigation technique under operating pressure from 0.05-0.3 (bar) and using the GPIMOD model for predicting water distribution to evaluate the model's capability as a design tool to maximize irrigation efficiency. **Materials and Methods:** Two irrigation types were selected; the first was a traditional gated pipe, while the second was pressure compensating gated pipe. The field measurements were carried out at the private farm, Monufia Governorate, Egypt. **Results:** The results showed that a higher regulated observed and simulated discharge for pressure compensating gated pipe comparing with the traditional gated pipe under operating pressure 0.05-0.3 bar. This was due to the pressure compensating gated pipe was designed to adjust the pressure differences and improve discharge uniformity from each gate along the pipeline. The total outflow was increased by increasing pressure under traditional and pressure compensating gated pipe. Their slight variation between the total outflow for traditional and pressure compensating gated pipe. The total outflow under operating pressure from 0.05-0.3 bar were between 63.54-165.32 and 49.33-115.33 lit sec^{-1}, respectively. The outlet discharge and total outflow coefficient "Cd" indicated that a good relationship between the measured and the simulated discharge through the gates along the pipeline. The results obtained of a uniformity coefficient %, coefficient of variation and standard deviation summarized, an acceptable percentage for the pressure compensating gated pipe comprising with traditional gated pipe for testing gated pipe irrigation. The results of GPIMOD model confirmed, there was an agreement good data between simulated and measured data. **Conclusion:** GIPMOD proved its high sensitivity to predict gate discharge and total outflow along the pipeline of gated pipe under different operating pressure.

Key words: Gated pipe, pressure compensating, gate discharge, discharge coefficient, uniformity coefficient and GPIMOD model

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Flood irrigation is the oldest irrigation method in the world. Also, the surface irrigation efficiency, ranged between 60 and 70% Keller and Keller[1]. The main problem is the low application efficiency with the use of surface irrigation in the old land of Egypt[2]. However, gated pipes help to reduce water losses commonly associated with the use of the flood irrigation. Gated pipe irrigation is recognized as a more efficient system of surface irrigation[3]. The pressure compensating gated pipe irrigation, usually has an internal piece of flexible silicone rubber inside the gate that changes shape to maintain constant pressure along the pipe[3,4]. The study of hydraulic analysis of compensating gated outlet showed that the average discharge of 29 lit min^{-1} was obtained under pressure range of 5-9 k Pa with coefficients of variation of less[5] than 0.9%. El-Hagarey *et al*.[6] who, developed and evaluated auto-compensating gated nozzle (pop-pet nozzle) and reported that poppet nozzle compensates the pressure head difference along the gated pipe and produces stable and harmonized flow along the pipes. The gated pipe irrigation does not reach the optimal water distribution uniformity, because the farmer cannot adequately adjust this system. Uniform water flow along the pipeline is regulated by sliding gates adjusting the gated area opening manually to obtain the acceptable head and discharge along the flexible gated pipe[7]. The farmer, especially small farms holders, does not know the exact numbers of open gates along the pipeline to irrigate his farm efficiently as well as the optimal gate area to achieve the highest value of water distribution uniformity along the pipeline. The advantages of using models, the simulation testing is faster and cheaper than field trials. The second advantage of using models is a lot of the detail that you can get from a simulation. El-Shafie *et al*.[3] designed and evaluated the gated pipe irrigation simulation model GPIMOD and reported that (GPIMOD) is a good tool for predicting water distribution uniformity along the gated pipe.

Therefore, the main objectives of this study focused on hydraulic performance analysis of low cost, flexible traditional and pressure compensating gated pipe irrigation technique for predicting water distribution using GPIMOD model and to assess the model's ability as a design tool to maximize the irrigation efficiency.

MATERIALS AND METHODS

Experimental site: The field experiment was carried out during March and April, 2018 at private Farm, Monufia Governorate, Egypt. To study the hydraulic water distribution along the pipeline and performance analysis of low cost flexible gated pipe irrigation technique, field and modeling data, for maximizing the gated pipe irrigation efficiency in Egypt.

Irrigation description: A centrifugal pump (130 m^3 h^{-1} discharge, 1460 rpm, max. pressure 1.0 bar, Suction and Discharge Flanges DN 6/6 inch and with Diesel engine 5.9 kW), was located at the source of the water supply (open canal). Control valve, pressure gauges and P.V.C pipes main line were used to convey the water from the water source to the main control points in the field. Two gated pipes were selected, the first was modified gated pipe with pressure compensating and the second was a traditional gated pipe. The gated pipe irrigation pipeline was made of a flexible polyethylene pipe 160 mm diameter. Gate body was made of a P.V.C of 50 mm diameter, the distance between gates along pipeline was 70 cm.

Theoretical and structural equation modeling

Friction loss in the gated pipeline: Gated pipe was an example of divided manifold flow. The flow in the pipeline was spaciously varied and in this case reduces approximate uniformly to zero at the closed or downstream end of the line.

The total friction loss in a multi orifices pipeline was determined by:

$$h_{\text{fat pipeline}} = L_s \times F_N \times N \left[\frac{V}{0.849 \times CHW \times \left(\frac{D}{4}\right)^{0.63}} \right]^{1.852} \quad (1)$$

where, V is the velocity of flow in the pipeline (m sec^{-1}), C_{HW} is the Hazen-Williams coefficient, L_s is the outlet spacing (m), N is the number of outlets from the closed end, D is the pipe diameter (m), h_f is the friction losses (m) and F_N is the factor accounts for the effect on friction losses of the spatial variation of the flow[8]:

$$F_N = \frac{1}{1+m} + \frac{1}{2 \times N} + \frac{(m-1)^{0.5}}{6 \times N^2} \quad (2)$$

where, m is the exponent on the velocity term in the relevant flow equation, in this case m = 1.852 and N is the number of outlets from the closed end[6,9].

Gated pipe outlet: In referenced classic paper, McNown[10], reviewed the theory of manifold flow and the experimental work to that time. The following model is drawn largely from McNown's analysis. Clearly, mass continuity must apply at each outlet such that:

$$Q = Q_c + Q_0 \tag{3}$$

where, Q is the discharge in the pipe upstream of the outlet ($m^3\ sec^{-1}$), Q_c is the discharge continuing downstream in the pipeline ($m^3\ sec^{-1}$) and Q_o is discharge from the outlet ($m^3\ sec^{-1}$).

Head losses between gates: Head losses h between any two gates calculated by Smith and Gillies[7] in the following equation:

$$\frac{\Delta h_p}{h_v} = 1 - \left(\frac{v_c}{v}\right)^2 \tag{4}$$

where, h_p is the velocity head term (m), h_v is the pressure in the pipeline (m), V_c is the flow velocity downstream of the outlet ($m\ sec^{-1}$) and V is the flow velocity upstream of the outlet ($m\ sec^{-1}$).

Outlet discharge: The outlets or gates in gated pipe were essentially orifices and any expression characterizing their outflows would be expected to follow the standard orifice equation[9]:

$$Q_0 = C_d\ A_0 \sqrt{2\ g\ H} \tag{5}$$

where, Q_o is the outlet discharge ($m^3\ sec^{-1}$), Cd is a coefficient of discharge, A_o was the cross section area of gate (m^2), H is the pressure head (m) and g is the gravity acceleration ($m\ sec^{-1}$).

Outlet discharge and total outflow coefficient "Cd": Outlets discharge coefficient and the total outflow coefficient along the gated pipe was calculated by Khurmi[11], in the following equation:

$$C_d = \frac{\text{Actual discharge}}{\text{Theoretical discharge}} = \frac{\text{Discharge measure from outflow}}{\text{Simulated discharge}} \tag{6}$$

Field measurements: Study the flexible gated pipe irrigation technique distribution uniformity by using two types of gates, traditional manufactured gate and an Egyptian innovated pressure compensating gated pipe with a self-compensating gate outlet (SCGO) (designed by El-Shafie *et al.*[5] and Hussein *et al.*[12], developed the design), under operating pressure (0.05, 0.1, 0.15, 0.2, 0.25 and 0.3 bar) as the following:

- Discharge of flow rate through gates along the pipeline (lit sec^{-1})
- Total outflow through the gates (lit sec^{-1})
- Uniformity coefficient (%)
- Coefficient of variation
- Standard deviation

Validation of gated pipe irrigation model (GPIMOD): The validation was carried out by comparing simulated with the measured data of total outflow and discharge of flow rate through gates along the pipeline, for gated pipe irrigation (traditional gated pipe and pressure compensating). The performance and model evaluation made by statistical and graphical methods. The response of the model, particularly the trend over time, can therefore be visually quantified. The statistical approach involved the use of the goodness of fit tests proposed[13] to compare observed data with the model predictions. The goodness of fit expressions used is the coefficient of determination (R^2):

$$R^2 = \left\{ \frac{1}{N} \frac{\Sigma(y_o - \bar{y_o})(y_s - \bar{y_s})}{\sigma y_o - \sigma y_s} \right\} \tag{7}$$

Where:

y_o^- = Averaged observed value
y_s^- = Averaged simulated value
σy_o = Observed data standard deviation
σy_s = Simulated data standard deviation

All the analyses were made using Excel 2010 (Microsoft Inc.).

RESULTS AND DISCUSSION

Total outflow (lit sec^{-1}) through the gates validation: The measured and simulated total outflow (lit sec^{-1}) through the gates along the pipeline under the traditional and pressure compensating gated pipe at all operating pressure levels from 0.05-0.3 (bar) were shown in Fig. 1 and 2. There was a slight variation in the total outflow of measured and simulated data

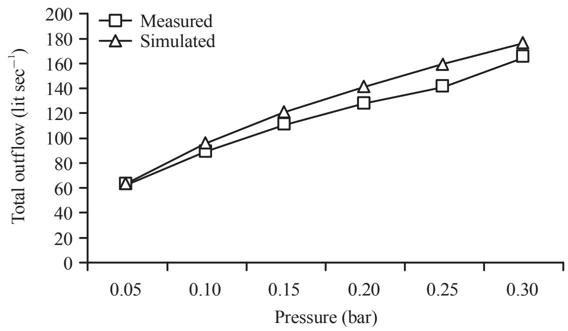

Fig. 1: Measured and simulated total outflow (lit sec^{-1}) through the gates for the traditional gated pipe under operating pressure (0.05-0.3 bar)

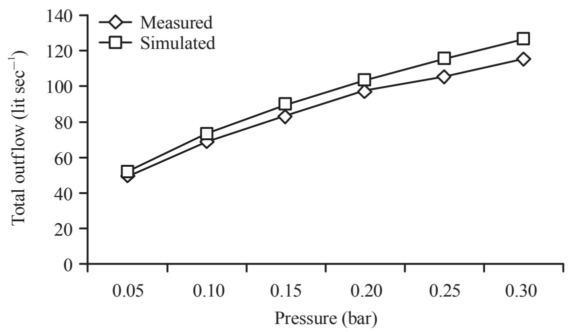

Fig. 2: Measured and simulated total outflow (lit sec^{-1}) through the gates for pressure compensating gated pipe under operating pressure (0.05-0.3 bar)

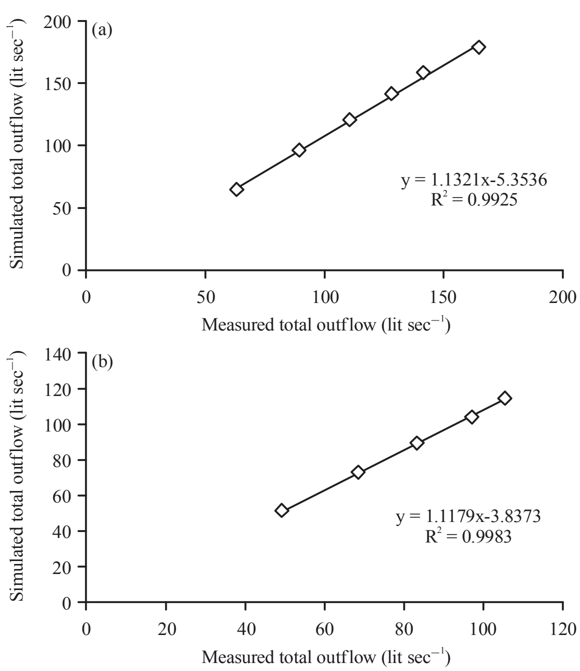

Fig. 3(a-b): Correlation between measured and simulated total outflow for traditional and pressure compensating gated pipe under operating pressure (0.05-0.3 bar)

under traditional and pressure compensating gated pipe. The total outflow was increased by increasing pressure under traditional and pressure compensating gated pipe. The total outflow of traditional was higher than the pressure compensating gated pipe at operating pressure from 0.05-0.3 (bar). As shown in Fig. 1, the measured and simulated total outflow for traditional gated pipe were kept between 63.54-165.32 and 64.09-176.31 lit sec^{-1}, respectively. As shown in Fig. 2, the measured and simulated total outflow for pressure compensating gated pipe were kept between 49.33-115.33 and 51.51-16.42 lit sec^{-1}, respectively.

On the contrary, El-Hagarey *et al.*[6] indicated that the flow rates were semi constant with higher operating pressure. There was a slight variation between the total outflow for traditional and pressure compensating gated pipe. The pressure compensating gated pipe needs an operating hours less than the traditional gated pipe due to application efficiency for the pressure compensating gated pipe is higher than the traditional gated pipe and received water for the pressure compensating gated pipe less than the traditional gated pipe El-Shafie *et al.*[3]. Therefore, the pressure compensating gated pipe was saving time and energy. The current results of the total outflow are in agreement with Ali and Mohammed[2], who indicated that, gated pipe irrigation achieved highest irrigation performance parameters compared to traditional systems.

As Fig. 3 showed the correlation between simulated and measured total outflow R^2 for the traditional and pressure compensating gated pipe. The results of GPIMOD model confirmed, there was an agreement good data between simulated and measured total outflow values after the validation process had been achieved for the traditional and pressure compensating gated pipe. The R^2 for the traditional gated pipe was 0.9925 and for the pressure compensating gated pipe was 0.9983.

The GPIMOD proved the high sensitivity predicting of gated discharge and total outflow along the pipeline of gated pipe under different of operating pressure.

Gate discharge along the pipeline (lit sec^{-1}): The water distribution with high uniformity under the pressure compensating gated pipe technique gave a better growth and good productivity compared with the traditional gated pipe[3]. The main goals of irrigation development are optimizing the water use in agriculture and increase the irrigation efficiency, especially surface irrigation system. To achieve these goals, ideal design must optimize and developer of surface irrigation.

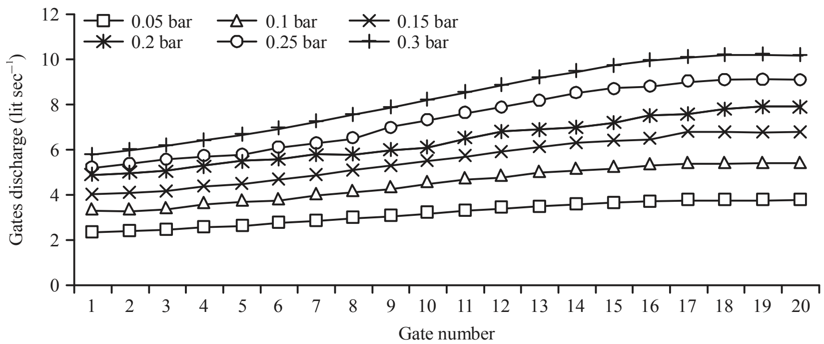

Fig. 4: Gate discharge along the pipeline (lit sec^{-1}) measured data for traditional gated pipe under operating pressure (0.05-0.3 bar)

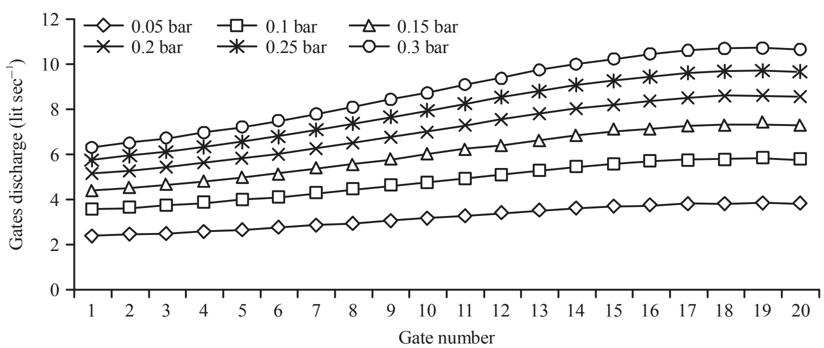

Fig. 5: Gate discharge along the pipeline (lit sec^{-1}) simulated data for traditional gated pipe under operating pressure (0.05-0.3 bar)

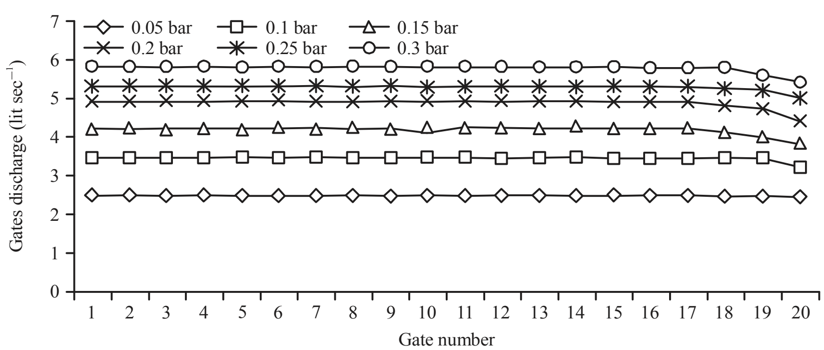

Fig. 6: Gate discharge along the pipeline (lit sec^{-1}) measured data for pressure compensating gated pipe under operating pressure (0.05-0.3 bar)

As Fig. 4-7 showed that the measured and simulated gate discharge data (from gate No. 1-20) along the pipeline (lit sec^{-1}) for traditional and pressure compensating gated pipe. There was a slight variation in the gate discharge along the pipeline of measured and simulated data under traditional and pressure compensating gated pipe. Figure 4 showed the measured discharge (from gate No. 1-20), it were between 2.35-3.75, 3.3-5.4, 4-6.8, 4.858-7.9, 5.2-9.1 and 5.8-10.16 lit sec^{-1} under operating pressure of 0.05-0.1-0.15-0.2-0.25-0.3 bar, respectively, for traditional gated pipe. The results previously mentioned are in harmony with those obtained by Ali and Mohammed [2], who found that the discharge along the pipeline were changed in the same trend with different pressure values. As shown in Fig. 4 and 5, the simulated data were similar to the measured data for traditional gated pipe under different operating pressure.

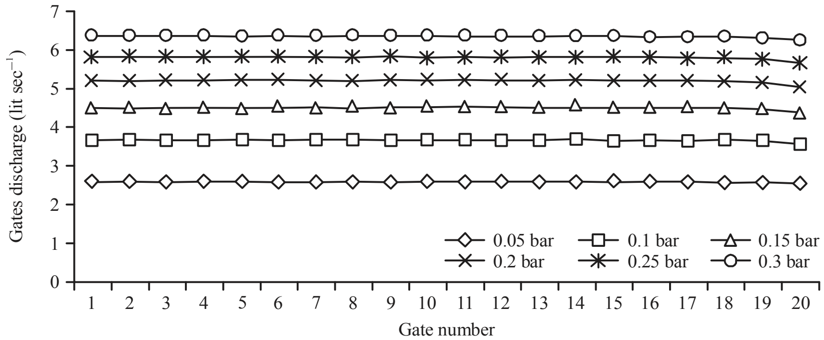

Fig. 7: Gate discharge along the pipeline (lit sec^{-1}) simulated data for pressure compensating gated pipe under operating pressure (0.05-0.3 bar)

Figure 5 showed the simulated discharge (from gate No. 1-20) for traditional gated pipe, it were between 2.4-3.85, 3.55-5.81, 4.41-7.33, 5.14-8.59, 5.77-9.7 and 6.34-10.71 lit sec^{-1} under operating pressure of 0.05-0.1-0.15-0.2-0.25-0.3 bar, respectively.

The data in Fig. 6 showed the measured discharge (from gate No. 1-20) for pressure compensating gated pipe, it were between 2.47-2.42, 3.45-3.2, 4.2-3.8, 4.9-4.4, 5.3-5 and 5.8-5.4 lit sec^{-1} under operating pressure of 0.05-0.1-0.15-0.2- 0.25-0.3 bar, respectively. Also, as shown in Fig. 6 and 7, the simulated data were still in the same trend with slight variation to the measured data for pressure compensating gated pipe.

As Fig. 7 showed the simulated discharge (from gate No. 1-20) for pressure compensating gated pipe, it were between 2.58-2.51, 3.65-3.56, 4.48-4.36, 5.17-5.03, 5.78-5.63 and 6.33-6.19 lit sec^{-1} under operating pressure of 0.05-0.1-0.15-0.2-0.25-0.3 bar, respectively. There is a higher regulated discharge under pressure compensating gated pipe comparing with the traditional gated pipe under operating pressure of 0.05-0.3 bar. This is due to the pressure compensating gated pipe was designed to compensate the pressure differences and improve uniformity of discharge from each gate along the pipeline. The pressure compensating gated pipe mechanism is changing the cross section of the area or the flow path structures (inlet orifice) caused by the change of the pressure on the internal orifice of the gate. When the pressure increased, the scale of the silicone rubber increased. Therefore, discharge rates continue to be consistent with this process.

Good correlation between the measured and simulated discharge along the pipeline values after the validation process has been achieved for the traditional and pressure compensating gated pipe as shown in Fig. 8 and 9, the R^2 for the traditional gated pipe was 0.9954, 0.9971, 0.9983, 0.9813, 0.9969 and 1, the R^2 for the pressure compensating gated pipes was 0.9941, 0.983, 0.9231, 0.9578, 0.9614 and 0.9575 under operating pressure 0.05-0.1-0.15-0.2-0.25-0.3 bar, respectively. There was an agreement data between simulated and measured values. The GPIMOD proved the high sensitivity predicting of gate discharge along the pipeline of gated pipe under different operating pressure.

Gate discharge coefficient and total outflow coefficient: The gate discharge coefficient (Cd_g) and total outflow coefficient (Cd_t) is the coefficient and the relationship between the actual (measured) and the theoretical (simulated) discharge. According to this value (Cd), if the value is approached to number one this is indicated that the goodness of fit between the measured and the simulated discharge. Figure 10 showed the total outflow coefficient (Cd_t) for traditional and pressure compensating gated pipe under operating pressure of 0.05-0.3 bar. The total outflow coefficient (Cd_t) was 0.99, 0.93, 0.91, 0.9, 0.88 and 0.93 for traditional gated pipe and the total outflow coefficient (Cd_t) was 0.95, 0.94, 0.93, 0.94, 0.91 and 0.91 for pressure compensating gated pipe under operating pressure 0.05-0.1-0.15-0.2-0.25-0.3 bar, respectively. The values indicated that a good relationship between the measured and the simulated discharge. As Fig. 11 and 12 showed that, the gate discharge coefficient (Cd_g) along the pipeline for traditional and pressure compensating gated pipe. The gate discharge coefficient (Cd_g) for the traditional gated pipe along the pipeline were between 0.97-0.99, 0.91-0.95, 0.9-0.93, 0.87-0.95, 0.88-0.94 and 0.91-0.95 under operating pressure 0.05-0.1-0.15-0.2-0.25-0.3 bar, respectively. The Cd_g for the pressure compensating gated pipe along the pipeline were between 0.957-0.964, 0.9-0.95, 0.87-0.94, 0.87-0.95, 0.89-0.92 and 0.87-0.92 under

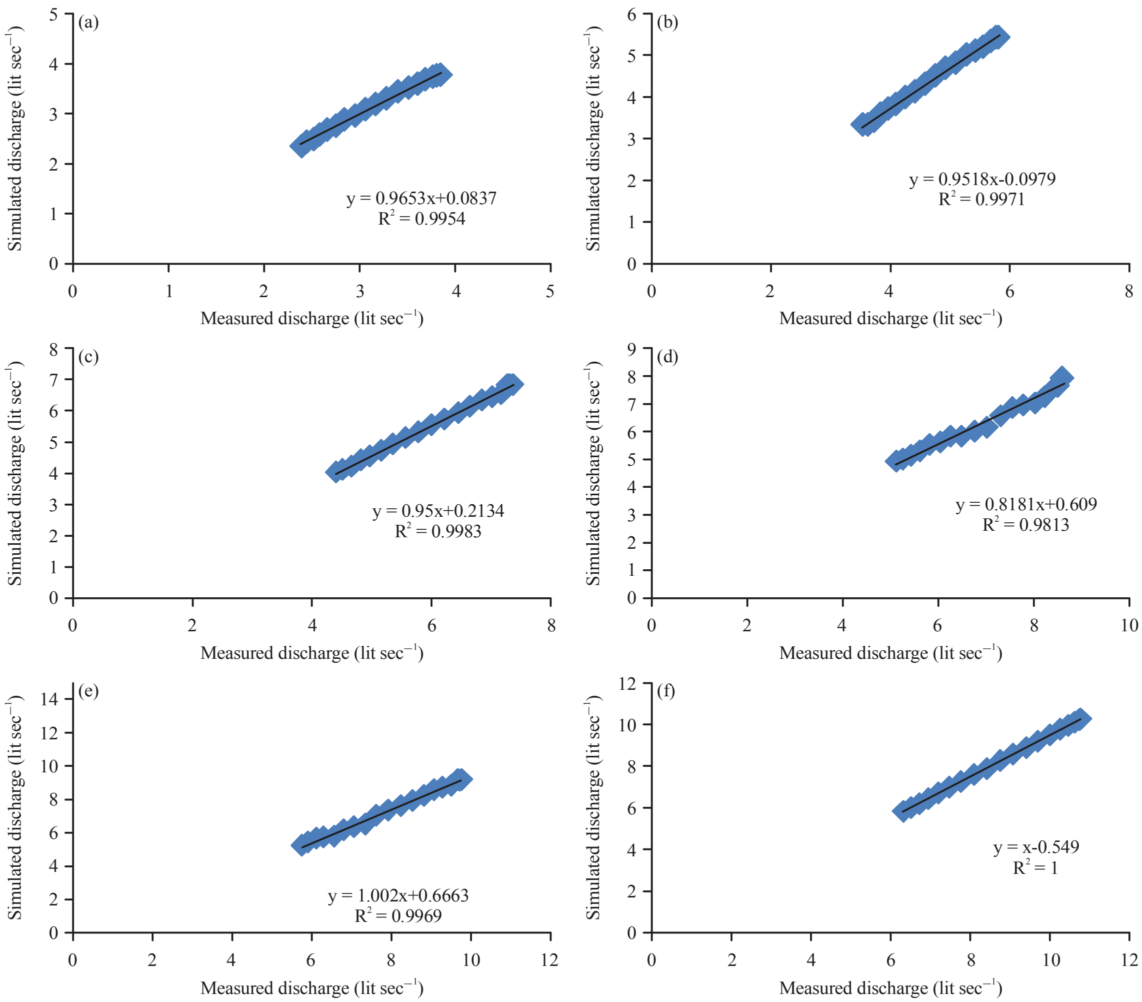

Fig. 8(a-f): Correlation between measured and simulated gate discharge for the traditional gated pipe at (a) 0.05 bar, (b) 0.1 bar, (c) 0.15 bar, (d) 0.2 bar, (e) 0.25 bar and (f) 0.3 bar under operating pressure

Table 1: Uniformity coefficient, coefficient of variation and standard deviation for traditional and pressure compensating gated pipe under operating pressure (0.05-0.3 bar)

	Pressure (bar)					
Gated pipe Irrigation	0.05	0.1	0.15	0.2	0.25	0.3
Uniformity coefficient (%)						
Traditional gated pipe	85.98	84.69	84.30	85.94	82.91	83.41
Pressure compensating gated pipe	99.76	99.28	98.55	98.60	99.23	99.08
Coefficient of variation						
Traditional gated pipe	0.167	0.180	0.185	0.161	0.199	0.197
Pressure compensating gated pipe	0.0046	0.0167	0.0249	0.0255	0.0137	0.0173
Standard deviation						
Traditional gated pipe	0.51	0.78	1.00	1.03	1.42	1.57
Pressure compensating gated pipe	0.011	0.056	0.100	0.119	0.071	0.097

operating pressure 0.05-0.1-0.15-0.2-0.25-0.3 bar, respectively. The results indicated that there was a good relationship between the measured and the simulated gate discharge along the pipeline. Those results are an agreement with El Awady *et al.*[14], who reported that, the discharge rate of gated pipe changed under experimental field due to fraction head losses.

Performance and hydraulic characteristics: The data in Table 1 summarized the hydraulic characteristic; uniformity

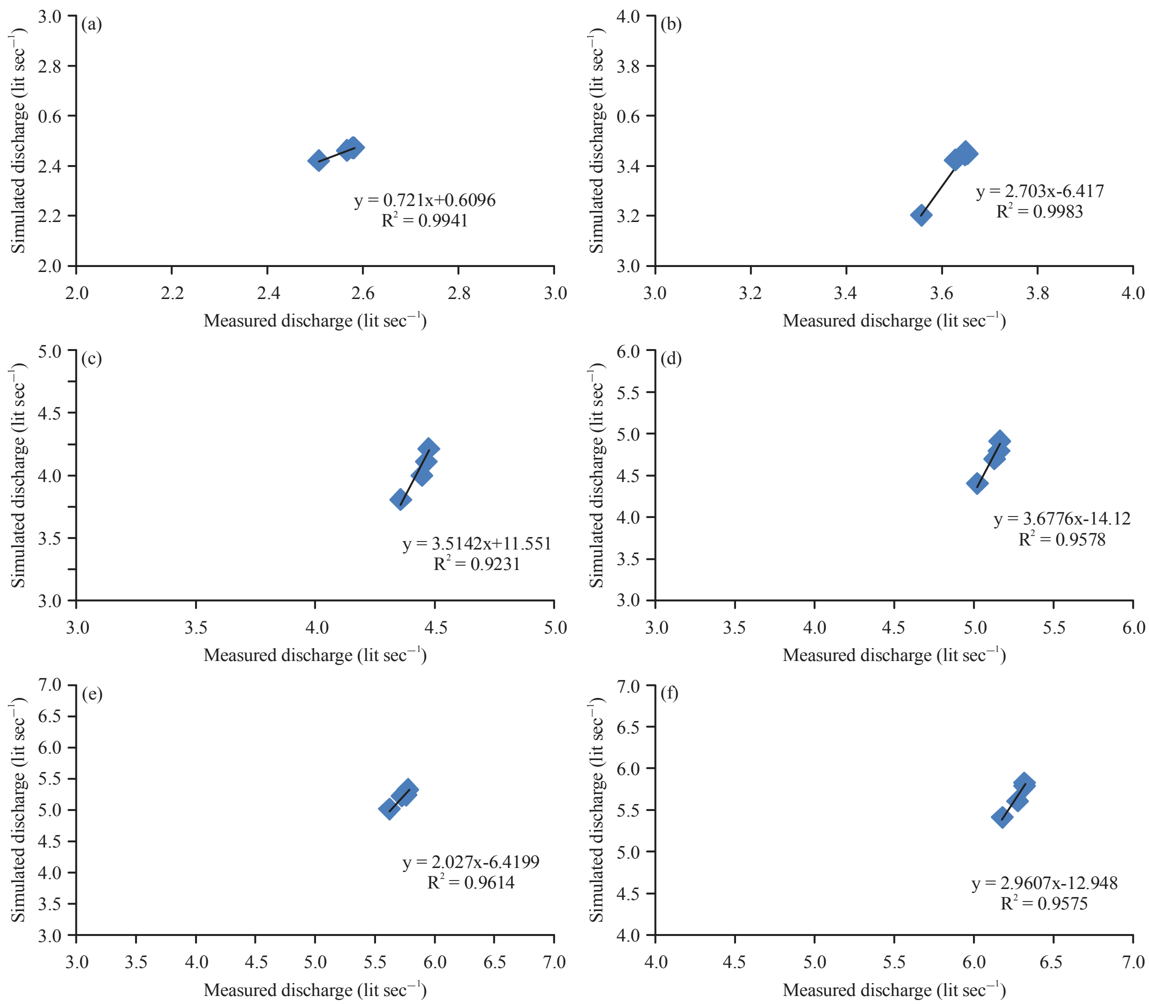

Fig. 9(a-f): Correlation between measured and simulated gate discharge for pressure compensating gated pipe at (a) 0.05 bar, (b) 0.1 bar, (c) 0.15 bar, (d) 0.2 bar, (e) 0.25 bar and (f) 0.3 bar under operating pressure

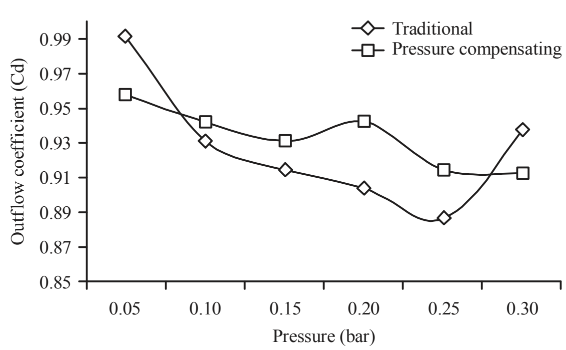

Fig. 10: Total outflow coefficient (Cd_t) for traditional and pressure compensating gated pipe under operating pressure (0.05-0.3 bar).

coefficient, coefficient of variation and standard deviation for traditional and pressure compensating gated pipe under operating pressure (0.05-0.3 bar). The data indicated that the uniformity coefficient % of pressure compensating gated pipe was higher than the traditional gated pipe, the data were between 82.91-85.98 and 98.55-99.76% for traditional and pressure compensating gated pipe under operating pressure from 0.05-0.3 (bar), respectively. According to Keller and Bliesner[15], the hydraulic design of lateral lines (manifold flow) was usually based on a design using an emitter flow variation (outlet). Therefore, the hydraulic characteristic of manufacture coefficient of variation were around 0.1610-0.1990 and 0.0046-0.0255 for traditional and pressure compensating gate, respectively under operating pressure 0.05-0.3 bar. Also, the standard deviation were between 0.51-1.57 and 0.011-0.119 for traditional and pressure compensating gate, respectively under operating pressure 0.05-0.3 bar. According to the classification of Keller and Bliesner[15], the coefficient of variation is within "Excellent" category, due to the fit design of pressure compensating gated pipe. The data

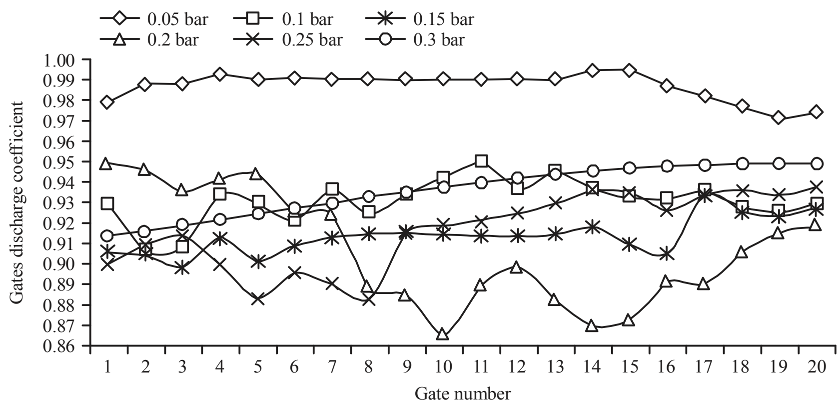

Fig. 11: Gate discharge coefficient (Cd_g) for traditional gated pipe at operating pressure (0.05-0.3 bar)

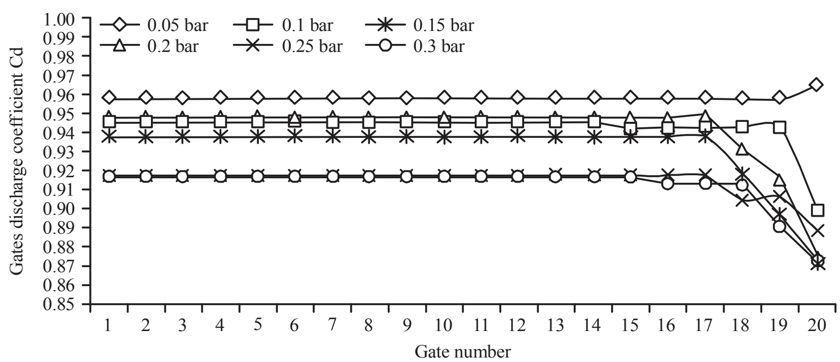

Fig. 12: Gate discharge coefficient (Cd_g) for pressure compensating gated pipe under operating pressure (0.05-0.3 bar)

indicated that, the coefficient of variation and standard deviation for pressure compensating gated pipe had an acceptable percentage comparing with traditional gated pipe.

CONCLUSION

The results indicated that, a slight variation between the total outflow for traditional and pressure compensating gated pipe. There is a higher regulated discharge under pressure compensating gated pipe compared with the traditional gated pipe under operating pressure (from 0.05-0.3 bar). The uniformity coefficient %, coefficient of variation and standard deviation data indicated that, an acceptable percentage of pressure compensating gated pipe when comparing with traditional gated pipe for testing the hydraulic analysis of gated pipe irrigation. The GPIMOD model was capable to predict the data with good accuracy. The GPIMOD proved the high sensitivity predicting of gate discharge and total outflow along the pipeline of gated pipe under different operating pressure. Also, as well as predicting results data without need to extra trials study.

SIGNIFICANCE STATEMENT

This study showed that, using the GPIMOD model can be useful for predicting the hydraulic performance of gate pipe irrigation. This study will help researchers and agronomists to identify critical areas and evaluate the gated pipe irrigation that many researchers face in conducting evaluation experiments. Thus, a new model can be reached to predict the gate discharge and total outflow along the pipeline of gated pipe irrigation technique under different operating pressure in Egypt may be arrived at.

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