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SUPPLEMENTARY EXAMINATION OF DISCHARGE MEASUREMENT BY A FLUME

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Summary: *Discharge measurement in the range of low flows characteristic to the beginning and end of runoff is feasible by a flume with horizontal bottom. In low flow conditions both viscosity and capillary effects influence the discharge-head relationship. In 2018, to get better insight into the phenomenon, physical model tests in flume with horizontal bottom have been carried out in the hydrtaulic laboratory of the Faculty of Civil Engineering Subotica, Serbia. The aim of this paper is to, with this addendum, enable flumes for measuring runoff hydrographs.*

Keywords: *flume, Parshall flume, flow measurement, hydrograph*

1. INTRODUCTION

The flow increasing from zero at the beginning of the runoff, while at the end of the runoff event it reduces back to zero. For these characteristics of the runoff event, just discharge measurement methods with no obstruction along the flow path are suitable, for example flumes without rising bottom meet this requirement.

1.1 Measurement of water discharge with flat bottom flumes, neglecting the influence of viscosity and surface tension of water on the flow

One of the most common means used for water discharge measurement by flumes is the Parshall flume. Discharge of water is determined with the following function:

$$Q=Ch_a^n \tag{1}$$

where $h_{a,min} \leq h_a \leq h_{a,max}$ is the measured depth, and C and n are the flume discharge constant and discharge exponent respectively, according to Table 1.

Table 1 Constant C and exponent n corresponding to different width small size Parshall flumes according to the international standards [1-2]

	b=0.152 m	b=0.25 m	b=0.30 m	b=0.45 m	b=0.6 m
$h_{a,min}$ (m)	0.03	0.03	0.03	0.03	0.05
$h_{a,max}$ (m)	0.45	0.6	0.75	0.75	0.75
C	0.381	0.561	0.679	1.038	1.403
n	1.58	1.513	1.521	1.537	1.548

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According to Heiner (2009) in the given range of measured head the discharge measurement accuracy varies from ±2% to ±5% [3]. The main problem of this device is the existence of a sill in the flume, which holds back the flow of water at the beginning and at the end of the runoff. For that the measurement error in the runoff hydrograph increases in case of rains of low intensity and short duration.

Over bridging of this problem is provided by the results of experimental study regarding flow measurements by flumes, carried out at the Faculty of Civil Engineering in Belgrade, led by Professor Georgije Hajdin [4].

In case of modular flow the relation between the discharge Q and the depth h of water in the measuring cross-section is provided by the following equations [4]:

- Bernoulli's equation for the no viscous fluid between the measured and contracted cross-sections:

$$z+h+\frac{Q_{id}^2}{2gA^2}=z_k+h_{kid}+\frac{Q_{id}^2}{2gA_{kid}^2} \tag{2}$$

- The Froude number for the no viscous fluid in the contracted cross-section:

$$\frac{Q_{id}^2 B_{kid}}{gA_{kid}^3}=1 \tag{3}$$

- and the relation between the discharges of viscous and no viscous fluids (with an error margin of ±2% at h> 0.1 m):

$$Q=0.95Q_{id} \tag{4}$$

where z, h and A are the bottom level, the depth of the water and the cross-sectional area in the measured section respectively, z_k, h_{kid}, B_{kid} and A_{kid} are the bottom level, depth of flow, water surface width and cross-section area of the contracted section for the no viscous fluid, and $g=9.81\ m/s^2$ is the acceleration due to gravity.

These equations allow dimensioning of flumes: a) with no sill in the contracted section, and b) without causing backwater effect in the channel within the range of significant flows. For Q_{max} the discharge of no viscous fluid is determined by equation (4). By equalizing the measured flow depth for the chosen flow with the water depth in the channel with no flume installed, the depth of flow and the water surface width corresponding to the adopted shape of the contracted section is determined by equations (2) and (3). (This method has been expanded to the contracted cross-section of complex shape, where the calculation is performed for multiple discharges.)

Functions (1) and (4) are corresponding to water flow without the influence of viscosity and surface tension.

1.2 Measurement of discharge with a flume taking in consideration the viscosity and surface tension of water

Performing measurements by Parshall flume of width $b=0.305$ m, Wright and Taheri (1991) have proved that for measured water depths $0.015 \text{ m}<h_a<0.3 \text{ m}$, function $Q=0.772\ h_a^{1.62}$ applies (Figure 1) [5].

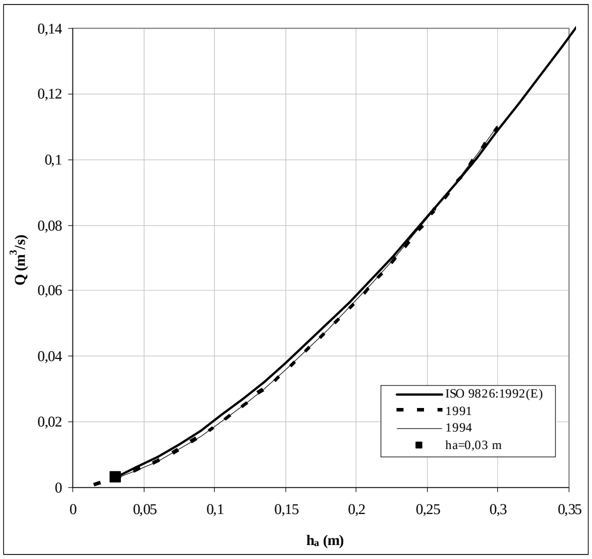

Figure 1 The relation between discharge Q and the measured depth h_a of the Parshall flume having width of 0.305 m according to the functions of the international standard, Wright and Taheri (1991) and Wright et al. (1994)

Since for this flume $h_{a,min}=0.03$ m and $h_{a,max}=0.75$ m (Table 1), the above declared function covers part of the domain concerning the declared ($h_{a,min}<h_a<0.3$ m) and undeclared ($h_a<h_{a,min}$) discharges. For heads $h_{a,min}<h_a<0.3$ m the declared function returns lower discharge than the function of the international standard [1]. The authors have not specified the cause of this phenomenon.

The first paper highlighting the reason of the above mentioned phenomenon is Wright et al. (1994) [3, 6-7]. They have examined Parshall flumes of width $b=0.076$, 0.152, 0.305 and 0.61 m. For the calculation of low discharges, due to the influence of viscosity on the flow, they have proposed new coefficients in function (1) (Table 2).

Table 2 Coefficients C and n for calculation of low discharges using relationship (1) by Wright et al. (1994)

	b=0.076 m	b=0.152 m	b=0.305 m	b=0.61 m
min. h_a (m), tested	0.0137	0.0131		
max. h_a (m)	0.134	0.085	0.305	0.075
C	0.199	0.451	0.778	1.429
n	1.607	1.648	1.622	1.55

Despite to the declared reason, the coefficients in Table 2 are of constant value for a particular flume width, therefore they are not dependent of viscosity. The same applies to the function published in 1991, which produces similar discharge/head relationship as the function published in 1994 (Figure 1).

In periods of 18-24.1.2014 and 6-14.1.2015 the possibility of measuring discharge by Parshall flume of width b=0.0254 m has been investigated in the hydraulic laboratory of the Faculty of Civil Engineering in Subotica [8-9]. The discharge of water was determined by measuring the volume of water and the time of derivation. In the first case the water depth was measured by a gauge (of accuracy 0.1 mm), in the second case EasyTREK SPA-380-4 ultrasonic sensor (of 1 mm accuracy) has been used, manufactured by Nivelco.

Errors in the determination of the declared discharges measured in 2014 were in the range between +4% and +7.2% [8]. To reach rather acceptable error margins (which have settled at -0.8% and +1.7%) a new measuring point location has been chosen, at which for $h_a > h_{a,min} = 0.019$ m the following discharge-head function was determined:

$$Q = 0.0604 h_a^{1.55} \tag{5}$$

If the following approximation is used for $0.0128\text{ m} < h_a < h_{a,min}$:

$$Q = 208.88 h_a^4 - 15.197 h_a^3 + 0.5402 h_a^2 + 0.0002 h_a + 0.0000001 \tag{6}$$

the errors in terms of discharges remain in the range between -3.1% and +3.7%. This function applies to water temperatures between 16 and 17°C. Since equation (6) gives 6% lower discharge for $h_{a,min}$ than the equation (5), the research was continued in the next year.

In experiments performed in 2015 the location of the measuring point was in accordance with the requirements of the international standard [9]. The following function has been adopted for the declared flows:

$$Q = 0.0575 h_a^{1.5407} \tag{7}$$

The errors in determining the flow rates were in the range between -3.46% and +1.83%. The increase of error range of the discharge measurement was due to the reduction of accuracy in water level measurement. If in the range $0.007\text{ m} < h_a < h_{a,min}$ the following function was used:

$$Q = 0.0519 h_a^{1.5119} \tag{8}$$

the errors in determining the flow rate remained within the range between -3.02% and +4.77%. Functions (7) and (8) apply for water temperatures between 11.5 and 16°C (12.7°C average). The error in discharge for $h_{a,min}$ calculated by equations (7) and (8) is 1.16%. Therefore, the solution based on the 2015 measurements did not eliminate the error at $h_{a,min}$.

Based on the results of the analysis of the possibility of measuring runoff hydrographs by a thin-plate weir, a new function for determining the discharge using a Parshall flume was proposed in 2018 [10]:

$$\frac{Q}{b_a h_a}=f\left(\frac{\sqrt[3]{\frac{Re^2}{We}}}{20000}\right)=f\left(\frac{\sqrt[3]{\frac{\sigma h_a}{\rho \upsilon^2}}}{20000}\right) \tag{9}$$

In the above relationship b_a is the width of the Parshall flume at the measuring point, We and Re are the Weber and Reynolds number respectively, ρ is density, σ is the coefficient of surface tension, and ν is the kinematic coefficient of the viscosity of water. Function type (9) was obtained based on the results of measurements performed in 2015 (Figure 2).

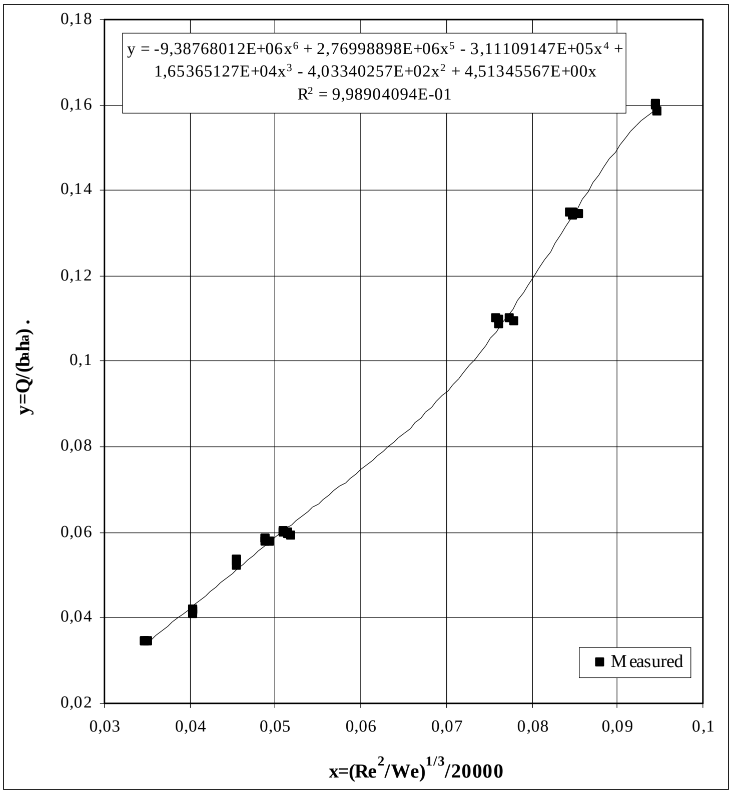

Figure 2 Function type (9) [10]

The errors in determining the discharge using the equation shown in Figure 2 are in the range between -4.02 and +5.22%. Since in case of this flume the measured minimum head is $h_{a,min}$=0.019 m, in accordance with the functions published in 1991 and 1994, function shown in Figure 2 covers part of the domain concerning the declared and undeclared discharges.

The aim of this paper is using function type (9) with flumes having flat bed in the longitudinal direction where water level is measured with a gauge (of accuracy ±0.1 mm) or a sensor (of accuracy ±1 mm).

2. DESCRIPTION OF THE INSTALLATION

In the hydraulic laboratory of the Faculty of Civil Engineering in Subotica, a flume having flat bed in the flow direction was installed at the downstream end of the experimental channel having width B=0.1 m and length 2.25 m (Figure 3).

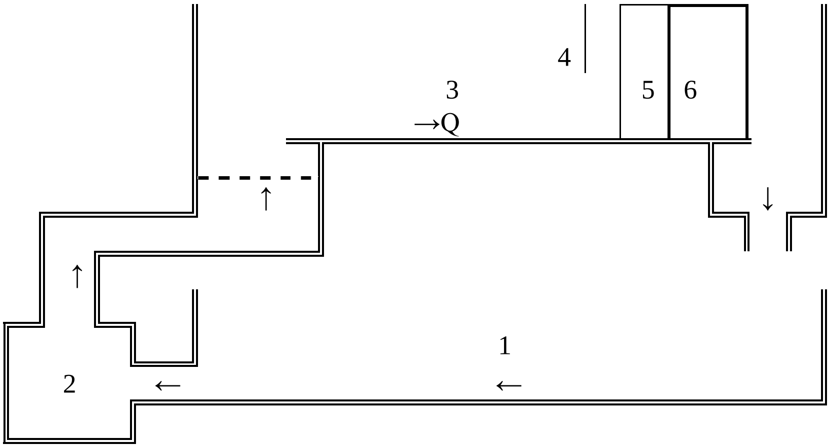

Figure 3 The experimental installation
1 – water tank, 2 – pump, 3 – channel of width B, 4 – gauge, 5 – transition section, 6 – contracted section having rectangular cross section of width b_s and length L_s

Following the flow along the experimental channel (brought by the pump from the water tank) passed the measuring flume, it was either returned to the water tank or redirected towards the water collecting vessel for volume measurement.

The width of the contracted cross-section was b_s=6.7 cm and its length was L_s=24.5 cm. Between the walls of the channel of width B and the contracted cross-section of width b_s a transition section is installed with a side slope of 1:6. In accordance with the recommendation in [4], the measuring cross section was B/2=5 cm upstream from the upstream cross section of the transition section. The bottom level of the measuring section was 1.6 mm lower than the bottom level of the contracted cross-section.

The water level was measured by a gauge of ±0.1 mm accuracy.

The water derivation lasted for at least 25 seconds. The weight of the water was measured using a scale accurate to 5 grams (within the range of up to 15 kg) and a scale accurate to 10 grams (in the range between 15 kg and 150 kg).

During water derivation, the temperature of the water was measured near the measuring cross-section. The temperature varied between 19 and 21, averaging at 19.47°C. Water density was established using a measuring cylinder of volume 1 dm^3, calibrated for water temperature of 20°C. The density of the water was 1 kg/dm^3. Due to this fact, the discharge was calculated using the following equation:

$$Q=\frac{G_{vessel+water}-G_{vessel}}{t}\ (l/s) \qquad (10)$$

$G_{vessel+water}$ is the weight of the vessel and the contained water (kg), G_{vessel} is the weight of the empty vessel (kg) and t is the duration of water derivation (s).
The error in discharge was calculated using equation: Error (%)=100*(Q_j-$Q_{(10)}$)/$Q_{(10)}$), where Q_j is the discharge of water calculated using the function in Figure 5, and $Q_{(10)}$ is the discharge of water calculated by equation (10).

3. MEASUREMENT RESULTS

During the 5th and 6th of November 2018, 32 measurements were performed.
The measurement depth was between 0.0058 m and 0.1046 m.
Using equations (2) and (4), coefficient C_Q was determined for each measurement (Figure 4).

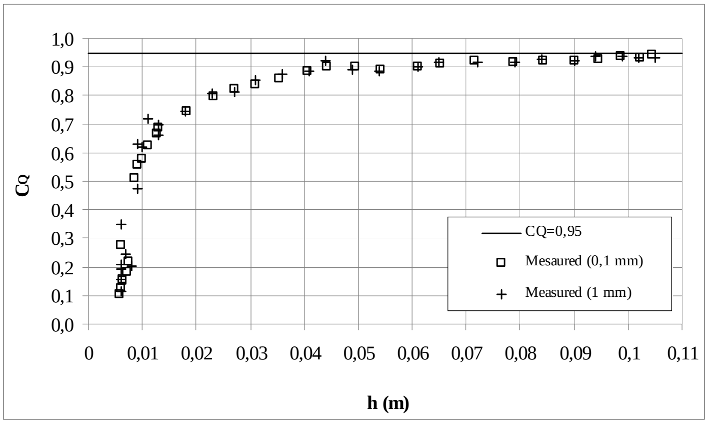

Figure 4 Coefficient C_Q for the measured discharges

Similarly to function (9), functions of the type (11) have been determined for the examined flume (Figure 5):

$$\frac{Q}{Bh}=f\left(\frac{\sqrt[3]{\frac{Re^2}{We}}}{20000}\right)=f\left(\frac{\sqrt[3]{\frac{\sigma h}{\rho \upsilon^2}}}{20000}\right) \tag{11}$$

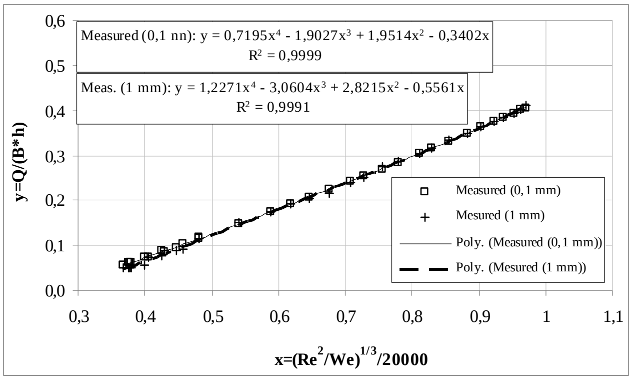

Figure 5 Functions of type (11) for the examined flume

4. DISCUSION

1. According to the obtained values of coefficient C_Q, the results of measurements verified the validity of equation (4) determined by the study carried out at the Faculty of Civil Engineering in Belgrade (Figure 4): for $h>0.1$ m, $C_Q=0.95$.
2. In contrast to functions (1) and (4) which apply to flows with influence of viscosity and surface tension neglected, functions of type (11) are valid for $h\leq 0.1046$ m (Figure 5). Combined with the method developed in Belgrade, this enables the measurement of runoff hydrographs.
3. Using the equation given in Figure 5 to calculate the discharge, the error in discharge will be between -2.77% and +3.39%, with water level measurement accuracy ±0.1 mm, and between -9.31% and +12.51% with water level measurement accuracy ±1 mm (Figure 6).

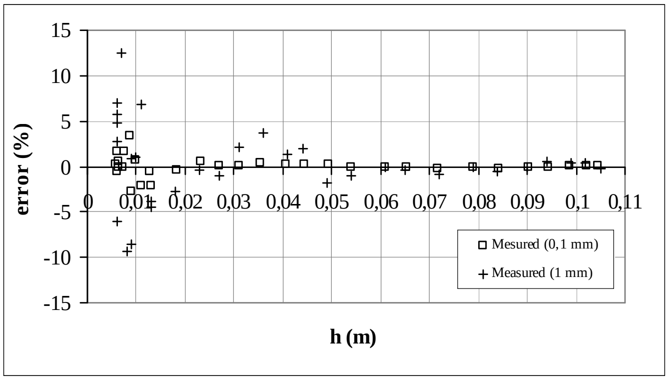

Figure 6 Discharge measurements error in the examined flume

4. According to the international standard the allowable error margin is ranging from ±2% to ±5%, which is achievable by water level measurements of accuracy not worse than ±0.1 mm.

5. CONCLUSION

Using function of type (11) for determining flow rate for $h<0.1$ m along with the method developed in Belgrade for $h>0.1$ m, measuring runoff hydrographs is feasible.

To meet accuracy in discharge measurement required by the international standard for $h<0.1$ m, the water level should be measured with a suitable device having accuracy of ±0.1 mm.

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ДОПУНСКО ИСПИТИВАЊЕ ЗА МЕРЕЊЕ ХИДРОГРАМА ОТИЦАЈА СУЖЕЊЕМ

Резиме: *За мерење протицаја у близини нуле вредности, на пр. на почетку и на крају отицаја кише може да послужи сужење без прага. При малим протицајима вискозност и површински напон воде утиче на везу протицај-мерена дубина воде. Поводом овог проблема 2018-е године у хидрауличкој лабораторији Грађевинског факултета у Суботици (Србија) вршена су нова испитивања струјанја воде у сужењу без прага.*

Кључне речи: *сужење, Паршалово сужење, мерење протицаја, хидрограм*