Estimating Flow Through Rock Weirs

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ABSTRACT

Rock weirs are small dam-like structures composed of large loose rock commonly found in ecological engineering design. By appearing more natural than concrete structures, rock weirs are preferred for use as hydraulic control structures in river engineering, stormwater management, and constructed wetlands. Rock weirs increase hydraulic head upstream, and facilitate fish passage, channel stabilization, floodplain reconnection, and in-stream habitat creation. When used in constructed wetlands, rock weirs play a valuable role in developing appropriate wetland hydrology. Although rock weirs are commonly used, a deficit of knowledge exists relating to the stage-discharge relationship of these structures. Therefore, the goal of this research was to determine a weir equation and corresponding discharge coefficients that improve predictions of flow through rock weirs.

A flume study was conducted to develop a rock weir equation and discharge coefficients. Scaled model rock weirs were tested in a 1 m x 8 m x 0.4 m recirculating flume. Rock weirs varied by length (0.152 m, 0.305 m, and 0.457 m), depth (0.152 m and 0.305 m), and minimum rock diameter (12.7 mm, 19.1 mm, 25.4 mm). Three channel slopes were used (0%, 0.5%, 1%), and the flume discharge was varied for five water stages for each rock weir. Buckingham Pi analysis was used to develop seven dimensionless parameters. Regression analyses were then used to develop a model for discharge and the discharge coefficient. Results showed that weir length and depth play a significant role in predicting the discharge coefficient of rock weirs.

Estimating Flow Through Rock Weirs

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GENERAL AUDIENCE ABSTRACT

Rock weirs are small dam-like structures composed of large loose rock; by appearing more natural, they are preferred for use in river engineering, stormwater management, and constructed wetlands. Rock weirs increase upstream water depth, improving fish passage, channel stabilization, floodplain reconnection, and in-stream habitat creation. When used in design of constructed wetlands, rock weirs are used to establish the necessary water depths for a given type of wetland. Although rock weirs are commonly used in engineering design, there are no equations to predict water velocity or flow rate across these structures. Therefore, the goal of this research was to determine a weir equation that improves predictions of flow through rock weirs.

A flume study was conducted to develop a rock weir equation. Miniature rock weirs were tested in a 1 m x 8 m x 0.4 m recirculating laboratory channel. Rock weirs varied by length (0.152 m, 0.305 m, and 0.457 m), depth (0.152 m and 0.305 m), and minimum rock diameter (12.7 mm, 19.1 mm, 25.4 mm). Three channel slopes were used (0%, 0.5%, 1%), and the water flow rate was varied for five water depths for each rock weir. Statistical analyses were conducted to determine an equation that predicts water flow through rock weirs for use in engineering design. Results showed that weir length and depth played a significant role in predicting water flow through rock weirs.

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Chapter 1: Introduction

Weirs facilitate and water storage (Chanson, 1999) in streams and impoundments; hence, these structures are applied to different aspects of hydraulic engineering, including dam, stormwater, and stream engineering (Brown et al, 2006). These hydrologic structures can span the width of a stream channel or act as a dam and can vary greatly, including in crest shape (e.g. broad-crested, sharp-crested, and ogee-crested), opening shape (e.g. V-notch, rectangular, and trapezoidal), material (e.g. rubber, concrete and rock), and size. In addition to water storage, weirs are also used to provide volumetric flow, or discharge, measurements with the use of stage-discharge relationships (Thorton et al., 2011). Such relationships are unique to each weir type.

Rock weirs are a distinctive class of weirs, where the structure is semi-porous. These weirs are akin to rockfill structures. Rock weirs are used in best management practices (BMPs) in stormwater engineering (Herrera & Felton, 1991; Sample & Doumar, 2013; Simmons & Admiraal, 2014). Moreover, rock weirs have increased in popularity in stream restoration as a result of the additional ecological benefits they may provide. As well as increasing hydraulic head upstream, such as for irrigation, rock weirs facilitate fish passage, channel stabilization, floodplain reconnection, and in-stream habitat creation (Thorton et al., 2011; Gordon et al., 2016). Additionally, the pores of these structures can accumulate organic matter, and by also providing appropriate habitat for microbes, rock weirs can aid water purification processes (Mohamed, 2010; Leu et al., 2013, Michioku et al., 2005). Not only can rock weirs be used in stream restoration efforts, they can also be used to assist in wetland restoration. Evans et al. (2007) demonstrated the use of rock weirs in channels to raise baseflow in the stream, thereby also raising the water level in an adjacent wetland and increasing overflow into the wetland. These porous weirs are also favored as hydraulic control structures because they appear more natural and are, therefore, more aesthetically pleasing and acceptable to the public (Rosgen, 2001).

Stage-discharge relationships have been developed for many types of weirs (Brown et al., 2012). However, established weir equations and discharge coefficients apply mainly to impermeable weirs with smooth crests, such as those made of concrete. Although design guidelines may recommend the use of broad-crested weir coefficients (Caltrans, 2014), rock weirs are porous and have irregular crests; consequently, standard weir equations and coefficients do not adequately predict discharge through and across these structures. Discrepancies in discharge measurements can affect the broader goals of the project for which the weir is being used. These goals can range from water supply and irrigation, flood or pollution control, and to wetland creation (Herschy, 1995).

Goals and Objectives

The purpose of this study was to develop a weir equation with corresponding discharge coefficients for rock weirs to improve discharge predictions across these structures. It was hypothesized that the flow through rock weirs could best be described by separate equations that describe flow through the weir and flow above the weir. The results of this study will be applied to Wetbud (Daniels, n. d.), a wetland modeling software, to improve water budget calculations of wetland restoration projects.

Chapter 2: Literature Review

Rock Weir Definition

Gordon et al. (2016) defines rock weirs as “river spanning loose rock structures” that have the following characteristics (Figure 1):

1. Construction material is loose rock (with little or no cement)
2. Extend across a stream channel
3. Cause an abrupt change in elevation at low flow

Types of rock weirs include A-, U-, V-, and W- weirs, J-hooks, and cross vanes (Rosgen, 2001; Gordon et al., 2016), while linear rock weirs are described as broad-crested (Thorton et al., 2011).

Figure 1. Rock weir implemented in Dividing Creek near Annapolis, MD (taken by Ben Smith).

Similar structures to the rock weir are gabion weirs (Figure 2) and rockfill dams (Figure 3). The primary difference between rock weirs and gabion weirs is that the latter uses a steel mesh basket to hold the rocks, typically in a cuboid shape. Rockfill dams, on the other hand, are comprised primarily of loose rock similar to rock weirs. These dams are typically much larger than rock weirs and have an impermeable central core and armored slopes (Leps, 1988). There is no strict definition of rockfill; however, particle sizes are typically larger than 12.7 mm (0.5 in.), with less than 10% by weight of material passing a US No. 4 sieve (opening: 4.75 mm (0.187 in.)) (Herrera & Felton, 1991).

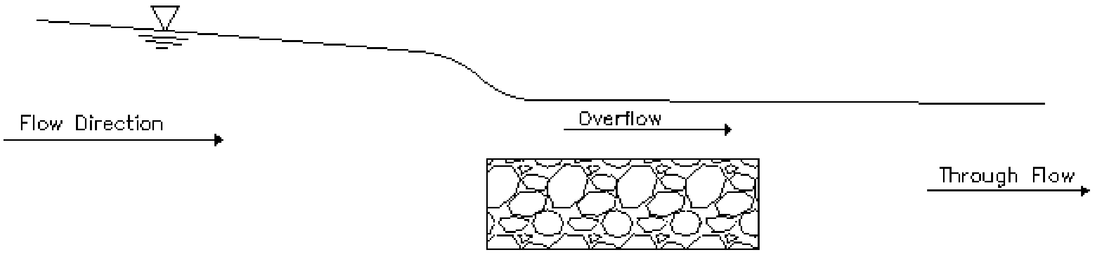

Figure 2. Schematic of gabion weir showing through flow and overflow, similar to rock weir.

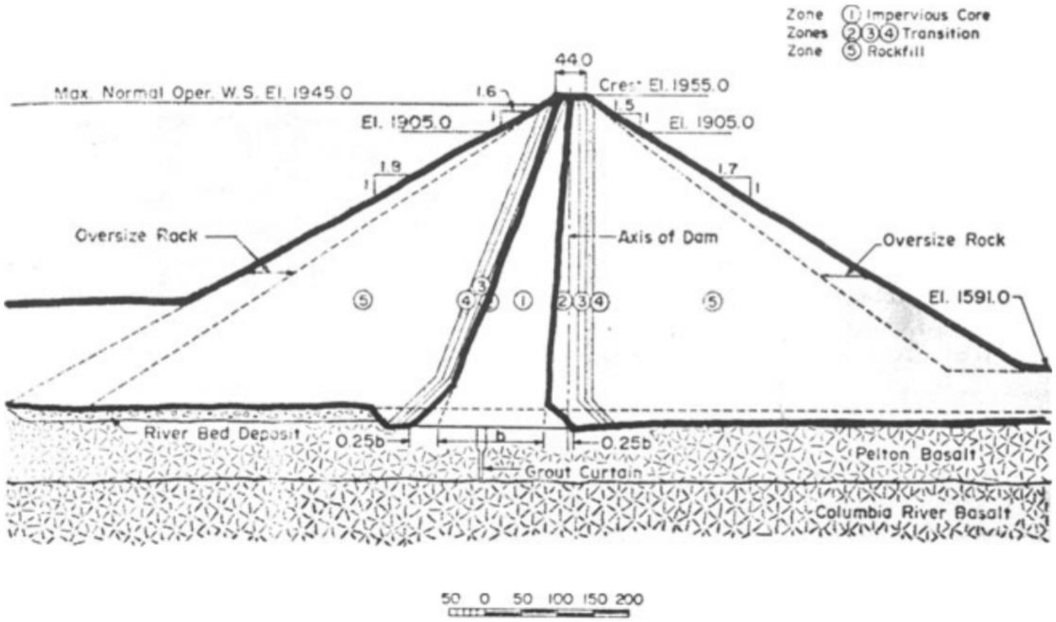

Figure 3. Plan of Round Butte Dam showing schematic of Central Core Rockfill Dam, adopted from Leps (1988).

Quantifying Discharge

Weirs are frequently used to measure volumetric flow, or discharge, in a channel with the use of stage-discharge relationships (Thorton et al., 2011). The weir equation is perhaps the most common expression used to estimate discharge:

$$Q = C_d L H_0^{\frac{3}{2}} \tag{1}$$

Where Q = discharge, C_d = discharge coefficient, L = length of the weir, and H_0 = total upstream head. The accuracy of Equation 1 is dependent on the discharge coefficient used (Brown et al., 2012; Thorton et al., 2011). A literature review completed to determine appropriate C_d for different weir cross sections can be found in Brown et al. (2012). Table 1 shows a summary of common forms of the weir equation for different types of weirs.

Table 1. Discharge weir equations for common types of weir shapes.

Weir Shape	Equation	Source	Equation
Broad-crested	$Q^{*}=CLH^{1.5}$, C: $2.34\text{-}3.32^{+}$	Brown et al. (1996)	2a
Sharp-crested, no end contractions (Trapezoidal), unsubmerged flow	$Q_{r}=CLH^{1.5}$, C: $3.27+0.4(H/H_{c})^{+}$		2b

[*] Q = discharge, C = weir coefficient, L = weir length (perpendicular to flow), H = hydraulic head above weir crest excluding velocity head, H_c = height of crest

[+] English units

Established coefficients apply mainly to impermeable weirs; consequently, standard weir coefficients do not report discharge through these structures. Studies of flow in rock weirs have focused on their ability to meet stream morphology protection goals, particularly in restoration, such as scour protection, as well as, stability and failure mechanisms (Leu et al., 2008). However, studies included in the following literature review, such as Michioku et al. (2005), Michioku & Maeno (2004), and Thorton et al. (2011), have investigated discharge through rock weirs. Mohamed (2010) studied discharge through gabion weirs, while Codell et al. (1990) studied flow in riprap, a type of rockfill cover. These works relied on older studies of turbulent flow in porous media, such as of rockfill dams, which were of interest in the second half of the 20th century, and for relatively rockier bottom streams, such as mountain streams. A comparison of the main equations to model flow in rock weirs are discussed below can be found in Table 2.

Table 2. Summary of governing parameters used in rock weir discharge equations and coefficients

Study	Weir Type	Channel Slope	Porosity	Representative Rock Diameter	Weir Height	Weir Length	Friction Factor	Stage Above Weir	Upstream Stage	Downstream Stage	Stream Width	Reynolds Number, Re	Coefficient of Correlation, R^2
Codell et al. (1990)	Armored Slope	X	X	X			X	X					0.967
Michioku et al. (2005)	Gabion	X	X	X		X			X	X			--
Mohammed (2010)	Gabion		X	X	X	X		X	X	X	X	X	0.93 – 0.97
Thorton et al. (2011)	Rock (grouted)			X	X	X			X		X		0.964 – 0.989

Through Flow

Through flow, also called seepage, interstitial, or subsurface flow, is the flow that passes within the pores of the permeable rock weir (Figure 1). Through flow can be observed when the upstream water level is below the height of the rock weir or if partial overtopping of the weir occurs before disappearing into the weir, as demonstrated by Curtis & Lawson (1967). However, through flow is also occurring—and contributing to discharge—when the weir is completely overtopped. The large voids (pores) of a rock structure (be it rock or gabion weir, rockfill dam, or rockfill cover) result in increasing turbulence, reducing the applicability of Darcy's law (Parkin et al., 1966; Lawson, 1987). Flow laws have been developed to describe non-Darcy flow, i.e. non-laminar or transitional and turbulent flows, in porous media, the two most widely accepted and used forms are as follows:

$$I = A_1 V + A_2 V^2 \tag{3}$$

$$I = A_3 V^W \tag{4}$$

where I = hydraulic gradient, V = bulk velocity in porous media, and A_1, A_2, A_3, and W are empirically or theoretically derived constants (Michioku et al., 2005). The value of W ranges from 1, representing laminar flow, to 2, representing fully turbulent flow (Curtis and Lawson, 1967; Lawson, 1987).

Stephenson (1979) determined the following equation for non-laminar flow within rockfill:

$$V = n\left(\frac{igd}{K'}\right)^{\frac{1}{2}} \tag{5}$$

where V = mean velocity through the rock, n = porosity, i = head loss gradient, g = gravity, d = representative rock diameter, and K' = dimensionless friction factor, which is defined as follows:

$$K' = K + \frac{800}{R} \tag{6}$$

where K = 1 for smooth marble, 2 for rounded gravel, and 4 for crushed rock, and R = Reynold's number. Further, Stephenson (1979) used the following equation to obtain the representative rock diameter:

$$d = \frac{1}{\sum_{i=1}^{N} \frac{p_i}{d_i}} \tag{7}$$

where p_i = the fraction of rocks of diameter d_i by mass, and N = the number of size classifications.

Codell et al. (1990) applied the equations developed by Stephenson (1979), replacing i (Eqn. 5) with the slope of rock surface, S, to model flow through armored slopes. Codell et al. (1990) referred to armored slopes in his study as layers of rip rap used to cover hazardous wastes produced by uranium mining. Although the rock layer is extensive, similar principles apply for flow through rip rap. Experimental runs were conducted in two flumes. A larger outdoor flume, 55 m (180 ft) long, 61 m (200 ft) wide, and 2.4 m (8 ft) deep, was used to test a slope of 0.2. A smaller indoor flume, 6.1 m (20 ft) long and 2.4 m (8 ft) wide, was used to test slopes ranging from 0.01 to 0.1. The armored slopes were arranged within the flumes in a manner similar to their use in covering uranium mill tailings. The slopes consisted of a 0.152 m thick sand (6 in.) filter layer covered by a 0.15 or 0.30 m thick (6 or 12 in.) rip rap layer for the outdoor flume or a 0.076 or 0.152 m thick (3 or 6 in.) rip rap layer for the indoor flume. The rip rap was placed on top of the sand layer, separated by geofabric. The nominal median stone size for the rip rap ranged from 26 to 157 mm (1 to 6.2 in.). Some runs utilized smaller sized rip rap for the filter layer of the larger rip rap. Water surface elevation, discharge, and surface and interstitial velocities were measured with salt tracer technique.

Discharge per unit width, q, was then calculated using the following equation when flow did not overtop the rip rap layer:

$$q = V_1 * H_1 + V_2 * (z - H_1) \tag{8}$$

Where z = stage measured from bottom of filter layer, V_1 = flux through the filter layer, H_1 = thickness of filter layer, and V_2 = flux through the rip rap layer (Figure 2). Flux was determined from equation 5 by solving equations 6 & 7. For convenience, calculated versus measured dimensionless discharge terms were plotted. The results show that for a given stage, the through flow model tends to overestimate flow, particularly for smaller rock diameters. Furthermore, Eqn. 5 assumes that for a given rock and slope, flux remains constant. However, the results show that stage is increasing faster than predicted, i.e. flux does not remain constant. Therefore, improved through flow modeling techniques may be necessary. Rating curves, of dimensionless stage versus dimensionless discharge, were plotted in this work and will be discussed in the overflow section.

Michioku et al. (2005) analyzed discharge through a permeable rubble mound, similar to a rock weir. This study focused on submerged flow through the weir, i.e. the flow depth is less than weir height. Contrary to the work conducted by Codell et al. (1990), Michioku et al. (2005) used an equation that takes the quadratic form of non-Darcy flow (Eqn. 3). The equation used was first proposed by Ward (1964):

$$I = \frac{\left(\frac{\nu}{gK}\right)U_s}{D_L} + \frac{\left(\frac{c}{g\sqrt{K}}\right)U_s^2}{D_T} \tag{9}$$

where ν = kinematic viscosity of water, and g = acceleration due to gravity, I = hydraulic gradient, U_s = macroscopic or apparent velocity, D_L = laminar flow component of flow resistance, D_T = turbulent flow component of flow resistance, c = dimensionless drag force coefficient (Eqn. 10), and K = permeability and was adopted from Arbhabhirama and Dinoy (1973) (Eqn. 11):

$$c = f * \left(\frac{d_m}{\sqrt{K/n}}\right)^{-\frac{3}{2}} \tag{10}$$

$$\sqrt{K} = ed_m \tag{11}$$

where $e = 0.028$, d_m = particle diameter, and $f = 100$. Michioku et al. (2005) argued that the power form (Eqn. 4) of non-Darcy flow equations had since lost popularity. Furthermore, variables (e, f) are roughness coefficients that were determined using least square correlation method. The authors opted to adopt different values for (e, f) using their own experimental and theoretical discharge measurements rather than values found in previous works to more accurately represent the flow (spatially varied pores with free water surface) occurring in the case of rock weirs.

One-dimensional analysis of steady non-uniform flow and laboratory experiments were conducted. Experimental runs were completed in two flumes; the shorter flume had a length, width, and height of 5.0 m, 0.4 m, and 0.6 m, while the longer flume dimensions were 7.0 m, 0.45 m, and 0.2 m. Each flume was outfitted with a V-notch orifice and point gauge to measure discharge and water surface profile, respectively. The rock weirs were constructed rectangular in shape to simplify the theoretical analysis. Additionally, the weirs were reinforced with wires to prevent collapse, effectively creating a gabion weir. Average grain (rock) diameter, weir length, flume slope, Reynolds number, and Froude number were varied in the runs. Experimental results were then compared to the theoretical solution (Michioku et al., 2005).

To obtain a theoretical solution for discharge, the flow profile was analyzed by conducting momentum balances for the following three regions: (1) upstream boundary, where the flow converges from an open channel into the weir pore space, (2) reach, where the flow is passing through the length of the weir, and (3) downstream boundary, where the flow diverges from the porous weir back to an open channel. Momentum balances (1) and (2) remained the same, regardless of flow type; however, the downstream boundary momentum balance changed depending on flow type. The first flow type occurs when flow on the downstream side is supercritical, while the second flow type occurs when flow on the downstream side is subcritical.

A function for normalized discharge (F_0) was then determined for each flow type from their corresponding momentum balances using one dimensional analysis. It was found that the governing parameters of discharge are:

1. Water depths on either side of the weir
2. Bed slope
3. Average rock diameter
4. Porosity
5. Weir length (parallel to flow).

Furthermore, the effect of the bed slope was found to be negligible when less than 0.01, and laminar flow component of resistance, D_L, was determined to have little effect on flow rate when upstream Reynolds number was greater than about 5,000 (Mickioku et al., 2005).

Plotting theoretical and experimental discharge, Michioku et al. (2005) found strong agreement between the measured and predicted data when flow was less than 0.003 m^3/s (0.106 cfs). At larger flows, however, greater disagreement occurred between the theoretical and experimental data. The authors argued that difficulty in measuring discharge using the larger flume or the greater influence of empirically determined constants (*e*, *f*) at higher flows may have been the cause of larger errors. The latter was a result of the turbulent flow component of resistance, D_T, having a greater effect as Reynolds number increased.

Michioku et al. (2005) included an extensive flow profile analysis, and presented an example of one discharge-curve developed from the analysis; however, a final simple, easy to use equation was not presented to practicing engineers for calculating flow through a rock weir. Consequently, a final relationship between upstream water level and discharge through a permeable weir warrants further study.

Overflow

Overflow refers to the flow which overtops the weir, i.e. passes above the height of the weir (Figure 1). It was found that flow in porous weirs is split: flow through the weir and flow above the weir (Mohammed, 2010; Michioku et al., 2004). As a result of the porosity and roughness of the rocks, as well as the interchange between the two types of flow, the overflow should not be computed as that of a standard impermeable weir. Furthermore, the characteristics of the overflow are vastly different from through flow—due to not being restrained in a porous medium—such that different methods may be necessary to determine discharge.

While Codell et al. (1990) adopted the work of Stephenson (1979) to model discharge of flow through the rip rap, the Darcy-Weisbach friction factor was used for overflow of the rock weir:

$$V = \frac{8gSY}{f}^{\frac{1}{2}} \tag{12}$$

where V = velocity, S = slope of rock surface, and Y = the water depth normal to the flow above the effective top-of-rock datum, and *f* = friction factor, adopted from Bathurst (1985) and defined below:

$$\frac{1}{\sqrt{f}} = \frac{5.62\log\left(\frac{Y}{d_{84}}\right)+4}{\sqrt{8}} \tag{13}$$

where d_{84} = the riprap diameter for which 84% of the rocks are finer. It was also found that the friction factor expression developed by Hey (1979) gave similar results for velocity, V:

$$\frac{1}{\sqrt{f}} = 2.03\log\left(\frac{\alpha Y}{3.5d_{84}}\right) \tag{14}$$

where α ranges from 11.08 to 13.46. Codell et al (1990) used a value of 11.08 for wide, flat channels.

Equation 12 assumes some flow within the riprap. Consequently, the effective top-of-rock datum, where Y = 0, is below the physical top of the weir. Codell et al. (1990) defined the effective datum as the point where flux within the rock layer, V_2 (Eqn. 5), equals flux in the overflow layer, V_3 (Eqn. 12), at the physical top of weir. To determine the effective top-of-rock datum, Codell et al. (1990) equated V_2 and V_3 at $Y = \Delta H$, the stage at physical top of weir and iteratively solved for ΔH (Figure 2). In later works, Rice et al. (1998) found that effective top-of-rock datum can be adequately estimated to be where 95% of the riprap is covered by water for constructed channel slopes ranging from 0.028 to 0.33. The following equation was then used to develop a rating curve for flow overtopping the rock weir:

$$q = V_1 H_1 + V_2 H_2 + V_3 (z - H_1 - H_2) \tag{15}$$

where H_2 = thickness of riprap layer and V_3 = flux in overflow layer (Figure 2). It was found that overflow is typically larger than through flow and, consequently, tends to control total discharge. No significant difference between the abilities of Eqn. 13 & 14 (friction factor) to predict flow was observed. The model demonstrated good agreement with the measured data when overflow occurs, with coefficient of correlation r = 0.967; however, the iterative calculation for effective top-of-rock may be found as a hindrance to the design process by practicing engineers. Additionally, the estimate of effective top-of-rock determined by Rice et al. (1998), unfortunately, does not encompass the lower range of water slopes occurring in mitigation wetlands, where rock weirs are commonly used to control flow.

In their later work, Michioku & Maeno (2004) investigated the case whereby flow overtops the rock weir. A similar experiment was conducted as in Michioku et al. (2005); however, slope remained constant. The flow was found to be split into two parts: the upper layer (overflow) and the lower layer (through flow). Momentum balances were completed to determine an equation for dimensionless discharge, using dimensional analysis. Results show that discharge decreased when the height and depth of weir increased, but increased when rock diameter increased.

Mohamed (2010) investigated flow through and over gabion weirs to determine discharge as a function of parameters including flow depth, porosity, rock diameter, and weir dimensions. Two flow types were investigated: free surface flow and submerged flow. Experiments were conducted in two flumes: the first was a 10 m long flume with height and width both equal to 0.3 m, while the second was a 17 m long flume with height of 0.5 m and width of 0.3 m. Gabion weir baskets were constructed from steel rods and metal wire screen to fit each flume. Additionally, solid concrete broad crested weirs of similar dimensions as the gabion weirs were constructed and tested for comparison. Weir height and depth, Reynolds number, and Froude number were varied in the experimental runs; further, gravel of three different average diameters were tested.

Dimensional analysis and transformation were used to determine non-dimensional discharge, F_0. Three non-dimensional parameters were developed for discharge for free surface flow and submerged flow, as well as, a fourth parameter that applies to the latter only:

$$\frac{Q}{\sqrt{g}By_1^{1.5}} = \Phi\left(\frac{Q\rho}{B\mu}, \frac{H}{L}, \frac{d_m}{P}, \frac{y_1 - y_2}{H}\right) \tag{16}$$

where Q = discharge, g = acceleration due to gravity, B = channel width, y_1 and y_2 are depth up and downstream of the weir, ρ = fluid density, μ = fluid dynamic viscosity, H = water head above weir, L = length of weir in the direction of flow, d_m = mean rock diameter, P = weir height, non-dimensional discharge, $F_0 = \frac{Q}{\sqrt{g}By_1^{1.5}}$, Reynolds number, $Re = \frac{Q\rho}{B\mu}$, and $S_r = \frac{y_1 - y_2}{H}$. S_r only applies to submerged flow (Mohamed, 2010).

Through multilinear regression analysis the following equations were determined for dimensionless discharge of free surface flow (Eqn. 17) and submerged flow (Eqn. 18):

$$\frac{q}{\sqrt{gy_1^{1.5}}} = -0.37 + 0.095 \log R_e + 0.063 \frac{H}{L} + 0.114 \frac{d_m}{P} \tag{17}$$

$$\frac{q}{\sqrt{gy_1^{1.5}}} = -0.41 + 0.105 \log R_e + 0.031 \frac{H}{L} + 0.057 \frac{d_m}{P} + 0.018\, S_r \tag{18}$$

The value of R^2 was greater for free surface versus submerged flow (0.97 versus 0.93). Additionally, a standard solid weir discharge equation (Eqn. 19) was analyzed for their study:

$$Q = \frac{2}{3} c_d B \sqrt{2g} H^{1.5} \tag{19}$$

where $C = \frac{2}{3} c_d$. Regression analysis was once again used to develop an equation for gabion weir coefficient, C, for free surface flow (Eqn. 17) and submerged surface flow (Eqn. 18), as a function of the non-dimensional parameters of discharge:

$$C = -1.31 + 0.47 \log(R_e) - 0.84 \frac{H}{L} + 1.01 \frac{d_m}{P} \tag{20}$$

$$C = -1.77 + 0.55 \log(R_e) - 0.78 \frac{H}{L} + 0.35 \frac{d_m}{P} + 0.085 S_r \tag{21}$$

This study found that, for a given discharge, the head over the gabion weir decreased with increase in particle size. Furthermore, when comparing porous and solid weirs, for equal discharge, the head over the weir was greater in solid weirs. Equations for discharge over solid weirs did not accurately predict discharge through the gabion weir; however, these solid weir discharge equations could be used if appropriate gabion weir discharge coefficients are used (Mohamed, 2010).

While the previous works focused more on broad-crested weirs, Thorton et al. (2011) aimed to develop stage-discharge relationships for A-, U-, and W- rock weirs (a.k.a. “alphabet weirs”). Scaled prototype weirs were built in a flume 15.22 m long, 4.88 m wide, and 1.22 m in height. Tests were conducted under subcritical, unsubmerged flow conditions, and bed slope and/or material and rock size was varied with each weir type. Rocks were grouted to ensure all flow passed above the weir, preventing flow within the pores of the rocks. Flows at 1/3 bankfull, 2/3 bankfull, and bankfull were modeled. A general dimensionless stage-discharge relationship was developed for rock weirs from equations for broad crested weirs developed in previous studies:

$$Q = \frac{2}{3} b_i C_d (2g)^{0.5} (y_{us} - z_i)^{\frac{3}{2}} \tag{22}$$

where Q = discharge, b_i = effective length along the weir crest (i.e. the width of the rock weir that was submerged), C_d = discharge coefficient, y_{us} = upstream flow depth, and z_i = mean weir height. Dimensional analysis was conducted to obtain an expression for C_d, which is unique to each weir:

$$C_{U,A,W,d} = \alpha \left[\frac{d_{50}}{z_i}\right]^b \left[\frac{b_i}{B}\right]^c \tag{23}$$

Where α, b, and c are regression constants, d_{50} = median crest stone size, and B = stream width. Multivariable regression analysis was used to obtain values of C_d for each weir shape, and a similar regression was then conducted to obtain a general value for C_d. Discharge coefficients, unique to each weir shape, had desired mean percent error less than 5%; however, that of the composite C_d was equal to 12%. The rock weirs designed in Thorton et al. (2011) differed from those that were the focus of this research in two main ways: the rock weirs were grouted (not typical in engineering design), which does did not account for flow through the weirs and the weirs were built with a longitudinal slope, which was not a focus of this research.

Connection to Wetbud

Wetland Definition

Wetlands are unique ecosystems that come in many different forms but share the distinct feature of having anaerobic soil conditions for extended periods during the growing season that support wetland vegetation. The current definition of wetlands used by the United States Army

Corps of Engineers (ACE) and the United States Environmental Protection Agency (EPA) is taken from the federal regulatory 404 Program Definitions (2015), and it reads as follows:

> "Wetlands are areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs, and similar areas."

The three major characteristics of wetlands associated with this definition are appropriate hydrology, hydric soils, and hydrophytic vegetation. Wetlands types vary greatly as a result of the different representations of the aforementioned characteristics, and different methods exist to further classify types of wetlands, including Brinson (1993), Cowardin et al. (1979), and Mitch and Gosselink (2015) among others.

Wetland Value

Wetlands provide a variety of ecosystem services as a result of the functions that arise from their unique, defining characteristics. These ecosystem functions are only considered services (and thus having value) if they provide benefits to humans and society. Functions include aquifer buffering, water quality control, nutrient cycling, habitat for wildlife, biomass production, flood protection, and stabilization of sediment. Services, i.e. the benefits to humans, garnered from these functions include increased water quantity, improved fisheries and wildlife on and off site for commercial or recreational purposes, reduction in water purification and flood or storm damage costs, and erosion control (Woodson and Wui, 2001).

Globally, Costanza et al. (1997) valued wetlands at \$14,785 ha^{-1} yr^{-1}, with water regulation, disturbance regulation, and water supply being the top three services obtained from these ecosystems. Examples of studies at more local scales include Sharma et al. (2015) in Asia and Meenakshi et al. (2016) in the USA. Sharma et al. (2015) valued the Koshi Tappu Wildlife Reserve (KTWR) in eastern Nepal at \$16 million yr^{-1}. KTWR is located on the floodplains of the Koshi Sapta River, and is comprised of different types of wetlands such as marshes, oxbows lakes, swamp lakes, and depressional wetlands. The study valued ten provision services, including fish, timber, and floodplain agriculture, flood protection, carbon sequestration, and tourism, but it was unable to value regulating services, such as water protection due to lack of information on these ecosystem services. Meenakshi et al. (2016) found that the total economic value of carbon stored in the Everglades National Park, alone, ranges from \$2 – \$3.4 billion. Furthermore, Peh et al. (2014) compared the value of services provided by a restored wetland to those of the previous farm land and found a net gain of \$199 ha^{-1} yr^{-1}.

The value of wetlands has resulted in a range of federal policies, such as the “no net loss” of wetlands and permitting under the Clean Water Act, that have placed rules on the degradation, destruction, and subsequent rehabilitation of wetlands (Wigham, 1999). The concept of wetland mitigation is defined in the Federal Register as “the restoration, creation, enhancement and, in exceptional circumstances, preservation of wetlands and other aquatic resources expressly for the purpose of providing compensatory mitigation in advance of authorized impacts to similar resources” (Brown & Lant, 1999).

What is Wetbud?

Wetbud is a wetland water budget modeling software. It was developed through the collaboration of faculty from Old Dominion University, University of Kentucky, and Virginia

Tech. Wetbud was developed with the funding from and cooperation of Wetland Studies and Solutions Inc. (WSSI), The Peterson Family Foundation, and the Resource Protection Group, Inc. Wetbud was created to provide wetland designers with a tool to more quickly and easily estimate the water budget of a wetland project to ensure compliance with wetland mitigation regulations. The wetland water budget refers to the wetland hydroperiod, which is the seasonal variation in water levels (in both the surface and soil) of a wetland. Wetbud has two main models: Basic and Advanced. The Basic model is a 2-D version, while the Advanced model incorporates MODFLOW (Harbaugh et al., 2005) to create a 3-D version with advanced groundwater modeling capabilities. The focus of this research, however, was to improve the weir-related surface water flow component of the Basic 2-D model.

Wetbud (either model) requires the user to first create a project. When using the Basic model, and if projects are located in the state of Virginia, the Project Wizard can be used to facilitate set up. The user must input the wetland's project information: latitude and longitude, area, surface elevation, curve number, and watershed area. The Project Wizard allows for use of preloaded weather databases. To calculate the water budget, the water inputs and outputs are summed. In the Basic model, inputs include precipitation, runoff, initial fill depth, overflow (from an adjacent stream), and groundwater inflow, while outputs are evapotranspiration (ET), surface water outflow and groundwater outflow. Wetbud also allows the user to select the inflow weir structure, which controls overflow from a local stream. Currently, the user has three options for inflow structure: broad-crested weir, cipoletti weir, or trapezoidal weir. Because rock weirs are commonly used structures in wetland restoration projects, the results of this research will be applied to Wetbud to improve the accuracy of water budget calculations.

Summary

Rock weirs provide environmental and ecological benefits in stormwater, dam, and ecological restoration design that may not be provided by standard impermeable weirs. Few studies have been conducted that evaluate actual stage-discharge relationships across a rock weir. Of the works reviewed above, two studies used dimensional analysis to obtain dimensionless discharge using the Froude number. Additionally, regression analysis was used to obtain a value for a discharge coefficient that can be used in a standard weir equation. It was determined that flow in a porous weir is split into two components: flow through the weir and flow above the weir. Furthermore, it was found that the geometry of the weir and rock size are properties of the weir itself that influence discharge. However, the experiments were conducted in flumes in a laboratory, and field data were not tested. Additionally, of the studies described above, one grouted the rock weir to remove the through flow component while forcing flow over the weir, and two placed the rocks in steel baskets, giving them a rigid cuboid shape. Consequently, the lack of literature indicates that the derivation of actual discharge coefficient for rock weirs should be further investigated.

Chapter 3: Methods

Scaling Methods

Wetland Studies and Solutions, Inc. (WSSI) provided plans for the North Fork Wetlands and Stream Bank (established 1998; 38°49’30”, 77°40’45”) (Figure 4). The plans, as well as experience from committee members, were used to determine appropriate dimensions to be used in the flume experiment (Table 3). A 10:1 physical scaling of rock weirs, similar to those used in mitigation wetlands (Figure 5, Figure 6), was then created in a laboratory flume.

Figure 4. Google maps satellite image of North Fork Wetlands and Stream Bank located in Prince William County, Virginia, USA.

Table 3. Dimensions used to create scaled rock weir configurations.

Dimension	Real-World (1:1) Sizing	Model Scale (10:1) Sizing
Length (m)	1.52, 3.05, 4.57	0.152, 0.305, 0.457
Depth (m)	1.52, 3.05	0.152, 0.305
Bed Slope (%)	0, 0.5, 1.0	0, 0.5, 1.0
d_{min} (mm)	152, 305	12.7, 19.1, 25.4

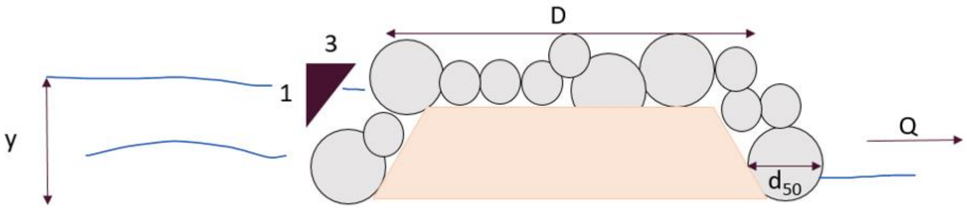

Figure 5. Schematic showing side view of rock weir, where Q = discharge, y = upstream depth, D = depth of weir, d_{min} = minimum rock diameter.

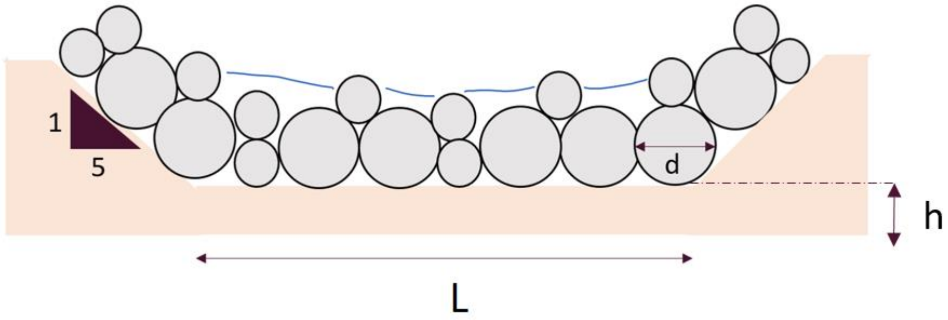

Figure 6. Schematic showing cross sectional view of rock weir, where L = length of weir crest, and h = weir height of clay core only.

Buckingham Pi Analysis

A Buckingham Pi analysis (see detailed analysis in Appendix A: Buckingham Pi Analysis) was conducted in order to develop a set of dimensionless parameters that describe the flow of water through rock weirs. Table 4 lists the variables used and corresponding dimensionless parameters, called Pi terms, resulting from the analysis. The variables selected for this analysis were determined from the information derived from the literature review.

Table 4. Parameters and resulting pi terms describing the flow through porous rock weirs.

Variables	Q, v, h, L, D, y, H, d_{50}, g, ρ, μ
Π Terms	Fr, Re, d_{min}/h, D/h, H/h, L/h, S

* v is water velocity; h is weir height of the clay core only; L is weir crest length (perpendicular to flow; cross-stream direction); D is weir depth (parallel to flow; streamwise direction); y is water depth upstream of weir; d_{min} is minimum rock diameter; g is gravity; ρ is water density; μ is water viscosity; Fr is Froude No.; Re is Reynolds No.; and, H is upstream hydraulic head, y-h.

Flume Methods

An 8.0 m x 1.0 m x 0.4 m recirculating hydraulic flume (Engineering Laboratory Design, Inc., Minneapolis, MN, USA) was used to conduct the laboratory experiments. A scaled model of rock weirs was created within the test section of the flume, located between 4.5 m and 6.0 m along the flume channel. The core of the flume was constructed from Highwater Little Loafer's Stoneware Cone 6 clay (Asheville, NC, USA; Figure 7). A total of six unique core configurations were created using the depth and length dimensions described in Table 3.

Figure 7. Rock weir core, constructed from porcelain clay. Configuration: depth= 0.305 m (1.0 ft.), length = 0.152 m (0.5 ft.), bed slope = 0%.

Table 5. Dimensions of unique core rock weir configurations constructed in the flume, where weir length is the center dimension normal to flow direction and weir depth is the center dimension parallel to the flow.

Core Configuration	Length (m)	Depth (m)
1	0.152	0.152
2	0.152	0.305
3	0.305	0.152
4	0.305	0.305
5	0.457	0.152
6	0.457	0.305

The clay core was then covered with a layer of rocks of minimum diameter (d_m) 12.7 mm (0.5 in.), 19.1 mm (0.75 in.), or 25.4 mm (1.0 in.) (Figure 8). Crushed stone, #3 and 57, was obtained from a nearby quarry. The appropriate rock class sizes where then collected by using 20.3 cm (8 in.)

stainless steel test sieves (VWR, Radnor, PA, USA) ranging from 19.1 mm (¾ in.) to 76.2 mm (3 in.) (Table 6).

Table 6. Mean rock diameter and rocks diameter ranges for stones used in flume experiments.

Crushed Stone #	d_{min}(mm)	d_{min} Range (mm)
3	25.4	25.4 – 31.8
57	12.7	12.7 – 19.1
	19.1	19.1– 25.4

Figure 8. Completed rock weir configuration (Depth = 0.305 m (1.0 ft.), Length = 0.152 m (0.5 ft.), d_m= 12.7 mm (0.5 in.), bed slope = 0%).

Once flow was fully developed, discharge measurements were taken at five water stages (Figure 9) using an orifice meter connected to the flume. Equation 24 was used to calculate discharge from the orifice meter:

$$Q = 0.0013\sqrt{\frac{\Delta p}{12}}$$

where Q = discharge (m^3/s), Δp = change in pressure (in. of H_2O)

Flow was considered fully developed when the water surface elevation remained constant for a 10-minute period. Two discharge measurements were taken at water levels that were below the rocks on the weir crest, i.e. water flowed within the rocks and a continuous water surface had not formed on the weir crest (stages 1 and 2 in Figure 9). The remaining three discharge measurements were taken at water levels flowing above the rocks on the crest, when a continuous water surface had formed on the weir crest (stages 3, 4, and 5 in Figure 9; Table 7). The highest water stage at which measurements were taken was when the entire core of the weir was covered. Higher stages were not utilized in order to reduce sidewall effects. The slope of the flume channel was then varied, as shown in Table 3, for each weir configuration.

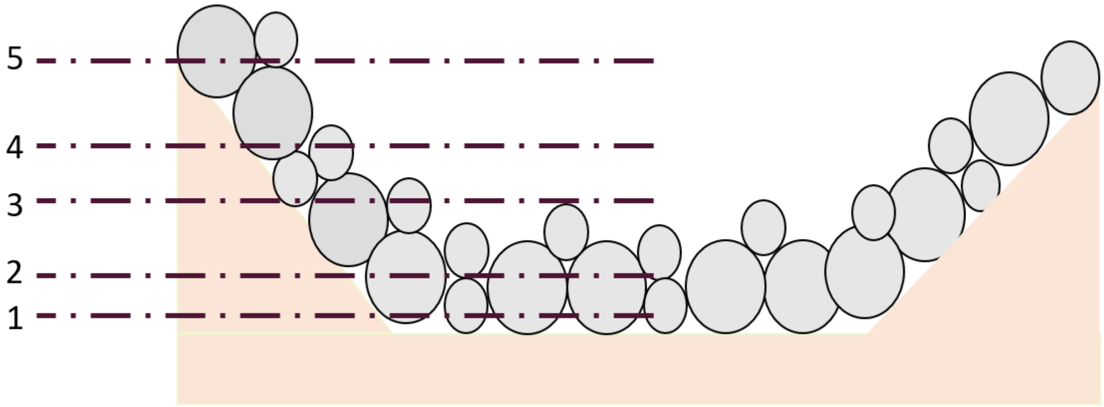

Figure 9. Five water stages at which measurements were taken for each rock weir configuration.

Table 7. Description of water stages at which discharge measurements were collected.

Water Stage	Description	Velocity Measured?
1	a continuous surface has not formed, rocks on weir crest less than ½ covered	NO
2	an emerging, discontinuous water surface can be seen across weir crest, rocks on weir crest more than ½ covered	NO
3	a continuous water surface has formed across weir crest, all rocks on weir crest have been completely covered	NO
4	water has covered halfway up the side slope of the weir	YES*
5	water has covered the top of the weir core	YES*

* Velocity measurements can only be collected for weir configurations with 0.152 m (0.5 ft) length

In addition to discharge measurements, surface water elevation and velocity measurements were collected at each water stage at the center of the width of the channel. Surface water measurements were collected using a point gage, which was zeroed 15.2 cm (6.0 in.) upstream of the edge of the weir. The point gage was only zeroed for each unique core and rock configuration. Upstream depth measurements, used to calculate hydraulic depth, were then taken, also at 15.2 cm (6.0 in.) upstream of the edge of the weir. Additionally, depth measurements were taken at the center of the weir and immediately upstream of the first ripples to appear along the weir length. Furthermore, three water depth and bed measurements were collected 84 cm (33.1 in.), 184 cm (72.4 in.), and 284 cm (112 in.) upstream of the weir to determine bed and water surface slope. Velocity measurements were also recorded 15.2 cm (6.0 in.) upstream using a Vectrino II acoustic Doppler profiler (Nortek, Vangkroken 2, Rud, Norway). Velocity measurements could only be collected when the upstream depth was greater than approx. 7.1 cm (2.8 in.) because the probe needed to be fully submerged for data collection. Therefore, the Vectrino II probe was used only for discharges 4 & 5 of weirs with 0.152 m (0.5 ft) length. Similarly, discharge, water surface, and velocity measurements were obtained for the core of the weir at each slope with no rocks present.

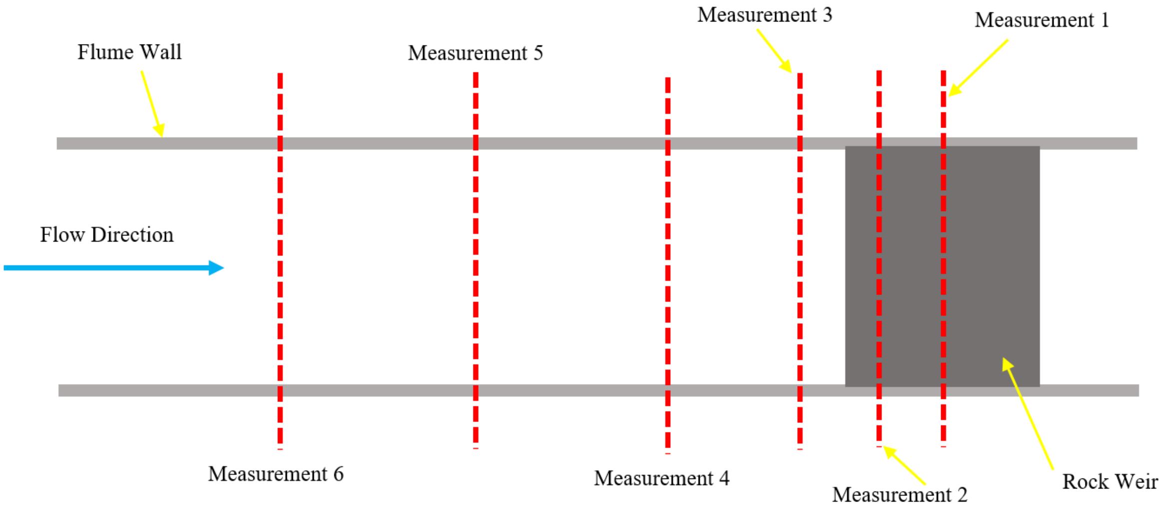

Figure 10. Schematic showing the location of measurements recorded along flume, where Measurement 1 = water depth at center of rock weir (mm), Measurement 2 = water depth at location of first riffle formation (mm), Measurement 3 = water depth upstream of rock (mm), Measurement 4 = (slope measurement 1) water depth and depth to bed (mm), Measurement 5 = (slope measurement 2) water depth and depth to bed (mm), Measurement 6 = (slope measurement 3) water depth and depth to bed (mm).

Statistical Methods

The programming language R (R Core Team, 2018) was used to conduct linear regressions to develop a formula that predicts the discharge coefficient of rock weirs from dimensionless parameters. Linear regressions were conducted using the log of equation 25 to determine overall equations for discharge. The results of the linear transformation of equation 25 is presented later on in equation 31. Additionally, linear regressions were conducted to explore relevant Pi terms that describe discharge. Rock weir configurations were grouped by width, length, mean rock diameter, as well as, by width, length, mean rock diameter, and slope. Linear regressions were conducted to determine the discharge coefficient and exponent of each unique subset of weir configuration, using equation 25:

$$Q = C_d L H^b \tag{25}$$

where, Q is discharge (m^3/s), C_d is discharge coefficient, L is weir crest length perpendicular to flow (m), H is hydraulic height (m), and b is exponent. A linear regression was then conducted to determine a formula for the discharge coefficient. Variance inflation factors (VIFs) were used to assess multicollinearity between PI terms. Separate regressions were conducted for parameters that had VIF values greater than 10. The adjusted R^2 was used to determine the best combination of Pi terms that predict the discharge coefficient. Adjusted R^2 describes the prediction ability of the model, considering additional independent variables.

Chapter 4: Results and Discussion

Flume Results

Six unique core configurations were constructed in the flume (Table 5). Each unique core configuration was then covered with rock and subsequently tested at five water stages (Figure 9) at three different slopes; this process was repeated for three different rock sizes (Table 6), resulting in 270 flume runs of weirs with rock. Table 8 shows a summary of measurements for the experimental flume runs. The six core configurations were also tested without rock at three water levels (No. 3, 4, & 5; Figure 9) resulting in 54 flume runs of weir with no rock. A summary of the range of measurements are provided in Table 9. Detailed results for each rock weir are presented in Appendix B: Data Collection. Generally, the flow upstream of the weirs was subcritical and transitioned to supercritical downstream of the weirs. As discharge increased, the flow upstream of the weir was more turbulent and surface waves formed; additionally, the turbulence increased as weir length increased.

Table 8. Range of flow rate, water surface slope, and hydraulic depth measurements for each water stage for all rock weirs, where NM = not measurable (slope was close to 0). The top of each weir was chosen as the top of the clay core.

Water Stage	Flow Rate (m^3/s)	Water Surface Slope (%)	Water Depth above Weir (mm)
1	0.00013 – 0.00049	NM – 1.2	4.56 – 31.48
2	0.00021 – 0.00072	NM – 1.2	16.89 – 50.48
3	0.00081 – 0.00172	NM – 1.2	28.51 – 63.10
4	0.00153 – 0.00614	NM – 1.1	36.71 – 89.10
5	0.00131 – 0.00971	NM – 1.2	47.33 – 91.89

Table 9. Range of flow rate, water surface slope, and hydraulic depth for each water stage for weirs with no rock, where NM = not measurable (slope was close to 0). The top of each weir was chosen as the top of the clay core.

Water Stage	Flow Rate (m^3/s)	Water Surface Slope (%)	Water Depth above Weir (mm)
3	0.00014 – 0.00088	NM – 0.7	1.03 – 14.51
4	0.00507 – 0.00951	NM – 1.7	24.2 – 62.33
5	0.01198– 0.01981	0.001 – 1.1	33.75 – 88.65

Median rock diameters used in weir configurations were similar in size to the ranges used in Mohamed (2010), which used rock of mean size ranging from 2.8 to 29 mm, and Michioku et al. (2005), which used rock of mean size ranging from 19.1 to 41.1 mm. Discharge values were within the range of the smaller flume used in Michioku et al. (2005), which ranged from 0.0001 to 0.00172 m/s.

Seven dimensionless parameters were developed to predict the discharge coefficient of rock weirs (Eqn. 25). The parameters were calculated using the measured flow rate, water surface slope, and water depths. Hydraulic head was calculated by subtracting the height of the weir core from the upstream water depth. Table 10 and Table 11 show the range of each parameter for each water stage for rock weirs and weirs with no rock, respectively.

$$\frac{Q}{\sqrt{gh}\,(Lh)} = \Phi\left(\frac{\rho v h}{\mu}, \frac{d_{50}}{h}, \frac{D}{h}, \frac{H}{h}, \frac{L}{h}, S\right) \qquad (26)$$

Table 10. Range of dimensionless parameters for all rock weirs.

Water Stage	Fr No.*	Re No.	d_{50}/h	D/h	H/h	L/h	S
1	0.0896 – 0.470	51.45 – 277.9	0.9442 – 2.002	11.33 – 24.02	0.3593 – 2.481	11.33 – 36.03	NM – 0.012
2	0.1129 – 0.528	140.0 – 533.9	0.9442 – 2.002	11.33 – 24.02	1.331 – 3.978	11.33 – 36.03	NM – 0.012
3	0.268 – 1.027	522.3 – 1337	0.9442 – 2.002	11.33 – 24.02	2.247 – 4.916	11.33 – 36.03	NM – 0.012
4	0.365 – 3.43	2450 – 30116	0.9442 – 2.002	11.33 – 24.02	2.893 – 6.922	11.33 – 36.03	NM – 0.011
5	0.319 – 5.27	3785 – 27302	0.9442 – 2.002	11.33 – 24.02	3.730 – 7.241	11.33 – 36.03	NM – 0.012

* Re No. = $\rho vh/\mu$, Fr No. = $Q/(g^{0.5}\ h^{1.5}L)$, d_{50} is median rock diameter, is weir height, D is weir depth (parallel to flow), H is upstream hydraulic head, L is weir crest length (perpendicular to flow), S is water surface slope, and NM = not measurable (close to 0).

Table 11. Range of dimensionless parameters for weirs with no rock.

Water Stage	Fr No.	Re No.	D/h	H/h	L/h	S
3	0.1733 – 0.986	49.42 – 3307	11.33 – 24.02	0.0812 – 1.144	11.33 – 36.03	NM – 0.007
4	1.759 – 5.89	3398 – 8536	11.33 – 24.02	1.908 – 4.634	11.33 – 36.03	NM – 0.017
5	3.05 – 10.86	8338 – 22083	11.33 – 24.02	2.660 – 6.986	11.33 – 36.03	0.001 – 0.011

* Re No. = $\rho vh/\mu$, Fr No. = $Q/(g^{0.5}\ h^{1.5}L)$, d_{50} is median rock diameter, is weir height, D is weir depth (parallel to flow), H is upstream hydraulic head, L is weir crest length (perpendicular to flow), S is water surface slope, and NM = not measurable (close to 0)

Statistical Analysis

As described in the Chapter 3: Methods, a regression analysis was conducted to develop an equation that predicts the discharge coefficient of rock weirs. The outputs from the statistical tool R are found in Appendix C: R Outputs.

Discharge as a Function of Pi Terms

To explore the relevant dimensionless parameters, their influence on discharge, and how it may change due to the presence of rock and the type of flow (low versus high), a linear regression study was conducted to model dimensionless discharge as a function of the remaining six Buckingham Pi terms. Unlike Mohamed (2010), the intercept of the equation was set to 0 and the log of dimensionless discharge was used in the regression to obtain a linear fit (Eqn. 27a). Similar terms as found in Mohamed (2010) – including the upstream head, weir length and width, Reynolds No., median rock diameter, and slope – were significant in predicting dimensionless discharge. However, the coefficients of the dimensionless parameters in this study were relatively smaller, by more than a magnitude, except for channel slope, which was greater by more than a magnitude. However, discharge values in this study were mostly below the range used in Mohamed (2010). Through further analysis, it was determined that not including the channel slope (Eqn. 27b) in the regression produced a comparable adjusted R-squared value of 0.941 to that of equation 27a. Because mitigation wetlands are typically built to have low bed slopes, and the water surface slope develops from difficult to predict parameters, such as vegetative resistance, engineers may find equation 27b more suitable. Figure 11Figure *11* shows a plot of predicted dimensionless discharge versus the log of observed dimensionless discharge, where negative values indicate dimensionless discharge values less than 1.

The data were then broken down by low and high flows to determine whether significant changes to the flow regime occurred as upstream water head increased. Low flows were defined as occurring when a continuous water surface had not formed above the rocks on the center of the weir crest (Stages 1 and 2 in Figure 9), while high flows were defined as occurring when a continuous water surface had formed (Stages 3, 4, and 5 in Figure 9). Similar to the overall discharge equation (Eqn. 27), the log of dimensionless discharge was taken to improve the homoscedasticity of the regression residuals for the high flows (Eqn. 29); on the other hand, it was not necessary to take the log of dimensionless discharge for low flows (Eqn. 28). These results align with the conclusion of Michioku and Maeno (2004): flow through and above the permeable rock weir require different equations. A summary of results are in Table 12. The p-values for all the regressions and coefficients were <0.05, indicating that the values are statistically significant. P-values for each regression are found in Appendix C: R Ouputs. Figure 12 plots predicted discharge against observed discharge for low flows, while Figure 13 plots predicted discharge against the log of observed discharge for high flows.

Table 12. Results of linear regression for all, low, and high flow regimes of rock weirs as a function of dimensionless parameters.

Flow Condition	Equation	R^2	Eqn.
Overall	$\log\left(\frac{Q}{\sqrt{gh}(Lh)}\right) = 0.0000256\,Re - 0.678\frac{d_{50}}{h} - 0.0325\frac{D}{h} + 0.443\frac{H}{h} - 0.0297\frac{L}{h} + 11.96\,S$	0.931	(27a)
Overall (no slope)	$\log\left(\frac{Q}{\sqrt{gh}(Lh)}\right) = 0.000026\,Re - 0.66\frac{d_{50}}{h} - 0.0313\frac{D}{h} + 0.444\frac{H}{h} - 0.0293\frac{L}{h}$	0.929	(27b)
Low	$\frac{Q}{\sqrt{gh}(Lh)} = 0.0939\frac{H}{h} + 8.515\,S$	0.908	(28)
High	$\log\left(\frac{Q}{\sqrt{gh}(Lh)}\right) = 0.0000249\,Re - 0.538\frac{d_{50}}{h} - 0.01822\frac{D}{h} + 0.388\frac{H}{h} - 0.0370\frac{L}{h} + 15.81\,S$	0.953	(29)
No Rock	$\frac{Q}{\sqrt{gh}(Lh)} = 0.000271\,Re + 0.6\frac{H}{h} - 0.0352\frac{L}{h} + 89.3\,S$	0.945	(30)

[*] Re No. = ρvh/μ, d_{50} is median rock diameter, is weir height, D is weir depth (parallel to flow), H is upstream hydraulic head, L is weir crest length (perpendicular to flow), and S is water surface slope

Interestingly, the minimum rock diameter, d_{min}, does not play a significant role in predicting low flow discharges through rock weirs, but it does so at higher flows. At higher flows, the rocks introduce a greater roughness factor. This contradicts results of Michioku et al. (2005), which found the median rock diameter to be a significant parameter. However, equation 29 (high flows) is consistent with previous studies, including Mohamed (2010), which only tested water stages completely above the rock weir. The low water stages were more difficult to achieve because the pump was performing at its lowest range for experimental runs. Therefore, there was greater error at low flows, which would contribute to median rock diameter not being statistically significant; additionally, only two low stages were used in experimental runs.

Additionally, the equation for weirs with no rock component indicated the weir length and water depth above weir are significant parameters for predicting discharge over the weir. These parameters are identical to those in the standard weir equation. This finding indicates that the rocks significantly influence flow characteristics such that the water surface slope, median rock diameter, and weir depth have a significant effect on discharge. The addition of the rocks to the weir surface – done to prevent erosion of earthen weirs – increases flow resistance, which then controls the water surface slope, maintaining subcritical flow upstream of the weir, while the weir depth may be indicative of the surface area that rocks cover on the weir.

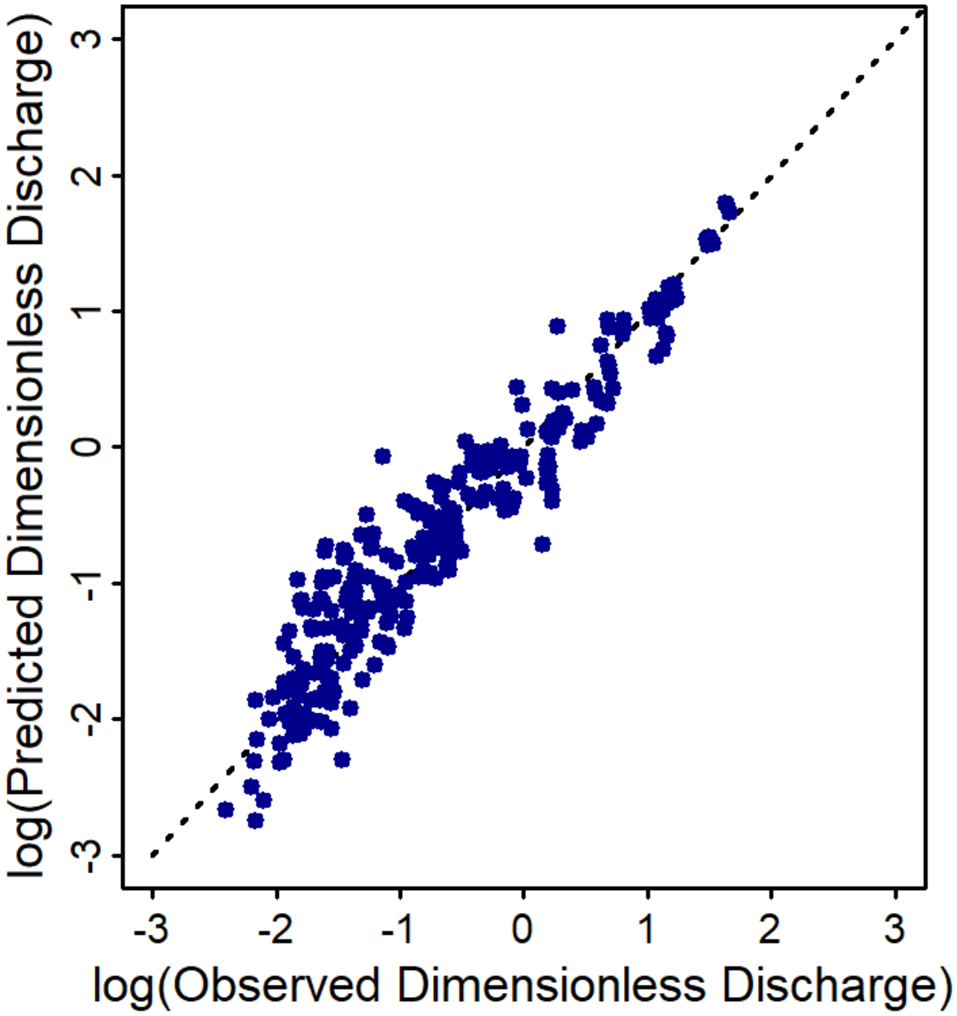

Figure 11. Log of predicted versus log of observed dimensionless discharge for all flow conditions of rock weirs.

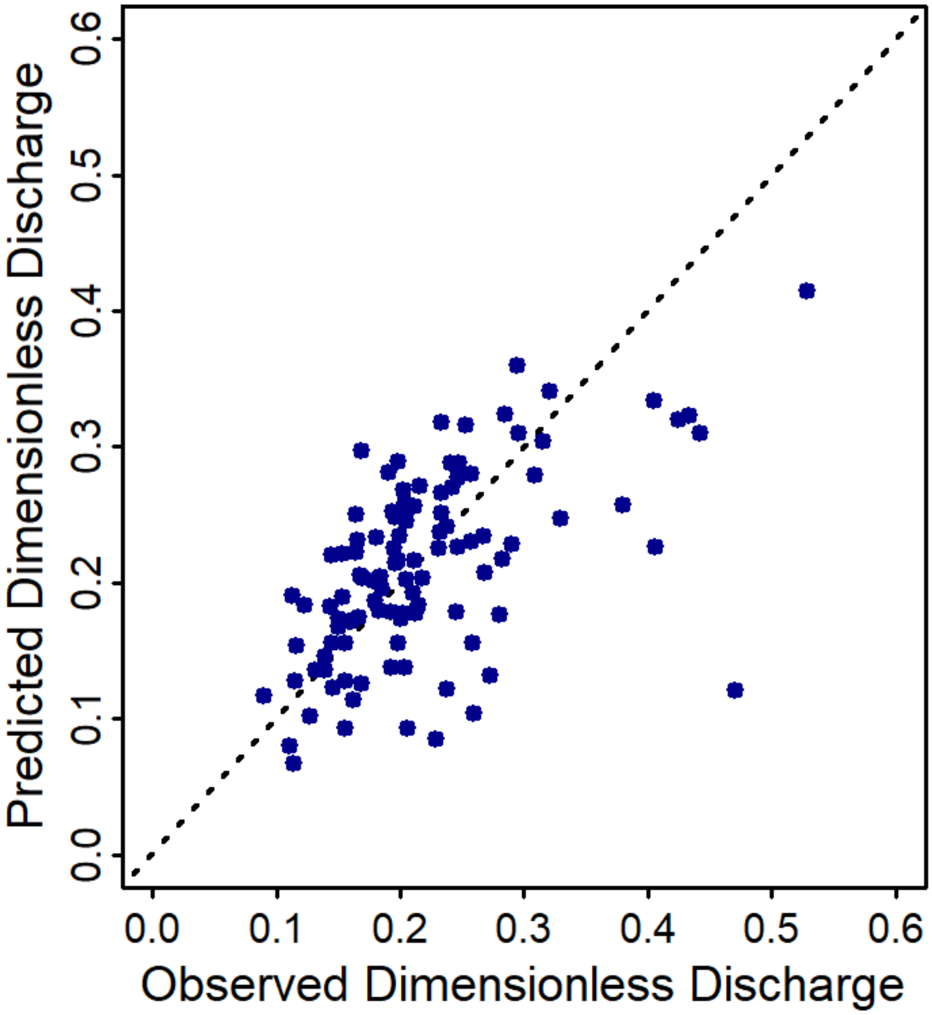

Figure 12. Predicted versus observed dimensionless discharge for low flow conditions of rock weirs.

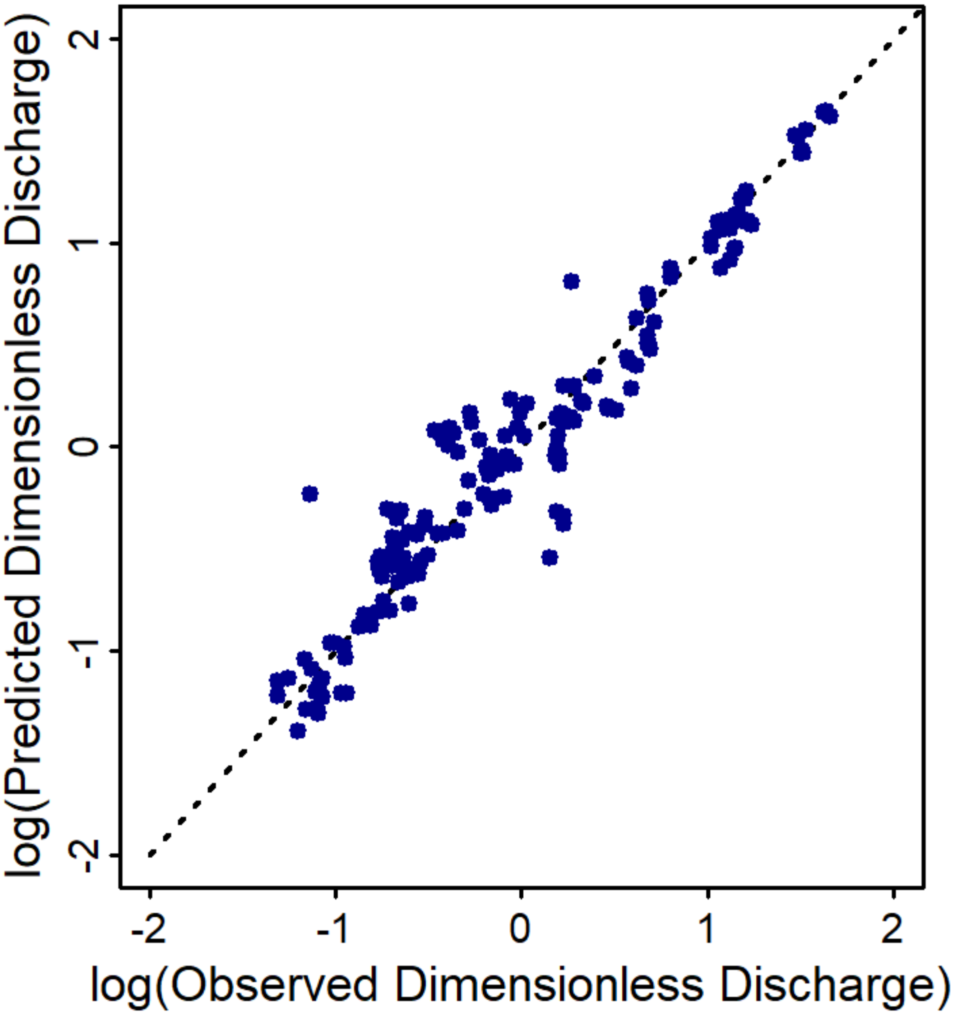

Figure 13. Log of predicted versus log of observed dimensionless discharge for high flow conditions of rock weirs.

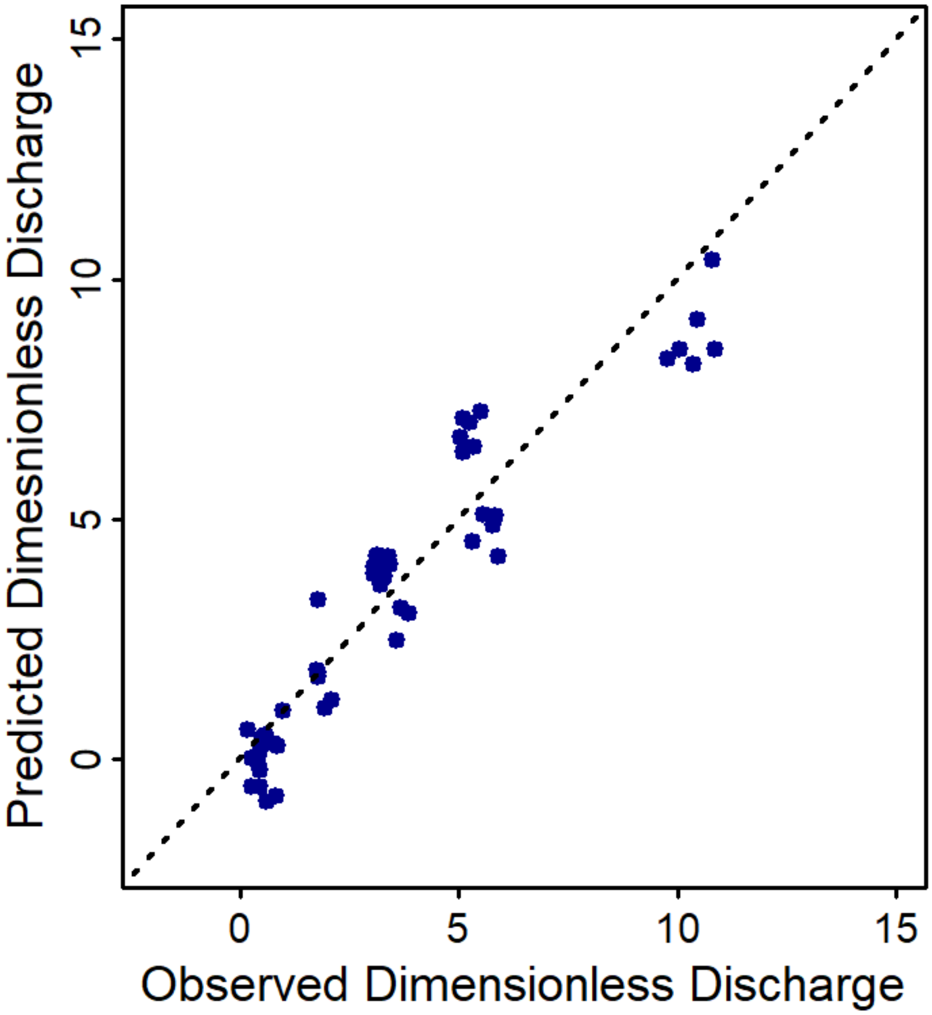

Figure 14. Predicted versus observed dimensionless discharge for all weir configurations with no rock component, i.e. flume runs were conducted with only the weir core configuration.

Linear Model

The result of the transformation of the weir equation to linear form is:

$$\ln(Q) - \ln(L) = b * \ln(H) + \ln(C_d) \qquad (31)$$

where Q is discharge (m^3), L is weir length perpendicular to flow (m), b is the head exponent, H is upstream head (m), and C_d is the discharge coefficient. Additionally, the head exponent, b, differs from the commonly used value of 1.5. For low flows (Eqn. 33), the exponent is less than 1.

This is likely a result of the placement of rocks controlling the flow across the weirs. It would take a greater increase in head to increase the flow rate because flow is between the rocks, not above them. As discharge increases, the head exponent increases, indicating that as water begins to flow above the rocks, there is a greater change in discharge per unit increase in hydraulic head, particularly as a result of the additional flow through the rock, thus a larger head exponent for rock weirs than is typically used in the standard weir equation.

Table 13 shows the results of the linear regression analysis conducted to obtain values for the discharge coefficient for all flows, low flows, and high flows. The overall discharge coefficient is close to the range of those used for sharp-crested and broad-crested weirs (Brown et al., 1996). However, the low flow and high flow discharge coefficients, do not fall within the range for previously reported coefficients. Additionally, the head exponent, b, differs from the commonly used value of 1.5. For low flows (Eqn. 33), the exponent is less than 1. This is likely a result of the placement of rocks controlling the flow across the weirs. It would take a greater increase in head to increase the flow rate because flow is between the rocks, not above them. As discharge increases, the head exponent increases, indicating that as water begins to flow above the rocks, there is a greater change in discharge per unit increase in hydraulic head, particularly as a result of the additional flow through the rock, thus a larger head exponent for rock weirs than is typically used in the standard weir equation.

Table 13. Results of linear regression for all, low, and high flow regimes of rock weirs.

Flow Condition	Equation	Adjusted R^2	Eqn.
All	$Q = 2.967*L*H^{2.02}$	0.846	(32)
Low	$Q = 0.03494*L*H^{0.875}$	0.538	(33)
High	$Q = 65.45*L*H^{3.08}$	0.853	(34)

* Q is discharge (m^3/s), L is weir length (m), and H is upstream hydraulic head

Figure 15 shows a plot of the overall equation for discharge as a function of water depth above the weir for the three weir widths used in the flume experiment. Graphs of predicted discharge against observed discharge were also plotted with a 1:1 line to visually assess the model (Figure 16, Figure 17, and Figure 18, respectively). The overall model and the high flow model performed satisfactorily ($R^2 > 0.8$). However, both models tended to under predict high flows for rock weirs of width 0.152 m (0.500 ft.) (Figure 16, Figure 18). This may indicate that as the length of the weir decreases, there may be sidewall effects from the weir itself. Previous studies focused on flat broad-crested shaped weirs, not on the trapezoidal shape used in mitigation wetlands. However, friction losses on the side of the trapezoidal weir may affect the lower flows of narrower weirs, and as the hydraulic head increases, the effect of the side wall is reduced; therefore, the equation may under-predict flow rates at higher stages for the narrow weirs. The low flow model under-predicted flow as discharge increased and weir length was at a minimum; although, it had the opposite effect when weir length was at a maximum, whereby it over predicted flow as discharge increased (Figure 17). The physical scaling of the rock weirs in the flume required relatively small discharges to be used to meet the low flow water stage characteristics depicted in Figure 9. Therefore, the laboratory flume's pump was performing at the minimum range, which may have affected error. Moreover, the variance observed in the low flow model may be explained by future studies that incorporate additional parameters.

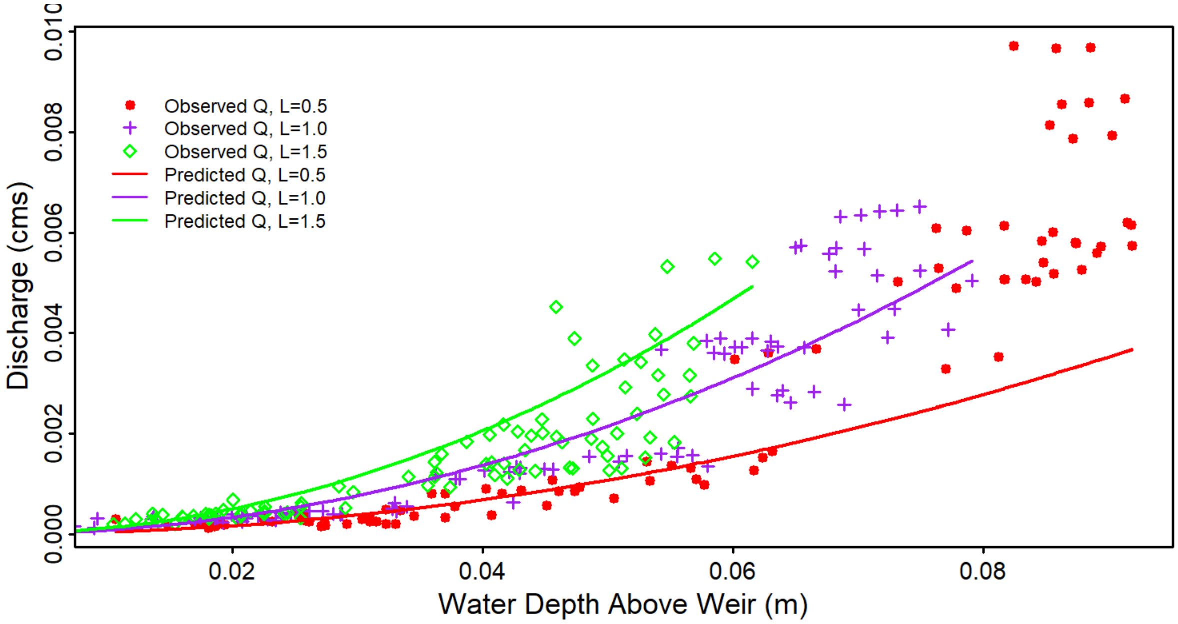

Figure 15. Observed and predicted discharge for rock weirs of lengths 0.152 m (0.500 ft.), 0.305 m (1.000 ft.), and 0.457 m (1.500 ft.) versus water depth above the weir for all rock weirs.

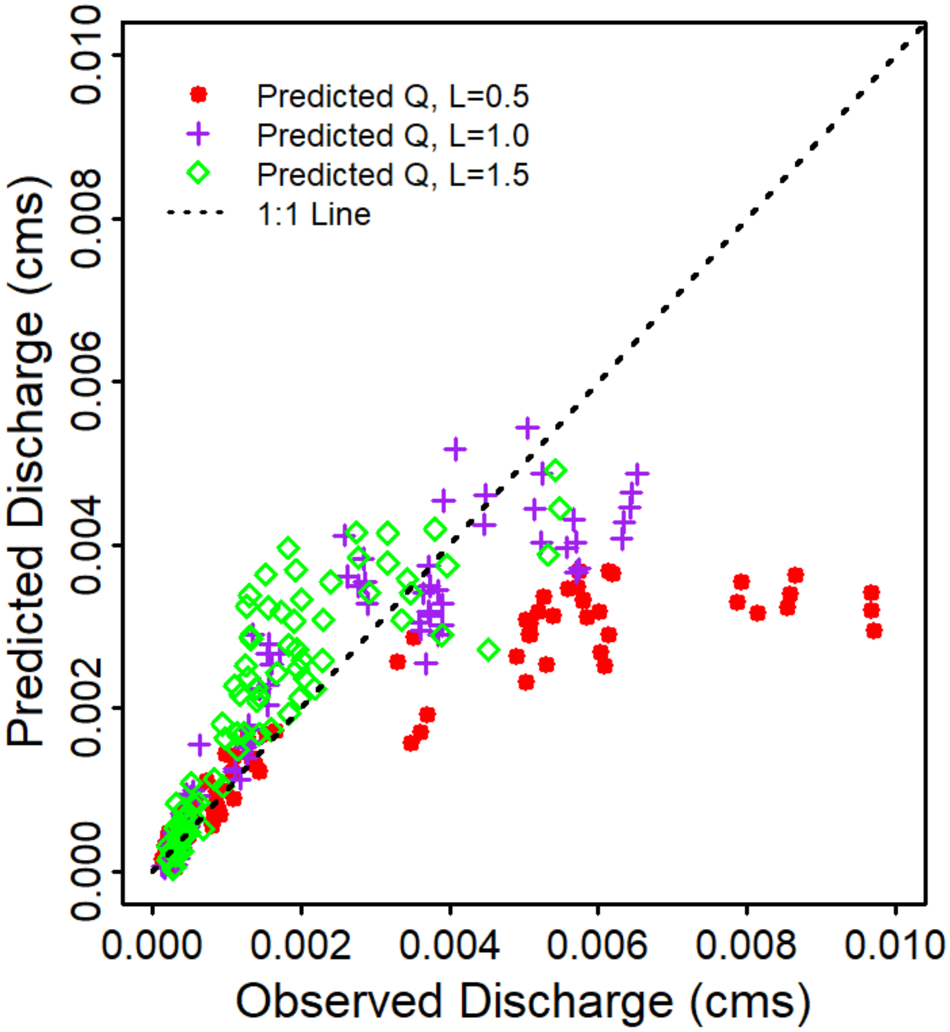

Figure 16. Predicted versus observed discharge of all rock weirs.

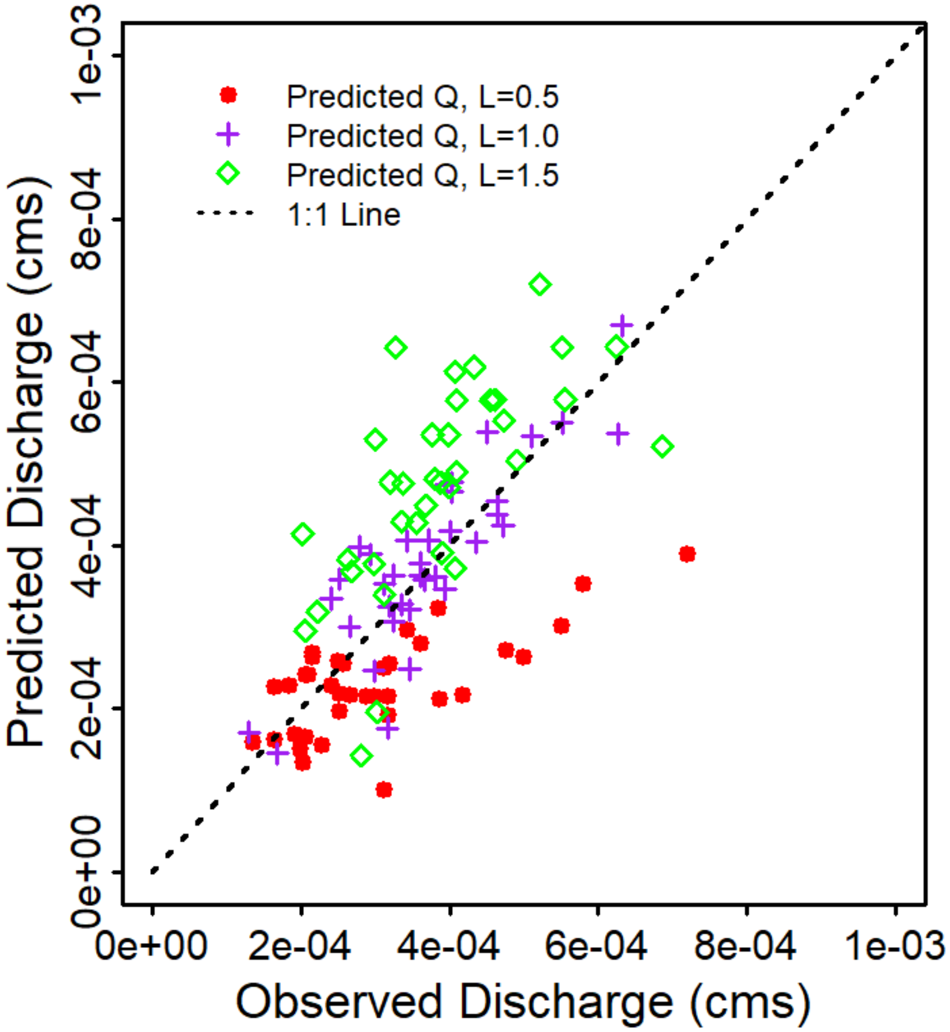

Figure 17. Predicted versus observed discharge of rock weir for low flow conditions.

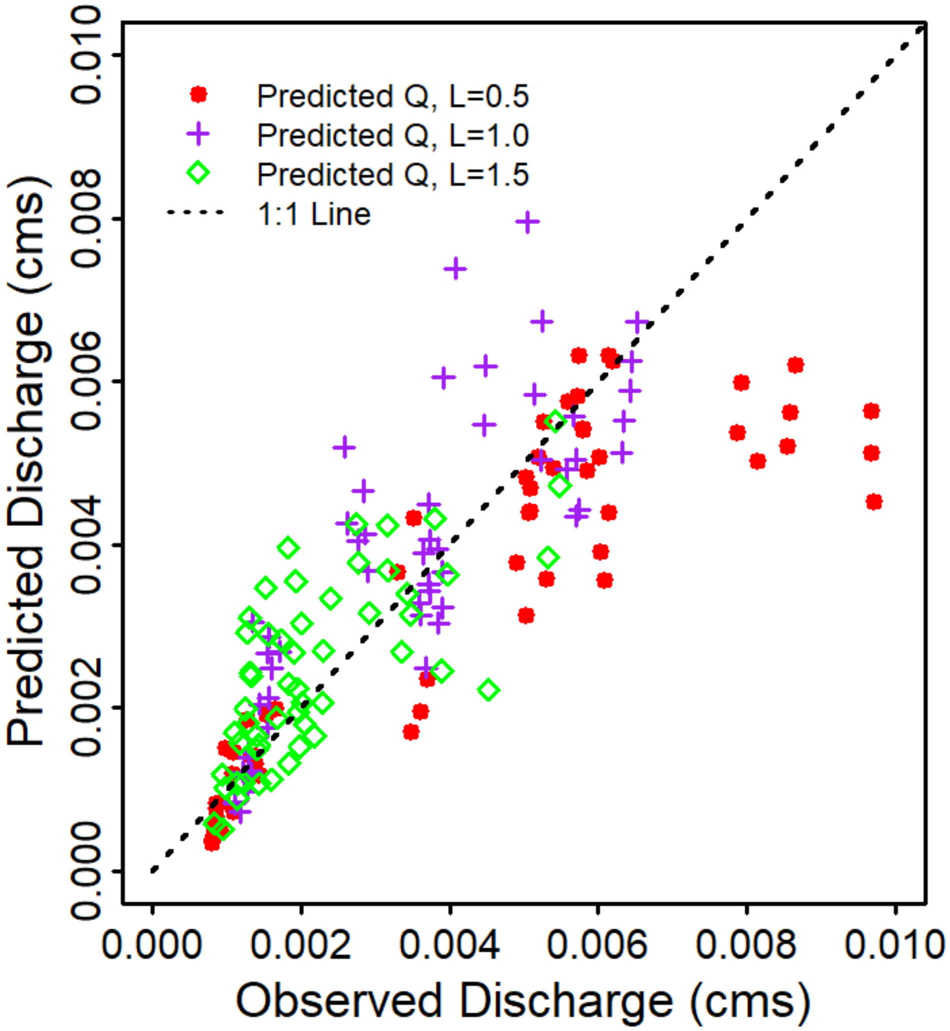

Figure 18. Predicted versus observed discharge of rock weir for high flow conditions.

The linear model uses a common form of the standard weir equation. Further, it does not require an iterative method to determine discharge, as did Codell et al. (1990). Additionally, the model is better suited for rock weirs used in constructed wetlands, rather than those developed using rigid, rectangular gabion weirs or grouted rock weirs in previous studies. Additionally, this discharge model accounts for changes in the exponent due to the effect the rocks have on flow and the shape of the core of the weir, typically used in mitigation wetlands.

No Rock Analysis

The result of the linear regressions conducted to predict flow over the weir configurations with no rock component are found in equation 35:

$$Q = 1.815 * L * H^{1.3} \text{ , } \mathrm{R}^2 = 0.90 \tag{35}$$

Figure 19 shows a plot of the predicted discharge of the linear model versus the observed discharge. The discharge coefficient of the model for weirs with no rock is relatively smaller than that of the weirs with rock (1.81 versus 2.967), however, not greatly so, and is also close in range to previously reported coefficients. The exponent head, b, is very close to the standard weir exponent (1.3 versus 1.5). Although the model has a relatively high R-squared, variance appears to increase at higher flows for the weir of width 0.154 m (0.500 ft.), similar to the results of the rock weirs. This finding may indicate that the narrowing of the weir length changes the flow characteristics within the channel. The high turbulence of the flume channel may have resulted in increased error of water depth measurements. Additionally, the results may indicate that the discharge coefficient is a function of other parameters, similar to the broad-crested weir and sharp-crested weir coefficients (see Table 1).

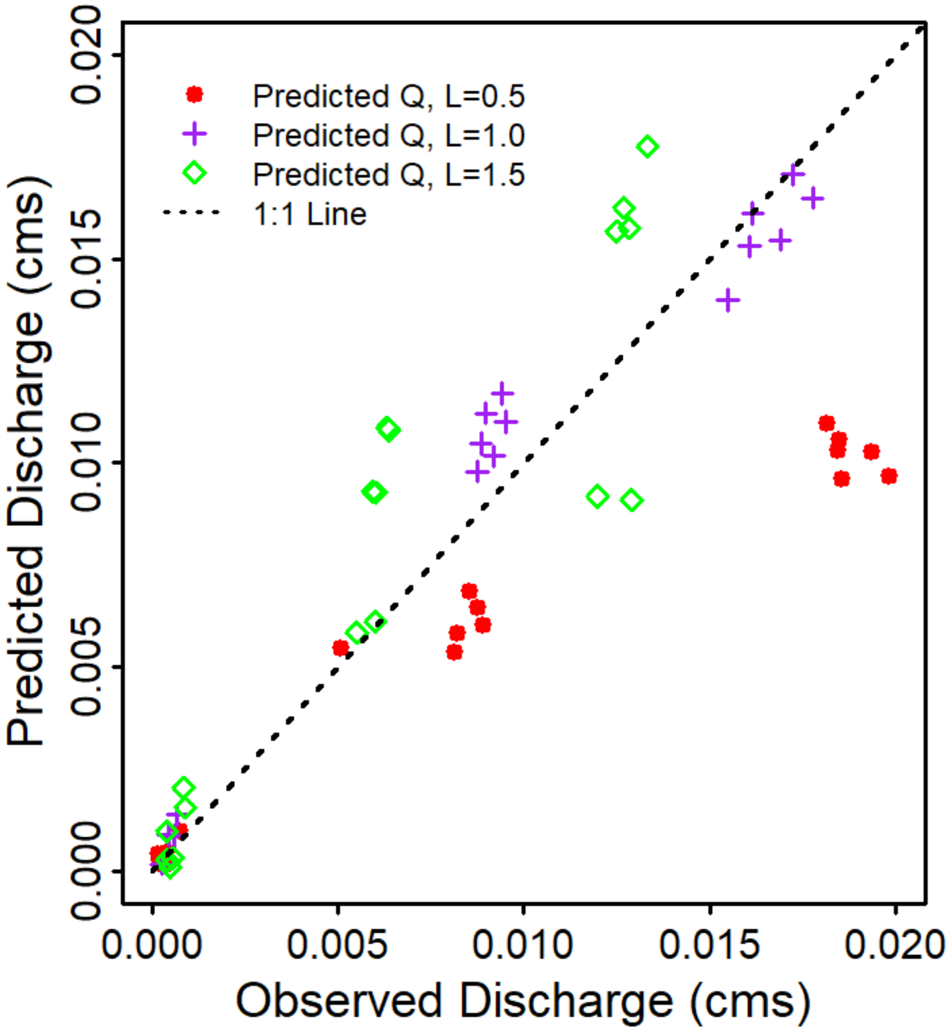

Figure 19. Predicted versus observed discharge for weirs with no rock.

Discharge Coefficient Regression

As described in the Chapter 3: Methods, all weir configurations were grouped twice. Group 1 (grouped by length, width, and mean rock diameter) resulted in a sample size of 15 for each configuration, and group 2 (grouped by length, width, mean rock diameter, and slope) resulted in sample size of 5 for each configuration (Table 14). Results of the linear regression of the transformation of the standard weir equation (Eqn. 28) are summarized in Table 15 (Group 1, n=15) and Table 16 (Group 2, n=5).

Table 14. Characteristics of each weir configuration grouping.

Weir Configuration ID for Group 1	Length (L)	Depth (D)	Mean Rock Diameter (d_{50})	Slope (%)	Weir Configuration ID for Group 2
A	0.5	0.5	0.5	0.0	1
				0.5	19
				1.0	37
G	0.5	0.5	0.75	0.0	7
				0.5	25
				1.0	43
M	0.5	0.5	1.0	0.0	13
				0.5	31
				1.0	49
B	0.5	1.0	0.5	0.0	2
				0.5	20
				1.0	38
H	0.5	1.0	0.75	0.0	8
				0.5	26
				1.0	44
N	0.5	1.0	1.0	0.0	14
				0.5	32
				1.0	50
C	1.0	0.5	0.5	0.0	3
				0.5	21
				1.0	39
I	1.0	0.5	0.75	0.0	9
				0.5	27
				1.0	45
O	1.0	0.5	1.0	0.0	15
				0.5	33
				1.0	51
D	1.0	1.0	0.5	0.0	4
				0.5	22
				1.0	40
J	1.0	1.0	0.75	0.0	10
				0.5	28
				1.0	46
P	1.0	1.0	1.0	0.0	16
				0.5	34
				1.0	52
E	1.5	0.5	0.5	0.0	5
				0.5	23
				1.0	41

Table 14 cont. Characteristics of weir configuration grouping.

Weir Configuration ID for Group 1	Length (L)	Depth (D)	Mean Rock Diameter (d_{50})	Slope (%)	Weir Configuration ID for Group 2
K	1.5	0.5	0.75	0.0	11
				0.5	29
				1.0	47
Q	1.5	0.5	1.0	0.0	17
				0.5	35
				1.0	53
F	1.5	1.0	0.5	0.0	6
				0.5	24
				1.0	42
L	1.5	1.0	0.75	0.0	12
				0.5	30
				1.0	48
R	1.5	1.0	1.0	0.0	18
				0.5	36
				1.0	54

Table 15. Results of linear regression for each group 1 weir configuration (unique combination of L, W, and d50).

Weir Configuration	Discharge Coefficient, C_d	Exponent, b	Adjusted R^2
A	6.92	2.07	0.88
B	26.94	2.64	0.95
C	5.55	2.17	0.94
D	1.60	1.81	0.88
E	0.24	1.29	0.82
F	0.29	1.36	0.72
G	15.04	2.38	0.96
H	54.27	3.02	0.98
I	1.70	1.80	0.88
J	15.04	1.96	0.91
K	1.17	1.79	0.93
L	0.99	1.77	0.92
M	17.78	2.57	0.97
N	28.30	2.81	0.96
O	2.32	2.03	0.92
P	2.40	2.07	0.94
Q	0.84	1.75	0.95
R	0.44	1.61	0.82

Table 16. Results of linear regression for each group 2 weir configuration (unique combination of L, W, d_{50}, and slope).

Weir Configuration	Discharge Coefficient, C_d	Exponent, b	Adjusted R^2
1	16.62	2.41	0.95
2	22.42	2.61	0.94
3	6.62	2.27	0.96
4	1.62	1.83	0.90
5	1.00	1.70	0.95
6	2.30	2.01	0.91
7	7.43	2.15	0.93
8	46.87	3.01	0.98
9	3.75	2.08	0.96
10	3.51	2.12	0.92
11	0.82	1.72	0.95
12	0.57	1.63	0.91
13	32.38	2.84	0.97
14	39.07	2.97	0.98
15	3.40	2.21	0.92
16	2.21	2.09	0.94
17	0.75	1.75	0.96
18	0.54	1.74	0.97
19	2.21	1.66	0.80
20	34.23	2.74	0.95
21	14.47	2.49	0.98
22	16.41	2.58	0.97
23	0.05	0.90	0.74
24	3.00	2.06	0.91
25	24.60	2.55	0.99
26	66.58	3.11	0.99
27	8.54	2.34	0.97
28	4.32	2.14	0.96
29	2.38	2.02	0.96
30	1.14	1.81	0.91
31	17.97	2.57	0.99
32	38.79	2.94	0.97
33	3.02	2.11	0.95
34	1.60	1.92	0.94
35	0.86	1.76	0.97
36	0.22	1.40	0.95
37	24.43	2.46	0.98
38	25.67	2.59	0.94

Table 16 cont. Results of linear regression for each group 2 weir configuration (unique combination of L, W, d50, and slope).

Weir Configuration	Discharge Coefficient, C_d	Exponent, b	Adjusted R^2
39	3.31	1.97	0.93
40	1.01	1.61	0.88
41	1.11	1.69	0.91
42	0.12	1.06	0.66
43	28.95	2.58	0.98
44	51.30	2.96	0.97
45	0.81	1.51	0.84
46	1.60	1.77	0.89
47	1.17	1.75	0.92
48	2.95	2.07	0.93
49	16.26	2.48	0.99
50	25.00	2.70	0.98
51	1.69	1.88	0.93
52	5.29	2.30	0.95
53	0.99	1.76	0.95
54	1.36	1.87	0.69

Discharge coefficient values ranged from 0.24 to 54.27 for rock weir grouping 1, with adjusted R^2 values ranging from 0.72 – 0.97. Discharge coefficient values ranged from 0.05 – 66.58 for weir grouping 2, with adjusted R^2 values within the range of 0.66 – 0.98. Discharge coefficients are larger for the smallest crest length, although discharge values, themselves, are smaller. The head exponent is also relatively larger for the narrow weirs, though the difference is not as great as that of the discharge coefficients. This finding indicates that as the weir length narrows, the flow characteristics begin to change, which may be a result of the sidewall effect from the arms of the weir itself.

Linear regression was then conducted to predict the discharge coefficient, C_d, in Table 15 and Table 16. The analysis showed that Reynolds No. and Froude No. were highly collinear. Therefore, regressions were conducted for each of these terms separately. The best subset of dimensionless parameters were determined for discharge coefficients listed in Table 15 (Eqn. 36) and those listed in Table 16 (Eqn. 37):

$$C_d = -\ 0.998\frac{L}{h} + 0.632\frac{D}{h} + 21.92,\ Adj.R^2 = 0.56 \qquad (36)$$

$$C_d = -\ 1.14\frac{L}{h} + 0.558\frac{D}{h} + 28.91,\ Adj.R^2 = 0.58 \qquad (37)$$

where C_d is discharge coefficient, L is weir length perpendicular to flow (m), h is weir height (m), and D is weir depth parallel to flow (m). The two groupings of data resulted in similar equations and adjusted R-squared values. The median rock diameter was not significant, which is inconsistent with results from previous studies. However, both length and depth, attributes of area, are significant in predicting the discharge coefficient of rock weirs. The results show that the discharge coefficient decreases as length increases, but increases as depth increases. The predicted discharge (calculated using equation 37) was then plotted against observed discharge values (Figure 20).

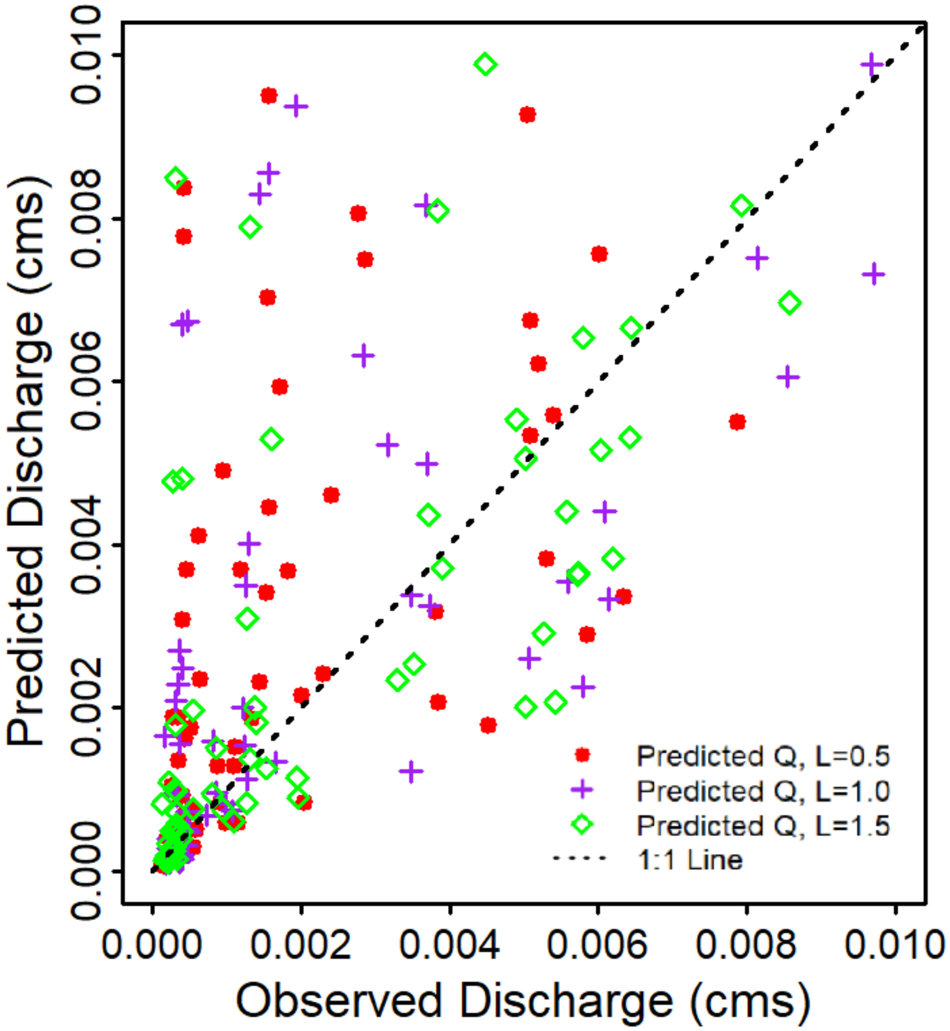

Figure 20. Predicted versus observed discharge using equation 37 to model discharge coefficient.

Equation 37 has greater variance in discharge predictions than the fitted weir equation and dimensionless parameters discussed earlier. This may be due to additional extrapolation conducted to determine values of the discharge coefficient for each grouping, as well as, the small number of data points used in the analysis of each grouping of weirs. Interestingly, it is noted that the median rock diameter of the weir did not play a role in estimating the discharge coefficient. However, depth and length, represent the area covered by the rocks on the weir. The results of the fitted weir equation and dimensionless models indicate that low and high flows behave differently as the rocks become submerged. Therefore, a more detailed analysis of low and high flows may reveal the role the rock size plays in controlling flow over rock weirs. However, the low number of data points in each grouping makes such analysis inadequate for this study. Overall, using the fitted weir equation and equation to predict the discharge coefficient does not predict discharge as accurately as the dimensionless parameters.

Application of Study Results to Wetbud

Rock weirs differ from similar weirs, such as the broad-crested and the sharp-crested, trapezoidal weirs (Cipolleti), by the porous rock material used in their construction, as well as, their shape, a blend of the previously mentioned standard weirs. These structures are commonly used in wetland mitigation design, and are, therefore, modeled in Wetbud as the primary hydraulic control structures. Previous studies have either not considered the shape of the weir – a trapezoid with depth – such as by creating rectangular gabion weirs, or the flow through the voids in the rock, such as by grouting the structure. However, the need to meet specific wetland hydroperiods to ensure appropriate wetland function requires a better understanding of the flow through rock weirs. Equations 27 – 29 (overall, low flow, and high flow discharge equations) provide appropriate models for discharge using dimensionless parameters. Equations 32-34 (also overall, low flow, and high flow discharge equations), provide a more straightforward calculation for discharge through rock weirs. By implementing these equations in Wetbud, the prediction of wetland water levels may be more accurate than the existing equations developed from different weir structures.

Figure 21 shows a comparison of the broad-crested weir, sharp-crested, trapezoidal weir, and linear model (Eqn. 32) fits to the observed discharge measurements. The broad-crested and sharp-crested, trapezoidal (Cipolleti) weir equations greatly over predict flow for the rock weir of length 0.305 m (1.000 ft.). Consequently, use of these standard weir equations in the design of wetland outflow structures may result in the need for additional outlet structures to ensure that the appropriate water depth is maintained in the wetland.

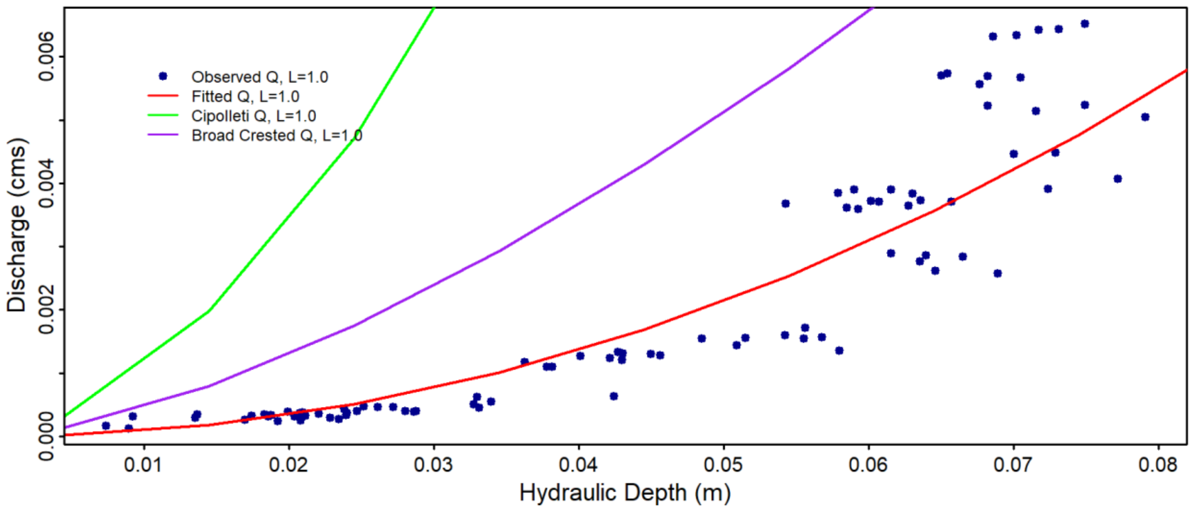

Figure 21. Comparison of broad-crested, Cipolleti and weir equation model fit to observed discharge measurements (m^3/s) for weir of length 0.305 m (1.0 ft).

Chapter 5: Conclusions

Model rock weirs of varying lengths, depths, and mean rock diameters were built at a 10:1 scale in a laboratory flume. Over 300 flow runs were conducted, at three different slopes and five different water stages. Dimensionless parameters were calculated from measured variables in the flume and used to develop a model for discharge coefficient of rock weirs. The weir length and depth, normalized by weir height, were the parameters that most influenced the discharge coefficient. Linear regression analyses were also conducted to determine overall, low flow, and high flow models for discharge. The study found that the characteristics of flow through the rocks differ from that above the rocks, indicating that two different equations for predicting flow through and over rock weirs should be used. Study results show that the presence of rocks on the weir surface significantly affects flow rates across the weirs. Consequently, the use of a rock weir model or discharge coefficient is necessary to accurately predict discharges, particularly in wetlands where hydrology is a very important determinant of wetland health and function. Therefore, the dimensionless model developed in this study is recommended to estimate flow across rock weirs to improve discharge predictions.

Future Work

Further analysis of the exponent used in the standard weir equation may improve the use of the discharge coefficient model provided in this study. Additionally, studies conducted at full scale or in field conditions would allow for a broader range of discharges that can be encompassed in the model for the discharge coefficient.

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Appendix A: Buckingham Pi Analysis

Dimensional variables (n = 10): Q, v, h, L, D, H, d_{50}, g, ρ, μ

Fundamental dimensions (m = 3): mass, length, time

Repeating Variables: h

Pi Terms (n – m = 7):

$$\frac{Q}{\sqrt{gh}\,(Lh)} = \Phi\left(\frac{\rho v h}{\mu}, \frac{d_{50}}{h}, \frac{D}{h}, \frac{H}{h}, \frac{L}{h}, S\right)$$

where, Q = discharge (m^3/s), v = velocity (m/s), g = 9.807 N/kg, h = height of weir (m), ρ = 998.5 kg/m^3, μ = 0.0010385 N s/m^2, d_{50} = mean rock diameter (m), L = length of weir crest perpendicular to flow (m), H = upstream hydraulic head (m), D = depth of weir crest parallel to flow (m), S = slope (m/m)

Appendix B: Data Collection

Table 17 B1. Pump frequency (Hz) and orifice meter reading (in. of H_2O) data collected for each weir.

Weir No.	W (m)	L (m)	Bed Slope (%)	D_{50} (mm)	Water Stage	Pump Frequency (Hz)	Pressure (in. of H_2O)
1	0.152	0.152	0	12.7	1	4.4	0.28
2	0.152	0.152	0	12.7	2	4.6	0.59
3	0.152	0.152	0	12.7	3	5.1	4.73
4	0.152	0.152	0	12.7	4	9.2	96.85
5	0.152	0.152	0	12.7	5	10.1	8.35
6	0.152	0.152	0	19.1	1	4.4	0.29
7	0.152	0.152	0	19.1	2	4.6	0.45
8	0.152	0.152	0	19.1	3	5.3	6.33
9	0.152	0.152	0	19.1	4	7.5	3.36
10	0.152	0.152	0	19.1	5	9.5	6.69
11	0.152	0.152	0	25.4	1	4.7	0.72
12	0.152	0.152	0	25.4	2	5.0	2.38
13	0.152	0.152	0	25.4	3	6.2	19.46
14	0.152	0.152	0	25.4	4	7.5	2.79
15	0.152	0.152	0	25.4	5	7.9	3.43
16	0.152	0.152	0.5	12.7	1	4.4	0.69
17	0.152	0.152	0.5	12.7	2	4.6	1.24
18	0.152	0.152	0.5	12.7	3	5.0	4.65
19	0.152	0.152	0.5	12.7	4	9.0	92.25
20	0.152	0.152	0.5	12.7	5	10.0	8.33
21	0.152	0.152	0.5	19.1	2	4.6	0.63
22	0.152	0.152	0.5	19.1	1	4.5	0.26
23	0.152	0.152	0.5	19.1	3	5.4	8.39
24	0.152	0.152	0.5	19.1	4	7.4	3.25

Table B1, cont. Pump frequency (Hz) and orifice meter reading (in. of H_2O) data collected for each weir.

Weir No.	W (m)	L (m)	Bed Slope (%)	D_{50} (mm)	Water Stage	Pump Frequency (Hz)	Pressure (in. of H_2O)
25	0.152	0.152	0.5	19.1	5	9.3	6.56
26	0.152	0.152	0.5	25.4	1	4.6	0.50
27	0.152	0.152	0.5	25.4	2	4.9	2.15
28	0.152	0.152	0.5	25.4	3	5.8	13.43
29	0.152	0.152	0.5	25.4	4	7.3	2.40
30	0.152	0.152	0.5	25.4	5	7.6	3.00
31	0.152	0.152	1	12.7	1	4.7	0.37
32	0.152	0.152	1	12.7	2	4.8	1.06
33	0.152	0.152	1	12.7	3	4.9	4.63
34	0.152	0.152	1	12.7	4	8.8	86.35
35	0.152	0.152	1	12.7	5	10.0	8.40
36	0.152	0.152	1	19.1	1	4.9	0.71
37	0.152	0.152	1	19.1	2	5.0	1.77
38	0.152	0.152	1	19.1	3	5.3	5.86
39	0.152	0.152	1	19.1	4	7.3	3.30
40	0.152	0.152	1	19.1	5	9.2	6.52
41	0.152	0.152	1	25.4	1	4.9	0.71
42	0.152	0.152	1	25.4	2	5.0	1.60
43	0.152	0.152	1	25.4	3	5.9	14.84
44	0.152	0.152	1	25.4	4	7.1	2.30
45	0.152	0.152	1	25.4	5	7.7	3.22
46	0.152	0.305	0	12.7	1	4.3	0.19
47	0.152	0.305	0	12.7	2	4.5	0.30
48	0.152	0.305	0	12.7	3	5.1	5.26
49	0.152	0.305	0	12.7	4	6.8	2.14
50	0.152	0.305	0	12.7	5	8.9	5.61
51	0.152	0.305	0	19.1	1	4.5	0.24

Table B1, cont. Pump frequency (Hz) and orifice meter reading (in. of H_2O) data collected for each weir.

Weir No.	W (m)	L (m)	Bed Slope (%)	D_{50} (mm)	Water Stage	Pump Frequency (Hz)	Pressure (in. of H_2O)
52	0.152	0.305	0	19.1	2	4.6	0.33
53	0.152	0.305	0	19.1	3	5.4	6.94
54	0.152	0.305	0	19.1	4	7.0	2.47
55	0.152	0.305	0	19.1	5	7.6	3.37
56	0.152	0.305	0	25.4	1	4.6	0.44
57	0.152	0.305	0	25.4	2	4.8	1.05
58	0.152	0.305	0	25.4	3	5.7	11.44
59	0.152	0.305	0	25.4	4	9.0	88.14
60	0.152	0.305	0	25.4	5	7.4	2.93
61	0.152	0.305	0.5	12.7	1	4.3	0.13
62	0.152	0.305	0.5	12.7	2	4.5	0.31
63	0.152	0.305	0.5	12.7	3	5.1	5.23
64	0.152	0.305	0.5	12.7	4	7.0	2.50
65	0.152	0.305	0.5	12.7	5	8.9	5.52
66	0.152	0.305	0.5	19.1	1	4.5	0.19
67	0.152	0.305	0.5	19.1	2	4.6	0.33
68	0.152	0.305	0.5	19.1	3	5.5	8.51
69	0.152	0.305	0.5	19.1	4	7.0	2.25
70	0.152	0.305	0.5	19.1	5	7.5	2.99
71	0.152	0.305	0.5	25.4	1	4.7	0.47
72	0.152	0.305	0.5	25.4	2	5.1	3.67
73	0.152	0.305	0.5	25.4	3	6.0	16.73
74	0.152	0.305	0.5	25.4	4	8.6	77.17
75	0.152	0.305	0.5	25.4	5	7.4	2.92
76	0.152	0.305	1	12.7	1	4.6	0.30
77	0.152	0.305	1	12.7	2	4.7	0.69
78	0.152	0.305	1	12.7	3	5.1	5.36

Table B1, cont. Pump frequency (Hz) and orifice meter reading (in. of H_2O) data collected for each weir.

Weir No.	W (m)	L (m)	Bed Slope (%)	D_{50} (mm)	Water Stage	Pump Frequency (Hz)	Pressure (in. of H_2O)
79	0.152	0.305	1	12.7	4	6.9	2.25
80	0.152	0.305	1	12.7	5	9.1	5.90
81	0.152	0.305	1	19.1	1	4.7	0.41
82	0.152	0.305	1	19.1	2	4.8	0.83
83	0.152	0.305	1	19.1	3	5.4	8.09
84	0.152	0.305	1	19.1	4	7.0	2.29
85	0.152	0.305	1	19.1	5	7.5	3.04
86	0.152	0.305	1	25.4	1	4.7	0.45
87	0.152	0.305	1	25.4	2	4.8	0.92
88	0.152	0.305	1	25.4	3	5.7	12.45
89	0.152	0.305	1	25.4	4	7.0	2.30
90	0.152	0.305	1	25.4	5	7.1	2.60
91	0.305	0.152	0	12.7	1	4.5	0.50
92	0.305	0.152	0	12.7	2	4.6	0.61
93	0.305	0.152	0	12.7	3	5.5	10.43
94	0.305	0.152	0	12.7	4	9.2	98.07
95	0.305	0.152	0	12.7	5	8.0	3.70
96	0.305	0.152	0	19.1	1	4.5	0.75
97	0.305	0.152	0	19.1	2	4.6	0.92
98	0.305	0.152	0	19.1	3	5.6	11.97
99	0.305	0.152	0	19.1	4	9.4	104.39
100	0.305	0.152	0	19.1	5	7.9	3.79
101	0.305	0.152	0	25.4	1	4.6	0.45
102	0.305	0.152	0	25.4	2	5.1	2.83
103	0.305	0.152	0	25.4	3	6.1	17.55
104	0.305	0.152	0	25.4	4	7.9	57.15
105	0.305	0.152	0	25.4	5	7.0	2.27
106	0.305	0.152	0.5	12.7	1	4.6	0.92

Table B1, cont. Pump frequency (Hz) and orifice meter reading (in. of H_2O) data collected for each weir.

Weir No.	W (m)	L (m)	Bed Slope (%)	D_{50} (mm)	Water Stage	Pump Frequency (Hz)	Pressure (in. of H_2O)
107	0.305	0.152	0.5	12.7	2	4.7	1.53
108	0.305	0.152	0.5	12.7	3	5.5	11.41
109	0.305	0.152	0.5	12.7	4	9.4	105.21
110	0.305	0.152	0.5	12.7	5	7.9	3.59
111	0.305	0.152	0.5	19.1	1	4.6	1.03
112	0.305	0.152	0.5	19.1	2	4.7	1.53
113	0.305	0.152	0.5	19.1	3	5.5	10.94
114	0.305	0.152	0.5	19.1	4	9.5	108.12
115	0.305	0.152	0.5	19.1	5	7.8	3.68
116	0.305	0.152	0.5	25.4	1	4.6	0.75
117	0.305	0.152	0.5	25.4	2	4.9	2.16
118	0.305	0.152	0.5	25.4	3	6.1	18.28
119	0.305	0.152	0.5	25.4	4	7.9	58.08
120	0.305	0.152	0.5	25.4	5	10.6	142.71
121	0.305	0.152	1	12.7	1	4.8	0.63
122	0.305	0.152	1	12.7	2	4.9	1.35
123	0.305	0.152	1	12.7	3	5.5	9.86
124	0.305	0.152	1	12.7	4	9.1	96.04
125	0.305	0.152	1	12.7	5	7.5	2.94
126	0.305	0.152	1	19.1	1	4.7	0.71
127	0.305	0.152	1	19.1	2	4.8	1.10
128	0.305	0.152	1	19.1	3	5.4	8.63
129	0.305	0.152	1	19.1	4	9.5	108.09
130	0.305	0.152	1	19.1	5	7.7	3.56
131	0.305	0.152	1	25.4	1	4.8	0.85
132	0.305	0.152	1	25.4	2	5.0	2.78
133	0.305	0.152	1	25.4	3	6.0	17.33
134	0.305	0.152	1	25.4	4	7.9	59.42

Table B1, cont. Pump frequency (Hz) and orifice meter reading (in. of H_2O) data collected for each weir.

Weir No.	W (m)	L (m)	Bed Slope (%)	D_{50} (mm)	Water Stage	Pump Frequency (Hz)	Pressure (in. of H_2O)
135	0.305	0.152	1	25.4	5	10.5	141.44
136	0.305	0.305	0	12.7	1	4.3	0.12
137	0.305	0.305	0	12.7	2	4.6	0.55
138	0.305	0.305	0	12.7	3	5.6	11.77
139	0.305	0.305	0	12.7	4	9.1	94.56
140	0.305	0.305	0	12.7	5	7.3	2.87
141	0.305	0.305	0	19.1	1	4.5	0.72
142	0.305	0.305	0	19.1	2	4.7	1.15
143	0.305	0.305	0	19.1	3	5.8	14.83
144	0.305	0.305	0	19.1	4	9.2	97.93
145	0.305	0.305	0	19.1	5	6.9	2.36
146	0.305	0.305	0	25.4	1	4.6	0.83
147	0.305	0.305	0	25.4	2	4.8	1.44
148	0.305	0.305	0	25.4	3	5.9	13.04
149	0.305	0.305	0	25.4	4	7.6	47.24
150	0.305	0.305	0	25.4	5	9.9	117.74
151	0.305	0.305	0.5	12.7	1	4.5	0.41
152	0.305	0.305	0.5	12.7	2	4.7	1.11
153	0.305	0.305	0.5	12.7	3	5.6	12.36
154	0.305	0.305	0.5	12.7	4	9.3	98.62
155	0.305	0.305	0.5	12.7	5	7.2	2.77
156	0.305	0.305	0.5	19.1	1	4.5	0.80
157	0.305	0.305	0.5	19.1	2	4.6	0.98
158	0.305	0.305	0.5	19.1	3	5.9	16.98
159	0.305	0.305	0.5	19.1	4	9.2	98.85
160	0.305	0.305	0.5	19.1	5	6.9	2.44
161	0.305	0.305	0.5	25.4	1	4.6	0.95
162	0.305	0.305	0.5	25.4	2	4.7	1.15

Table B1, cont. Pump frequency (Hz) and orifice meter reading (in. of H_2O) data collected for each weir.

Weir No.	W (m)	L (m)	Bed Slope (%)	D_{50} (mm)	Water Stage	Pump Frequency (Hz)	Pressure (in. of H_2O)
163	0.305	0.305	0.5	25.4	3	6.0	17.01
164	0.305	0.305	0.5	25.4	4	7.5	48.63
165	0.305	0.305	0.5	25.4	5	9.6	108.92
166	0.305	0.305	1	12.7	1	4.7	0.20
167	0.305	0.305	1	12.7	2	4.8	0.69
168	0.305	0.305	1	12.7	3	5.4	8.63
169	0.305	0.305	1	12.7	4	9.0	92.59
170	0.305	0.305	1	12.7	5	7.2	2.90
171	0.305	0.305	1	19.1	1	4.8	0.85
172	0.305	0.305	1	19.1	2	4.9	1.58
173	0.305	0.305	1	19.1	3	5.7	12.68
174	0.305	0.305	1	19.1	4	9.0	91.68
175	0.305	0.305	1	19.1	5	7.3	2.89
176	0.305	0.305	1	25.4	1	4.8	1.14
177	0.305	0.305	1	25.4	2	4.9	1.85
178	0.305	0.305	1	25.4	3	6.2	20.91
179	0.305	0.305	1	25.4	4	7.7	54.28
180	0.305	0.305	1	25.4	5	7.3	2.45
181	0.457	0.152	0	12.7	1	4.5	0.69
182	0.457	0.152	0	12.7	2	4.6	0.96
183	0.457	0.152	0	12.7	3	5.5	10.79
184	0.457	0.152	0	12.7	4	6.9	37.13
185	0.457	0.152	0	12.7	5	9.6	112.08
186	0.457	0.152	0	19.1	1	4.5	0.51
187	0.457	0.152	0	19.1	2	4.6	0.73
188	0.457	0.152	0	19.1	3	5.5	9.95
189	0.457	0.152	0	19.1	4	6.3	23.88
190	0.457	0.152	0	19.1	5	8.3	71.39

Table B1, cont. Pump frequency (Hz) and orifice meter reading (in. of H_2O) data collected for each weir.

Weir No.	W (m)	L (m)	Bed Slope (%)	D_{50} (mm)	Water Stage	Pump Frequency (Hz)	Pressure (in. of H_2O)
191	0.457	0.152	0	25.4	1	4.6	0.81
192	0.457	0.152	0	25.4	2	4.7	1.19
193	0.457	0.152	0	25.4	3	5.7	12.53
194	0.457	0.152	0	25.4	4	6.2	21.31
195	0.457	0.152	0	25.4	5	7.7	53.56
196	0.457	0.152	0.5	12.7	1	4.5	0.65
197	0.457	0.152	0.5	12.7	2	4.7	1.59
198	0.457	0.152	0.5	12.7	3	5.7	14.68
199	0.457	0.152	0.5	12.7	4	6.7	33.92
200	0.457	0.152	0.5	12.7	5	9.6	12.16
201	0.457	0.152	0.5	19.1	1	4.6	1.07
202	0.457	0.152	0.5	19.1	2	4.7	1.47
203	0.457	0.152	0.5	19.1	3	5.7	14.01
204	0.457	0.152	0.5	19.1	4	6.5	28.84
205	0.457	0.152	0.5	19.1	5	8.7	83.56
206	0.457	0.152	0.5	25.4	1	4.6	1.03
207	0.457	0.152	0.5	25.4	2	4.7	1.51
208	0.457	0.152	0.5	25.4	3	5.6	11.74
209	0.457	0.152	0.5	25.4	4	6.3	25.72
210	0.457	0.152	0.5	25.4	5	7.7	54.76
211	0.457	0.152	1	12.7	1	4.9	1.18
212	0.457	0.152	1	12.7	2	5.0	3.34
213	0.457	0.152	1	12.7	3	5.3	6.44
214	0.457	0.152	1	12.7	4	6.4	18.22
215	0.457	0.152	1	12.7	5	9.5	107.84
216	0.457	0.152	1	19.1	1	4.9	1.08
217	0.457	0.152	1	19.1	2	5.0	2.19

Table B1, cont. Pump frequency (Hz) and orifice meter reading (in. of H_2O) data collected for each weir.

Weir No.	W (m)	L (m)	Bed Slope (%)	D_{50} (mm)	Water Stage	Pump Frequency (Hz)	Pressure (in. of H_2O)
218	0.457	0.152	1	19.1	3	5.5	9.35
219	0.457	0.152	1	19.1	4	6.5	27.91
220	0.457	0.152	1	19.1	5	8.6	80.16
221	0.457	0.152	1	25.4	1	4.9	1.71
222	0.457	0.152	1	25.4	2	5.0	2.77
223	0.457	0.152	1	25.4	3	5.8	14.53
224	0.457	0.152	1	25.4	4	6.1	19.95
225	0.457	0.152	1	25.4	5	7.9	60.58
226	0.457	0.305	0	12.7	1	4.5	0.80
227	0.457	0.305	0	12.7	2	4.6	1.01
228	0.457	0.305	0	12.7	3	5.2	6.29
229	0.457	0.305	0	12.7	4	6.4	26.92
230	0.457	0.305	0	12.7	5	6.9	2.62
231	0.457	0.305	0	19.1	1	4.4	0.30
232	0.457	0.305	0	19.1	2	4.6	0.64
233	0.457	0.305	0	19.1	3	5.6	11.24
234	0.457	0.305	0	19.1	4	7.1	40.75
235	0.457	0.305	0	19.1	5	8.3	71.08
236	0.457	0.305	0	25.4	1	4.5	0.29
237	0.457	0.305	0	25.4	2	4.7	0.76
238	0.457	0.305	0	25.4	3	5.7	11.54
239	0.457	0.305	0	25.4	4	6.0	16.53
240	0.457	0.305	0	25.4	5	6.4	23.76
241	0.457	0.305	0.5	12.7	1	4.5	0.90
242	0.457	0.305	0.5	12.7	2	4.6	1.13
243	0.457	0.305	0.5	12.7	3	5.2	6.74
244	0.457	0.305	0.5	12.7	4	6.4	27.39
245	0.457	0.305	0.5	12.7	5	6.9	2.68

Table B1, cont. Pump frequency (Hz) and orifice meter reading (in. of H_2O) data collected for each weir.

Weir No.	W (m)	L (m)	Bed Slope (%)	D_{50} (mm)	Water Stage	Pump Frequency (Hz)	Pressure (in. of H_2O)
246	0.457	0.305	0.5	19.1	1	4.5	0.63
247	0.457	0.305	0.5	19.1	2	4.7	1.33
248	0.457	0.305	0.5	19.1	3	5.7	13.98
249	0.457	0.305	0.5	19.1	4	6.9	37.65
250	0.457	0.305	0.5	19.1	5	9.3	102.50
251	0.457	0.305	0.5	25.4	1	4.5	0.35
252	0.457	0.305	0.5	25.4	2	4.7	1.18
253	0.457	0.305	0.5	25.4	3	5.7	12.30
254	0.457	0.305	0.5	25.4	4	6.0	17.34
255	0.457	0.305	0.5	25.4	5	6.5	26.43
256	0.457	0.305	1	12.7	1	4.8	0.56
257	0.457	0.305	1	12.7	2	4.9	1.19
258	0.457	0.305	1	12.7	3	5.2	4.99
259	0.457	0.305	1	12.7	4	6.2	24.08
260	0.457	0.305	1	12.7	5	6.8	2.53
261	0.457	0.305	1	19.1	1	4.9	1.13
262	0.457	0.305	1	19.1	2	5.0	2.16
263	0.457	0.305	1	19.1	3	5.5	9.26
264	0.457	0.305	1	19.1	4	6.6	29.67
265	0.457	0.305	1	19.1	5	7.4	85.84
266	0.457	0.305	1	25.4	1	4.8	0.49
267	0.457	0.305	1	25.4	2	5.0	1.93
268	0.457	0.305	1	25.4	3	5.5	8.79
269	0.457	0.305	1	25.4	4	5.9	145.34
270	0.457	0.305	1	25.4	5	6.6	28.68
271	0.152	0.305	0	NA	2	4.2	0.14
272	0.152	0.305	0	NA	4	11.4	182.77
273	0.152	0.305	0	NA	5	17.3	29.36

Table B1, cont. Pump frequency (Hz) and orifice meter reading (in. of H_2O) data collected for each weir.

Weir No.	W (m)	L (m)	Bed Slope (%)	D_{50} (mm)	Water Stage	Pump Frequency (Hz)	Pressure (in. of H_2O)
274	0.152	0.305	0.5	NA	2	4.7	3.68
275	0.152	0.305	0.5	NA	4	8.5	5.90
276	0.152	0.305	0.5	NA	5	17.5	30.31
277	0.152	0.305	1	NA	2	4.7	0.70
278	0.152	0.305	1	NA	4	8.8	6.00
279	0.152	0.305	1	NA	5	17.5	30.63
280	0.152	0.152	0	NA	2	4.2	0.24
281	0.152	0.152	0	NA	4	9.2	6.49
282	0.152	0.152	0	NA	5	17.6	30.37
283	0.152	0.152	0.5	NA	2	4.4	0.88
284	0.152	0.152	0.5	NA	4	9.3	6.79
285	0.152	0.152	0.5	NA	5	18.3	33.38
286	0.152	0.152	1	NA	2	4.7	0.63
287	0.152	0.152	1	NA	4	9.5	7.04
288	0.152	0.152	1	NA	5	18.6	34.98
289	0.305	0.305	0	NA	2	4.4	1.29
290	0.305	0.305	0	NA	4	9.9	7.90
291	0.305	0.305	0	NA	5	16.5	26.47
292	0.305	0.305	0.5	NA	2	4.6	2.51
293	0.305	0.305	0.5	NA	4	9.9	8.06
294	0.305	0.305	0.5	NA	5	16.9	28.15
295	0.305	0.305	1	NA	2	4.7	0.31
296	0.305	0.305	1	NA	4	9.7	7.53
297	0.305	0.305	1	NA	5	16.2	25.46
298	0.305	0.152	0	NA	2	4.6	3.10
299	0.305	0.152	0	NA	4	9.7	7.19
300	0.305	0.152	0	NA	5	15.6	23.28
301	0.305	0.152	0.5	NA	2	4.6	2.39

Table B1, cont. Pump frequency (Hz) and orifice meter reading (in. of H_2O) data collected for each weir.

Weir No.	W (m)	L (m)	Bed Slope (%)	D_{50} (mm)	Water Stage	Pump Frequency (Hz)	Pressure (in. of H_2O)
302	0.305	0.152	0.5	NA	4	9.6	6.98
303	0.305	0.152	0.5	NA	5	15.5	23.03
304	0.305	0.152	1	NA	2	4.7	0.46
305	0.305	0.152	1	NA	4	9.6	6.81
306	0.305	0.152	1	NA	5	15.0	21.38
307	0.457	0.305	0	NA	2	4.4	1.03
308	0.457	0.305	0	NA	4	7.7	3.61
309	0.457	0.305	0	NA	5	12.7	14.37
310	0.457	0.305	0.5	NA	2	4.5	1.14
311	0.457	0.305	0.5	NA	4	7.6	3.24
312	0.457	0.305	0.5	NA	5	12.5	13.92
313	0.457	0.305	1	NA	2	4.8	1.65
314	0.457	0.305	1	NA	4	7.0	2.70
315	0.457	0.305	1	NA	5	12.0	12.80
316	0.457	0.152	0	NA	2	4.8	4.99
317	0.457	0.152	0	NA	4	7.7	3.56
318	0.457	0.152	0	NA	5	13.2	15.83
319	0.457	0.152	0.5	NA	2	4.9	5.53
320	0.457	0.152	0.5	NA	4	7.5	3.13
321	0.457	0.152	0.5	NA	5	12.8	14.69
322	0.457	0.152	1	NA	2	4.9	2.14
323	0.457	0.152	1	NA	4	7.5	3.21
324	0.457	0.152	1	NA	5	12.7	14.84

Table 18 B2. Water depth measurements and depth to flume bed measurements collected for each weir.

Weir No.	Surface 3 (mm)	Bed 3 (mm)	Surface 2 (mm)	Bed 2 (mm)	Surface 1 (mm)	Bed 1 (mm)	Upstream Water Depth (mm)	Center Water Depth (mm)	Water Depth at Ripple (mm)
1	29.26	0.06	30.70	0.73	30.47	0.94	30.43	27.96	NA
2	39.88	0.12	41.33	0.72	41.07	1.00	39.12	36.30	NA
3	54.25	0.00	55.87	0.58	55.60	0.83	54.97	52.05	53.39
4	78.90	-0.02	80.78	0.48	80.59	0.74	80.12	69.96	75.94
5	101.03	-0.11	102.75	0.43	102.50	0.70	102.02	85.86	95.57
6	28.05	0.19	29.35	0.75	29.28	1.02	28.27	25.70	NA
7	38.43	0.15	39.98	0.67	39.17	1.01	36.61	33.91	NA
8	60.37	0.09	61.68	0.71	61.35	0.94	61.18	54.57	58.62
9	94.47	0.27	95.94	0.81	95.50	1.05	95.11	79.64	71.76
10	104.25	0.20	105.87	0.77	105.31	1.06	104.78	87.66	101.19
11	43.51	0.04	45.13	0.57	44.48	0.82	44.42	38.46	NA
12	56.66	-0.01	58.16	0.62	58.22	0.81	58.58	50.81	NA
13	75.82	-0.03	77.52	0.58	77.16	0.78	76.55	67.61	73.82
14	101.61	-0.08	103.29	0.49	102.78	0.75	102.55	88.59	98.13
15	104.25	-0.09	105.73	0.44	105.51	0.72	104.98	91.35	100.87
16	9.32	0.10	16.41	0.67	21.39	0.87	24.11	24.47	NA
17	24.44	0.07	31.55	0.64	36.55	0.81	39.23	38.37	NA
18	35.38	0.00	42.54	0.61	47.61	0.88	50.46	49.78	50.78
19	60.76	-0.04	67.89	0.56	73.00	0.75	76.23	66.87	74.16
20	86.91	-0.10	92.96	0.41	96.89	0.64	99.28	83.27	93.53
21	23.52	0.12	30.39	0.75	35.55	0.94	39.11	36.92	NA
22	17.66	0.18	24.66	0.76	29.98	0.94	32.82	31.42	NA
23	44.49	0.09	51.50	0.67	57.42	0.98	59.03	55.33	60.86
24	76.85	0.09	83.85	0.64	89.13	0.95	92.10	79.12	91.18
25	86.38	0.09	93.55	0.60	98.81	0.93	101.90	86.81	99.24
26	23.29	0.03	30.64	0.61	35.87	0.89	39.32	35.89	NA

Table B2, cont. Water depth measurements and depth to flume bed measurements collected for each weir.

Weir No.	Surface 3 (mm)	Bed 3 (mm)	Surface 2 (mm)	Bed 2 (mm)	Surface 1 (mm)	Bed 1 (mm)	Upstream Water Depth (mm)	Center Water Depth (mm)	Water Depth at Ripple (mm)
27	36.53	0.08	43.42	0.61	48.81	0.90	51.18	47.12	NA
28	54.64	0.00	61.81	0.58	67.00	0.83	68.52	63.43	70.51
29	86.85	-0.04	92.52	0.45	95.93	0.72	99.05	85.24	95.61
30	89.90	-0.08	95.40	0.49	98.91	0.71	100.80	87.38	98.01
31	4.32	0.06	15.71	0.67	25.29	0.84	31.04	32.49	NA
32	13.12	0.08	24.33	0.68	33.76	0.86	38.69	40.34	NA
33	22.74	0.07	34.31	0.63	43.51	0.87	49.35	49.05	51.85
34	46.44	0.06	58.01	0.53	67.79	0.87	73.60	67.96	73.09
35	71.52	-0.02	81.91	0.44	90.68	0.73	95.86	82.02	91.48
36	7.77	0.18	20.69	0.78	31.72	1.04	35.93	37.04	NA
37	14.87	0.17	27.94	0.73	39.19	0.99	45.73	45.89	NA
38	22.60	0.18	35.50	0.74	47.39	1.01	53.70	51.65	58.04
39	65.20	0.15	75.80	0.68	84.67	0.97	89.70	78.11	89.95
40	75.23	0.12	86.03	0.62	94.43	0.93	99.71	87.51	97.33
41	7.36	0.03	20.64	0.60	32.23	0.87	38.98	38.16	NA
42	15.23	0.06	28.66	0.69	40.90	0.93	46.84	44.91	NA
43	36.35	0.03	49.74	0.63	61.03	0.87	66.57	63.36	70.88
44	71.81	0.00	82.03	0.47	90.25	0.77	95.18	84.22	95.01
45	75.88	0.00	86.02	0.45	94.16	0.84	99.01	87.78	98.55
46	25.32	0.26	28.76	0.80	30.42	1.12	31.26	29.76	NA
47	35.78	0.30	39.14	0.81	41.03	1.10	41.85	38.17	NA
48	53.61	0.17	57.27	0.76	59.13	0.99	60.01	54.93	58.53
49	89.44	0.28	91.01	0.67	90.72	0.94	90.50	76.55	85.15
50	102.17	0.10	103.54	0.61	103.08	0.84	102.97	86.68	86.67
51	39.10	0.34	40.55	0.86	40.15	1.03	40.09	38.59	NA
52	44.21	0.32	45.90	0.77	45.68	1.07	45.71	43.21	NA
53	70.30	0.31	71.84	0.85	71.48	1.02	70.40	65.88	69.22

Table B2, cont. Water depth measurements and depth to flume bed measurements collected for each weir.

Weir No.	Surface 3 (mm)	Bed 3 (mm)	Surface 2 (mm)	Bed 2 (mm)	Surface 1 (mm)	Bed 1 (mm)	Upstream Water Depth (mm)	Center Water Depth (mm)	Water Depth at Ripple (mm)
54	99.80	0.15	101.20	0.74	100.93	1.08	100.53	88.30	97.12
55	103.64	0.31	105.30	0.84	104.80	0.99	104.54	91.84	100.57
56	42.35	0.06	44.04	0.69	44.03	0.80	44.17	41.37	NA
57	52.04	0.13	53.67	0.69	53.45	0.98	53.39	47.79	NA
58	72.85	0.10	74.73	0.65	74.62	0.85	74.35	70.00	72.22
59	92.24	0.05	94.23	0.64	94.28	0.82	93.93	86.03	91.95
60	103.24	0.08	104.93	0.57	104.87	0.79	104.58	93.35	101.94
61	17.66	0.30	24.02	0.89	28.03	1.01	30.76	29.26	NA
62	28.70	0.29	34.66	0.73	49.01	1.00	41.82	40.11	NA
63	45.39	0.24	51.82	0.78	56.47	1.18	58.76	56.68	58.17
64	74.63	0.23	81.54	0.73	86.30	1.09	89.08	77.67	85.78
65	85.21	0.30	92.25	0.74	97.06	1.01	99.83	86.47	86.98
66	23.74	0.37	31.21	0.89	36.43	1.00	39.78	38.21	NA
67	29.22	0.35	36.61	0.84	42.08	1.09	44.98	43.65	NA
68	53.91	0.33	60.68	0.84	66.55	1.15	69.77	65.36	70.63
69	80.23	0.39	88.36	0.84	93.60	1.04	96.89	88.42	93.25
70	84.42	0.28	91.67	0.81	97.10	1.04	100.12	91.70	97.58
71	30.61	0.12	37.09	0.68	41.26	0.84	43.66	41.59	NA
72	49.98	0.11	56.06	0.64	60.50	0.89	63.17	57.52	NA
73	62.18	0.05	68.25	0.63	72.57	0.83	75.08	68.46	74.99
74	76.40	0.70	82.90	0.62	87.35	0.86	89.69	84.87	88.50
75	88.81	0.04	95.26	0.54	99.69	0.79	102.11	93.75	101.47
76	4.52	0.41	16.05	0.93	25.32	1.16	31.67	34.13	NA
77	16.09	0.17	27.62	0.76	37.31	1.30	43.06	45.47	NA
78	28.57	0.51	40.01	1.14	49.63	1.38	55.76	55.50	58.21
79	58.59	0.14	69.96	0.70	79.84	0.96	85.87	77.57	85.42

Table B2, cont. Water depth measurements and depth to flume bed measurements collected for each weir.

Weir No.	Surface 3 (mm)	Bed 3 (mm)	Surface 2 (mm)	Bed 2 (mm)	Surface 1 (mm)	Bed 1 (mm)	Upstream Water Depth (mm)	Center Water Depth (mm)	Water Depth at Ripple (mm)
80	70.74	0.17	82.35	0.66	92.26	0.87	97.99	87.79	96.41
81	13.07	0.36	24.59	1.02	34.37	1.23	40.02	49.80	NA
82	22.39	0.42	33.86	0.91	43.60	1.15	49.66	48.23	NA
83	39.08	0.39	50.83	0.84	60.23	1.15	66.03	66.98	69.68
84	67.17	0.33	79.01	0.83	88.54	1.08	94.38	88.67	94.32
85	70.36	0.32	82.22	0.75	99.88	1.01	97.37	91.02	97.17
86	11.31	0.15	23.02	0.76	32.77	1.00	38.82	39.79	NA
87	20.22	0.13	31.91	0.73	41.75	0.97	47.22	48.46	NA
88	42.04	0.17	53.39	0.68	63.36	0.94	69.28	67.67	72.47
89	68.78	0.15	80.34	0.67	90.32	0.92	96.08	90.15	98.02
90	70.35	0.17	81.89	0.63	91.43	0.85	97.48	90.83	99.50
91	29.59	0.33	30.99	0.86	30.95	1.07	29.65	25.91	NA
92	34.45	0.27	36.03	0.87	35.59	1.09	35.51	29.94	NA
93	54.49	0.27	56.11	0.81	55.66	0.06	55.65	48.47	53.94
94	72.50	0.01	74.24	0.60	73.86	0.85	73.37	63.00	69.94
95	84.84	0.01	86.79	0.57	86.38	0.82	85.79	73.50	81.14
96	27.37	0.12	28.89	0.70	29.81	0.92	30.11	26.83	NA
97	31.22	0.10	33.70	0.67	34.45	0.91	34.75	31.50	NA
98	53.87	0.16	56.58	0.72	57.36	0.95	57.63	53.91	57.25
99	72.12	0.06	74.80	0.67	75.89	0.87	75.71	68.90	74.17
100	87.01	0.23	88.25	0.52	88.07	0.82	87.59	78.26	84.39
101	32.50	0.10	34.17	0.55	33.83	0.88	33.47	20.65	NA
102	54.13	0.05	55.73	0.63	55.31	0.86	55.12	49.16	NA
103	68.72	0.05	70.25	0.58	69.85	0.87	69.46	64.24	68.47
104	78.46	0.05	80.05	0.55	79.83	0.87	79.17	69.75	76.83
105	90.77	0.05	92.34	0.54	92.01	0.82	91.77	81.27	89.81

Table B2, cont. Water depth measurements and depth to flume bed measurements collected for each weir.

Weir No.	Surface 3 (mm)	Bed 3 (mm)	Surface 2 (mm)	Bed 2 (mm)	Surface 1 (mm)	Bed 1 (mm)	Upstream Water Depth (mm)	Center Water Depth (mm)	Water Depth at Ripple (mm)
106	18.97	0.28	25.87	0.85	31.03	1.09	33.74	30.91	NA
107	23.94	0.26	31.11	0.86	36.34	1.10	39.89	37.00	NA
108	37.28	0.32	44.63	0.85	49.82	1.10	52.79	50.12	53.62
109	54.92	0.24	62.10	0.84	67.49	1.04	70.56	62.41	69.76
110	69.14	0.03	75.78	0.56	80.35	0.87	82.90	72.73	80.92
111	18.34	0.13	25.34	0.71	30.57	0.96	33.64	31.67	NA
112	23.67	0.12	30.69	0.69	35.86	0.93	38.82	37.67	NA
113	39.58	0.08	46.70	0.62	51.90	0.90	54.82	54.39	56.45
114	58.72	0.07	65.86	0.59	71.06	0.86	74.21	67.96	73.96
115	70.81	0.15	77.21	0.50	81.70	0.78	84.40	77.26	83.27
116	21.20	0.17	27.11	0.68	31.06	0.94	33.81	29.26	NA
117	34.65	0.09	40.55	0.65	44.46	0.90	46.61	41.96	NA
118	53.87	0.08	60.23	0.64	64.58	0.90	66.92	61.36	68.45
119	63.39	0.07	69.81	0.57	74.20	0.86	76.64	69.59	76.31
120	72.51	0.10	78.71	0.62	83.02	0.85	85.58	76.22	85.72
121	2.21	0.29	9.43	0.87	19.76	0.08	26.21	25.73	NA
122	8.33	0.33	20.37	0.88	30.66	1.06	36.51	36.54	NA
123	21.02	0.31	32.88	0.83	43.19	1.08	48.94	48.01	52.02
124	38.26	0.25	49.71	0.81	60.80	1.06	66.96	60.71	68.24
125	51.36	0.02	63.02	0.57	72.47	0.86	78.11	70.98	77.13
126	1.94	0.18	7.89	0.77	16.32	1.00	21.89	20.60	NA
127	7.84	0.16	18.64	0.69	27.27	0.99	32.61	31.69	NA
128	26.15	0.14	36.88	0.66	45.75	0.94	50.84	53.81	54.28
129	46.63	0.06	57.59	0.63	66.43	0.92	71.69	69.28	73.00
130	56.74	0.04	67.72	0.66	76.45	0.87	81.26	76.86	81.85
131	5.38	0.17	16.63	0.84	25.45	1.06	31.00	29.23	NA

Table B2, cont. Water depth measurements and depth to flume bed measurements collected for each weir.

Weir No.	Surface 3 (mm)	Bed 3 (mm)	Surface 2 (mm)	Bed 2 (mm)	Surface 1 (mm)	Bed 1 (mm)	Upstream Water Depth (mm)	Center Water Depth (mm)	Water Depth at Ripple (mm)
132	20.43	0.13	31.54	0.70	40.44	0.92	45.64	41.66	NA
133	38.35	0.12	49.53	0.65	58.63	0.89	64.17	62.38	67.44
134	48.68	0.09	59.84	0.62	68.80	0.90	74.24	70.28	76.07
135	57.15	0.13	68.40	0.61	77.44	0.92	82.70	76.59	84.54
136	21.30	0.08	22.69	0.74	22.47	0.89	21.61	19.29	NA
137	36.09	0.05	37.53	0.63	37.22	0.83	36.14	32.45	NA
138	57.33	0.06	58.91	0.57	58.62	0.83	58.28	50.94	57.00
139	74.64	-0.06	76.27	0.45	75.74	0.79	75.43	67.31	73.45
140	79.57	0.07	82.50	0.55	83.27	0.87	83.17	73.93	81.79
141	30.93	0.33	32.41	0.88	31.98	1.06	31.27	30.25	NA
142	40.67	0.28	42.18	0.82	41.79	1.06	41.47	37.43	NA
143	62.10	0.24	63.59	0.80	63.51	0.90	63.56	58.15	61.35
144	78.22	0.16	79.69	0.73	79.07	0.98	78.38	69.77	76.07
145	80.66	0.00	83.28	0.54	83.97	0.82	84.22	73.34	82.79
146	35.42	0.24	37.07	0.82	36.65	1.06	36.62	30.35	NA
147	45.34	0.22	46.95	0.82	46.57	1.02	45.79	40.30	NA
148	69.83	0.11	71.48	0.74	71.23	1.02	70.66	63.81	70.13
149	80.13	0.13	81.77	0.69	81.53	0.92	81.57	70.75	79.62
150	88.64	0.10	90.24	0.68	90.04	0.85	89.88	78.22	87.73
151	19.09	0.10	25.18	0.64	29.51	0.90	31.89	29.92	NA
152	28.34	0.06	34.38	0.67	38.73	0.93	41.30	39.98	NA
153	43.30	0.06	49.48	0.60	53.65	0.85	55.69	51.35	56.69
154	60.02	0.14	66.12	0.43	70.53	0.75	72.84	67.33	73.01
155	65.49	0.09	72.49	0.63	77.53	0.84	80.34	73.12	80.44
156	19.16	0.32	25.17	0.88	29.15	1.01	31.44	30.68	NA
157	24.07	0.36	30.10	0.90	34.03	0.94	36.66	34.91	NA

Table B2, cont. Water depth measurements and depth to flume bed measurements collected for each weir.

Weir No.	Surface 3 (mm)	Bed 3 (mm)	Surface 2 (mm)	Bed 2 (mm)	Surface 1 (mm)	Bed 1 (mm)	Upstream Water Depth (mm)	Center Water Depth (mm)	Water Depth at Ripple (mm)
158	49.18	0.24	54.92	0.83	59.11	1.03	61.18	58.77	62.04
159	64.04	0.20	70.04	0.74	73.95	0.91	76.25	69.24	76.06
160	62.00	0.05	70.64	0.53	77.11	0.80	80.87	72.84	80.86
161	21.33	0.26	27.85	0.86	32.31	1.08	33.42	29.86	NA
162	26.75	0.25	33.43	0.84	38.18	1.07	40.72	37.88	NA
163	54.61	0.21	61.16	0.77	65.95	1.01	68.21	67.04	70.16
164	63.14	0.20	69.82	0.75	74.56	1.03	77.26	75.29	78.14
165	71.01	0.19	77.76	0.74	82.59	0.97	85.04	80.38	85.47
166	1.78	0.16	5.10	0.65	14.42	0.88	20.06	22.03	NA
167	7.27	0.16	18.85	0.73	28.27	0.98	33.06	34.37	NA
168	23.78	0.11	35.04	0.64	44.69	0.82	50.49	49.29	53.78
169	45.01	0.13	55.71	0.58	64.54	0.67	71.15	66.30	71.49
170	53.73	0.11	64.32	0.63	73.23	0.88	77.70	72.59	78.90
171	2.25	0.37	10.19	0.88	20.53	1.14	26.35	29.34	NA
172	8.94	0.28	21.23	0.89	31.51	1.03	37.84	38.79	NA
173	26.59	0.27	39.09	0.80	49.36	1.07	55.36	54.89	59.28
174	42.84	0.25	55.47	0.82	65.77	1.04	71.98	65.55	74.41
175	52.24	0.25	64.76	0.81	75.08	0.95	80.91	75.50	82.51
176	14.36	0.28	24.57	0.85	33.05	1.02	37.38	35.30	NA
177	21.36	0.26	31.75	0.84	39.87	1.05	45.45	43.41	NA
178	44.13	0.27	54.69	0.76	63.23	0.96	68.30	69.10	70.92
179	52.04	0.22	62.51	0.77	71.17	0.99	76.23	75.94	78.56
180	60.46	0.20	72.58	0.71	83.18	0.99	87.62	81.75	91.17
181	24.15	0.12	25.68	0.72	25.18	0.91	24.96	20.84	NA
182	28.59	0.10	30.30	0.68	30.21	0.93	29.58	25.11	NA
183	48.74	0.06	50.36	0.65	50.09	0.93	48.99	45.94	48.36

Table B2, cont. Water depth measurements and depth to flume bed measurements collected for each weir.

Weir No.	Surface 3 (mm)	Bed 3 (mm)	Surface 2 (mm)	Bed 2 (mm)	Surface 1 (mm)	Bed 1 (mm)	Upstream Water Depth (mm)	Center Water Depth (mm)	Water Depth at Ripple (mm)
184	56.60	0.08	58.13	0.62	58.03	0.90	57.41	52.55	56.50
185	65.52	0.09	67.20	0.65	66.76	0.86	66.47	59.07	63.80
186	25.04	0.15	26.61	0.76	26.03	0.96	26.19	23.59	NA
187	30.09	0.19	31.70	0.75	31.16	0.97	30.83	27.89	NA
188	52.88	0.15	54.44	0.72	54.03	0.98	53.65	50.61	51.96
189	58.14	0.16	59.59	0.71	59.43	0.93	59.03	55.78	57.37
190	65.99	0.16	67.39	0.73	66.88	0.93	66.70	60.68	63.98
191	29.87	0.16	31.31	0.71	30.88	0.98	30.75	27.31	NA
192	34.78	0.19	36.04	0.72	35.75	0.99	35.24	31.47	NA
193	57.82	0.16	59.49	0.68	59.17	0.98	59.64	53.46	58.25
194	61.54	0.15	63.27	0.65	62.52	1.04	62.26	55.20	61.96
195	68.09	0.13	69.77	0.69	69.37	0.92	69.30	61.18	68.16
196	5.02	0.18	11.32	0.73	16.14	0.95	19.23	18.59	NA
197	20.39	0.19	26.86	0.71	31.37	0.96	34.14	32.55	NA
198	35.45	0.16	41.97	0.68	46.52	0.91	48.83	48.91	50.29
199	40.65	0.12	47.24	0.64	51.84	0.91	54.35	52.31	54.96
200	50.30	0.11	56.66	0.64	61.33	0.89	63.79	59.47	63.41
201	18.74	0.17	24.45	0.76	28.47	0.99	30.81	29.59	NA
202	22.94	0.19	28.88	0.80	32.91	1.02	35.24	33.22	NA
203	40.92	0.16	46.79	0.73	50.67	0.97	52.97	50.78	53.76
204	45.26	0.15	51.08	0.73	55.23	0.95	57.47	55.48	57.48
205	53.03	0.12	58.91	0.69	63.10	0.90	65.31	60.20	65.16
206	19.28	0.21	24.90	0.76	28.68	0.99	30.99	29.43	NA
207	23.70	0.21	29.35	0.74	32.97	0.98	35.26	33.28	NA
208	44.04	0.20	49.85	0.72	53.42	0.95	55.62	50.30	57.35
209	49.76	0.17	55.35	0.70	59.27	0.94	61.36	55.66	62.63

Table B2, cont. Water depth measurements and depth to flume bed measurements collected for each weir.

Weir No.	Surface 3 (mm)	Bed 3 (mm)	Surface 2 (mm)	Bed 2 (mm)	Surface 1 (mm)	Bed 1 (mm)	Upstream Water Depth (mm)	Center Water Depth (mm)	Water Depth at Ripple (mm)
210	55.67	0.17	61.12	0.66	64.84	0.94	67.15	59.83	67.35
211	2.05	0.20	10.60	0.73	20.77	0.95	26.31	27.32	NA
212	5.86	0.23	17.60	0.78	27.86	0.96	32.73	35.29	NA
213	13.66	0.17	25.15	0.71	35.17	0.95	41.20	44.69	45.76
214	22.39	0.17	34.19	0.72	43.81	0.94	49.40	51.80	53.45
215	32.38	0.22	43.57	0.69	54.75	0.93	60.02	58.71	62.39
216	2.18	0.23	10.37	0.77	21.05	0.96	27.11	28.58	NA
217	6.72	0.20	18.92	0.76	29.56	0.96	35.28	36.53	NA
218	18.23	0.20	30.98	0.80	40.64	0.97	46.77	49.58	51.05
219	24.79	0.16	36.81	0.69	46.99	0.93	53.25	55.21	57.01
220	32.40	0.24	44.17	0.72	55.45	0.99	61.45	59.63	62.04
221	5.97	0.18	17.20	0.77	26.66	0.93	31.96	32.68	NA
222	12.23	0.21	23.07	0.75	32.69	0.96	38.19	36.12	NA
223	27.20	0.21	38.72	0.75	48.47	0.98	53.40	50.92	57.22
224	29.20	0.23	40.93	0.72	50.48	1.00	56.08	53.25	59.43
225	37.46	0.23	49.11	0.73	58.91	0.95	64.07	60.14	64.57
226	27.17	0.16	29.09	0.73	28.91	0.94	28.74	25.65	NA
227	32.31	0.10	34.14	0.71	34.05	0.94	33.38	30.19	NA
228	48.93	0.12	50.59	0.54	50.51	0.92	50.09	46.78	49.50
229	57.35	0.12	59.27	0.62	58.87	0.91	58.58	54.55	57.33
230	73.00	0.06	74.72	0.50	74.50	0.75	74.25	67.19	70.96
231	22.15	0.08	23.69	0.63	23.51	0.88	23.16	21.37	NA
232	32.10	0.06	33.62	0.59	33.28	0.88	33.13	30.71	NA
233	55.91	0.04	57.47	0.54	57.30	0.85	56.90	53.07	56.77
234	64.18	0.03	65.71	0.52	65.34	0.84	65.02	59.76	63.63
235	68.49	0.03	70.23	0.55	69.72	0.84	69.22	63.44	67.90

Table B2, cont. Water depth measurements and depth to flume bed measurements collected for each weir.

Weir No.	Surface 3 (mm)	Bed 3 (mm)	Surface 2 (mm)	Bed 2 (mm)	Surface 1 (mm)	Bed 1 (mm)	Upstream Water Depth (mm)	Center Water Depth (mm)	Water Depth at Ripple (mm)
236	27.06	0.04	28.34	0.70	28.26	0.93	28.10	26.23	NA
237	36.93	0.12	38.79	0.66	38.34	0.92	38.13	34.61	NA
238	61.91	0.11	63.52	0.63	63.27	0.88	62.80	56.76	61.18
239	64.38	0.08	66.15	0.63	65.79	0.92	65.67	61.14	64.09
240	67.37	0.09	68.96	0.60	68.55	0.87	68.01	62.97	66.48
241	16.84	0.13	22.66	0.66	26.67	0.96	28.67	27.00	NA
242	21.64	0.16	27.40	0.71	31.16	0.88	33.37	31.31	NA
243	36.29	0.10	42.14	0.65	45.92	0.85	48.29	48.26	49.89
244	44.36	0.12	50.34	0.62	54.27	0.87	56.56	54.60	56.89
245	56.60	0.00	63.51	0.50	68.34	0.77	71.25	67.03	70.47
246	12.99	0.04	18.12	0.59	23.66	0.83	26.56	26.71	NA
247	24.09	0.02	30.47	0.61	34.76	0.83	37.08	36.33	NA
248	41.83	-0.10	48.07	0.50	52.08	0.84	54.39	54.00	56.57
249	48.24	0.01	54.63	0.50	58.94	0.78	61.49	59.94	62.53
250	56.38	0.01	62.68	0.54	66.99	0.83	69.56	64.87	69.85
251	10.49	0.16	17.03	0.72	21.54	0.95	24.11	24.59	NA
252	23.51	0.10	29.88	0.71	34.24	0.95	36.83	34.66	NA
253	46.41	0.13	52.81	0.68	57.27	0.92	59.88	56.54	61.14
254	48.99	0.11	55.47	0.63	60.09	0.90	62.66	59.56	62.91
255	52.38	0.11	58.86	0.66	63.32	0.92	66.06	62.67	66.53
256	1.57	0.10	2.49	0.78	10.83	0.98	17.25	19.74	NA
257	2.17	0.15	15.15	0.71	26.00	0.97	31.36	34.14	NA
258	13.46	0.13	25.53	0.67	36.38	0.92	42.33	45.32	46.96
259	21.84	0.14	34.17	0.67	44.69	0.87	51.40	51.92	55.09
260	40.40	0.00	51.87	0.54	62.03	0.81	67.44	65.33	69.03
261	2.19	0.06	13.95	0.62	24.42	0.84	30.56	33.39	NA

Table B2, cont. Water depth measurements and depth to flume bed measurements collected for each weir.

Weir No.	Surface 3 (mm)	Bed 3 (mm)	Surface 2 (mm)	Bed 2 (mm)	Surface 1 (mm)	Bed 1 (mm)	Upstream Water Depth (mm)	Center Water Depth (mm)	Water Depth at Ripple (mm)
262	9.05	0.07	21.23	0.63	31.95	0.88	38.17	39.57	NA
263	19.38	0.06	31.64	0.59	42.82	0.87	48.88	51.82	53.71
264	27.05	0.04	38.33	0.55	49.40	0.84	55.48	58.56	60.42
265	35.26	0.03	47.02	0.57	57.95	0.85	64.00	64.22	67.65
266	1.90	0.15	11.97	0.77	21.26	0.96	26.76	28.61	NA
267	15.70	0.14	27.12	0.71	36.51	0.95	41.71	41.78	NA
268	27.95	0.14	39.85	0.68	49.03	0.92	54.65	54.59	57.79
269	32.36	0.15	43.84	0.69	53.17	0.94	58.55	58.50	61.94
270	36.64	0.11	48.52	0.68	58.01	0.90	63.43	64.15	65.77
271	18.44	0.18	20.23	0.76	20.13	1.01	20.46	20.22	NA
272	63.95	0.11	65.48	0.62	65.50	0.93	65.15	56.48	61.28
273	100.19	0.18	102.00	0.58	101.54	0.84	101.34	88.27	93.02
274	7.50	0.14	16.42	0.75	23.25	0.88	27.21	29.59	NA
275	50.79	0.10	59.52	0.65	66.55	0.85	64.61	64.99	64.51
276	79.81	0.03	87.96	0.55	94.56	0.86	97.34	86.05	89.99
277	1.74	0.21	2.80	0.76	9.87	0.97	16.49	21.17	NA
278	39.43	0.24	51.38	0.81	63.33	1.22	67.92	66.13	67.32
279	60.62	0.03	75.10	0.57	84.59	0.89	93.00	80.79	NA
280	17.62	0.00	19.20	0.57	18.96	0.91	18.59	16.89	NA
281	75.02	0.07	76.36	0.59	76.17	0.78	75.78	61.22	65.54
282	99.41	0.04	100.77	0.45	100.11	0.78	99.83	80.46	88.57
283	8.12	0.11	14.52	0.72	19.12	0.92	21.56	19.68	21.62
284	57.53	0.04	64.73	0.56	70.02	0.87	73.04	60.93	66.57
285	81.89	0.02	89.36	0.50	95.25	0.79	97.91	81.34	90.63
286	1.99	0.09	2.94	0.67	11.55	0.91	17.28	18.30	18.84
287	35.80	0.03	51.60	0.47	60.02	0.77	70.00	57.08	64.35

Table B2, cont. Water depth measurements and depth to flume bed measurements collected for each weir.

Weir No.	Surface 3 (mm)	Bed 3 (mm)	Surface 2 (mm)	Bed 2 (mm)	Surface 1 (mm)	Bed 1 (mm)	Upstream Water Depth (mm)	Center Water Depth (mm)	Water Depth at Ripple (mm)
288	64.98	0.04	77.41	0.62	87.79	0.82	94.12	79.67	NA
289	19.12	0.07	21.10	0.71	21.10	0.85	20.67	19.76	NA
290	66.18	0.00	68.14	0.59	68.17	0.85	68.01	57.33	62.63
291	84.37	-0.04	86.86	0.53	86.31	0.83	86.16	72.86	80.08
292	6.38	0.08	13.04	0.75	17.43	0.95	20.42	20.53	22.42
293	52.45	0.07	58.72	0.54	63.05	0.72	65.52	57.02	61.28
294	71.11	0.00	77.76	0.47	82.19	0.87	84.27	72.36	79.64
295	2.06	0.14	2.93	0.78	6.80	0.89	12.60	16.61	17.00
296	37.79	0.08	49.07	0.53	57.00	0.84	62.48	54.64	61.99
297	55.75	0.06	66.65	0.60	75.73	0.90	80.89	70.61	NA
298	21.81	-0.12	23.69	0.57	24.02	0.75	23.77	21.26	22.83
299	64.45	-0.11	66.46	0.45	66.60	0.63	66.30	52.32	NA
300	81.32	-0.11	83.18	0.37	83.62	0.66	83.06	65.86	NA
301	7.14	-0.01	13.42	0.55	17.87	0.81	20.41	20.27	NA
302	48.33	-0.11	55.68	0.39	60.68	0.63	63.61	51.19	NA
303	63.89	-0.14	72.05	0.36	77.23	0.57	80.40	65.20	NA
304	2.30	0.13	3.35	0.71	9.76	0.99	14.90	16.46	18.60
305	32.61	-0.06	44.21	0.42	54.68	0.67	61.06	50.31	NA
306	45.02	-0.03	58.31	0.50	70.04	0.72	75.97	62.64	NA
307	15.45	0.02	17.96	0.64	18.44	0.89	18.99	18.57	18.57
308	1.07	51.43	50.13	0.52	50.89	0.82	51.14	44.73	47.14
309	59.36	1.27	63.97	0.89	63.34	0.95	64.93	56.48	61.39
310	2.29	0.03	7.09	0.64	12.04	0.88	15.06	17.61	17.36
311	38.31	1.21	44.52	0.87	41.14	0.99	46.96	42.89	NA
312	57.44	1.28	62.44	1.01	59.44	1.05	63.50	55.39	NA
313	2.37	0.10	3.37	0.64	8.24	0.89	13.72	18.37	17.31

Table B2, cont. Water depth measurements and depth to flume bed measurements collected for each weir.

Weir No.	Surface 3 (mm)	Bed 3 (mm)	Surface 2 (mm)	Bed 2 (mm)	Surface 1 (mm)	Bed 1 (mm)	Upstream Water Depth (mm)	Center Water Depth (mm)	Water Depth at Ripple (mm)
314	26.70	1.30	34.90	0.80	31.50	0.90	36.90	43.70	NA
315	36.90	1.40	43.40	0.90	10.00	1.10	46.70	52.10	NA
316	23.38	0.14	24.89	0.77	24.42	1.00	23.68	22.40	NA
317	50.63	0.11	52.28	0.71	51.83	0.98	51.27	42.88	44.58
318	67.17	0.08	68.90	0.66	68.67	0.90	68.50	54.79	NA
319	8.42	0.21	14.75	0.80	18.96	1.00	21.66	22.02	22.03
320	35.32	0.19	40.92	0.76	43.85	0.99	47.05	41.06	NA
321	49.82	0.14	55.71	0.60	60.57	96.00	63.72	52.29	NA
322	13.13	0.93	11.71	1.10	10.12	1.01	15.34	18.84	19.47
323	26.47	1.31	35.56	0.88	30.86	0.86	37.74	35.41	NA
324	34.99	1.28	43.56	0.88	39.88	0.92	46.44	37.91	NA

Table 19 B3. Calculated parameters and Buckingham PI terms for each weir, where NM = not measureable (value close to 0).

Weir No.	Velocity (m/s)	Discharge (m^3/s)	Water Depth above Weir (mm)	Water Surface Slope	Fr No.	Re No.	d_{50}/h
1	0.006	1.99E-04	16.98	NM	0.237	97.96	0.94
2	0.007	2.88E-04	25.67	NM	0.280	172.77	0.94
3	0.015	8.16E-04	41.52	NM	0.624	598.81	0.94
4	0.053	3.69E-03	66.67	NM	2.228	3397.41	0.94
5	0.103	9.68E-03	88.57	NM	5.064	8771.33	0.94
6	0.007	2.02E-04	14.82	NM	0.259	99.74	1.42
7	0.007	2.52E-04	23.16	NM	0.258	155.88	1.42
8	0.015	9.44E-04	47.73	NM	0.673	688.37	1.42
9	0.070	6.14E-03	81.66	NM	3.346	5496.03	1.42
10	0.091	8.66E-03	91.33	NM	4.464	7990.91	1.42
11	0.007	3.18E-04	30.97	NM	0.282	208.44	1.89
12	0.010	5.79E-04	45.13	0.1%	0.424	433.92	1.89
13	0.021	1.66E-03	63.10	NM	1.027	1274.06	1.89
14	0.063	5.59E-03	89.10	NM	2.919	5397.09	1.89
15	0.066	6.20E-03	91.53	NM	3.193	5808.30	1.89
16	0.013	3.12E-04	10.66	0.6%	0.470	133.24	0.94
17	0.011	4.18E-04	25.78	0.6%	0.405	272.66	0.94
18	0.016	8.09E-04	37.01	0.6%	0.655	569.35	0.94
19	0.057	3.60E-03	62.78	0.6%	2.241	3440.63	0.94
20	0.116	9.66E-03	85.83	0.5%	5.138	9572.79	0.94
21	0.008	2.98E-04	25.66	0.6%	0.290	197.37	1.42
22	0.006	1.91E-04	19.37	0.6%	0.214	111.74	1.42
23	0.018	1.09E-03	45.58	0.6%	0.793	788.84	1.42
24	0.076	6.04E-03	78.65	0.6%	3.353	5747.17	1.42
25	0.097	8.58E-03	88.45	0.6%	4.492	8249.19	1.42
26	0.007	2.65E-04	25.87	0.6%	0.257	174.11	1.89
27	0.011	5.50E-04	37.73	0.6%	0.441	399.04	1.89

Table B3, cont. Calculated parameters and Buckingham PI terms for each weir, where NM = not measureable (value close to 0).

Weir No.	Velocity (m/s)	Discharge (m^3/s)	Water Depth above Weir (mm)	Water Surface Slope	Fr No.	Re No.	d_{50}/h
28	0.020	1.38E-03	55.07	0.5%	0.913	1058.98	1.89
29	0.063	5.19E-03	85.60	0.4%	2.762	5185.09	1.89
30	0.064	5.80E-03	87.35	0.4%	3.057	5375.07	1.89
31	0.007	2.28E-04	17.59	1.0%	0.268	118.39	0.94
32	0.010	3.86E-04	25.24	1.0%	0.379	242.68	0.94
33	0.016	8.08E-04	35.90	1.0%	0.664	552.28	0.94
34	0.051	3.49E-03	60.15	1.0%	2.215	2949.49	0.94
35	0.121	9.71E-03	82.41	0.9%	5.266	9587.53	0.94
36	0.009	3.16E-04	22.48	1.1%	0.329	194.53	1.42
37	0.011	4.99E-04	32.28	1.2%	0.433	341.40	1.42
38	0.017	9.08E-04	40.25	1.2%	0.705	657.89	1.42
39	0.076	6.08E-03	76.25	0.9%	3.431	5571.79	1.42
40	0.098	8.55E-03	86.26	0.9%	4.535	8127.88	1.42
41	0.008	3.16E-04	25.53	1.2%	0.308	196.37	1.89
42	0.010	4.75E-04	33.39	1.2%	0.405	321.04	1.89
43	0.022	1.45E-03	53.12	1.1%	0.977	1123.63	1.89
44	0.069	5.08E-03	81.73	0.9%	2.767	5422.16	1.89
45	0.073	6.01E-03	85.56	0.9%	3.200	6005.31	1.89
46	0.005	1.64E-04	18.57	0.2%	0.198	89.27	1.00
47	0.005	2.06E-04	29.16	0.2%	0.199	140.18	1.00
48	0.014	8.61E-04	47.32	0.2%	0.653	636.96	1.00
49	0.064	4.90E-03	77.81	NM	2.899	4788.03	1.00
50	0.086	7.93E-03	90.28	NM	4.358	7465.03	1.00
51	0.005	1.84E-04	27.40	NM	0.183	131.72	1.50
52	0.005	2.16E-04	33.02	NM	0.196	158.74	1.50
53	0.014	9.89E-04	57.71	NM	0.679	776.82	1.50
54	0.055	5.26E-03	87.84	NM	2.931	4645.12	1.50

Table B3, cont. Calculated parameters and Buckingham PI terms for each weir, where NM = not measureable (value close to 0).

Weir No.	Velocity (m/s)	Discharge (m^3/s)	Water Depth above Weir (mm)	Water Surface Slope	Fr No.	Re No.	d_{50}/h
55	0.063	6.15E-03	91.85	NM	3.349	5563.67	1.50
56	0.006	2.49E-04	31.48	0.1%	0.232	181.60	2.00
57	0.007	3.85E-04	40.70	NM	0.315	273.93	2.00
58	0.018	1.27E-03	61.66	0.1%	0.844	1067.13	2.00
59	0.042	3.52E-03	81.24	0.1%	2.041	3280.66	2.00
60	0.054	5.73E-03	91.89	NM	3.122	4770.94	2.00
61	0.004	1.35E-04	18.07	0.5%	0.166	69.50	1.00
62	0.005	2.09E-04	29.13	0.6%	0.202	140.04	1.00
63	0.014	8.58E-04	46.07	0.5%	0.660	620.14	1.00
64	0.075	5.29E-03	76.39	0.5%	3.163	5508.58	1.00
65	0.093	7.87E-03	87.14	0.5%	4.400	7791.88	1.00
66	0.004	1.64E-04	27.09	0.6%	0.164	104.19	1.50
67	0.005	2.16E-04	32.29	0.6%	0.198	155.23	1.50
68	0.016	1.09E-03	57.08	0.6%	0.756	878.10	1.50
69	0.063	5.02E-03	84.20	0.6%	2.858	5100.28	1.50
70	0.068	5.79E-03	87.43	0.6%	3.233	5716.25	1.50
71	0.006	2.57E-04	30.97	0.5%	0.241	178.66	2.00
72	0.011	7.19E-04	50.48	0.5%	0.528	533.89	2.00
73	0.020	1.53E-03	62.39	0.5%	1.015	1199.74	2.00
74	0.039	3.30E-03	77.00	0.5%	1.961	2887.33	2.00
75	0.059	5.72E-03	89.42	0.5%	3.159	5072.57	2.00
76	0.006	2.06E-04	18.98	1.0%	0.246	109.49	1.00
77	0.007	3.12E-04	30.37	1.0%	0.295	204.40	1.00
78	0.015	8.69E-04	43.07	1.0%	0.691	621.17	1.00
79	0.080	5.02E-03	73.18	1.0%	3.065	5628.91	1.00
80	0.104	8.13E-03	85.30	1.0%	4.598	8529.51	1.00
81	0.006	2.40E-04	27.33	1.0%	0.240	157.66	1.50

Table B3, cont. Calculated parameters and Buckingham PI terms for each weir, where NM = not measureable (value close to 0).

Weir No.	Velocity (m/s)	Discharge (m^3/s)	Water Depth above Weir (mm)	Water Surface Slope	Fr No.	Re No.	d_{50}/h
82	0.007	3.42E-04	36.97	1.0%	0.294	248.82	1.50
83	0.016	1.07E-03	53.34	1.0%	0.763	820.57	1.50
84	0.065	5.07E-03	81.69	1.0%	2.927	5105.33	1.50
85	0.069	5.84E-03	84.68	1.1%	3.312	5617.87	1.50
86	0.006	2.52E-04	26.13	1.0%	0.257	150.74	2.00
87	0.008	3.60E-04	34.53	1.0%	0.320	265.60	2.00
88	0.019	1.32E-03	56.59	1.0%	0.919	1033.80	2.00
89	0.063	5.08E-03	83.39	1.0%	2.903	5051.22	2.00
90	0.063	5.40E-03	84.79	1.0%	3.061	5136.02	2.00
91	0.009	2.65E-04	16.96	NM	0.168	146.76	1.00
92	0.008	2.93E-04	22.82	NM	0.160	175.53	1.00
93	0.022	1.21E-03	42.96	NM	0.483	908.72	1.00
94	0.060	3.72E-03	60.68	NM	1.245	3500.57	1.00
95	0.091	6.44E-03	73.10	NM	1.967	6395.88	1.00
96	0.011	3.25E-04	17.42	0.1%	0.203	184.24	1.50
97	0.010	3.60E-04	22.06	0.1%	0.200	212.10	1.50
98	0.022	1.30E-03	44.94	0.1%	0.506	950.60	1.50
99	0.062	3.83E-03	63.02	0.1%	1.261	3756.74	1.50
100	0.074	6.52E-03	74.90	NM	1.966	5329.12	1.50
101	0.007	2.52E-04	20.78	NM	0.144	139.86	2.00
102	0.011	6.31E-04	42.43	NM	0.253	448.75	2.00
103	0.022	1.57E-03	56.77	NM	0.545	1200.83	2.00
104	0.045	2.84E-03	66.48	NM	0.908	2876.37	2.00
105	0.059	5.05E-03	79.08	NM	1.481	4522.78	2.00
106	0.011	3.60E-04	21.05	0.6%	0.205	222.63	1.00
107	0.012	4.64E-04	27.20	0.6%	0.232	313.83	1.00
108	0.024	1.27E-03	40.10	0.6%	0.523	925.33	1.00

Table B3, cont. Calculated parameters and Buckingham PI terms for each weir, where NM = not measureable (value close to 0).

Weir No.	Velocity (m/s)	Discharge (m^3/s)	Water Depth above Weir (mm)	Water Surface Slope	Fr No.	Re No.	d_{50}/h
109	0.064	3.85E-03	57.87	0.6%	1.321	3561.03	1.00
110	0.084	6.34E-03	70.21	0.5%	1.977	5670.48	1.00
111	0.011	3.81E-04	20.95	0.6%	0.217	221.57	1.50
112	0.012	4.64E-04	26.13	0.6%	0.237	301.48	1.50
113	0.022	1.24E-03	42.13	0.6%	0.499	891.16	1.50
114	0.062	3.90E-03	61.52	0.6%	1.299	3667.33	1.50
115	0.090	6.42E-03	71.71	0.5%	1.980	6205.31	1.50
116	0.010	3.25E-04	21.12	0.5%	0.185	203.07	2.00
117	0.012	5.52E-04	33.92	0.4%	0.247	391.36	2.00
118	0.024	1.60E-03	54.23	0.5%	0.569	1251.39	2.00
119	0.046	2.86E-03	63.95	0.5%	0.934	2828.39	2.00
120	0.062	4.48E-03	72.89	0.5%	1.371	4345.11	2.00
121	0.011	2.98E-04	13.52	0.9%	0.211	142.99	1.00
122	0.012	4.36E-04	23.82	1.1%	0.233	274.83	1.00
123	0.024	1.18E-03	36.25	1.0%	0.511	836.49	1.00
124	0.485	3.68E-03	54.27	1.1%	1.303	25307.14	1.00
125	0.080	5.74E-03	65.42	1.0%	1.853	5032.02	1.00
126	0.014	3.16E-04	9.20	0.8%	0.272	123.84	1.50
127	0.012	3.94E-04	19.92	0.9%	0.230	229.83	1.50
128	0.021	1.10E-03	38.15	0.9%	0.466	770.29	1.50
129	0.066	3.90E-03	59.00	0.9%	1.326	3744.01	1.50
130	0.097	6.32E-03	68.57	0.9%	1.992	6395.10	1.50
131	0.011	3.46E-04	18.31	1.0%	0.211	193.65	2.00
132	0.014	6.26E-04	32.95	0.9%	0.285	443.53	2.00
133	0.024	1.56E-03	51.48	1.0%	0.568	1187.93	2.00
134	0.046	2.89E-03	61.55	1.0%	0.962	2722.25	2.00
135	0.065	4.46E-03	70.01	1.0%	1.392	4375.37	2.00

Table B3, cont. Calculated parameters and Buckingham PI terms for each weir, where NM = not measureable (value close to 0).

Weir No.	Velocity (m/s)	Discharge (m^3/s)	Water Depth above Weir (mm)	Water Surface Slope	Fr No.	Re No.	d_{50}/h
136	0.006	1.30E-04	8.92	NM	0.114	51.46	1.00
137	0.008	2.78E-04	23.45	NM	0.150	180.37	1.00
138	0.022	1.29E-03	45.59	NM	0.498	964.35	1.00
139	0.058	3.65E-03	62.74	NM	1.203	3498.76	1.00
140	0.078	5.67E-03	70.48	0.1%	1.764	5286.04	1.00
141	0.010	3.18E-04	18.58	NM	0.193	178.64	1.50
142	0.010	4.02E-04	28.78	NM	0.196	276.71	1.50
143	0.023	1.45E-03	50.87	NM	0.529	1124.94	1.50
144	0.054	3.71E-03	65.69	NM	1.196	3410.63	1.50
145	0.068	5.14E-03	71.53	0.1%	1.588	4676.69	1.50
146	0.009	3.42E-04	23.93	NM	0.182	207.07	2.00
147	0.010	4.50E-04	33.1	NM	0.204	318.25	2.00
148	0.019	1.36E-03	57.97	NM	0.465	1059.01	2.00
149	0.037	2.58E-03	68.88	NM	0.811	2450.40	2.00
150	0.051	4.07E-03	77.19	NM	1.210	3785.06	2.00
151	0.007	2.40E-04	19.2	0.5%	0.143	129.22	1.00
152	0.009	3.95E-04	28.61	0.5%	0.193	247.57	1.00
153	0.023	1.32E-03	43	0.5%	0.525	950.91	1.00
154	0.062	3.73E-03	60.15	0.5%	1.254	3585.66	1.00
155	0.080	5.57E-03	67.65	0.6%	1.769	5220.58	1.00
156	0.011	3.36E-04	18.75	0.5%	0.202	198.31	1.50
157	0.010	3.72E-04	23.97	0.5%	0.198	230.47	1.50
158	0.025	1.55E-03	48.49	0.5%	0.580	1165.56	1.50
159	0.057	3.73E-03	63.56	0.5%	1.222	3483.38	1.50
160	0.073	5.23E-03	68.18	0.7%	1.654	4785.44	1.50
161	0.011	3.66E-04	20.73	0.5%	0.210	219.25	2.00
162	0.010	4.02E-04	28.03	0.5%	0.198	269.50	2.00

Table B3, cont. Calculated parameters and Buckingham PI terms for each weir, where NM = not measureable (value close to 0).

Weir No.	Velocity (m/s)	Discharge (m^3/s)	Water Depth above Weir (mm)	Water Surface Slope	Fr No.	Re No.	d_{50}/h
163	0.022	1.55E-03	55.52	0.5%	0.542	1174.39	2.00
164	0.043	2.62E-03	64.57	0.5%	0.850	2669.57	2.00
165	0.056	3.92E-03	72.35	0.5%	1.202	3895.54	2.00
166	0.008	1.68E-04	7.37	0.7%	0.161	56.69	1.00
167	0.009	3.12E-04	20.37	1.0%	0.180	176.27	1.00
168	0.022	1.10E-03	37.8	1.0%	0.468	799.57	1.00
169	0.066	3.61E-03	58.46	1.0%	1.233	3714.87	1.00
170	0.087	5.70E-03	65.01	0.9%	1.846	5436.60	1.00
171	0.013	3.46E-04	13.66	0.9%	0.244	170.74	1.50
172	0.012	4.72E-04	25.15	1.1%	0.246	290.18	1.50
173	0.024	1.34E-03	42.67	1.1%	0.534	984.64	1.50
174	0.047	3.59E-03	59.29	1.1%	1.218	2679.30	1.50
175	0.104	5.69E-03	68.22	1.1%	1.799	6821.61	1.50
176	0.011	4.01E-04	24.69	0.9%	0.210	261.13	2.00
177	0.011	5.10E-04	32.76	0.9%	0.233	346.48	2.00
178	0.025	1.72E-03	55.61	0.9%	0.601	1336.70	2.00
179	0.049	2.76E-03	63.54	0.9%	0.905	2993.54	2.00
180	0.085	5.24E-03	74.93	1.0%	1.581	6123.73	2.00
181	0.012	3.12E-04	12.27	NM	0.155	141.57	1.00
182	0.012	3.68E-04	16.89	NM	0.156	194.87	1.00
183	0.025	1.23E-03	36.3	NM	0.356	872.55	1.00
184	0.352	2.29E-03	44.72	NM	0.595	15135.13	1.00
185	0.528	3.97E-03	53.78	NM	0.943	27302.11	1.00
186	0.010	2.68E-04	13.5	NM	0.127	129.80	1.50
187	0.010	3.21E-04	18.14	NM	0.131	174.41	1.50
188	0.022	1.18E-03	40.96	NM	0.322	866.41	1.50
189	0.274	1.83E-03	46.34	NM	0.469	12208.10	1.50

Table B3, cont. Calculated parameters and Buckingham PI terms for each weir, where NM = not measureable (value close to 0).

Weir No.	Velocity (m/s)	Discharge (m^3/s)	Water Depth above Weir (mm)	Water Surface Slope	Fr No.	Re No.	d_{50}/h
190	0.420	3.17E-03	54.01	NM	0.751	21810.47	1.50
191	0.011	3.38E-04	18.06	NM	0.138	191.01	2.00
192	0.012	4.09E-04	22.55	NM	0.150	260.18	2.00
193	0.022	1.33E-03	46.95	0.1%	0.337	993.12	2.00
194	0.246	1.73E-03	49.57	NM	0.428	11724.53	2.00
195	0.350	2.75E-03	56.61	NM	0.635	19050.34	2.00
196	0.016	3.03E-04	6.54	0.5%	0.206	100.61	1.00
197	0.014	4.73E-04	21.45	0.5%	0.178	288.73	1.00
198	0.029	1.44E-03	36.14	0.5%	0.416	1007.69	1.00
199	0.355	2.19E-03	41.66	0.5%	0.589	14219.66	1.00
200	0.181	1.31E-03	51.1	0.5%	0.319	8892.85	1.00
201	0.012	3.88E-04	18.12	0.4%	0.159	209.06	1.50
202	0.013	4.55E-04	22.55	0.5%	0.167	281.86	1.50
203	0.026	1.40E-03	40.28	0.4%	0.385	1006.94	1.50
204	0.310	2.02E-03	44.78	0.5%	0.524	13347.11	1.50
205	0.464	3.43E-03	52.62	0.5%	0.823	23475.26	1.50
206	0.012	3.81E-04	18.3	0.4%	0.155	211.14	2.00
207	0.013	4.61E-04	22.57	0.4%	0.169	282.11	2.00
208	0.023	1.29E-03	42.93	0.4%	0.342	949.36	2.00
209	0.274	1.90E-03	48.67	0.4%	0.475	12821.93	2.00
210	0.365	2.78E-03	54.46	0.4%	0.655	19112.26	2.00
211	0.015	4.08E-04	13.62	0.9%	0.192	196.43	1.00
212	0.021	6.86E-04	20.04	1.0%	0.267	404.63	1.00
213	0.023	9.52E-04	28.51	1.0%	0.310	630.47	1.00
214	0.286	1.60E-03	36.71	1.0%	0.460	10094.67	1.00
215	0.574	3.90E-03	47.33	1.1%	0.986	26121.01	1.00
216	0.014	3.90E-04	14.42	0.9%	0.179	194.10	1.50

Table B3, cont. Calculated parameters and Buckingham PI terms for each weir, where NM = not measureable (value close to 0).

Weir No.	Velocity (m/s)	Discharge (m^3/s)	Water Depth above Weir (mm)	Water Surface Slope	Fr No.	Re No.	d_{50}/h
217	0.016	5.55E-04	22.59	1.1%	0.203	347.52	1.50
218	0.024	1.15E-03	34.08	1.1%	0.342	786.42	1.50
219	0.329	1.98E-03	40.56	1.1%	0.542	12830.26	1.50
220	0.483	3.36E-03	48.76	1.1%	0.837	22643.96	1.50
221	0.015	4.91E-04	19.27	1.0%	0.195	277.92	2.00
222	0.016	6.25E-04	25.5	1.0%	0.215	392.29	2.00
223	0.027	1.43E-03	40.71	1.0%	0.390	1056.83	2.00
224	0.264	1.68E-03	43.39	1.0%	0.443	11013.75	2.00
225	0.403	2.92E-03	51.38	1.0%	0.709	19908.60	2.00
226	0.012	3.36E-04	16.05	0.1%	0.146	185.18	1.00
227	0.011	3.77E-04	20.69	NM	0.144	218.82	1.00
228	0.019	9.41E-04	37.4	NM	0.268	683.23	1.00
229	0.294	1.95E-03	45.89	NM	0.500	12972.00	1.00
230	0.072	5.42E-03	61.56	NM	1.202	4253.75	1.00
231	0.009	2.06E-04	10.47	NM	0.111	90.60	1.50
232	0.009	3.00E-04	20.44	NM	0.116	176.87	1.50
233	0.022	1.26E-03	44.21	NM	0.329	935.16	1.50
234	0.326	2.40E-03	52.33	NM	0.576	16402.49	1.50
235	0.404	3.16E-03	56.53	NM	0.732	21958.46	1.50
236	0.007	2.02E-04	15.41	NM	0.090	103.72	2.00
237	0.008	3.27E-04	25.44	NM	0.113	195.68	2.00
238	0.020	1.27E-03	50.11	NM	0.313	963.60	2.00
239	0.205	1.53E-03	52.98	NM	0.365	10442.57	2.00
240	0.238	1.83E-03	55.32	NM	0.428	12659.04	2.00
241	0.012	3.56E-04	15.98	0.4%	0.155	184.37	1.00
242	0.012	3.99E-04	20.68	0.4%	0.153	238.60	1.00
243	0.020	9.74E-04	35.6	0.4%	0.284	684.58	1.00

Table B3, cont. Calculated parameters and Buckingham PI terms for each weir, where NM = not measureable (value close to 0).

Weir No.	Velocity (m/s)	Discharge (m^3/s)	Water Depth above Weir (mm)	Water Surface Slope	Fr No.	Re No.	d_{50}/h
244	0.307	1.96E-03	43.87	0.5%	0.516	12949.34	1.00
245	0.072	5.48E-03	58.56	0.5%	1.247	4053.92	1.00
246	0.011	2.98E-04	13.87	0.5%	0.139	146.69	1.50
247	0.012	4.33E-04	24.39	0.5%	0.153	281.41	1.50
248	0.026	1.40E-03	41.7	0.5%	0.378	1042.44	1.50
249	0.331	2.30E-03	48.8	0.5%	0.574	15530.64	1.50
250	0.483	3.80E-03	56.87	0.5%	0.877	26410.21	1.50
251	0.009	2.22E-04	11.42	0.5%	0.114	98.82	2.00
252	0.011	4.08E-04	24.14	0.5%	0.144	255.31	2.00
253	0.022	1.32E-03	47.19	0.5%	0.333	998.19	2.00
254	0.220	1.56E-03	49.97	0.5%	0.385	10569.97	2.00
255	0.258	1.93E-03	53.37	0.5%	0.460	13239.10	2.00
256	0.016	2.81E-04	4.56	0.6%	0.229	70.15	1.00
257	0.013	4.09E-04	18.67	1.1%	0.165	233.36	1.00
258	0.020	8.38E-04	29.64	1.1%	0.268	569.97	1.00
259	0.317	1.84E-03	38.71	1.1%	0.515	11798.42	1.00
260	0.078	5.33E-03	54.75	1.0%	1.253	4106.01	1.00
261	0.013	3.99E-04	17.87	1.1%	0.164	223.36	1.50
262	0.014	5.52E-04	25.48	1.1%	0.190	342.98	1.50
263	0.023	1.14E-03	36.19	1.1%	0.330	800.31	1.50
264	0.326	2.04E-03	42.79	1.1%	0.544	13412.24	1.50
265	0.480	3.48E-03	51.31	1.1%	0.845	23680.17	1.50
266	0.010	2.63E-04	14.07	0.9%	0.122	135.28	2.00
267	0.012	5.21E-04	29.02	1.0%	0.168	334.83	2.00
268	0.020	1.11E-03	41.96	1.0%	0.299	806.88	2.00
269	0.683	4.52E-03	45.86	1.0%	1.163	30115.93	2.00
270	0.280	2.01E-03	50.74	1.0%	0.491	13659.98	2.00

Table B3, cont. Calculated parameters and Buckingham PI terms for each weir, where NM = not measureable (value close to 0).

Weir No.	Velocity (m/s)	Discharge (m^3/s)	Water Depth above Weir (mm)	Water Surface Slope	Fr No.	Re No.	d_{50}/h
271	0.007	1.40E-04	7.77	0.1%	0.263	52.30	NA
272	0.077	5.07E-03	52.46	NM	3.657	3883.83	NA
273	0.205	1.81E-02	88.65	NM	10.061	17473.27	NA
274	0.026	7.20E-04	14.52	0.7%	0.986	362.98	NA
275	0.125	8.13E-03	51.92	0.6%	5.893	6240.02	NA
276	0.227	1.84E-02	84.65	0.7%	10.461	18475.42	NA
277	0.019	3.14E-04	3.8	0.6%	0.841	69.42	NA
278	0.120	8.20E-03	55.23	1.1%	5.762	6372.32	NA
279	0.286	1.85E-02	80.31	1.2%	10.796	22083.97	NA
280	0.010	1.84E-04	5.14	0.0%	0.399	49.42	NA
281	0.132	8.53E-03	62.33	0.0%	5.322	7910.66	NA
282	0.217	1.85E-02	86.38	0.0%	9.780	18022.48	NA
283	0.016	3.52E-04	8.11	0.5%	0.609	124.76	NA
284	0.149	8.73E-03	59.59	0.6%	5.568	8536.92	NA
285	0.196	1.93E-02	84.46	0.6%	10.369	15916.54	NA
286	0.017	2.98E-04	3.83	0.6%	0.750	62.60	NA
287	0.126	8.88E-03	56.55	1.2%	5.820	6850.85	NA
288	0.208	1.98E-02	80.67	1.1%	10.861	16133.07	NA
289	0.182	4.26E-04	7.98	0.1%	0.394	1396.42	NA
290	0.137	9.41E-03	55.32	0.1%	3.303	7286.93	NA
291	0.226	1.72E-02	73.47	0.1%	5.247	15982.34	NA
292	0.257	5.95E-04	7.73	0.5%	0.558	1910.09	NA
293	0.144	9.51E-03	52.83	0.5%	3.414	7314.50	NA
294	0.229	1.78E-02	71.58	0.5%	5.482	15732.27	NA
295	0.147	2.09E-04	-0.09	0.4%	0.173	1400.66	NA
296	0.146	9.19E-03	49.79	0.9%	3.399	6989.35	NA
297	0.186	1.69E-02	68.2	0.9%	5.341	12170.29	NA

Table B3, cont. Calculated parameters and Buckingham PI terms for each weir, where NM = not measureable (value close to 0).

Weir No.	Velocity (m/s)	Discharge (m^3/s)	Water Depth above Weir (mm)	Water Surface Slope	Fr No.	Re No.	d_{50}/h
298	0.246	6.61E-04	11.08	0.1%	0.518	2620.69	NA
299	0.134	8.98E-03	53.61	0.1%	3.201	6907.04	NA
300	0.227	1.62E-02	70.37	0.1%	5.028	15358.72	NA
301	0.251	5.80E-04	7.72	0.5%	0.545	1863.08	NA
302	0.138	8.85E-03	50.92	0.6%	3.236	6756.30	NA
303	0.239	1.61E-02	67.71	0.6%	5.098	15559.38	NA
304	0.151	2.55E-04	2.21	0.5%	0.447	320.86	NA
305	0.142	8.74E-03	48.37	1.1%	3.280	6603.98	NA
306	0.194	1.55E-02	63.28	1.2%	5.081	11803.47	NA
307	0.177	3.81E-04	6.3	0.1%	0.264	1072.15	NA
308	0.123	6.36E-03	38.45	1.7%	1.786	4547.19	NA
309	0.194	1.27E-02	52.24	0.2%	3.056	9744.21	NA
310	0.235	4.01E-04	2.37	0.5%	0.453	535.50	NA
311	0.127	6.03E-03	34.27	0.2%	1.792	4184.65	NA
312	0.195	1.25E-02	50.81	0.2%	3.050	9526.32	NA
313	0.310	4.82E-04	1.03	0.4%	0.827	307.00	NA
314	0.146	5.50E-03	24.21	0.3%	1.946	3398.52	NA
315	0.255	1.20E-02	34.01	NM	3.575	8338.51	NA
316	0.313	8.38E-04	10.99	NM	0.440	3307.38	NA
317	0.122	6.32E-03	38.58	NM	1.770	4525.47	NA
318	0.193	1.33E-02	55.81	NM	3.103	10356.45	NA
319	0.360	8.83E-04	8.97	0.5%	0.513	3104.82	NA
320	0.125	5.92E-03	34.36	0.4%	1.759	4129.57	NA
321	0.199	1.28E-02	51.03	0.5%	3.127	9763.83	NA
322	0.316	5.49E-04	2.65	0.0%	0.587	805.15	NA
323	0.157	6.00E-03	25.05	0.3%	2.086	3781.37	NA
324	0.275	1.29E-02	33.75	0.3%	3.864	8923.76	NA

Table 20 B4. Calculated Buckingham Pi terms for each weir.

Weir No.	D/h	H/h	L/h	S
1	11.33	1.26	11.33	3.83E-04
2	11.33	1.91	11.33	-2.11E-04
3	11.33	3.09	11.33	2.47E-04
4	11.33	4.96	11.33	4.22E-04
5	11.33	6.59	11.33	3.37E-04
6	11.33	1.10	11.33	1.10E-04
7	11.33	1.72	11.33	-6.10E-04
8	11.33	3.55	11.33	2.54E-04
9	11.33	6.07	11.33	1.93E-04
10	11.33	6.79	11.33	1.48E-04
11	11.33	2.30	11.33	2.51E-04
12	11.33	3.36	11.33	6.57E-04
13	11.33	4.69	11.33	2.41E-04
14	11.33	6.62	11.33	2.83E-04
15	11.33	6.81	11.33	2.52E-04
16	11.33	0.79	11.33	5.52E-03
17	11.33	1.92	11.33	5.53E-03
18	11.33	2.75	11.33	5.63E-03
19	11.33	4.67	11.33	5.75E-03
20	11.33	6.38	11.33	4.59E-03
21	11.33	1.91	11.33	5.78E-03
22	11.33	1.44	11.33	5.68E-03
23	11.33	3.39	11.33	5.58E-03
24	11.33	5.85	11.33	5.70E-03
25	11.33	6.58	11.33	5.79E-03
26	11.33	1.92	11.33	5.95E-03
27	11.33	2.81	11.33	5.53E-03
28	11.33	4.09	11.33	5.28E-03
29	11.33	6.36	11.33	4.45E-03
30	11.33	6.49	11.33	4.06E-03
31	11.33	1.31	11.33	1.00E-02
32	11.33	1.88	11.33	9.62E-03
33	11.33	2.67	11.33	9.92E-03
34	11.33	4.47	11.33	1.02E-02
35	11.33	6.13	11.33	9.12E-03
36	11.33	1.67	11.33	1.07E-02
37	11.33	2.40	11.33	1.16E-02
38	11.33	2.99	11.33	1.17E-02
39	11.33	5.67	11.33	9.19E-03

Table B4, cont. Calculated Buckingham Pi terms for each weir.

Weir No.	D/h	H/h	L/h	S
40	11.33	6.41	11.33	9.12E-03
41	11.33	1.90	11.33	1.19E-02
42	11.33	2.48	11.33	1.20E-02
43	11.33	3.95	11.33	1.14E-02
44	11.33	6.08	11.33	8.74E-03
45	11.33	6.36	11.33	8.65E-03
46	24.02	1.46	12.01	2.19E-03
47	24.02	2.30	12.01	2.26E-03
48	24.02	3.73	12.01	2.37E-03
49	24.02	6.13	12.01	3.47E-04
50	24.02	7.11	12.01	2.35E-04
51	24.02	2.16	12.01	3.05E-04
52	24.02	2.60	12.01	4.96E-04
53	24.02	4.55	12.01	4.15E-05
54	24.02	6.92	12.01	2.41E-04
55	24.02	7.24	12.01	2.71E-04
56	24.02	2.48	12.01	6.24E-04
57	24.02	3.21	12.01	4.48E-04
58	24.02	4.86	12.01	5.19E-04
59	24.02	6.40	12.01	6.05E-04
60	24.02	7.24	12.01	4.70E-04
61	24.02	1.42	12.01	4.84E-03
62	24.02	2.30	12.01	6.30E-03
63	24.02	3.63	12.01	5.01E-03
64	24.02	6.02	12.01	5.38E-03
65	24.02	6.87	12.01	5.44E-03
66	24.02	2.13	12.01	5.95E-03
67	24.02	2.54	12.01	5.90E-03
68	24.02	4.50	12.01	5.96E-03
69	24.02	6.64	12.01	6.17E-03
70	24.02	6.89	12.01	5.87E-03
71	24.02	2.44	12.01	4.85E-03
72	24.02	3.98	12.01	4.91E-03
73	24.02	4.92	12.01	4.81E-03
74	24.02	6.07	12.01	4.96E-03
75	24.02	7.05	12.01	4.96E-03
76	24.02	1.50	12.01	1.01E-02
77	24.02	2.39	12.01	1.01E-02
78	24.02	3.39	12.01	1.02E-02

Table B4, cont. Calculated Buckingham Pi terms for each weir.

Weir No.	D/h	H/h	L/h	S
79	24.02	5.77	12.01	1.02E-02
80	24.02	6.72	12.01	1.02E-02
81	24.02	2.15	12.01	1.01E-02
82	24.02	2.91	12.01	1.02E-02
83	24.02	4.20	12.01	1.01E-02
84	24.02	6.44	12.01	1.02E-02
85	24.02	6.67	12.01	1.13E-02
86	24.02	2.06	12.01	1.03E-02
87	24.02	2.72	12.01	1.01E-02
88	24.02	4.46	12.01	1.02E-02
89	24.02	6.57	12.01	1.02E-02
90	24.02	6.68	12.01	1.01E-02
91	12.01	1.34	24.02	6.91E-05
92	12.01	1.80	24.02	3.26E-04
93	12.01	3.39	24.02	3.56E-04
94	12.01	4.78	24.02	2.82E-04
95	12.01	5.76	24.02	3.11E-04
96	12.01	1.37	24.02	1.03E-03
97	12.01	1.74	24.02	1.29E-03
98	12.01	3.54	24.02	1.37E-03
99	12.01	4.97	24.02	1.36E-03
100	12.01	5.90	24.02	2.02E-04
101	12.01	1.64	24.02	3.16E-04
102	12.01	3.34	24.02	3.08E-04
103	12.01	4.47	24.02	2.31E-04
104	12.01	5.24	24.02	2.50E-04
105	12.01	6.23	24.02	3.22E-04
106	12.01	1.66	24.02	5.53E-03
107	12.01	2.14	24.02	5.92E-03
108	12.01	3.16	24.02	5.78E-03
109	12.01	4.56	24.02	5.84E-03
110	12.01	5.53	24.02	5.13E-03
111	12.01	1.65	24.02	5.71E-03
112	12.01	2.06	24.02	5.66E-03
113	12.01	3.32	24.02	5.69E-03
114	12.01	4.85	24.02	5.77E-03
115	12.01	5.65	24.02	5.06E-03
116	12.01	1.66	24.02	4.66E-03
117	12.01	2.67	24.02	4.46E-03

Table B4, cont. Calculated Buckingham Pi terms for each weir.

Weir No.	D/h	H/h	L/h	S
118	12.01	4.27	24.02	4.87E-03
119	12.01	5.04	24.02	4.94E-03
120	12.01	5.74	24.02	4.86E-03
121	12.01	1.07	24.02	9.11E-03
122	12.01	1.88	24.02	1.06E-02
123	12.01	2.86	24.02	1.05E-02
124	12.01	4.28	24.02	1.08E-02
125	12.01	5.16	24.02	1.00E-02
126	12.01	0.72	24.02	7.55E-03
127	12.01	1.57	24.02	9.25E-03
128	12.01	3.01	24.02	9.25E-03
129	12.01	4.65	24.02	9.37E-03
130	12.01	5.40	24.02	9.19E-03
131	12.01	1.44	24.02	9.55E-03
132	12.01	2.60	24.02	9.43E-03
133	12.01	4.06	24.02	9.65E-03
134	12.01	4.85	24.02	9.55E-03
135	12.01	5.52	24.02	9.56E-03
136	24.02	0.70	24.02	1.20E-04
137	24.02	1.85	24.02	2.92E-05
138	24.02	3.59	24.02	3.13E-04
139	24.02	4.94	24.02	2.32E-04
140	24.02	5.55	24.02	1.33E-03
141	24.02	1.46	24.02	1.03E-04
142	24.02	2.27	24.02	2.50E-04
143	24.02	4.01	24.02	4.96E-04
144	24.02	5.18	24.02	2.00E-05
145	24.02	5.64	24.02	1.29E-03
146	24.02	1.89	24.02	3.74E-04
147	24.02	2.61	24.02	1.49E-04
148	24.02	4.57	24.02	2.85E-04
149	24.02	5.43	24.02	4.73E-04
150	24.02	6.08	24.02	4.16E-04
151	24.02	1.51	24.02	4.78E-03
152	24.02	2.25	24.02	4.83E-03
153	24.02	3.39	24.02	4.64E-03
154	24.02	4.74	24.02	4.80E-03
155	24.02	5.33	24.02	5.55E-03
156	24.02	1.48	24.02	4.57E-03

Table B4, cont. Calculated Buckingham Pi terms for each weir.

Weir No.	D/h	H/h	L/h	S
157	24.02	1.89	24.02	4.66E-03
158	24.02	3.82	24.02	4.50E-03
159	24.02	5.01	24.02	4.54E-03
160	24.02	5.37	24.02	7.05E-03
161	24.02	1.63	24.02	4.60E-03
162	24.02	2.21	24.02	5.22E-03
163	24.02	4.38	24.02	5.11E-03
164	24.02	5.09	24.02	5.27E-03
165	24.02	5.70	24.02	5.25E-03
166	24.02	0.58	24.02	7.06E-03
167	24.02	1.61	24.02	9.70E-03
168	24.02	2.98	24.02	1.00E-02
169	24.02	4.61	24.02	9.69E-03
170	24.02	5.12	24.02	9.03E-03
171	24.02	1.08	24.02	9.17E-03
172	24.02	1.98	24.02	1.08E-02
173	24.02	3.36	24.02	1.08E-02
174	24.02	4.67	24.02	1.09E-02
175	24.02	5.38	24.02	1.08E-02
176	24.02	1.95	24.02	8.67E-03
177	24.02	2.58	24.02	8.95E-03
178	24.02	4.38	24.02	9.04E-03
179	24.02	5.01	24.02	9.06E-03
180	24.02	5.90	24.02	1.03E-02
181	12.01	0.97	36.03	2.38E-04
182	12.01	1.33	36.03	3.59E-04
183	12.01	2.86	36.03	1.03E-04
184	12.01	3.52	36.03	2.95E-04
185	12.01	4.24	36.03	2.96E-04
186	12.01	1.06	36.03	3.33E-04
187	12.01	1.43	36.03	2.15E-04
188	12.01	3.23	36.03	2.40E-04
189	12.01	3.65	36.03	3.08E-04
190	12.01	4.26	36.03	2.01E-04
191	12.01	1.42	36.03	2.66E-04
192	12.01	1.78	36.03	1.50E-04
193	12.01	3.70	36.03	5.79E-04
194	12.01	3.91	36.03	1.83E-04
195	12.01	4.46	36.03	3.81E-04

Table B4, cont. Calculated Buckingham Pi terms for each weir.

Weir No.	D/h	H/h	L/h	S
196	12.01	0.52	36.03	5.29E-03
197	12.01	1.69	36.03	5.11E-03
198	12.01	2.85	36.03	5.01E-03
199	12.01	3.28	36.03	5.11E-03
200	12.01	4.03	36.03	5.05E-03
201	12.01	1.43	36.03	4.50E-03
202	12.01	1.78	36.03	4.58E-03
203	12.01	3.17	36.03	4.48E-03
204	12.01	3.53	36.03	4.56E-03
205	12.01	4.15	36.03	4.59E-03
206	12.01	1.44	36.03	4.35E-03
207	12.01	1.78	36.03	4.28E-03
208	12.01	3.38	36.03	4.29E-03
209	12.01	3.84	36.03	4.33E-03
210	12.01	4.29	36.03	4.26E-03
211	12.01	1.07	36.03	9.22E-03
212	12.01	1.58	36.03	1.02E-02
213	12.01	2.25	36.03	1.03E-02
214	12.01	2.89	36.03	1.01E-02
215	12.01	3.73	36.03	1.05E-02
216	12.01	1.14	36.03	9.48E-03
217	12.01	1.78	36.03	1.07E-02
218	12.01	2.69	36.03	1.06E-02
219	12.01	3.20	36.03	1.06E-02
220	12.01	3.84	36.03	1.10E-02
221	12.01	1.52	36.03	9.76E-03
222	12.01	2.01	36.03	9.75E-03
223	12.01	3.21	36.03	9.87E-03
224	12.01	3.42	36.03	1.01E-02
225	12.01	4.05	36.03	1.00E-02
226	24.02	1.26	36.03	5.32E-04
227	24.02	1.63	36.03	3.89E-04
228	24.02	2.95	36.03	4.11E-04
229	24.02	3.62	36.03	3.97E-04
230	24.02	4.85	36.03	4.21E-04
231	24.02	0.83	36.03	3.46E-04
232	24.02	1.61	36.03	3.28E-04
233	24.02	3.48	36.03	3.42E-04
234	24.02	4.12	36.03	2.66E-04

Table B4, cont. Calculated Buckingham Pi terms for each weir.

Weir No.	D/h	H/h	L/h	S
235	24.02	4.45	36.03	2.21E-04
236	24.02	1.21	36.03	3.59E-04
237	24.02	2.00	36.03	3.78E-04
238	24.02	3.95	36.03	3.02E-04
239	24.02	4.17	36.03	4.15E-04
240	24.02	4.36	36.03	2.02E-04
241	24.02	1.26	36.03	4.43E-03
242	24.02	1.63	36.03	4.36E-03
243	24.02	2.81	36.03	4.45E-03
244	24.02	3.46	36.03	4.54E-03
245	24.02	4.61	36.03	5.45E-03
246	24.02	1.09	36.03	5.15E-03
247	24.02	1.92	36.03	4.84E-03
248	24.02	3.29	36.03	4.67E-03
249	24.02	3.85	36.03	4.93E-03
250	24.02	4.48	36.03	4.90E-03
251	24.02	0.90	36.03	5.07E-03
252	24.02	1.90	36.03	4.95E-03
253	24.02	3.72	36.03	5.02E-03
254	24.02	3.94	36.03	5.10E-03
255	24.02	4.21	36.03	5.08E-03
256	24.02	0.36	36.03	6.02E-03
257	24.02	1.47	36.03	1.10E-02
258	24.02	2.34	36.03	1.09E-02
259	24.02	3.05	36.03	1.10E-02
260	24.02	4.31	36.03	1.02E-02
261	24.02	1.41	36.03	1.06E-02
262	24.02	2.01	36.03	1.09E-02
263	24.02	2.85	36.03	1.11E-02
264	24.02	3.37	36.03	1.07E-02
265	24.02	4.04	36.03	1.08E-02
266	24.02	1.11	36.03	9.34E-03
267	24.02	2.29	36.03	9.76E-03
268	24.02	3.31	36.03	9.96E-03
269	24.02	3.61	36.03	9.81E-03
270	24.02	4.00	36.03	1.00E-02
271	24.02	0.61	12.01	6.76E-04
272	24.02	4.13	12.01	4.32E-04
273	24.02	6.99	12.01	3.60E-04

Table B4, cont. Calculated Buckingham Pi terms for each weir.

Weir No.	D/h	H/h	L/h	S
274	24.02	1.14	12.01	7.37E-03
275	24.02	4.09	12.01	5.58E-03
276	24.02	6.67	12.01	6.63E-03
277	24.02	0.30	12.01	5.56E-03
278	24.02	4.35	12.01	1.09E-02
279	24.02	6.33	12.01	1.18E-02
280	11.33	0.38	11.33	3.26E-04
281	11.33	4.63	11.33	2.60E-04
282	11.33	6.42	11.33	8.94E-05
283	11.33	0.60	11.33	5.03E-03
284	11.33	4.43	11.33	5.79E-03
285	11.33	6.28	11.33	6.04E-03
286	11.33	0.28	11.33	5.94E-03
287	11.33	4.20	11.33	1.23E-02
288	11.33	6.00	11.33	1.09E-02
289	24.02	0.63	24.02	5.54E-04
290	24.02	4.36	24.02	6.43E-04
291	24.02	5.79	24.02	5.70E-04
292	24.02	0.61	24.02	5.19E-03
293	24.02	4.16	24.02	4.87E-03
294	24.02	5.64	24.02	4.93E-03
295	24.02	-0.01	24.02	3.81E-03
296	24.02	3.92	24.02	9.14E-03
297	24.02	5.37	24.02	9.43E-03
298	12.01	0.87	24.02	7.23E-04
299	12.01	4.22	24.02	6.67E-04
300	12.01	5.55	24.02	6.70E-04
301	12.01	0.61	24.02	4.95E-03
302	12.01	4.01	24.02	5.69E-03
303	12.01	5.34	24.02	6.12E-03
304	12.01	0.17	24.02	4.81E-03
305	12.01	3.81	24.02	1.07E-02
306	12.01	4.99	24.02	1.17E-02
307	24.02	0.50	36.03	1.25E-03
308	24.02	3.03	36.03	1.74E-02
309	24.02	4.12	36.03	1.80E-03
310	24.02	0.19	36.03	4.81E-03
311	24.02	2.70	36.03	2.42E-03
312	24.02	4.00	36.03	1.63E-03

Table B4, cont. Calculated Buckingham Pi terms for each weir.

Weir No.	D/h	H/h	L/h	S
313	24.02	0.08	36.03	4.21E-03
314	24.02	1.91	36.03	2.97E-03
315	24.02	2.68	36.03	-1.49E-03
316	12.01	0.87	36.03	8.58E-05
317	12.01	3.04	36.03	1.98E-04
318	12.01	4.40	36.03	4.44E-04
319	12.01	0.71	36.03	4.91E-03
320	12.01	2.71	36.03	4.23E-03
321	12.01	4.02	36.03	5.18E-03
322	12.01	0.21	36.03	3.93E-04
323	12.01	1.97	36.03	3.15E-03
324	12.01	2.66	36.03	3.33E-03

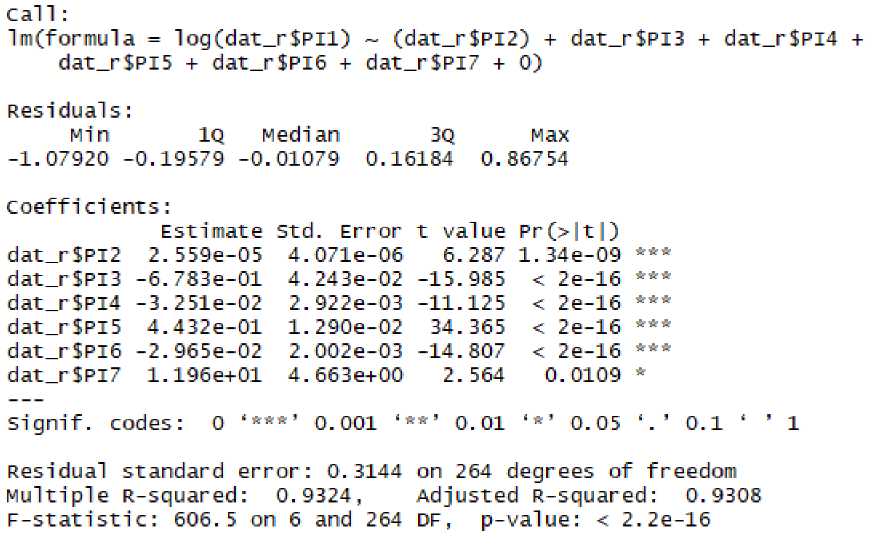
Appendix C: R Outputs

Rock Weir Analysis

Exploring discharge as a function of dimensionless Buckingham Pi terms.

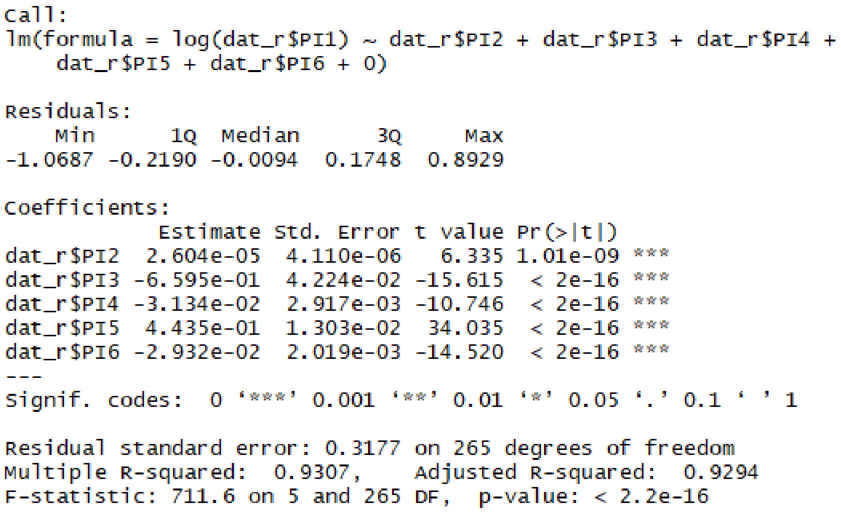
Overall Discharge

Results for regression with all Pi terms, intercept set to 0:



```
Call:
lm(formula = log(dat_r$PI1) ~ (dat_r$PI2) + dat_r$PI3 + dat_r$PI4 + 
    dat_r$PI5 + dat_r$PI6 + dat_r$PI7 + 0)

Residuals:
     Min       1Q   Median       3Q      Max 
-1.07920 -0.19579 -0.01079  0.16184  0.86754 

Coefficients:
            Estimate Std. Error t value Pr(>|t|)    
dat_r$PI2  2.559e-05  4.071e-06   6.287 1.34e-09 ***
dat_r$PI3 -6.783e-01  4.243e-02 -15.985  < 2e-16 ***
dat_r$PI4 -3.251e-02  2.922e-03 -11.125  < 2e-16 ***
dat_r$PI5  4.432e-01  1.290e-02  34.365  < 2e-16 ***
dat_r$PI6 -2.965e-02  2.002e-03 -14.807  < 2e-16 ***
dat_r$PI7  1.196e+01  4.663e+00   2.564   0.0109 *  
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.3144 on 264 degrees of freedom
Multiple R-squared:  0.9324,	Adjusted R-squared:  0.9308 
F-statistic: 606.5 on 6 and 264 DF,  p-value: < 2.2e-16
```

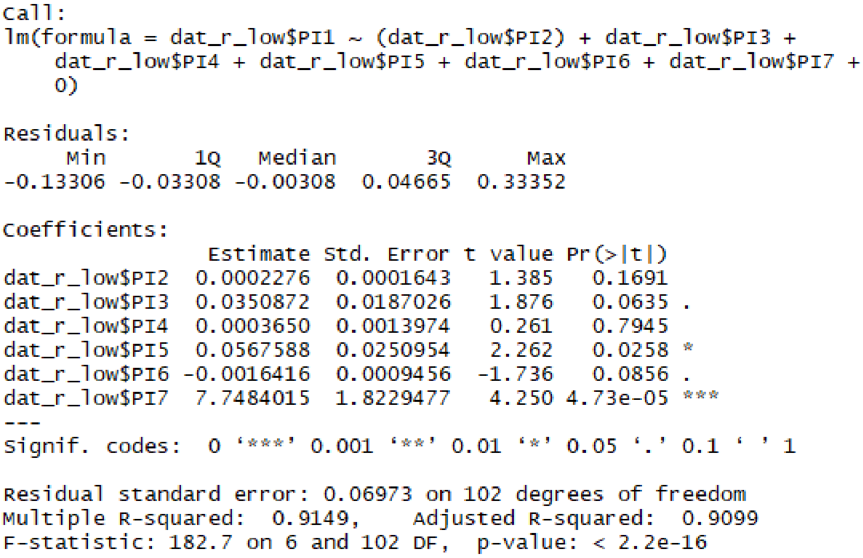
Results for regression with all Pi terms, except slope:



```
Call:
lm(formula = log(dat_r$PI1) ~ dat_r$PI2 + dat_r$PI3 + dat_r$PI4 +
    dat_r$PI5 + dat_r$PI6 + 0)

Residuals:
    Min      1Q  Median      3Q     Max 
-1.0687 -0.2190 -0.0094  0.1748  0.8929 

Coefficients:
            Estimate Std. Error t value Pr(>|t|)    
dat_r$PI2  2.604e-05  4.110e-06   6.335 1.01e-09 ***
dat_r$PI3 -6.595e-01  4.224e-02 -15.615  < 2e-16 ***
dat_r$PI4 -3.134e-02  2.917e-03 -10.746  < 2e-16 ***
dat_r$PI5  4.435e-01  1.303e-02  34.035  < 2e-16 ***
dat_r$PI6 -2.932e-02  2.019e-03 -14.520  < 2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.3177 on 265 degrees of freedom
Multiple R-squared:  0.9307,	Adjusted R-squared:  0.9294 
F-statistic: 711.6 on 5 and 265 DF,  p-value: < 2.2e-16
```

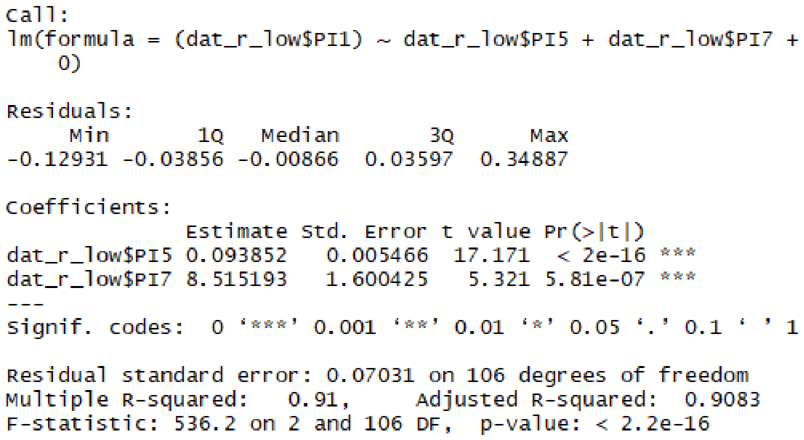
Low Flow

Regression of low flows against all Pi terms, intercept set to 0:



```
Call:
lm(formula = dat_r_low$PI1 ~ (dat_r_low$PI2) + dat_r_low$PI3 +
    dat_r_low$PI4 + dat_r_low$PI5 + dat_r_low$PI6 + dat_r_low$PI7 +
    0)

Residuals:
     Min       1Q   Median       3Q      Max 
-0.13306 -0.03308 -0.00308  0.04665  0.33352 

Coefficients:
                Estimate Std. Error t value Pr(>|t|)    
dat_r_low$PI2  0.0002276  0.0001643   1.385   0.1691    
dat_r_low$PI3  0.0350872  0.0187026   1.876   0.0635 .  
dat_r_low$PI4  0.0003650  0.0013974   0.261   0.7945    
dat_r_low$PI5  0.0567588  0.0250954   2.262   0.0258 *  
dat_r_low$PI6 -0.0016416  0.0009456  -1.736   0.0856 .  
dat_r_low$PI7  7.7484015  1.8229477   4.250 4.73e-05 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.06973 on 102 degrees of freedom
Multiple R-squared:  0.9149,	Adjusted R-squared:  0.9099 
F-statistic: 182.7 on 6 and 102 DF,  p-value: < 2.2e-16
```

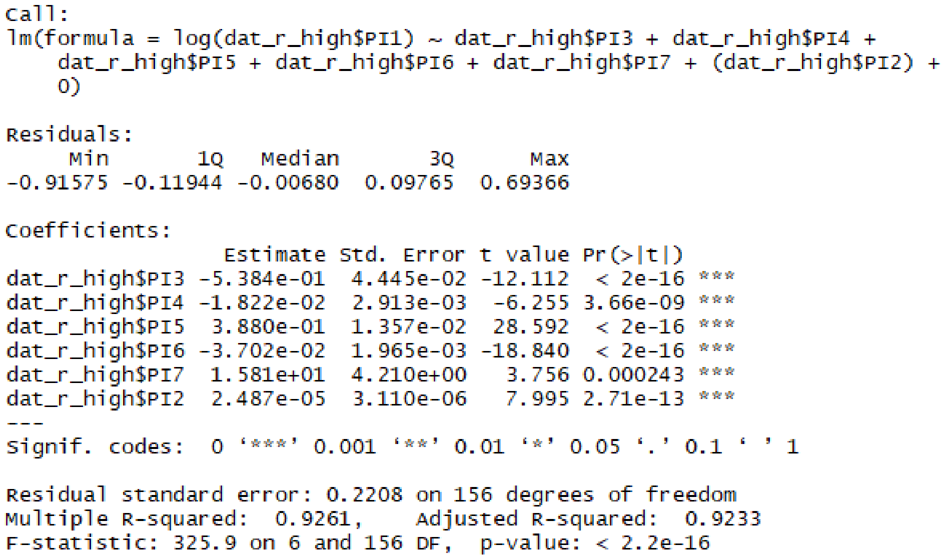
Final regression for low flows over rock weirs:



```
Call:
lm(formula = (dat_r_low$PI1) ~ dat_r_low$PI5 + dat_r_low$PI7 + 
    0)

Residuals:
     Min       1Q   Median       3Q      Max 
-0.12931 -0.03856 -0.00866  0.03597  0.34887 

Coefficients:
              Estimate Std. Error t value Pr(>|t|)    
dat_r_low$PI5 0.093852   0.005466  17.171  < 2e-16 ***
dat_r_low$PI7 8.515193   1.600425   5.321 5.81e-07 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.07031 on 106 degrees of freedom
Multiple R-squared:   0.91,	Adjusted R-squared:  0.9083 
F-statistic: 536.2 on 2 and 106 DF,  p-value: < 2.2e-16
```

High Flow Discharge

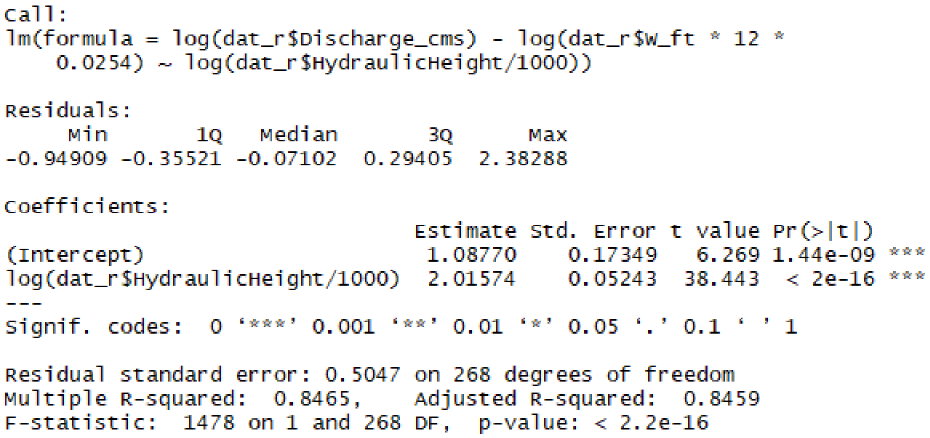
Regression of high flows against all Pi terms, intercept set to 0:



```
Call:
lm(formula = log(dat_r_high$PI1) ~ dat_r_high$PI3 + dat_r_high$PI4 + 
    dat_r_high$PI5 + dat_r_high$PI6 + dat_r_high$PI7 + (dat_r_high$PI2) + 
    0)

Residuals:
     Min       1Q   Median       3Q      Max 
-0.91575 -0.11944 -0.00680  0.09765  0.69366 

Coefficients:
                 Estimate Std. Error t value Pr(>|t|)    
dat_r_high$PI3 -5.384e-01  4.445e-02 -12.112  < 2e-16 ***
dat_r_high$PI4 -1.822e-02  2.913e-03  -6.255 3.66e-09 ***
dat_r_high$PI5  3.880e-01  1.357e-02  28.592  < 2e-16 ***
dat_r_high$PI6 -3.702e-02  1.965e-03 -18.840  < 2e-16 ***
dat_r_high$PI7  1.581e+01  4.210e+00   3.756 0.000243 ***
dat_r_high$PI2  2.487e-05  3.110e-06   7.995 2.71e-13 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.2208 on 156 degrees of freedom
Multiple R-squared:  0.9261,	Adjusted R-squared:  0.9233 
F-statistic: 325.9 on 6 and 156 DF,  p-value: < 2.2e-16
```

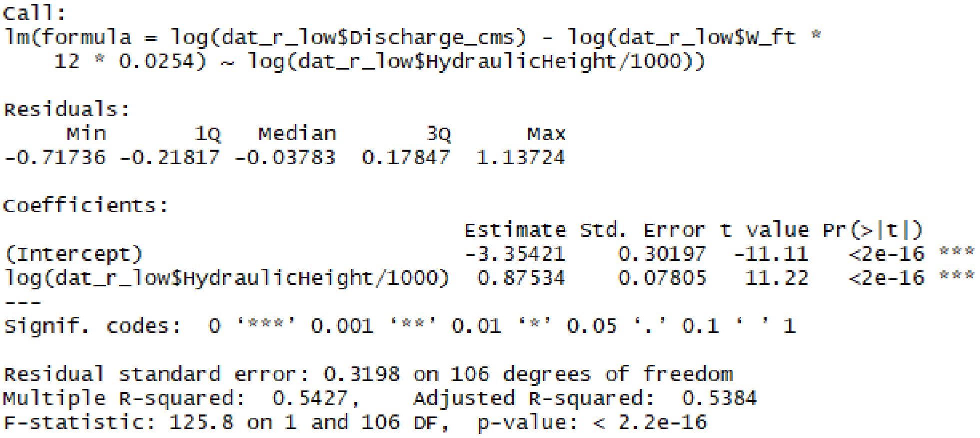
Linear regression to find an equation for discharge over rock weirs

Overall Discharge



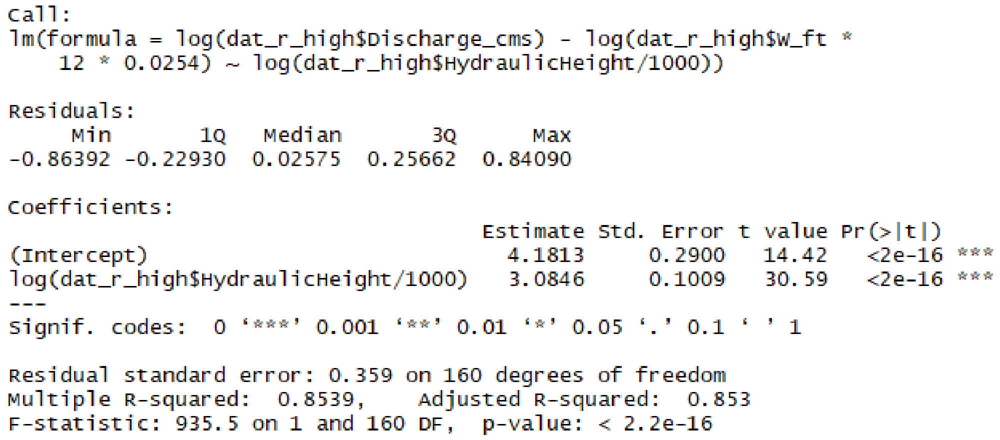
```
Call:
lm(formula = log(dat_r$Discharge_cms) - log(dat_r$W_ft * 12 *
    0.0254) ~ log(dat_r$HydraulicHeight/1000))

Residuals:
     Min       1Q   Median       3Q      Max 
-0.94909 -0.35521 -0.07102  0.29405  2.38288 

Coefficients:
                                Estimate Std. Error t value Pr(>|t|)    
(Intercept)                      1.08770    0.17349   6.269 1.44e-09 ***
log(dat_r$HydraulicHeight/1000)  2.01574    0.05243  38.443  < 2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.5047 on 268 degrees of freedom
Multiple R-squared:  0.8465,	Adjusted R-squared:  0.8459 
F-statistic:  1478 on 1 and 268 DF,  p-value: < 2.2e-16
```

Low Flow



```
Call:
lm(formula = log(dat_r_low$Discharge_cms) - log(dat_r_low$W_ft *
    12 * 0.0254) ~ log(dat_r_low$HydraulicHeight/1000))

Residuals:
     Min       1Q   Median       3Q      Max 
-0.71736 -0.21817 -0.03783  0.17847  1.13724 

Coefficients:
                                    Estimate Std. Error t value Pr(>|t|)    
(Intercept)                         -3.35421    0.30197  -11.11   <2e-16 ***
log(dat_r_low$HydraulicHeight/1000)  0.87534    0.07805   11.22   <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.3198 on 106 degrees of freedom
Multiple R-squared:  0.5427,	Adjusted R-squared:  0.5384 
F-statistic: 125.8 on 1 and 106 DF,  p-value: < 2.2e-16
```

High Flow

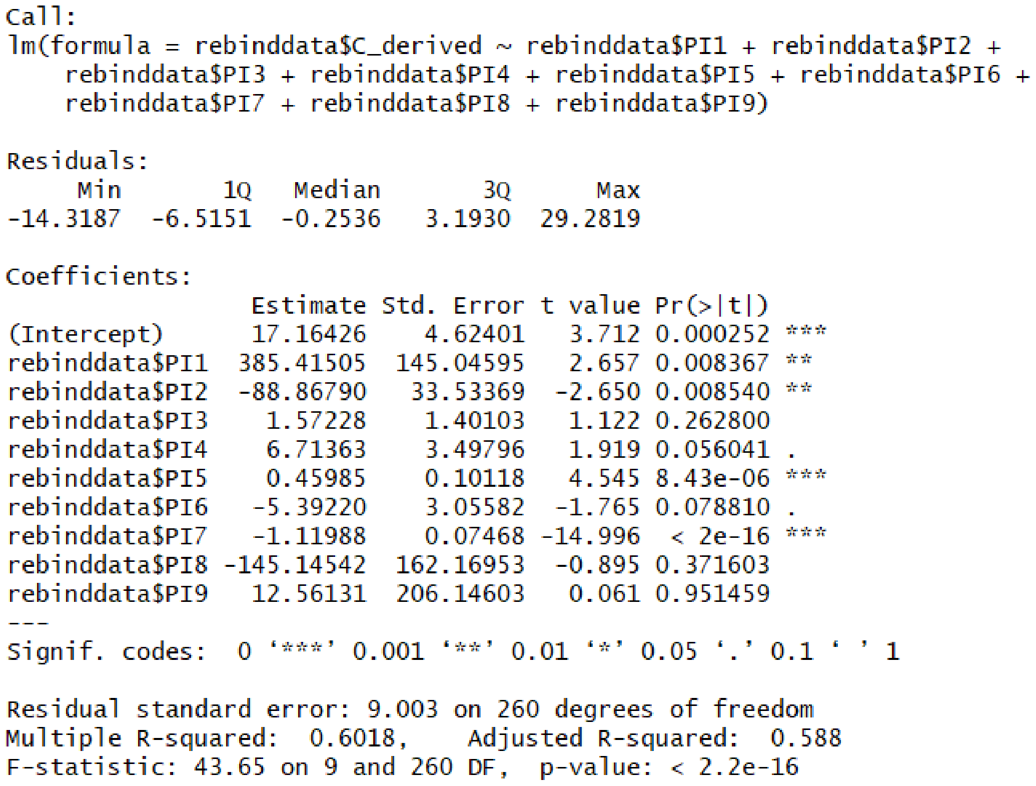


```
Call:
lm(formula = log(dat_r_high$Discharge_cms) - log(dat_r_high$w_ft *
    12 * 0.0254) ~ log(dat_r_high$HydraulicHeight/1000))

Residuals:
     Min       1Q   Median       3Q      Max
-0.86392 -0.22930  0.02575  0.25662  0.84090

Coefficients:
                                     Estimate Std. Error t value Pr(>|t|)
(Intercept)                            4.1813     0.2900   14.42   <2e-16 ***
log(dat_r_high$HydraulicHeight/1000)   3.0846     0.1009   30.59   <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.359 on 160 degrees of freedom
Multiple R-squared:  0.8539,    Adjusted R-squared:  0.853
F-statistic: 935.5 on 1 and 160 DF,  p-value: < 2.2e-16
```

Linear regression to determine discharge coefficient, C_d, as a function of all Pi terms

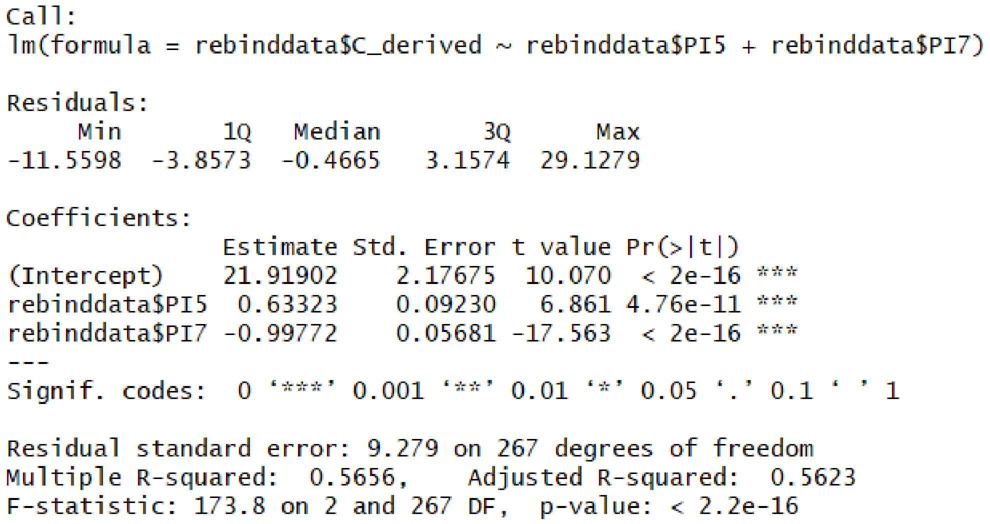
Weir Grouping 1

Results for regression using all Pi terms:



```
Call:
lm(formula = rebinddata$C_derived ~ rebinddata$PI1 + rebinddata$PI2 +
    rebinddata$PI3 + rebinddata$PI4 + rebinddata$PI5 + rebinddata$PI6 +
    rebinddata$PI7 + rebinddata$PI8 + rebinddata$PI9)

Residuals:
     Min       1Q   Median       3Q      Max
-14.3187  -6.5151  -0.2536   3.1930  29.2819

Coefficients:
                 Estimate Std. Error t value Pr(>|t|)
(Intercept)      17.16426    4.62401   3.712 0.000252 ***
rebinddata$PI1  385.41505  145.04595   2.657 0.008367 **
rebinddata$PI2  -88.86790   33.53369  -2.650 0.008540 **
rebinddata$PI3    1.57228    1.40103   1.122 0.262800
rebinddata$PI4    6.71363    3.49796   1.919 0.056041 .
rebinddata$PI5    0.45985    0.10118   4.545 8.43e-06 ***
rebinddata$PI6   -5.39220    3.05582  -1.765 0.078810 .
rebinddata$PI7   -1.11988    0.07468 -14.996  < 2e-16 ***
rebinddata$PI8 -145.14542  162.16953  -0.895 0.371603
rebinddata$PI9   12.56131  206.14603   0.061 0.951459
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 9.003 on 260 degrees of freedom
Multiple R-squared:  0.6018,    Adjusted R-squared:  0.588
F-statistic: 43.65 on 9 and 260 DF,  p-value: < 2.2e-16
```

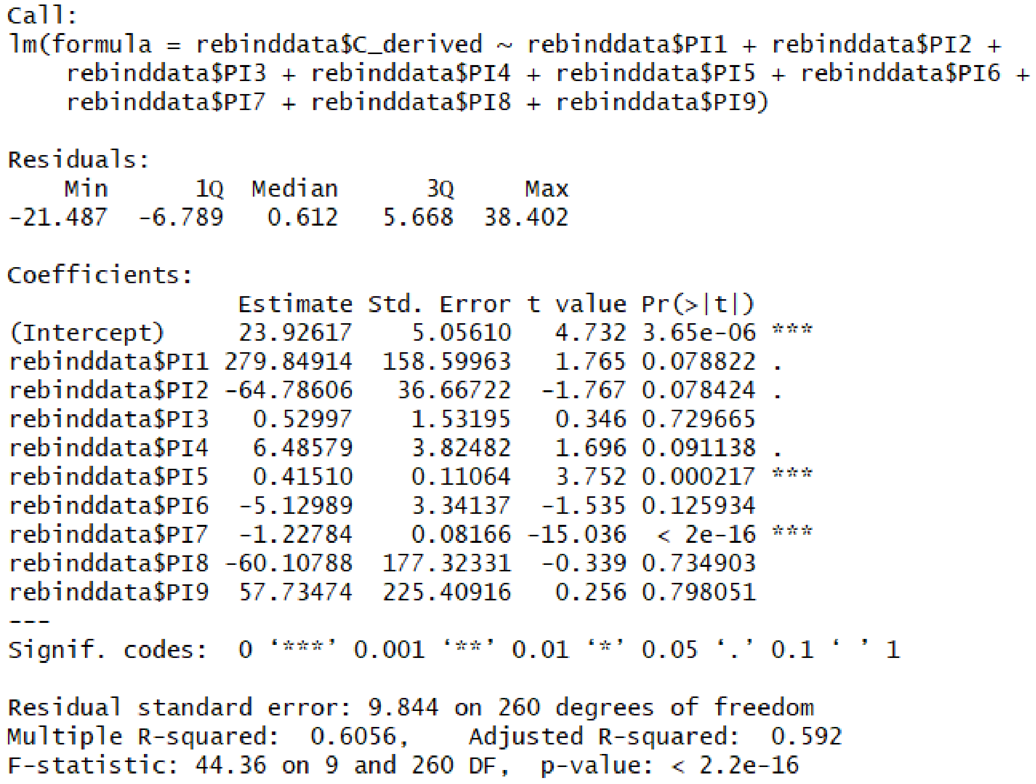
Final regression of discharge coefficient:



```
Call:
lm(formula = rebinddata$C_derived ~ rebinddata$PI5 + rebinddata$PI7)

Residuals:
     Min       1Q   Median       3Q      Max 
-11.5598  -3.8573  -0.4665   3.1574  29.1279 

Coefficients:
               Estimate Std. Error t value Pr(>|t|)    
(Intercept)    21.91902    2.17675  10.070  < 2e-16 ***
rebinddata$PI5  0.63323    0.09230   6.861 4.76e-11 ***
rebinddata$PI7 -0.99772    0.05681 -17.563  < 2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 9.279 on 267 degrees of freedom
Multiple R-squared:  0.5656,	Adjusted R-squared:  0.5623 
F-statistic: 173.8 on 2 and 267 DF,  p-value: < 2.2e-16
```

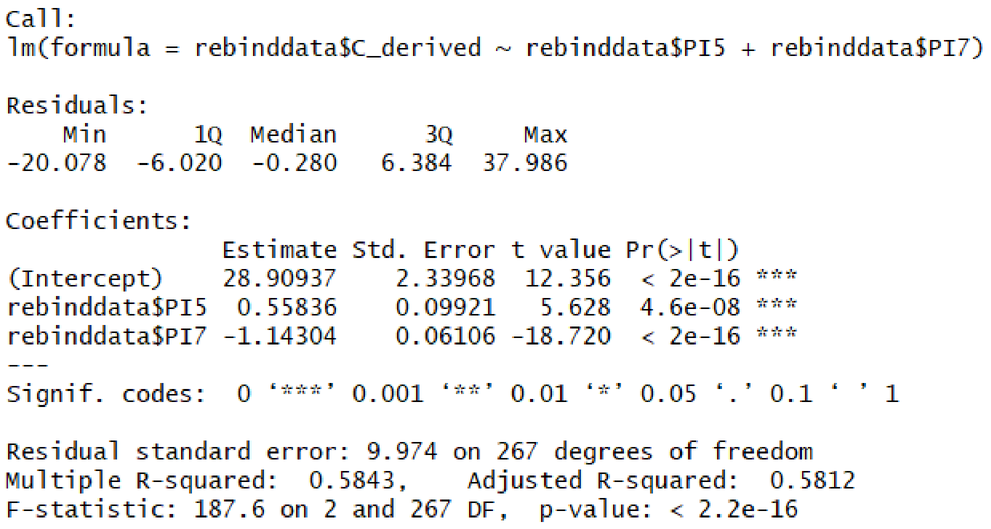
Weir Grouping 2

Results for regression using all Pi terms:



```
Call:
lm(formula = rebinddata$C_derived ~ rebinddata$PI1 + rebinddata$PI2 + 
    rebinddata$PI3 + rebinddata$PI4 + rebinddata$PI5 + rebinddata$PI6 + 
    rebinddata$PI7 + rebinddata$PI8 + rebinddata$PI9)

Residuals:
    Min      1Q  Median      3Q     Max 
-21.487  -6.789   0.612   5.668  38.402 

Coefficients:
                Estimate Std. Error t value Pr(>|t|)    
(Intercept)     23.92617    5.05610   4.732 3.65e-06 ***
rebinddata$PI1 279.84914  158.59963   1.765 0.078822 .  
rebinddata$PI2 -64.78606   36.66722  -1.767 0.078424 .  
rebinddata$PI3   0.52997    1.53195   0.346 0.729665    
rebinddata$PI4   6.48579    3.82482   1.696 0.091138 .  
rebinddata$PI5   0.41510    0.11064   3.752 0.000217 ***
rebinddata$PI6  -5.12989    3.34137  -1.535 0.125934    
rebinddata$PI7  -1.22784    0.08166 -15.036  < 2e-16 ***
rebinddata$PI8 -60.10788  177.32331  -0.339 0.734903    
rebinddata$PI9  57.73474  225.40916   0.256 0.798051    
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 9.844 on 260 degrees of freedom
Multiple R-squared:  0.6056,	Adjusted R-squared:  0.592 
F-statistic: 44.36 on 9 and 260 DF,  p-value: < 2.2e-16
```

Final regression of discharge coefficient:

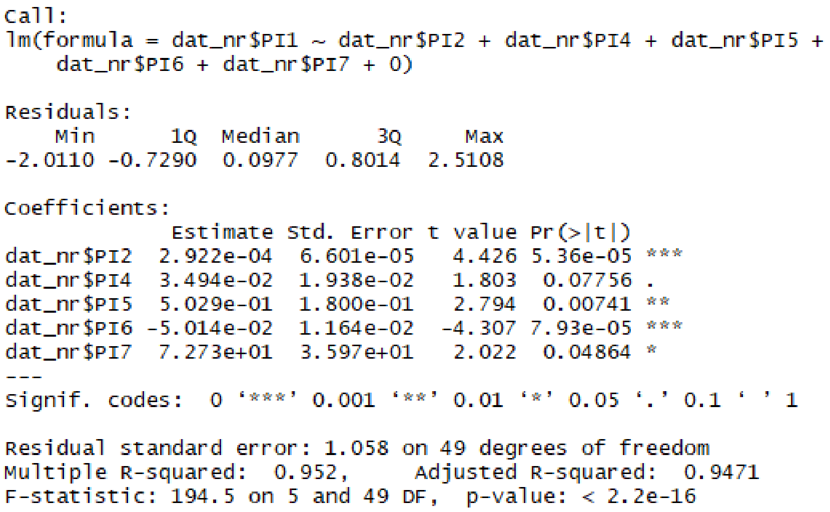


```
Call:
lm(formula = rebinddata$C_derived ~ rebinddata$PI5 + rebinddata$PI7)

Residuals:
    Min      1Q  Median      3Q     Max 
-20.078  -6.020  -0.280   6.384  37.986 

Coefficients:
                Estimate Std. Error t value Pr(>|t|)    
(Intercept)     28.90937    2.33968  12.356  < 2e-16 ***
rebinddata$PI5   0.55836    0.09921   5.628  4.6e-08 ***
rebinddata$PI7  -1.14304    0.06106 -18.720  < 2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 9.974 on 267 degrees of freedom
Multiple R-squared:  0.5843,	Adjusted R-squared:  0.5812 
F-statistic: 187.6 on 2 and 267 DF,  p-value: < 2.2e-16
```

No Rock Analysis

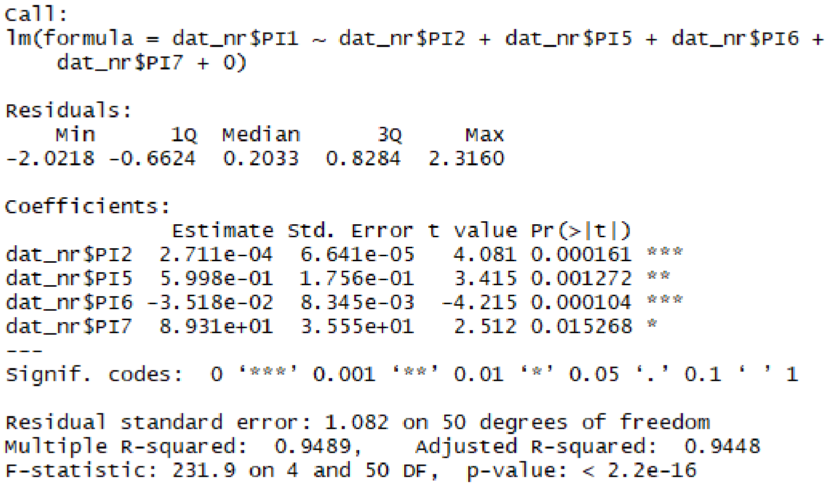
Exploring discharge as a function of dimensionless Buckingham Pi terms.

Results for regression with all Pi terms:



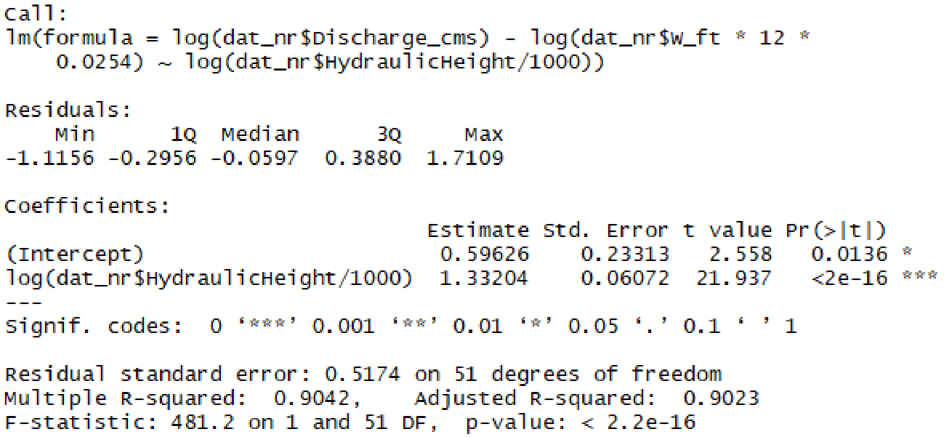
```
Call:
lm(formula = dat_nr$PI1 ~ dat_nr$PI2 + dat_nr$PI4 + dat_nr$PI5 + 
    dat_nr$PI6 + dat_nr$PI7 + 0)

Residuals:
    Min      1Q  Median      3Q     Max 
-2.0110 -0.7290  0.0977  0.8014  2.5108 

Coefficients:
            Estimate Std. Error t value Pr(>|t|)    
dat_nr$PI2  2.922e-04  6.601e-05   4.426 5.36e-05 ***
dat_nr$PI4  3.494e-02  1.938e-02   1.803  0.07756 .  
dat_nr$PI5  5.029e-01  1.800e-01   2.794  0.00741 ** 
dat_nr$PI6 -5.014e-02  1.164e-02  -4.307 7.93e-05 ***
dat_nr$PI7  7.273e+01  3.597e+01   2.022  0.04864 *  
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 1.058 on 49 degrees of freedom
Multiple R-squared:  0.952,	Adjusted R-squared:  0.9471 
F-statistic: 194.5 on 5 and 49 DF,  p-value: < 2.2e-16
```

Final regression of discharge against Pi terms for weirs with no rock:



```
Call:
lm(formula = dat_nr$PI1 ~ dat_nr$PI2 + dat_nr$PI5 + dat_nr$PI6 +
    dat_nr$PI7 + 0)

Residuals:
    Min      1Q  Median      3Q     Max
-2.0218 -0.6624  0.2033  0.8284  2.3160

Coefficients:
             Estimate Std. Error t value Pr(>|t|)
dat_nr$PI2  2.711e-04  6.641e-05   4.081 0.000161 ***
dat_nr$PI5  5.998e-01  1.756e-01   3.415 0.001272 **
dat_nr$PI6 -3.518e-02  8.345e-03  -4.215 0.000104 ***
dat_nr$PI7  8.931e+01  3.555e+01   2.512 0.015268 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 1.082 on 50 degrees of freedom
Multiple R-squared:  0.9489,	Adjusted R-squared:  0.9448
F-statistic: 231.9 on 4 and 50 DF,  p-value: < 2.2e-16
```

Linear Regression



```
Call:
lm(formula = log(dat_nr$Discharge_cms) - log(dat_nr$W_ft * 12 *
    0.0254) ~ log(dat_nr$HydraulicHeight/1000))

Residuals:
    Min      1Q  Median      3Q     Max
-1.1156 -0.2956 -0.0597  0.3880  1.7109

Coefficients:
                                 Estimate Std. Error t value Pr(>|t|)
(Intercept)                       0.59626    0.23313   2.558   0.0136 *
log(dat_nr$HydraulicHeight/1000)  1.33204    0.06072  21.937   <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.5174 on 51 degrees of freedom
Multiple R-squared:  0.9042,	Adjusted R-squared:  0.9023
F-statistic: 481.2 on 1 and 51 DF,  p-value: < 2.2e-16
```