Flow estimations through spillways under submerged tidal conditions

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Abstract

The South Florida Water Management District (SFWMD), Florida, USA, operates and maintains about twenty-five coastal spillways that discharge excess runoff water directly into the environmentally sensitive area of Biscayne Bay, south of Miami. Over the past decade serious concerns have been raised regarding the large fluctuations of salinity levels in Biscayne Bay caused by the freshwater releases. At the SFWMD, discharges at gated spillways are computed from an instantaneous stage and operational control information by using basic formulas developed for the estimation of orifice and weir type of flows. However, the accuracy of discharge estimates is compromised whenever flow occurs under submerged conditions and particularly at tidally affected structures. This paper is focused on the estimation of discharges through gated spillways under tidal submerged flow conditions. Data are analyzed using dimensional analysis and an empirical model is developed based on data from two coastal spillways. The model relates the discharge as a function of the tail-water head and the low tide elevation during each tidal cycle. All of the other parameters are treated as constants and lumped into the empirical coefficients.
Keywords: dimensional analysis, empirical formulas, flow measurements, spillways, submerged flows, tidal effects.

1 Introduction

The South Florida Water Management District (SFWMD) operates and maintains over four hundred hydraulic structures including spillways, weirs, culverts and pump stations. The main driving force for the development of water controls in southern Florida is to maintain adequate water supplies for the rapidly growing population along the lower east coast, to sustain agricultural activities and to restore and protect the Everglades National Park and other delicate wetland and coastal ecosystems.

Approximately one hundred and twenty of the hydraulic structures are gated spillways and about twenty-five of them are coastal spillways that discharge excess runoff water directly into the environmentally sensitive area of Biscayne Bay, south of the Miami-Dade metropolitan area. Over the past decade serious concerns have been raised regarding the large fluctuations of salinity levels in Biscayne Bay caused by the freshwater releases and the negative impact that they have on the quality and biodiversity of the native environment. Thus, for an effective and efficient management of the regional water resources system there is a substantial need for accurate estimates of those freshwater discharges.

The purpose of this study is to improve the existing state-of-the-art for estimation of discharges at coastal spillways under tidally-affected and submerged flow conditions.

2 Spillway gate operations

Depending on the gate operating conditions and the water elevation on either side of the spillway flow at coastal spillways is classified into five different flow categories [1, 5]. More specifically those categories are:

- Free orifice-flow (partially opened gate – i.e. gate is in the water)
- Submerged orifice-flow (partially opened gate)
- Free weir-flow (fully opened gate – i.e. gate is out of the water)
- Submerged weir-flow (fully opened gate)
- Submerged tidally-affected weir-flow (fully or partially opened gate)

At the SFWMD flows at gated spillways are generally computed from instantaneous stage and operational control information using an in-house developed program based on orifice and weir type discharge formulas [6]. However, the accuracy of discharge estimates is compromised in cases where flow occurs under submerged tidal conditions. An improvement on the discharge calculations was done by using dimensional analysis and field measurements from coastal spillway S-26 [2]. That model incorporated tidal effects in lumped terms of the tidal range and period. This study improves the Ansar and Raymond model by incorporating and analyzing additional available data from spillway S-21.

3 Submerged tidal spillway flows

Generally, there are many parameters that control flow through tidally-affected submerged spillways. Those parameters can be categorized as being related to flow, fluid and geometric features of the structure [3]. Traditionally submerged flow is estimated as [6]:

$$Q = C_S B H_t \sqrt{2g(H - H_t)} \tag{1}$$

where B is the gate width, H is the upstream head, H_t is the tail-water elevation, g is the gravitational acceleration, and C_s is an empirical coefficient expressed as:

$$C_s = \alpha\left(\frac{H_t}{H}\right)^{\beta} \tag{2}$$

where α and β are experimental constants [5]. Another formula proposed by Skogerboe and Hyatt [4] estimates submerged flow as:

$$Q = \frac{C_1(H - H_t)^{\alpha_1}}{\left[-\left(\log\frac{H_t}{H} + C_2\right)\right]^{\beta_1}} \tag{3}$$

where both exponents α_1 and β_1 are empirical constants. However, application of the above formulas may lead to substantial inaccuracies particularly when the head difference, $H - H_t$, is too small or even a negative number. In certain occasion flow estimations for spillway S-26 using the above formulas provided negative flows, while field measurements indicated a positive flow.

In order to improve the discharge computational formulas under submerged tidal conditions, Ansar and Raymond [2] assumed that the flow rate, Q, at a tidal gate is a function of eight variables (fig. 1), i.e.

$$Q = f\left(H_t, P_W, B, g, \mu, \rho, A, T\right) \tag{4}$$

where P_w is the height of the spillway weir, μ is the dynamic viscosity, ρ is the water density, A is the tidal range and T is the tidal half-period (fig. 1). By applying dimensional analysis and π-theorem the eight variables are combined into four dimensional groups:

$$\frac{Q^{\frac{2}{3}}}{B^{\frac{2}{3}} g^{\frac{1}{3}} P_W} = \Phi\left[\frac{H_t}{P_W}, \frac{A}{T\sqrt{gP_W}}, \frac{\rho Q}{\mu B}\right] \tag{5}$$

Due to the high turbulent flow regime, the last dimensionless group within the parenthesis (Reynolds Number) was dropped from further consideration since the viscous effects are negligible. Thus, the expression (5) was re-written as:

$$\frac{Q^{\frac{2}{3}}}{B^{\frac{2}{3}} g^{\frac{1}{3}} P_W} = \frac{Y_c}{P_W} = \Phi\left[\frac{H_t}{P_W}, \frac{A}{T\sqrt{gP_W}}\right] \tag{6}$$

By using actual data from a coastal spillway in Southeast Florida (Structure S-26) the above relation was calibrated and verified as:

$$\frac{Q^{\frac{2}{3}}}{B^{\frac{2}{3}} g^{\frac{1}{3}} P_W} = \lambda\left[\frac{A}{T\sqrt{gP_W}} 10^6\right]^{\xi}\left[\frac{H_t}{P_W}\right]^{\zeta} \tag{7}$$

The values of the calibration coefficients that satisfy data for spillway S-26 are different for the falling and rising tide (Table 1).

Table 1: Calibration coefficients for S-26 discharge formula.

Tidal Conditions	λ	ξ	ζ
Flood	2,179.35	-0.44	-2.38
Ebb	111.77	-0.10	-1.48

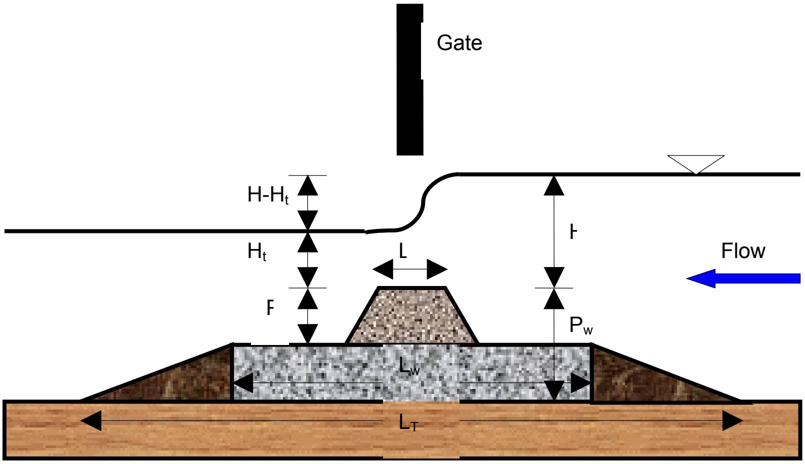


Figure 1: Standard geometric features of spillways.

The fact that in equation (7) only the tail-water was included is justifiable due to the fact that under submerged flow conditions H is approximately equal to H_t.

4 Data analysis and model development

The South Florida Water Management District (SFWMD) and the US Geological Survey (USGS) operate and maintain a number of Ultrasonic Velocity Meters (UVMs) upstream of various gated structures. UVMs are utilized to estimate flows through the structures. However, since UVMs are "point" instruments their discharge estimates are adjusted using flow data collected by Acoustic Doppler Current Profiler (ADCP) which integrates velocities throughout the entire cross-sectional area of the channel. Then the UVM and/or ADCP discharge data are used to calibrate the empirical formulas for discharge estimation which are based on real-time telemetry measurements of upstream and tail-water elevations at the gate. The Ansar and Raymond model was calibrated and verified using discharge and water elevation data obtained at structure S-26 [2]. In the present study, the proposed model utilizes data from spillway S-26 (events of June 1997 and February 1998) and also spillway S-21 (event of September 2005).

4.1 Discussion of the Ansar and Raymond model

The Ansar and Raymond model was tested under a variety of different conditions using data from spillway S-26 and the following conclusions were derived:

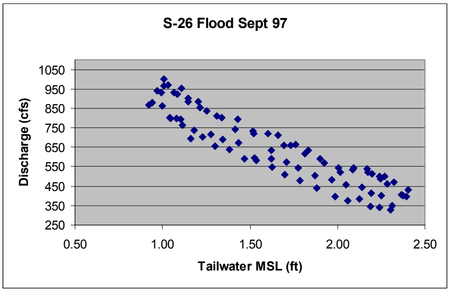
- The model is extremely sensitive to the value of the total weir height, P_w (fig. 1). By using instead the top weir height, P, flow estimations are improved, but in certain cases that height has still to be reduced in order to produce adequate discharge estimations.
- Both the tidal range, A, and the half-tidal period, T, may slightly affect the discharge estimation but not as drastically as the weir height.
- In cases that the upstream head, H, is noticeably different that the tail-water, H_t, discharge estimates improve by using H instead of H_t.
- In certain occasions, the ebb cycle is estimated better by using the calibration coefficients obtained for flood flow conditions.
- Adopting the value of P instead of P_w in the Ansar and Raymond model, the value of the parameter λ may be need to be reduced accordingly in order to improve flow calculations.

4.2 Critical review of the spillway S-26 and S-21 data

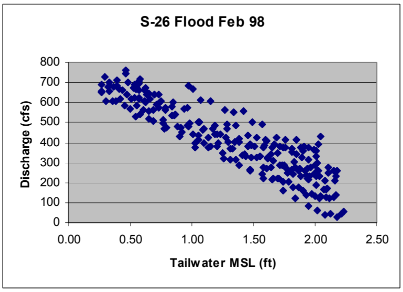
Since the focus of this study was on submerged tidal flows, only those data sets that the upstream and downstream heads were almost equal were considered. The data were analyzed separately for the flood (rising tide) and the ebb (falling tide) cycles.

4.2.1 Flood tide

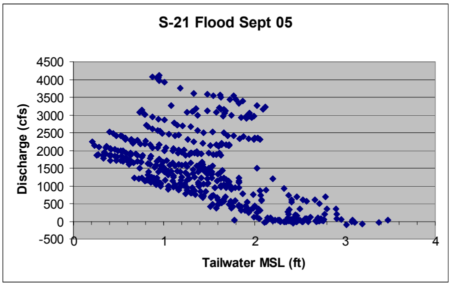
All of the data regarding the flood part of the tidal cycle showed a distinct linear, inversely proportional correlation between the discharge, Q, and the tail-water head, H_t, (as measured from the MSL) (figs. 2a,b,c). Thus, during the rising tide discharge decreased due to the decreasing energy gradient along the discharging canal. The slope of that linear relation remained almost constant for each discharge event and varied only slightly among different gate operation events.



(a)



(b)



(c)

Figure 2: Discharge versus tail-water elevation during rising tide.

Another interesting observation was that no identifiable correlation appeared to exist between the discharge and either the tidal range, A, or half-period, T, as defined in the Ansar and Raymond model [2]. On the other hand, from a close scrutiny of figs. 2a,b,c it is suggested that the discharge is correlated to the lowest tail-water stage, (H_{tmin}) during each tidal cycle. The discharge increases exponentially for increasing minimum tail-water stage (fig. 3). The exponential correlation that matches the data for spillway S-26 is plotted also in figure 3.

$$Q = 6.633 \exp(3.623H_{tmin}) + 675.1 \tag{8}$$

where Q is in cubic feet per second (cfs) and H_{tmin} is measured in feet (in reference to the mean sea level (MSL)). For very high values of the tail-water head ($H_t > 2.5$ ft) the discharge becomes negligible. This is an indication that due to the high tidal stage the energy gradient within the discharging canal is diminished.

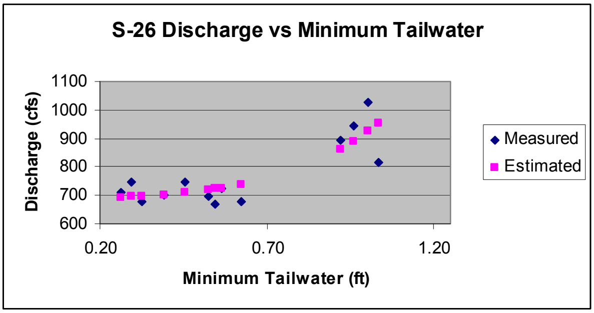
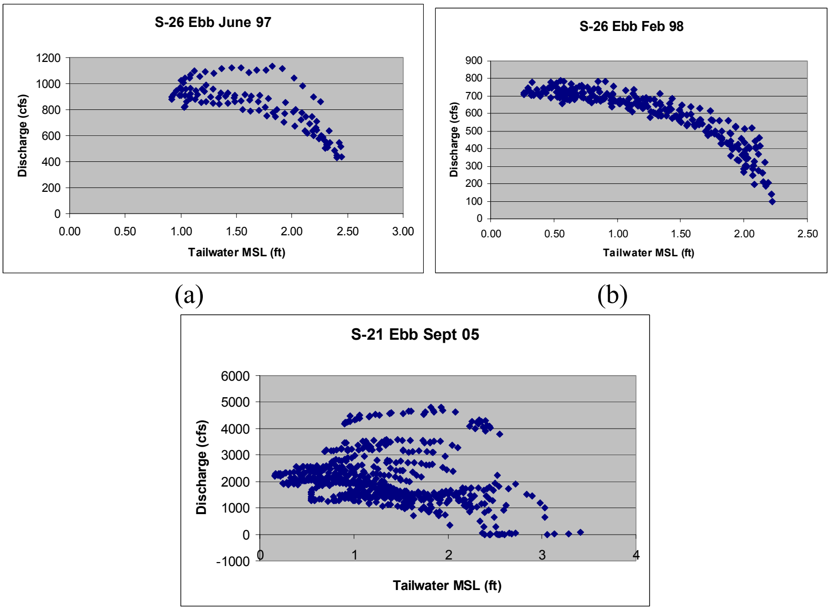


Figure 3: Discharge versus low tail-water during each tidal cycle.



(a) (b)

(c)

Figure 4: Discharge versus tail-water elevation during falling tide.

4.2.2 Ebb tide

The relationship between the discharge and tail-water for the falling water part of the tidal cycle is not linear. The discharge increases with the falling tail-water to a certain level but then before the end of the ebb cycle it levels or decreases even though the tide is still falling (fig. 4a,b,c).

Since the high's and low's of tidal elevations are common points for both ebb and flood cycles the preceding remarks on the relationship between H_{tmin} and Q, and diminishing Q for H_t > 2.5 ft are also observed. In addition, among the various expressions that were tried, the one that best fitted the nonlinear behavior for all of the data for spillway S-26 was a sinusoidal equation:

$$Q = 867 \sin(H_t + 260) + 102 \quad (9)$$

where Q is the discharge in cfs and H_t is the tail-water in ft (above MSL). The results are presented in fig. 5 (QF is the observed and QSIN are the simulated data).

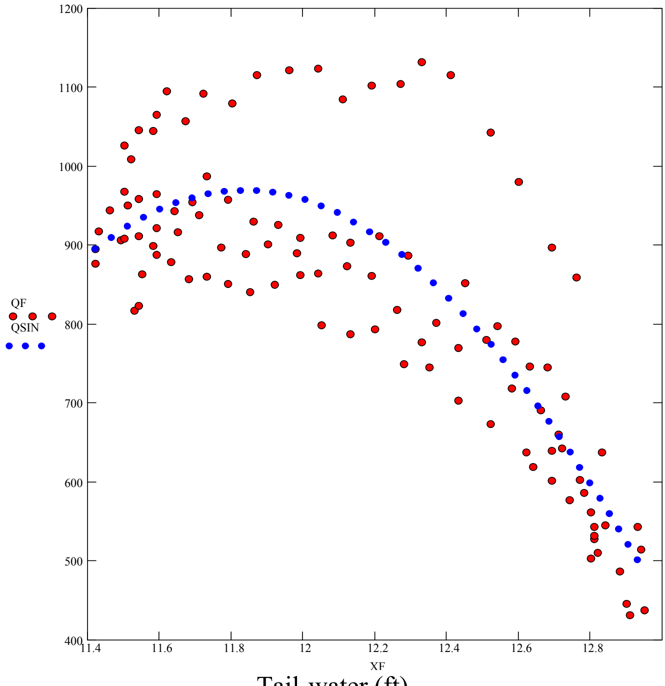


Figure 5: Measured versus simulated values of ebb tide discharges.

Once the trend (shape of the curve) was captured, the simulation was further improved by adjusting the discharge in terms of the minimum tidal water elevation, H_{tmin}, as was demonstrated by equation 6.

5 Conclusions

Based on the analysis of this study involving data from spillways S-21 and S-26 the following conclusions were derived:

- The weir height, P_w, (or the top weir height, P), do not have any direct significance in the discharge formula and can be treated as just another calibration constant.
- The variation in the tidal half-cycle period, T, in the Ansar Raymond model [2] is artificially introduced due to minor tailwater stage fluctuations and the

15 minutes data recording step. In reality the tide is astronomically driven with a fixed semi-diurnal period of 12.6 hours. Therefore, T should be treated as a constant.

- From the recorded data the tidal range, A, varies from 1.27 ft to 1.97 ft. However, no correlation was found between the tidal range and the flow rate. The tidal range showed a periodicity ranging from 2 to 3 tidal cycles (i.e., approximately 24 to 36 hours). This may be due to astronomical diurnal tidal effects and some prevailing weather conditions during the recorded event.
- During rising tide (flood), the discharge, Q, is inversely proportional to the tailwater elevation, H_t. In addition, the rate of flow reduction due to increasing tailwater stage is almost constant (linear relationship). Some inaccuracies to the above rule may occur in the neighbourhood of high tailwater stages ($H_t > 2.5$ ft).
- During falling tide (ebb), the discharge, Q, decreases with increasing tailwater elevation. The relationship although not linear as in the case of the rising tide, it follows a distinct pattern that can be described with a sinusoidal curve.
- The maximum flow rate, Q_{max}, occurring during the minimum tailwater elevation, H_{tmin}, depends on the H_{tmin}. As H_{tmin} increases, the maximum flow increases in an exponential manner. This explains the "overshooting" of the Ansar and Raymond model that was calibrated using the high values of H_{tmin} (S-26 June 1997 data) and was verified for lower values of H_{tmin} (S-26 February 1998 data).
- The discharge conditions approaching the minimum tailwater elevation are more close to "tidal-free" regime since the flow was moving unopposed during the entire ebb cycle. The energy gradient decreases with the rising tide until it reaches its minimum value at high tide. At that time the energy gradient is from one to three orders of magnitude less than the one during the low tide. The amount of energy gradient decrease appears to be correlated to the tidal range but no particular pattern was identifiable.
- The flow behaviour occurring under fully opened gate conditions (S-26) was very similar to that occurring under partially opened gates (S-21) as long as the upstream and tail-water stages were about the same.

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