Use of bottom slots and submerged vanes for controlling sediment upstream of duckbill weirs
Mahla Tajari, Amir Ahmad Dehghani, Mehdi Meftah Halaghi and Hazi Azamathulla

ABSTRACT
Duckbill weir is one of the water level control structures in irrigation networks, which is of interest to many engineers. Sediments transported in irrigation networks that accumulate upstream of duckbill weirs cause problems in operation, and affect the upstream water level. In this paper, submerged vanes and bottom slots are investigated for flushing the sediment downstream of the said weir. The experiments were conducted in a rectangular flume, 12 m long, and 0.6 m wide. The vanes placed in four sections were perpendicular to the sidewall. Flow-3D software was used for simulation of flow and sedimentation patterns. The results showed that submerged vanes create a secondary flow which is very useful for flushing the sediment, especially in the value of $\frac{H}{P} > 0.33$ (H is head over the sidewall and P is the weir height). Further, the results showed duckbill weir efficiency (which is defined as the ratio of sediment trap to flow capacity of the weir) is as high as 47% (for values of $H/P = 0.1$–0.5 and total models). Finally, image processing results showed a maximum relative error of 14.4% for the simulation of the sediment pattern with Flow-3D software.

Key words | discharge coefficient, duckbill weir, Flow-3D software, sedimentation pattern, submerged vanes

HIGHLIGHTS
● Submerged vanes and bottom slots are investigated for flushing the sediment downstream of the duckbill weir.
● Submerged vanes create a secondary flow for flushing the sediment.
● Image processing was used for comparison of results.
● There is good agreement between the simulated and experimental sedimentation pattern.
● Extensive tests were conducted for study of sedimentation upstream of the duckbill weir.

INTRODUCTION
The weirs are the most important regulating structure in irrigation canals. The weirs are classified based on the shape of the opening and shape of the crest. The shape of weir crests can be categorized as sharp-crested, broad-crested, long-crested, ogee-shaped, flat-crested, half-round-crested, and quarter-round-crested. Moreover, long-crested weirs are classified as duckbill weirs, or labyrinth weirs, and oblique weirs. The long-crested weirs can pass more flow with less head variation compared with standard weirs. They can be used even when the weir channel width is limited.

Duckbill weirs have been used in irrigation and drainage networks to keep the upstream water levels for turnout structures constant. This function is vital for providing a uniform discharge through the outlet structures. Canal systems are designed to provide water to farmers on demand.
When the channel’s width is short for passing a certain amount of flow, duckbill weirs are used, which extend the specific width of a channel. They are also regarded as a regulator and flow path structure because they are more efficient for discharge per unit canal width. Further, they have fewer variations of the water surface in the upstream, which occur due to flow fluctuation compared to other types of weirs.

Since labyrinth weirs consist of a series of duckbill-type weirs placed side-by-side across the channel, the labyrinth weirs’ hydraulics is studied extensively. In comparison, limited studies exist in the field of duckbill weirs (Taylor 1968; Hay & Taylor 1970; Darvas 1971; Tullis et al. 1995; Ghodsian 2009; Carollo et al. 2017; Crookston & Tullis 2013; Bijankhan & Kouchakzadeh 2017).

Shaghaghian & Sharifi (2015) simulated the flow over the triangular labyrinth weir using FLUENT software. They demonstrated that Fluent’s mathematical model has a high ability to simulate flow over labyrinth weirs. The maximum error for modeling of flow depth and overflow discharge was 8.25 and 6.22, respectively.

Sangsefidi et al. (2015) numerically investigated the effects of the downstream bed level on labyrinth weirs’ performance. According to their results, lowering the downstream bed level can decrease the local submergence extent in labyrinth weirs and subsequently increase their discharge efficiency, especially for high flow.

Sangsefidi et al. (2017) studied the discharge coefficient of in-reservoir arced weirs using traditional and response surface methodologies (RSM). They showed that RSM requires a much lower number of tests to estimate the arced weirs’ discharge coefficient. Also, an arced weir’s discharge efficiency can be improved by up to 50% compared to a linear one.

Carollo et al. (2017) studied the flow pattern over a triangular labyrinth weir. They also tested the proposed dimensionless equation by using experimental measurements carried out for a broad-crested triangular labyrinth weir.

Bilhan et al. (2018) studied the experimental investigation of labyrinth weirs’ discharge capacity with and without nappe breakers. Their results showed that the nappe breakers placed on the trapezoidal labyrinth weirs and circular labyrinth weirs reduce the discharge coefficient by up to 4%.

Tajari et al. (2018) studied a semi-analytical solution and numerical simulation of the water surface profile along a duckbill weir. Their results showed that the water surface profile along the duckbill weir structure can be obtained by solving the equation of spatially varied flow with decreasing flow discharge.

Sangsefidi et al. (2018) experimentally studied arced labyrinth weirs’ performance in a reservoir. They reported that an arced labyrinth weir’s efficiency can be improved by decreasing the sidewall angle and increasing arc angle.

The numerical studies of Sangsefidi et al. (2019) indicated that contraction of flow in upstream cycles of a labyrinth weir impacts its performance in high flow.

While many studies exist on labyrinth weirs, this is not the case for sediment control of duckbill weirs. Due to the extensive use of duckbill weirs in irrigation networks, these structures’ study is very important. Since sediments are transported in irrigation networks, they accumulate upstream of duckbill weirs and cause problems in operation and affect the upstream water level. To cope with this problem, designers use a bottom slot to flush the sediment. Because submerged vanes are also used for sediment control at lateral intakes, the authors decided to use submerged vanes as a sediment control structure upstream of a duckbill weir. Submerged vanes are small structures for flow control and bank protection. Submerged vanes create secondary flows and enable control of the sediment entry into intakes.

Looking at literatures shows that there are some typical dimensions for submerged vane design, which are based on experience obtained to date (Nakato et al. 1990; Odgaard & Wang 1991; Odgaard 2009). The angle of attack for designing submerged vanes is selected at between 10 and 20 degrees and the submerged vane height is selected at 0.2–0.4 times flow depth. The vane length and lateral spacing are selected as 3 times flow depth and the longitudinal spacing between submerged vanes is selected as 10–30 times the flow depth (Odgaard 2009). It must be noted that the submerged vane dimensions are only typical; site-specific conditions may require adjustments to those dimensions (Odgaard 2009).

In this study, attempts were made to control the accumulated sediment upstream of a duckbill weir using bottom slots and submerged vanes. The flow and sediment pattern upstream of the duckbill weir were also simulated.
with a CFD software, and the sediment pattern was compared with experimental results.

MATERIAL AND METHOD

The experiments were conducted in a recirculating rectangular flume 12 m in length, 0.6 m in width, and 0.6 m in height. To avoid disturbance of the flow, the duckbill gate-weir models were installed 5 m from the beginning of the flume. An ultrasonic flowmeter measured the discharge of the flow with an accuracy of 0.1 L/s, and the water surface profile was measured using a digital point gauge with an accuracy of 0.1 mm. To study the effect of an opening at the bottom of the weir on the sedimentation pattern, different geometries of opening were used, as shown in Table 1. The range of discharge in the experiments was between 0.01 and 0.03 m$^3$/s, and in all of the models, the weir height was kept constant and equal to 0.13 m. The angle between the sidewall and flow direction was 25° (i.e. $\alpha$ in Figure 1).

The duckbill gate-weir models and submerged vanes were made with galvanized iron sheet with a thickness of 2 mm, and unplasticized polyvinyl chloride (UPVC) with a thickness of 3 mm, respectively. The angle between submerged vanes and flow direction was equal to 25°. Geometric characteristics of the duckbill gate-weir structure and submerged vanes are presented in Figure 1 (plan view) and Figure 2 (3D view). The geometries of submerged vanes are described in Table 2.

To assess the efficiency of submerged vanes for controlling the sediment upstream of the duckbill weir, a specific amount of sediment was spread upstream of the weir at

Table 1 | Geometric dimension of bottom slot structures

<table>
<thead>
<tr>
<th>Model type</th>
<th>$p_{g1}$ (m)</th>
<th>$p_{g2}$ (m)</th>
<th>$p_w$ (m)</th>
<th>$L_{g1}$ (m)</th>
<th>$L_{g2}$ (m)</th>
<th>$L_w$ (m)</th>
<th>$b_0$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.01</td>
<td>0.01</td>
<td>0.099</td>
<td>0.108</td>
<td>0.108</td>
<td>0.108</td>
<td>0.463</td>
</tr>
<tr>
<td>B</td>
<td>0.01</td>
<td>0.017</td>
<td>0.099</td>
<td>0.108</td>
<td>0.108</td>
<td>0.108</td>
<td>0.463</td>
</tr>
<tr>
<td>C</td>
<td>0.01</td>
<td>0.01</td>
<td>0.099</td>
<td>0.108</td>
<td>0.054</td>
<td>0.108</td>
<td>0.463</td>
</tr>
<tr>
<td>D</td>
<td>0.01</td>
<td>0.01</td>
<td>0.099</td>
<td>0.108</td>
<td>0.162</td>
<td>0.108</td>
<td>0.463</td>
</tr>
</tbody>
</table>

$p_{g1}$: gate opening of gate in weir nappe, $p_{g2}$: gate opening of bottom slot, $p_w$: height of compound weir, $L_{g1}$: gate length in weir nappe, $L_{g2}$: bottom slot length, $L_w$: length of compound weir, $b_0$: the first width of weir.

Figure 1 | Geometric characteristics of duckbill gate-weir structure and submerged vanes (plan view): (a) without submerged vanes, (b) with submerged vanes.
the beginning of each run. The weight of settled sediment upstream of the weir was obtained after the equilibrium condition. Then the efficiency is obtained by dividing the amount of settled sediment by the initial weight of sediment.

The longitudinal distance \(dx\), lateral distance \(dy\) and the length of submerged vanes \(L\) are selected as Odgaard & Kennedy (1983) and Odgaard & Lee (1984) recommendation:

\[
\frac{dy}{b} = 0.4 - 0.5, \quad \frac{dx}{b} = \frac{0.24b_1}{1 + 0.24\tan(\alpha)}, \quad \frac{L}{b} = 0.15 - 0.22 \quad (1)
\]

**Dimensional analysis**

The Buckingham Pi method is used for calculating dimensionless parameters. Effective parameters on flow of a duckbill weir with gates were considered as:

\[
C_d = f\left(\frac{P_{g2}}{H}, \frac{H_{g2}}{H_w}\right)
\]

where \(L_w, H_w, L_d, H,\) and \(H_a\) are the weir length and water head over compound weir (sharp edge weir at nappe), duckbill weir length and water head over side sections of weir, and upstream water depth.

\(\rho, \mu, \sigma, B, S_0, d_s, \rho_s\) are the fluid density, fluid dynamic viscosity, surface tension, the width of the flume, bed slope of the flume, average sediment particle diameter, and the density of the sediment particles, respectively. By doing dimension analysis and regardless of the impact of Weber, particle Froude number, Reynolds number (turbulence flow), constant value for \(\alpha S_0 \theta\) and other parameters on length dimension \((L_{g1}, P_{g1}, P, L_d, L_w, B, W_1, W_2, h_v)\), the \(C_d\) can be calculated by Equation (3):

\[
C_d = f\left(\frac{P_{g2}}{H}, \frac{H_{g2}}{H_w}\right)
\]

**Numerical simulation**

The numerical simulation of flow over the duckbill weir gate structure was completed by solving the fully 3D transient conservation of mass and momentum equations in a computational fluid dynamic (CFD) model.

Mass continuity was represented according to (Hirt & Nichols 1981):

\[
\frac{V_F}{pc^2} \frac{\partial p}{\partial t} + \frac{\partial u A_x}{\partial x} + \frac{\partial v A_y}{\partial y} + \frac{\partial w A_z}{\partial z} = 0
\]

where \(V_F\) is the fractional volume open to flow, \(c\) is the speed of sound, \(t\) is time, \(Ai (A_x, A_y, and A_z)\) are the
fractional areas open to flow, with subscripts x, y, and z to denote the three flow directions, and u, v, and w denote the velocities in the x-direction, y-direction, and z-direction.

The Navier–Stokes equations for 1D, but valid for three directions (x, y, z), are presented in Equation (5):

$$\frac{\partial u}{\partial t} + \frac{1}{V_F} \left\{ u Ax \frac{\partial u}{\partial x} + v Ay \frac{\partial u}{\partial y} + w Az \frac{\partial u}{\partial z} \right\} = - \frac{1}{\rho} \frac{\partial p}{\partial x} + f_x \quad (5)$$

where fi (f_x, f_y, and f_z), are the viscous acceleration terms (Hirt & Nichols 1981).

Turbulent closure of the momentum equations was achieved using the kinetic energy and dissipation rate transport k-ε two-equation form of the dynamic Renormalization Group method (Yakhot & Orszag 1986; Yakhot & Smith 1992).

The Flow-3D CFD model solves Equations (4) and (5) at each computational node. Water surface boundary and air boundary were determined by using the Volume-of-Fluid (VOF) technique.

The cubic model mesh was set to 0.5 cm, and the number of meshes was 1,440,000. The timestep size was automatically adjusted to maintain stability and ensure fluid fraction advection did not exceed computational cell volumes.

No-flow boundary conditions were specified along the model bottom and sides, and free water surface boundaries were established at the upstream and downstream ends.

**Sediment scour model**

Sediment scour model predicts the erosion, settling, and deposition of sediments, such as sand and gravel. This model can be used in any flow, though all sediment motion must take place within one fluid.

The Flow-3D scour module applies the advection/diffusion scheme for predicting the transport of sediment. The drift and settling length scale (L_drift) of the suspended sediment is calculated using a Stokes formulation at the hydrodynamic time step (6):

$$L_{drift} = \frac{d_{50}^2}{18 \mu} \times \frac{\nabla p}{\rho} (\rho_s - \rho) \Delta t \quad (6)$$

where ρ_s is the sediment density; ρ is the density of the fluid; d_{50} is the median grain size; and Δt is the timestep. In this case, acceleration is represented by the mechanical gradient (∇p/ρ). Physically, the drift is assumed to be a result of the particle forcing due to gravity and advection. The local density ρ is given by:

$$\rho = \rho + f_s (\rho_s - \rho) \quad (7)$$

where f_s is the solid fraction in the cell. The lift length of the packed bed is calculated using an excess shear formulation:

$$L_{drift} = \frac{n_s \alpha \sqrt{\tau - \tau_{cr}}}{\rho} \Delta t \quad (8)$$

where τ_{cr} is the critical shear stress; n_s is the unit vector normal to the bed. The lift acts perpendicular to the bed. The parameter is dimensionless and represents the probability that a particle is lifted from the bed. The scour module continually provides feedback to the hydrodynamic solver by using an enhanced viscosity for the suspended sediment and a drag term to parameterize inter-granular collisions for the packed bed. These equations are given below (Abdelaziz et al. 2010).

$$\mu_s = \mu \left(1 - \min\left(f_s, \frac{f_{s,cr}}{f_{s,co}}\right)\right) \quad (9)$$

where f_s is the solid fraction in the cell. The solid fraction is a measure of the fraction of the cell volume that is occupied by sediments. The terms f_{s,co} and f_{s,cr} represent the cohesive solid fraction, and the critical solid fraction, or bed porosity, respectively.

This value corresponds to the point at which the bed material is bound together and acts as a solid mass. When the solid fraction exceeds the cohesive solid fraction, viscosity is no longer enhanced.

Bedload transport formulas, namely Meyer-Peter & Muller (1948), Nielsen (1992), Van Rijn (1984), are presented in Flow-3D software. In this study, we used the Meyer-Peter and Muller formula for greater precision compared to the Nielsen and Van Rijn formulas. The Meyer-Peter and
Muller formula is presented in Equation (10):

\[
\left( \frac{k}{k'} \right)^2 \gamma RS = 0.047(\gamma_s - \gamma)D_m + 0.25 \left( \frac{\gamma}{\gamma_s} \right) \left( \frac{\gamma_s - \gamma}{\gamma_s} \right) q_b^2
\]  

(10)

\(q_b\): bed load discharge, \(D_m\): the average particle diameter, \(\gamma\): the specific gravity of water, \(\gamma_s\): the specific gravity of sediment particle, \(R\): Hydraulic radius, \(S\): Longitudinal bed slope. Ratio \(\frac{k}{k'}\) is computed from Equation (11):

\[
\frac{k}{k'} = \left( \sqrt{\frac{f}{8}} \right) \left( \frac{V}{\sqrt{\gamma g RS}} \right)
\]  

(11)

where \(V\) is the mean velocity and \(f\) is the Darcy coefficient.

Critical Shields number, entrainment coefficient, and bedload coefficient have defined values of 0.05, 0.018, and 8, respectively. The drag coefficient is assumed to be equal to 1.5 for gravel and sand particles (10). Figure 3 shows the initial sediment pattern upstream of the duckbill weir.
A comparison between simulated and experimental sedimentation patterns was done by the image processing method in Matlab software. Image dimensions were 800 × 1,000 (width×height), and the number of total pixels was 800,000. In the end, the distinction between simulated and experimental images or simulation error of sedimentation pattern is calculated by Equation (12):

\[
\text{error (\%)} = \left( \frac{\text{number of different pixels}}{\text{number of total pixels}} \right) \times 100 \quad (12)
\]

RESULTS AND DISCUSSION

Flow pattern and sedimentation pattern

In this study, discharge ratio and residual sediments weight ratio are important for evaluation and comparison results. The efficiency of the weir should consider discharge ratio and sediment transportation. In the end, the efficiency of a duckbill weir with a bottom slot can be calculated by Equation (13):

\[
\xi = \left( 1 - \frac{\lambda_2}{\lambda_1} \right) \times 100 \quad (13)
\]

\(\xi\): efficiency of duckbill weir, \(\lambda_1\): discharge ratio of models with bottom slots and submerged vanes to discharge ratio of model without bottom slots and submerged vanes, \(\lambda_2\): residual sediments weight ratio of models with bottom slots and submerged vanes to a model without bottom slots and submerged vanes.

The experimental and numerical simulation of water surface profile with and without submerged vanes is shown in Figures 4 and 5 respectively. The simulated streamlines close to the bed are also presented in Figure 6. The results show that most streamlines divert to the bottom slots due to the induced secondary flow of the submerged vanes (Figure 6(b)). Therefore, some sediment part is also diverted to the bottom slots and flushed from behind the weir. The sedimentation pattern upstream of the duckbill weir with and without submerged vanes is presented for different values of H/P in Figures 7 and 8. The simulated sediment pattern is also presented for comparison of results (Figures 7(b) and 8(b)). The results show that the amount of sediment flushing from behind the weir increases by increasing H/P. The results also show that using the submerged vanes causes the trapped sediment to flush downstream effectively (Figure 8).

For evaluating the numerical scheme's ability to simulate the sedimentation pattern, an image processing technique is used. In this technique, comparisons were made between experimental and simulated sediment patterns by matching two binary images pixel by pixel. The maximum error between simulated and observed sediment patterns is presented in Table 3 for different values of H/P.

![Figure 4](http://iwaponline.com/wa/article-pdf/20/8/3393/812963/wa020083393.pdf) | 3D Water surface profile of duckbill weir without using submerged vanes. (a) Experimental; (b) simulated.
To better understand the effect of submerged vanes for controlling the sediment upstream of the duckbill weir, the amount of $C_d$ against of $\frac{P_E}{H} \cdot \frac{L_{Re}}{H_w}$ is presented in Figure 9.

The results show that by increasing the values of $\frac{P_E}{H}$ and $\frac{L_{Re}}{H_w}$, the amount of $C_d$ is increased. Equation (14) obtained the discharge coefficient by using experimental results and non-linear regression.

$$C_d = 0.756 \left( \frac{P_E}{H} \right)^{0.144}$$

Figure 5 | 3D Water surface profile of duckbill weir with using submerged vanes. (a) Experimental; (b) simulated.

Figure 6 | The simulated stream lines near the channel bed. (a) Without submerged vanes; (b) with submerged vanes.

Figure 7 | The experimental and simulated sedimentation pattern upstream of duckbill weir for different values of $H/P$. 
Duckbill weir efficiency

The efficiency of the duckbill weir against H/P is presented in Figure 10. The results show that the efficiency of the weir is minimum for a value of H/P = 0.26. The results show that the efficiency of Model C of the duckbill weir is smaller than the other types of duckbill weirs.

The results of duckbill efficiency in the presence of submerged vanes are presented in Figure 11. The results show that the efficiency of the duckbill weir is increased by increasing H/P. The results also show that using the submerged vanes can increase duckbill efficiency.

CONCLUSIONS

The results show that bottom slots and submerged vanes induce secondary flow, which is effective for sediment transport, especially in the higher value of $\frac{H}{P}$ ($H$ is head over the sidewall and $P$ is the height of the weir). The results also show that duckbill weir efficiency (which is defined as the ratio of sediment trap to flow capacity of the weir) increased to 47% (for values of H/P = 0.1–0.5 and total models) by use of submerged vanes, which means the maximum flushing and flow conveyance occurred for a given upstream head.

For preventing the sediment accumulation upstream of the duckbill weir, one can use the bottom slots and submerged vanes together for values of H/P = 0.1–0.5. Also, image processing results showed that the maximum relative error for simulation of sediment pattern is 14.4%, and there is good agreement between the simulated and experimental
sedimentation pattern. The results of this study can be applied for designing duckbill weirs in irrigation networks that suffer from sediment delivery from farm lands due to wind flow.

DATA AVAILABILITY STATEMENT

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

REFERENCES


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