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Application of gated conduits for fertigation in irrigation systems

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ABSTRACT

Fertigation involves dissolving fertilizer in irrigation water, and requires uniform water distribution and fertilization. A gated conduit can be used to inject liquid fertilizers or chemicals into a pressurized irrigation system. When the conduit gate is partially opened, a vacuum draws the fluid from the suction pipe into the conduit. An experimental study was conducted to investigate the fluid-injection ratio of gated conduits, which was shown to be high. The density and viscosity of the fluid were the most important parameters affecting the fluid-injection ratio. That ratio increased with increasing Froude number. It decreased as the gate opening proportion increased and with increasing conduit length. A design formula related to the Froude number, and the fluid's density and viscosity is presented to enable estimation of the fluid-injection ratio.

Key words: fertigation, gated conduit, injection, irrigation

HIGHLIGHTS

- A study was conducted to investigate the fluid-injection ratio of gated conduits.
- It was observed from the results that gated conduits had a high fluid-injection ratio.
- The specific weight and viscosity were the most important parameters affecting the fluid-injection ratio.
- A design formula was presented for estimating the fluid-injection ratio.
- The obtained data provide a good basis for the development of numerical models.

NOTATION

A_w	water flow cross-sectional area
B	water surface width
D	conduit diameter
Fr	Froude number based on effective depth in conduit
g	gravitational acceleration
h	gate opening
y_e	effective depth
L	conduit length
Q_F	fluid flow rate in suction pipe
Q_F/Q_W	fluid-injection ratio (ratio of fluid flow rate to that of water)
Q_W	water flow rate in conduit
V_W	water flow velocity at gate location
μ	dynamic viscosity
γ	density
φ	ratio of water cross-sectional flow area to conduit cross-sectional area

1. INTRODUCTION

Gated conduits ensure that water is transferred downstream from the reservoir, to facilitate lowering of the reservoir level and/or to ensure maintenance of the biological minimum flow required downstream. For small dams and reservoirs, gated conduits often also serve as water intakes for some users, mostly for irrigation (Tanchev 2014).

Gated conduits are hydraulic structures that involve high-velocity air-water flow. If the conduit gate is opened partially, flow velocity increases due to the reduced cross-section. High-velocity flow can cause structural damage, e.g., by cavitation. To reduce or eliminate this damage, a suction pipe is installed after the gate, where flow velocity is high, so that air is drawn into the conduit and the pressure downstream of the gate is maintained at a safe level.

Numerous studies have been reported concerning air-injection ratios in gated conduits, e.g., Aydin *et al.* (2021), Baylar *et al.* (2021, 2022); Hohermuth (2019), Hohermuth *et al.* (2020), Pengchengi *et al.* (2022). The study results, between them, show that the air-injection ratio is a function of geometry and hydraulics.

Fluid injection created in gated conduits can be used for many purposes such as solving environmental problems such as lack of dissolved oxygen (Baylar *et al.* 2010). They can also be used to inject liquid fertilizers or chemicals into pressurized irrigation systems, as investigated in this study.

2. FLUID INJECTION MECHANISM IN A GATED CONDUIT

When a conduit cross-section is partially closed by a gate, high-velocity and low-pressure flow occurs downstream of the gate, and pressure below atmospheric can occur within the conduit. Theoretically, these pressures could be as low as the vapor pressure of water. When an atmospheric connection is made by installing a suction pipe after the gate, fluid suction occurs in the suction pipe (Figure 1). The extent of fluid suction inside varies according to the flow's entraining and carrying capacity. The pressure reduction downstream of the gate is a function of the Froude number (Fr), gate opening proportion and conduit length, and the fluid's density and viscosity.

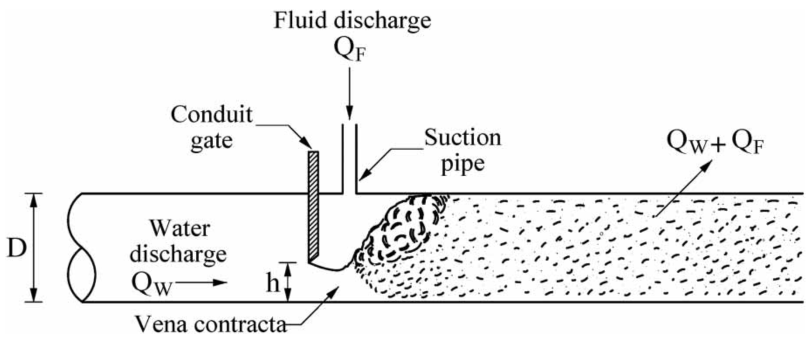

Figure 1 | Fluid injection via a gated conduit.

3. METHODOLOGY

The aim of the study was to understand the role of the gated conduit in the fluid-injection ratio. The experimental setup was built at Firat University Hydraulic Laboratory, Elazig, Turkey, and the components used are shown in Figure 2.

The gated conduit's fluid-injection ratio was investigated using fluids with different densities and viscosities – see Table 1. The oil used in the tests was used engine oil.

Gate opening proportions (φ) of 15, 30 and 60% of the conduit's cross-section were used (Figure 3) and water was passed at different flow rates (Q_W) under the gate. An electromagnetic flow meter was used to measure the flow rate. The conduit diameter (D) was 68 mm, and three conduit lengths (L) were used: 2, 4, and 6 m.

The values of Fr were between 2.4 and 48.4. In the literature, Fr is often considered in the vena contracta section. Because gated conduits involve high-velocity, two-phase flow, and to avoid the problem of determining flow depths and velocities in the vena contracta section, Fr in this study was based on the conduit's effective depth (Figure 4) and was calculated using Equation (1).

$$\mathrm{Fr} = \frac{V_w}{\sqrt{g\, y_e}} \tag{1}$$

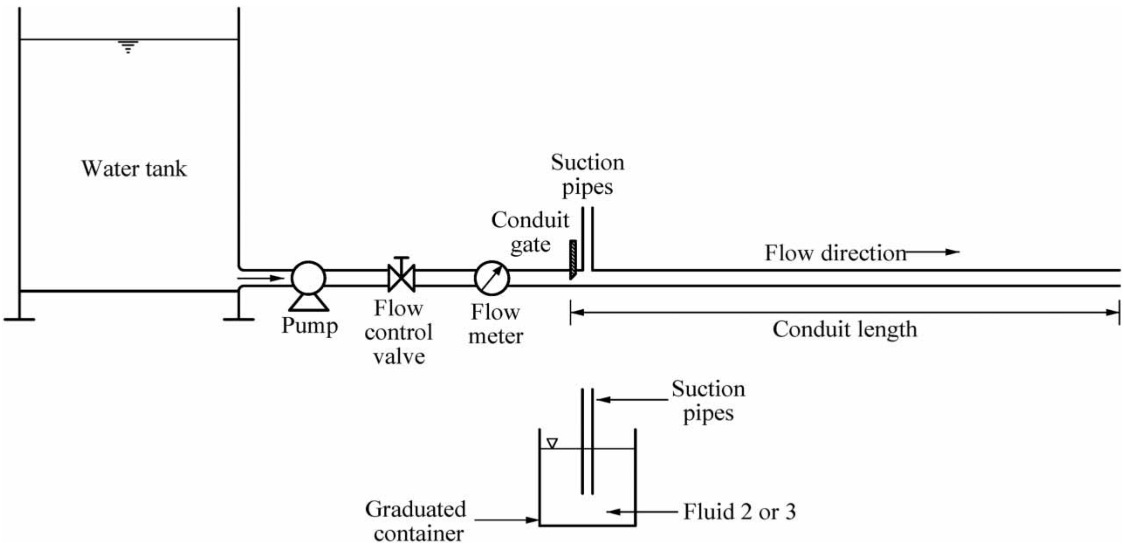

Figure 2 | Experimental apparatus.

Table 1 | Fluids injected into gated conduit

Fluid	Density γ (kg/m^3)	Dynamic viscosity μ (kg.s/m^2)
1 (air)	1.225	1.85×10^{-5}
2 (oil)	920	8×10^{-3}
3 (water)	1,000	1×10^{-3}

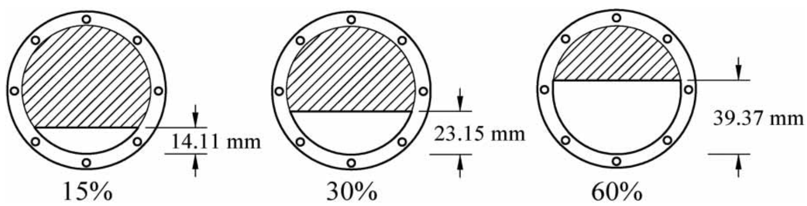

Figure 3 | Gate opening proportions.

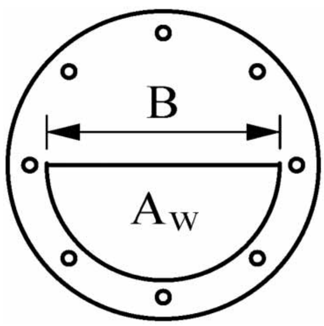

Figure 4 | Water flow cross-sectional area and water surface width.

where V_W is water velocity (m/s), g gravitational acceleration (m/s^2), and y_e the effective depth (m).

$$y_e = A_w/B \tag{2}$$

where A_w is the water flow cross-sectional area (m^2), and B the water surface width (m).

Table 2 | List of experiments

φ (%)	L (m)	Q_W (l/s)	V_W (m/s)	$A_W \times 10^{-4}$ (m^2)	$B \times 10^{-2}$ (m)	Fr (-)
(a) Air						
15	2	1	1.835	5.45	5.515	5.893
15	2	2	3.670	5.45	5.515	11.786
15	2	3	5.505	5.45	5.515	17.679
15	2	4	7.339	5.45	5.515	23.572
15	2	5	9.174	5.45	5.515	29.465
15	2	6	11.009	5.45	5.515	35.359
15	2	7	12.844	5.45	5.515	41.252
15	2	8	14.679	5.45	5.515	47.145
(b) Oil						
15	2	1	1.835	5.45	5.515	5.893
15	2	2	3.670	5.45	5.515	11.786
15	2	3	5.505	5.45	5.515	17.679
15	2	4	7.339	5.45	5.515	23.572
15	2	5	9.174	5.45	5.515	29.465
15	2	6	11.009	5.45	5.515	35.359
15	2	7	12.844	5.45	5.515	41.252
15	2	8	14.679	5.45	5.515	47.145
(c) Water						
15	2, 4, 6	1	1.835	5.45	5.515	5.893
15	2, 4, 6	2	3.670	5.45	5.515	11.786
15	2, 4, 6	3	5.505	5.45	5.515	17.679
15	2, 4, 6	4	7.339	5.45	5.515	23.572
15	2, 4, 6	5	9.174	5.45	5.515	29.465
15	2, 4, 6	6	11.009	5.45	5.515	35.359
15	2, 4, 6	7	12.844	5.45	5.515	41.252
15	2, 4, 6	8	14.679	5.45	5.515	47.145
30	2, 4, 6	1.5	1.375	10.91	6.445	3.374
30	2, 4, 6	3	2.750	10.91	6.445	6.748
30	2, 4, 6	4.5	4.125	10.91	6.445	10.122
30	2, 4, 6	6	5.500	10.91	6.445	13.496
30	2, 4, 6	7.5	6.874	10.91	6.445	16.869
30	2, 4, 6	9	8.249	10.91	6.445	20.243
30	2, 4, 6	10.5	9.624	10.91	6.445	23.617
30	2, 4, 6	12	10.999	10.91	6.445	26.991
30	2, 4, 6	15	12.374	10.91	6.445	30.365
60	2, 4, 6	3	1.377	21.79	6.757	2.448
60	2, 4, 6	6	2.754	21.79	6.757	4.896
60	2, 4, 6	9	4.130	21.79	6.757	7.343
60	2, 4, 6	12	5.507	21.79	6.757	9.791
60	2, 4, 6	15	6.884	21.79	6.757	12.239
60	2, 4, 6	18	8.261	21.79	6.757	14.687
60	2, 4, 6	21	9.637	21.79	6.757	17.135
60	2, 4, 6	25	10.785	21.79	6.757	19.175

The first injection fluid studied was air, the velocity of which was measured in suction pipes at four locations downstream of the gate with an anemometer (Testo Model 435). The anemometer was placed in the middle of the suction pipe and each measurement lasted for at least 60 seconds. The accuracy of the anemometer used is ± 0.2 m/s $+1.5\%$ of mv. Precautions were taken to ensure that the anemometer was always perpendicular to the direction of airflow. The fluid-injection ratios for oil and water were measured by delivering them into the system from a graduated container. Thus, after water passed through the conduit, the ends of the suction pipes were immersed in the graduated container for a measured time – about 20 seconds – and the volume change in the graduated container measured, so that the flow rate could be determined. The list of experiments is given in Table 2.

4. RESULTS AND DISCUSSION

The variation of the fluid-injection ratio (Q_F/Q_W) with Fr for φ and L is shown in Figures 5 and 6. As can be seen, Q_F/Q_W increased as Fr increased in all experiments. In other words, there is a direct relationship between Fr and Q_F/Q_W.

Q_F/Q_W decreased with increasing φ because the pressure difference between the upstream and downstream sides of the gate decreases as the gate's open proportion increases. Q_F/Q_W also decreased with increasing L, because the pressure difference between the upstream and downstream sides of the gate also decreases as L increases.

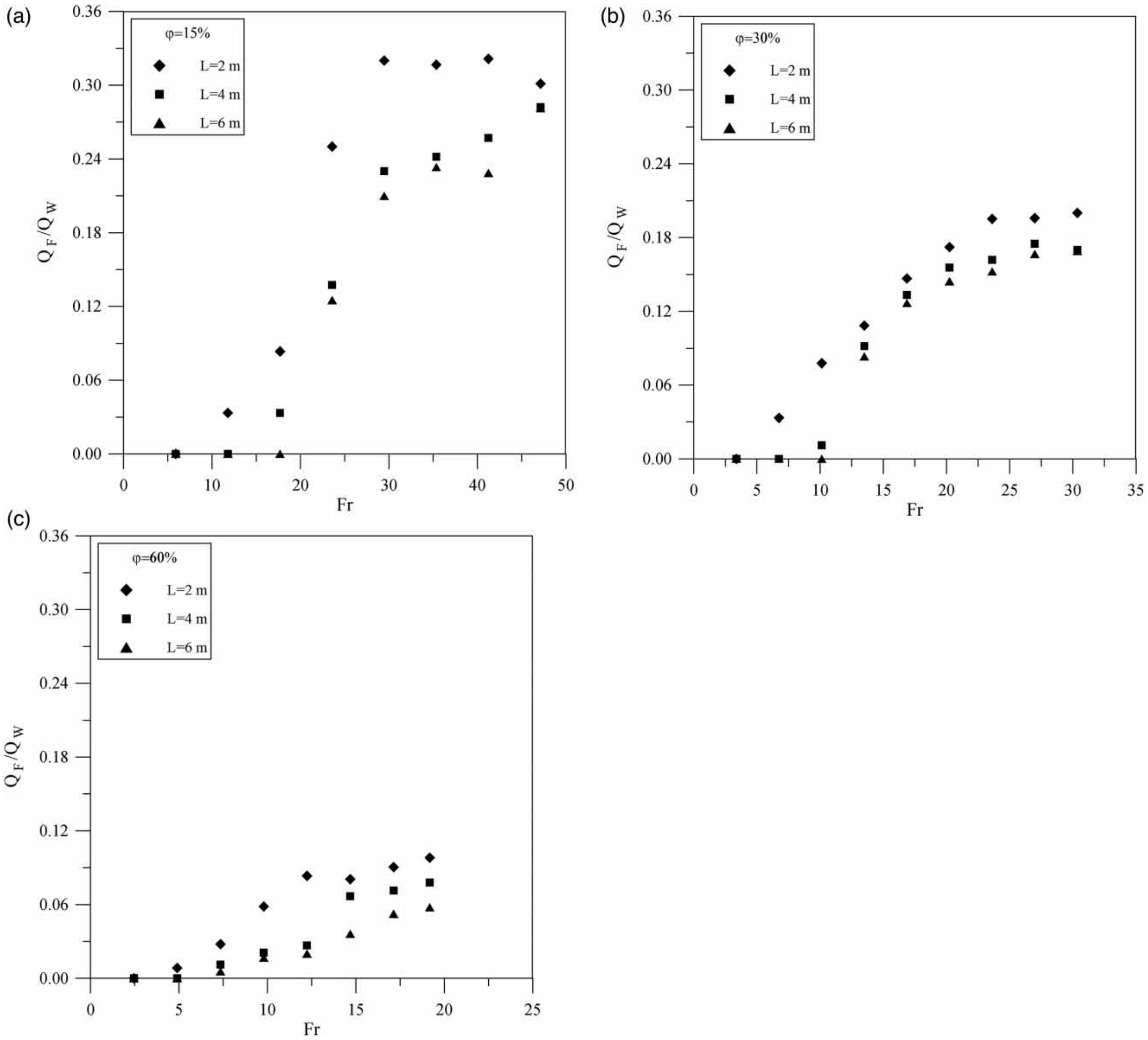

Figure 5 | Q_F/Q_W vs Fr for water, for $\varphi =$ (a) 15%, (b) 30%, (c) 60%.

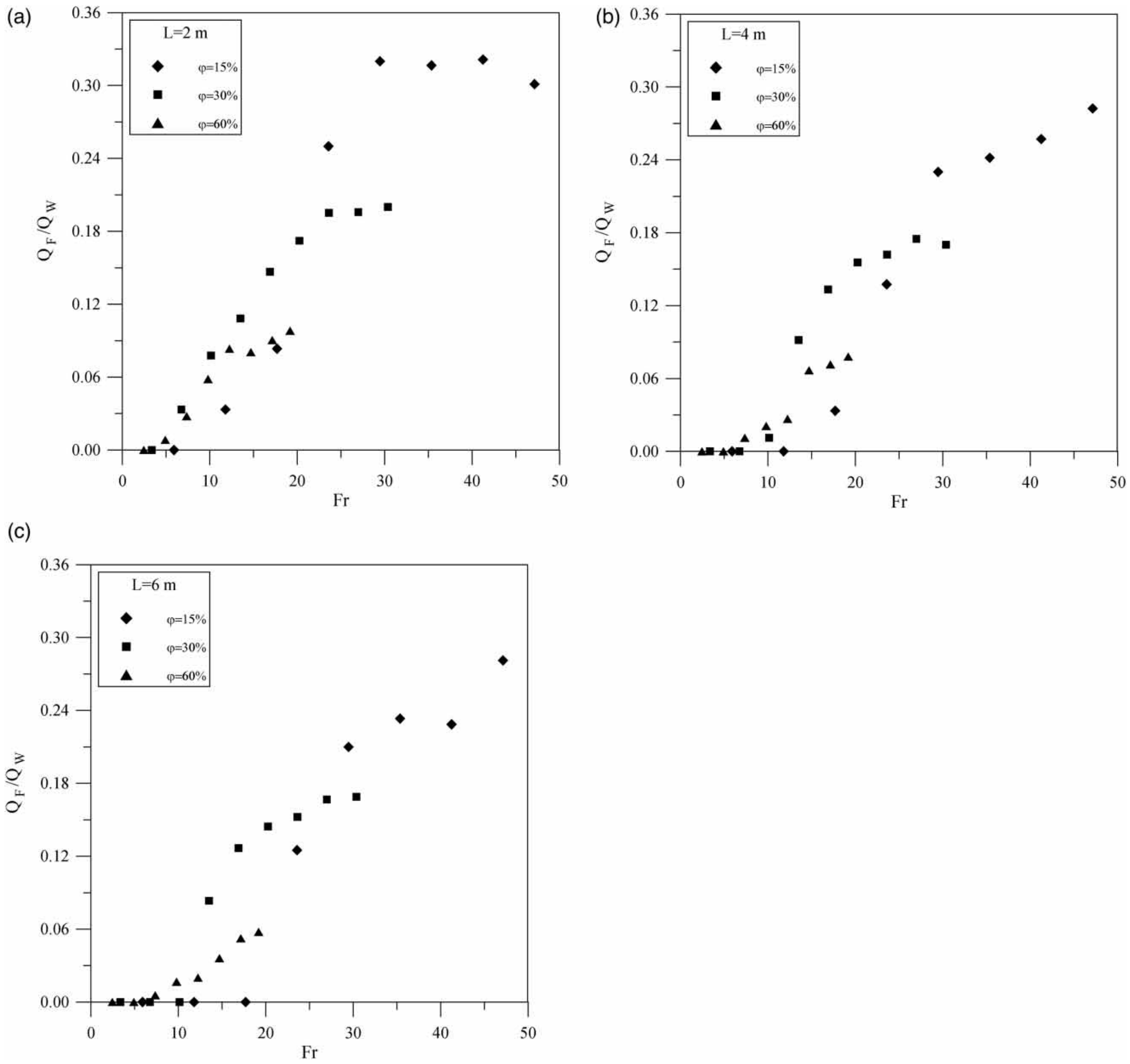

Figure 6 | Q_F/Q_W vs Fr for water, for L [m] = (a) 2, (b) 4, (c) 6.

Figures 5 and 6 show that the best Q_F/Q_W value was achieved in the gated conduit with φ = 15% and L = 2 m. The Q_F/Q_W values of all three fluids were, therefore, compared for φ = 15% and L = 2 m. Figure 7 shows plots of Q_F/Q_W vs Fr for all three fluids. As can be seen, Q_F/Q_W increases with increasing Fr in every case.

Fluid density (γ) is also an important parameter affecting Q_F/Q_W. It was observed that more air was injected than either water or oil. However, water's Q_F/Q_W exceeded that of oil, even though its density was higher, because its viscosity (μ) is lower.

Fluid viscosity is also an important influence on Q_F/Q_W, which increases with decreasing fluid viscosity, making it easier to inject the fluid into the system.

Many equations have been developed to determine Q_F/Q_W in gated conduits, but for a single type of fluid (usually air). In this study, an equation based on Fr, and fluid γ and μ was developed for prediction (Equation (3)). Nonlinear regression was used to determine the equation constants and the correlation coefficient (R^2) for the 91 data points used was 0.94. Comparison of the observed values of Q_F/Q_W with those predicted by Equation (3) showed good agreement. The quality of the correlation can be seen in Figure 8.

$$\frac{Q_F}{Q_W} = 3.5 \times 10^{-5}\, Fr^{1.154}\, \gamma^{0.072}\, \mu^{-0.604} \tag{3}$$

where *Fr* is the Froude number, γ the fluid density (kg/m^3), and μ its dynamic viscosity (kg.s/m^2).

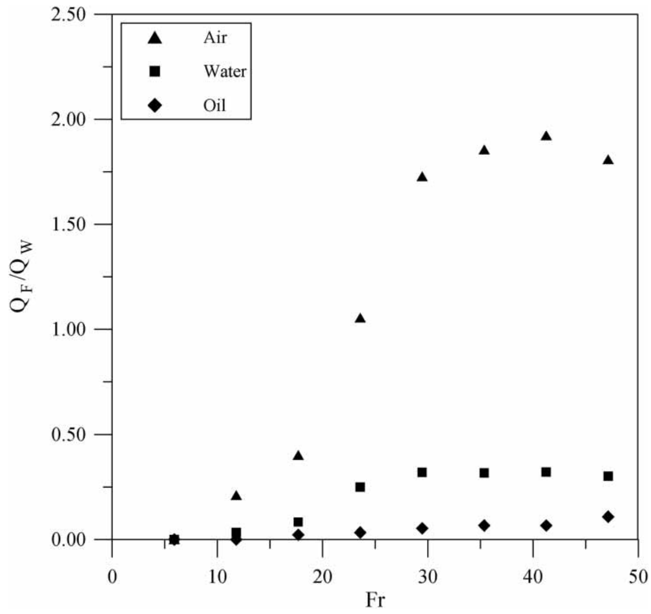

Figure 7 | Q_F/Q_W vs Fr for air, water and oil.

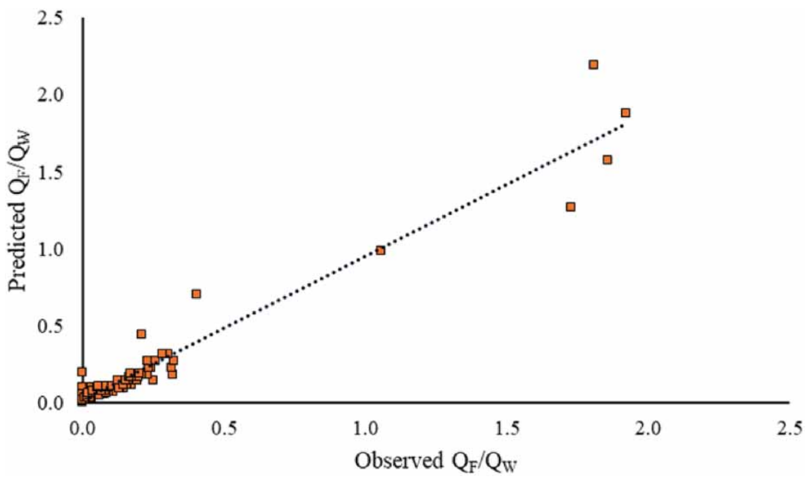

Figure 8 | Comparison of observed and predicted values of Q_F/Q_W.

5. CONCLUSIONS

In this study, the fluid-injection ratio of gated conduits was examined. When a gate is partially opened, the water flow velocity under it increases due to the reduced cross-section. As the flow velocity increases, the pressure downstream of the gate decreases, because of which fluid can be drawn into the conduit via a suction pipe opened downstream of the gate. Numerous field measurements and model studies were carried out to determine the air-injection ratio in the gated conduits, but extensive literature searches have not shown any published analytical or physical studies of the fluid-injection ratio in gated conduits. Laboratory experiments were done, therefore, to determine the fluid-injection ratio of gated conduits, from which it was concluded that:

- Gated conduits have a high fluid-injection ratio.
- The fluid-injection ratio increases as the Froude number increases as well as when the gate opening proportion decreases, but decreases with increasing conduit length.
- Fluid density affects the fluid-injection ratio, as does fluid viscosity – the fluid-injection ratio increasing with decreasing fluid viscosity.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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