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Investigating the Hydraulic Properties and Design Criteria for the River Subsurface Intake with a porous media without cut off

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ABSTRACT

Surface and subsurface water collection in small seasonal rivers is very crucial, particularly in dry seasons. In this study a type of intake is introduced which acts as a river drainage network. An experimental model of the subsurface intake was constructed and the effective parameters such as upstream discharge, installation depth, and drain intervals were evaluated. The results showed that the water diversion was mostly influenced by the upstream flow rate. The very small drain interval reduced the discharge of each drain. It was also revealed that the total drained discharge in the very transmitting media was mostly controlled with the number of drains and drain interval did have a marginal effect, the total discharge of drains in length of 100 cm has increased 63% in comparison to the total discharge of drains in length of 50 cm, whereas this increase was about 90% in length of 150 cm comparing to the length of 50 cm. Finally the regression equations were developed to estimate the discharge of each drain based on dimensional analysis, which facilitate the design of this structure.

Keywords

Subsurface intake, Porous media, Drainage system, Design criteria

1. Introduction

Rivers are considered as sources of water and energy for the nature and human beings. The provision of water has been the most important economical role of the rivers and the suitable design of a river intake is one of the oldest issues in hydraulic engineering. However, due to complexity of river flows, designing an intake in a natural river has remained as an important issue of the river engineering.

Water diversion method selection depends on flow conditions, topology and morphology of river and economical considerations. The numerous types of intakes from rivers can be divided into lateral intakes, frontal intakes and bottom intakes (Raudkivi, 1993). In bottom intakes that are used mostly in mountainous rivers the flow is diverted through a conduit installed underneath the river bed. Some parts or all of the length and width of the conduit in river bed are made as openings and water is delivered into the conduit through these openings.

Garot (1939) conducted experiments on the bottom intake with longitudinal bars as the

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horizontal grid. Other researches such as De Marchi (1947), Bouvard (1953), Kuntzmann and Bouvard (1954), Noseda (1956 a, b), Mostkow (1957), Brunella (2003), Righetti and Lanzoni (2008) and Maghrebi and Razaz (2009) investigated different aspects of the bottom intakes with the reticular bottom. Problems such as clogging, corrosion, freezing, storage and sediment discharge to the system limit the applicability of this type of intake (Castillo and Lima, 2010).

These disadvantages lead to the proposition of replacing meshed conduit with a porous media. Naqhavi et al. (2010) studied the properties of bottom intake with the porous material experimentally.

Sedimentation in porous media has been investigated in few studies (Sowers (1970), Sakthivadivel and Enistein (1970), Field et al. (1982), Cunningham et al. (1987), Schalchli (1992, 1995), Blazejeski and Sadzide (1997), Wu and Huang (2000), Tan et al. (2003), Mucha et al. (2006)). The efficiency of the porous bottom intake is also reduced by sedimentation and reduction of the media transmissivity (Koorosh Vahid et al., 2010). Furthermore, subsurface flow that is crucial in seasonal rivers of the arid and semiarid regions cannot be extracted using above surface intakes.

To diminish these problems a method (based on infiltration gallery idea) for diversion of surface and subsurface flows in the seasonal rivers has been implemented. In this type of intake a subsurface drainage system is buried in very a porous media buried in river bed. Although the bed type subsurface flow drainage is an old idea, hydraulic properties of this type of intake have been rarely investigated.

In this study effective parameters on subsurface intake efficiency are experimentally investigated. Moreover, based on the hydraulic parameters and dimensionless groups obtained by dimensional analysis, some regression equations between effective parameters and diversion discharge of each drain are developed that facilitate the design procedure of the intake structure.

2. Materials and Methods

2.1. Experimental Setup

A model representing a half of a longitudinal axisymmetric subsurface river intake was constructed as a rectangular box (1 m width × 2 m long × 1m height). To control the water level along the model, two reservoirs were considered on both sides of the model. Water was entered to the porous media through two perforated plates on both sides of the model (Fig.1). The 11-mm internal diameter perforated drain pipes were installed along the width of the model on two levels.

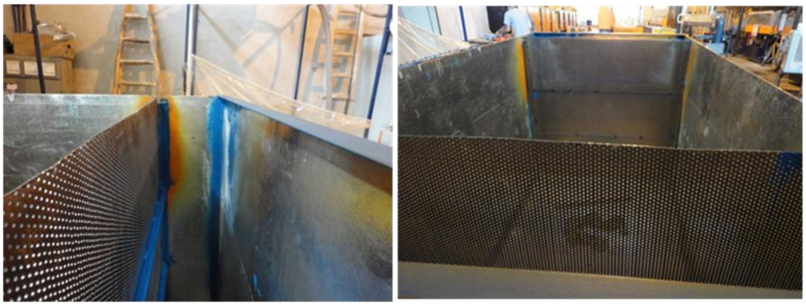

Fig.1. A view of the rectangular cube and installation of the perforated plates

15 and 14 lateral pipes were installed on 50 and 30 cm heights from the model bed with a crinkle shape. The original distance between the lateral drains was 10 cm. Longitudinal slopes of the model and lateral drains were considered as 1%. Based on FAO standards, the whole opening area of the pipe was 4% of the pipe surface. To prevent entrance of the fine particles into the drains they were folded by a layer of glass fiber.

A set of manometers were installed on the bottom of the box to check water level in the porous media. The space between two perforated plates was filled with graded sand (d_{50}=1.5 mm) up to the height of 80 cm from the cube bed (Fig. 2). The hydraulic conductivity of the porous media was measured via leading different discharges under different hydraulic gradients as 60 m/day. Water circulation was conducted using a pump and a water collection tank. The distance between laterals was changed by clogging the valves of the drain pipes.

More than 276 sets of experiments were designed to investigate the effect of different parameters such as installation depth (D = 30 and 50 cm), distance between lateral drains (10, 20, 30, 40, 50, 60, 150 cm), porous media length (50,100,150 cm), arrangement of drains (mono level and bi-level drains). The upstream discharge was considered in four rates (i.e., 0.4, 0.8, 1.2 and 1.6 L/s) that was measured by regulator valve. The constant inlet flow was associated with elimination of cut-off wall. For each set of experiments, the drain discharge was measured three times and the average values were stored. The manometers' water level was also measured for each test.

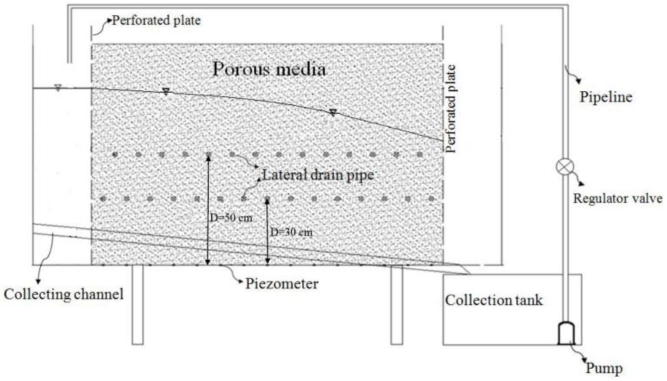

Fig. 2. Schematic view of the model constructed in the laboratory in constant level conditions

2.2. Dimensional Analysis

Dimensional analysis in this research could be accomplished based on known water head in the stream or known upstream subsurface flow rate. These two parameters are associated with the existence and elimination of the cutoff wall. In the former condition it is assumed that water is flowed through the stream with a constant upstream discharge. In this study the variables are divided into three groups namely; flow variables, drainage system properties, and porous media parameters.

In the case of elimination of the cut-off wall, all probable effective variables can be shown as the following equation.

$$f(\rho,g,\mu,q,n,d_{50},k,L,w,D,Q,x,d_p,\\ S_0,S_l,A_d,n_f,form)=0 \tag{1}$$

Where ρ is water density, g is gravity acceleration, μ is water viscosity, q is drain flow rate, Q is upstream discharge, n is media porosity, d_{50} is the diameter from which 50% of the material are smaller, k is hydraulic conductivity, L is length of porous media, w is lateral distance between drains, D is installation depth, x is distance from the media upstream, d_p is drain diameter, S_0 is the river bed slope, S_l is drain lateral slope, A_d is perforated drain opening area, n_f is envelop resistance factor, and *form* is installation form parameter.

Having selected an identical envelop and drain pipe diameter for all experiments, constant river bed and drain slopes the parameters can be categorized through the following dimensionless equation:

$$\phi\left(\frac{qw^2}{k^3},\frac{\mu}{\rho kw},\frac{Qw^2}{k^3},\frac{gw}{k^2},\frac{D}{w},\frac{L}{w},\frac{x}{w}\right)=0 \qquad (2)$$

Where, gw/k^2 and $\mu/\rho kw$ are representatives of Froude and Reynolds numbers, respectively. Notice that the hydraulic conductivity is related to d_{50} and n. Thus, k is used as the porous media parameter and the other two parameters are omitted and the effective parameters are reduced to the following form (Eq. (3)).

$$\phi\left(\frac{qw^2}{k^3},\mathrm{Re},\frac{Qw^2}{k^3},Fr,\frac{D}{w},\frac{L}{w},\frac{x}{w}\right)=0 \qquad (3)$$

3. Results and Discussion

3.1. Effect of drain distance and upstream discharge

As the first step, diverted water from the drainage system was measured under different upstream discharges and drain intervals. It was observed that the drains flow rate changed along the model. The water head measured with the piezometers also varied along the model even where the uniform surface water depth existed. The flow rate from the central drains (drain No. 7 and No. 8 for two installation depths of D= 30 and D= 50 cm, respectively) was evaluated in different upstream discharges and drain intervals that are depicted in Fig. 4. It was observed that increasing the drain intervals increased the drain flow rate. The greater drain interval in a constant model length led to a less number of drains and consequently, an increased upstream discharge which entered the greater flow rate. Note that the flow patterns were identical for different upstream discharges and no significant difference between 60 cm and 150 cm drain intervals was observed in all upstream discharges. Direct effect of upstream discharge on the drain discharge can be obviously observed in the following figure.

The upstream discharge relation for the central drain (Fig. 4) followed a logarithmic

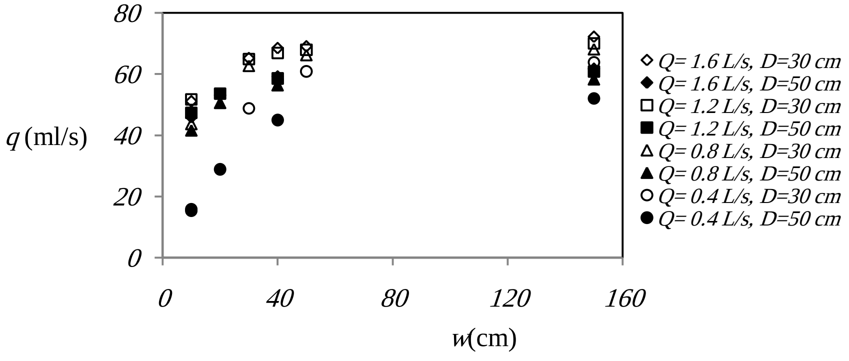

Fig. 3. The central drain discharge for different drain intervals and upstream discharges

function and the flow rate reached a constant value depending on the hydraulic conductivity of the media and the drain conducting capacity. The great difference between 10 cm interval and other intervals can be related to the side effect of the radial flow of the very close drains.

To clarify the effect of the distance between the drains, the total drains' discharge (q_{total}) was measured under different upstream discharges and drain intervals. Hence, drainage discharges were added together so the total discharge was achieved for the model length (150 cm). Figure 5 shows the results of this study.

According figure 5, trend of variations is the same for each upstream discharge. By increasing the distance between the drains and increasing the number of active drains, total output flow was reduced.

As a comparison, diverted flow for the upstream discharge is shown in Fig. 6 as the percentages of the flow diversion reduction for each interval and are compared with the highest flow diversion (the distance between the drains is 10 cm). Due to the increase in the distance between the drains, the reduction percent of flow diversion has an upward trend, but this trend is reduced by increasing the distance between the drains.

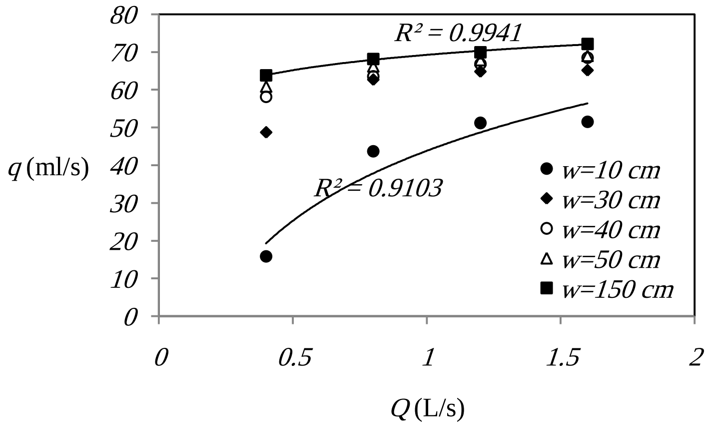

Fig. 4. The head-discharge relation for the central drain in different drain intervals for D=50 cm

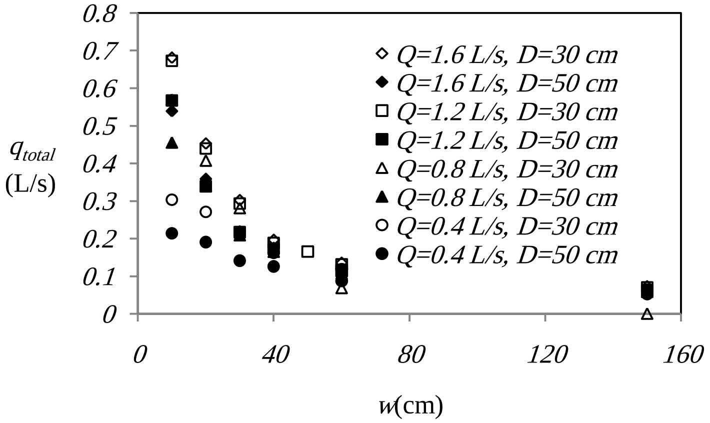

Fig. 5. The total drains' discharge (q_{total}) for different drain intervals and upstream discharges

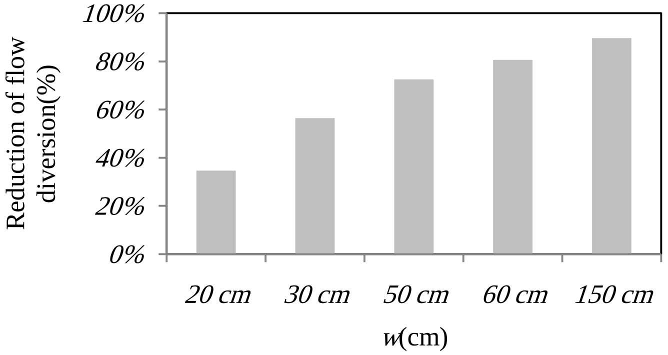

Fig. 6. The reduction ratio of diverted flow for different drain intervals

3.2. Effect of distance from upstream

The flow rates of each drain along the model for different upstream discharges and installation depths are presented in Fig. 7. The drain flow rate will be always reduced with different slopes in length of the model.

Variations of the drain flow rate in different intervals for Q=1.2 L/s and D= 30 are shown in Fig. 8. As the interval increases, the q variation along the model is decreased. It means that the flow rate of each drain is less influenced by the neighbor drains when the intervals are increased. Furthermore, there is a decreased parabolic trend of drainages' discharge along the porous media length.

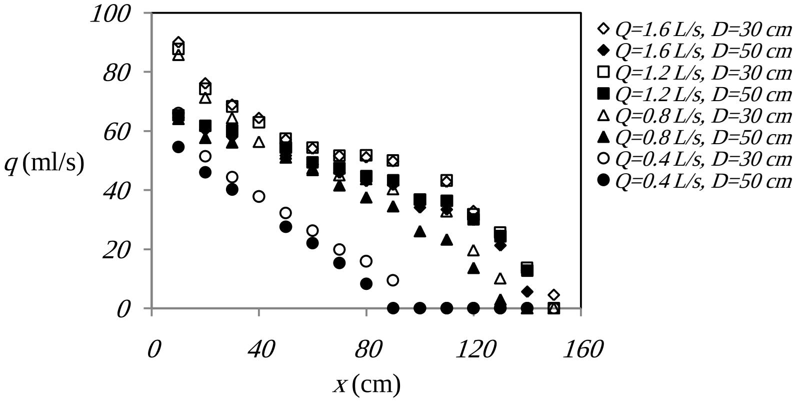

Fig.7. Drain discharge changes along the model for different water heads and installation depths

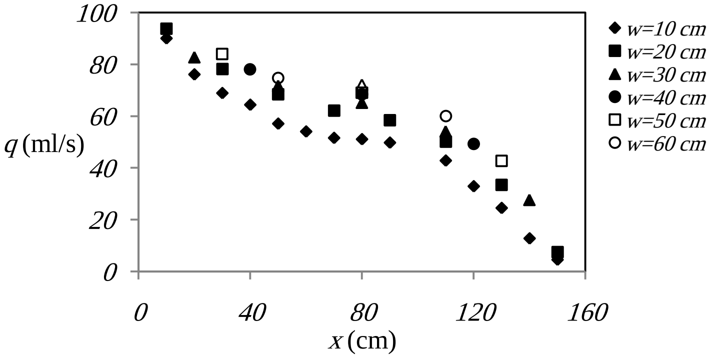

Fig.8. Drain discharge variations along the model length for Q= 1.2 L/s and D= 30 cm for different drain intervals.

3.3. Effect of porous media length

In this review, three porous media lengths (50, 100, and 150 cm) were examined. Results showed that the total drains' discharge increased when the length of the porous media is increased. But these two increases do not have a same trend.

The total drains' discharge in length of 100 cm increased 63% in comparison to the total drains' discharge in length of 50 cm, whereas this increase was about 90% in length of 150 cm than in the length of 50 cm.

3.3. Relationships between the effective parameters

Based on dimensional analysis and Buckingham theory, two effective dimensionless variables were selected and related to each other as follows:

$$qk^3\rho D/Q\mu gx=\emptyset(x/L) \qquad (4)$$

In this equation a dimensionless parameter including drain discharge, hydraulic conductivity and upstream discharge is related to the distance ratio. To obtain ∅ function in Eq. (4), a curve was fitted to the dimensionless variables (Fig. 9) based on the least square analysis.

For the curve fitting 70% of the experimental data were randomly selected and the last 30% were adopted for evaluation of the obtained equations. The statistical measures of the fitted model are tabulated in table 1. Figure 10 shows the curves fitted to the experimental data in different upstream discharge.

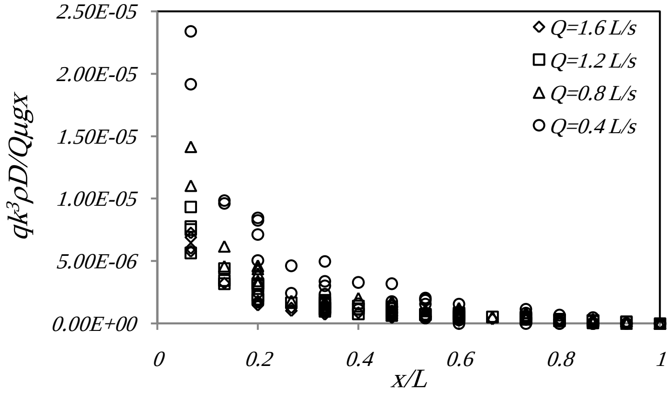

Fig. 9. Variations of dimensionless drain discharge in different distance ratios

Table 1. Model Obtained from the fitting over 70% of the Experimental data

Model	Upstream Discharge (Q)	Std. Error	Residual Sum	Residual Avg.	RSS	R^2	Ra^2	Variables	Value
$Y=a+b/x+c/x^2$	1.6 L/s	2.39×10^{-7}	-9.37×10^{-21}	-1.91×10^{-22}	2.62×10^{-12}	0.982	0.981	*a*	-2.61×10^{-7}
								b	4.15×10^{-7}
								c	2.42×10^{-9}
	1.2 L/s	4.77×10^{-7}	-3.59×10^{-19}	-7.19×10^{-21}	1.07×10^{-11}	0.948	0.946	*a*	-4.15×10^{-7}
								b	6.24×10^{-7}
								c	-6.21×10^{-9}
	0.8 L/s	5.50×10^{-7}	0	0	1.30×10^{-11}	0.962	0.960	*a*	-6.90×10^{-7}
								b	8.73×10^{-7}
								c	4.26×10^{-10}
	0.4 L/s	9.61×10^{-7}	-1.36×10^{-20}	-2.82×10^{-22}	4.16×10^{-11}	0.960	0.958	*a*	-1.88×10^{-6}
								b	1.71×10^{-6}
								c	-1.12×10^{-8}

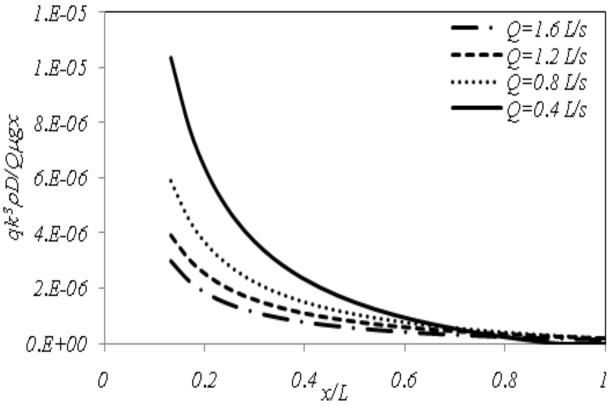

Fig. 10. Curves fitted to 70% of the observed value in different upstream discharges

To evaluate the goodness of the fitted curve, the equation was used to estimate the drain discharge of the 30% of the experimental data (Fig. 11). It was revealed that the maximum discrepancy was less than 37%. This error occurred for the minimum upstream discharge (*Q*=0.4 L/s).

Finally, the achieved model can be expressed as Eq. (5). The equation constants (a, b and c) are shown in Table 1 for the different water heads.

$$\frac{\rho qk3D}{\mu gQx} = a + \frac{b}{x/L} + \frac{c}{\left(x/L\right)^2} \qquad (5)$$

Estimated discharges using Eq. (5) have been compared with 30% of the observed values and a good agreement was observed (Table 2).

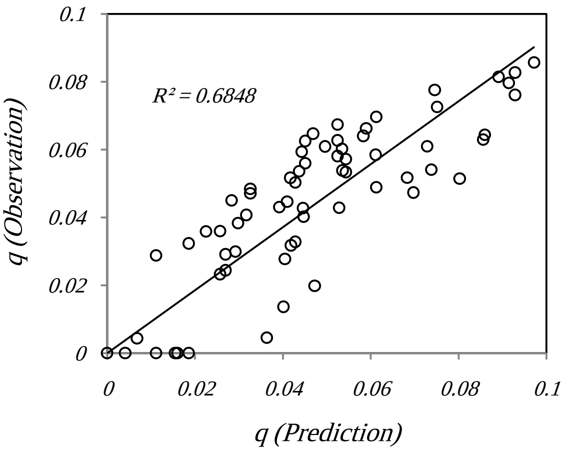

Fig. 11. Comparison of the estimated drain discharges to 30% of the observed values.

Table 2. Statistical measure for the comparison of the estimated drain discharges with 30% of the observed values

Upstream Discharge (Q)	d (Wilmot,1981)	RMSE	MAE	Relative Error	Mean Relative Error
1.6 L/s	0.849	0.0136	0.0011	18.94%	27.85%
1.2 L/s	0.865	0.0127	0.0017	29.35%	
0.8 L/s	0.922	0.0123	0.0021	20.88%	
0.4 L/s	0.916	0.0148	0.0032	42.23%	

4. Conclusion

In this study a rather new method for surface and subsurface water diversion in the seasonal rivers of the arid and semi-arid regions was introduced. In this type of intakes a subsurface drainage system is installed in a very porous media buried on the river bed. Effective parameters on water diversion efficiency of this type of intake were experimentally evaluated. It was shown that the water diversion was mostly influenced by the upstream flow rate. Water head also varied along the porous media even when a constant upstream discharge existed. The very small drain interval reduced the discharge of each drain. It was also revealed that the total drained discharge in the very transmitting media was mostly controlled by the number of drains and drain intervals did have a marginal effect. The total drains' discharge in length of 100 cm has increased 63% in comparison to the total drains' discharge in length of 50 cm, whereas this increase was about 90% in length of 150 cm than in the length of 50 cm. The regression equations were presented to relate the effective parameters of the water diversion. This equation can be utilized to design the subsurface intake with a porous media.

Nomenclature

ρ	fluid density
g	gravity acceleration
S_b	bed slope
μ	water viscosity
q	a drain flow rate
Q	upstream discharge
n	media porosity
d_{50}	the median diameter of the fill material
k	hydraulic conductivity
L	length of the porous media
D	installation depth
x	distance from the media upstream
d_p	drain diameter
S_0	river bed slope
S_l	drain lateral slope
A_d	perforated drain opening area
n_f	envelop resistance factor
form	installation form parameter.

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