

## New method for discharge hydrograph measurement of the free overflow with full-width, thin-plate weir

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The current standards recommend measuring water discharge with vented thin-plate weirs. The ventilation of full-width, thin-plate weirs during discharge hydrograph measurement still poses a problem. An experimental study regarding the design of a new type of ventilating device for hydrograph measurement was performed from 20 October through 5 December 2015 which proved that this device can be used measuring discharge at ventilated nappe according to standard recommendations. During the second part of the experiment, an opportunity was provided for measuring the discharge at non-ventilated nappe as a function of Reynolds and Weber numbers.

**Keywords:** Run-off hydrograph, water discharge, weirs, ventilated nappe.

In the present study, water discharge in full-width thin-plate weirs, in the case of non-submerged ventilated overflow is calculated using the equation

$$Q = m\sqrt{2g}BH^{3/2}, \quad (1)$$

where  $m$  is the discharge coefficient,  $B$  the width of the weir and  $H$  is the height of the nappe<sup>1</sup>. Generally, the discharge coefficient is a function of Reynolds number ( $Re$ ), Weber number ( $We$ ),  $H/P$  and  $H/B$ , where  $P$  is the height of the weir<sup>1-8</sup>. The following equations are suggested for the calculation of these numbers:  $Re = [(2gH)^{0.5}(BH)^{0.5}]/\nu$  and  $We = (2\rho gHB)/\sigma$ , where  $\nu$  the kinematic viscosity coefficient,  $\rho$  the density and  $\sigma$  is the surface tension of water<sup>4,9</sup>.

The valid international standards<sup>10,11</sup> and recent studies<sup>2,4,12,13</sup> recommend the equations listed in Table 1 for the discharge coefficient. These equations refer to ventilated nappe. For the height of the nappe  $H \geq 0.03$  m, the influence of  $Re$  and  $We$  on discharge is negligible<sup>3</sup>.

For ventilation of the nappe, the literature recommends making holes beneath it in the channel walls, or using pipes for air supply<sup>1,14</sup>. The problem of ventilation occurs when the nappe separates from the weir due to the position of the holes, while the use of pipes requires blowing air in them. Studies conducted by the present author<sup>1</sup> also confirmed the existence of this problem. The simplest and most efficient ventilation of the nappe has been achieved by running a finger across it.

In order to measure discharge using a thin-plate weir, a weir with dimensions  $B = 0.4$  m wide and  $P = 0.341$  m was tested<sup>15</sup>. It has been established that there is a nappe separation limit ( $H = 0.035$  m) when the discharge increases, and a nappe adherence limit (i.e. when the nappe adheres to the thin-plate weir) when the discharge decreases ( $H = 0.009$  m). Air for ventilation has been supplied by pipes and through holes on both sides of the channel. The holes on the channel walls are located at the middle of the weir, on the surface of the non-ventilated nappe. The following equations have been suggested for discharge coefficient calculations at water temperature of 11°–14°C.

(i) For  $0.009 \text{ m} < H < 0.035 \text{ m}$ :

For ventilated nappe

$$m = \frac{2}{3} \left( 0.605 + \frac{1}{1000H} + 0.08 \frac{H}{P} \right).$$

For non-ventilated nappe

$$m = \frac{2}{3} \left( 0.605 + \frac{1}{1000(1.1897H - 0.0008)} + 0.08 \frac{1.1897H - 0.0008}{P} \right).$$

(ii) For  $H < 0.009 \text{ m}$

$$m = \frac{2}{3} \left[ -1.8189 \left( 0.605 + \frac{1}{1000H} + 0.08 \frac{H}{P} \right) + 2.0598 \right],$$

where  $m$  is discharge coefficient. Modifications in the discharge coefficient are, most likely, consequences of the impact of viscosity and the surface tension of water.

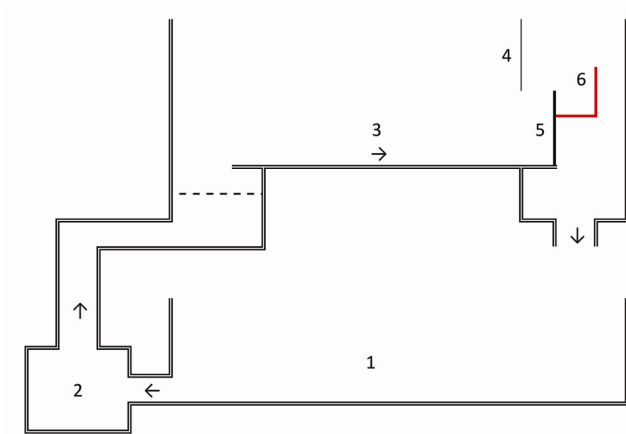
The impact of  $Re$  and  $We$  on the discharge coefficient has also been checked during the testing of contracted thin-plate weirs for low discharges<sup>2,16</sup>. It has been concluded that there is no sufficiently strong relation between the discharge coefficient and  $Re$ , especially at fully contracted thin-plate weirs<sup>2</sup>. In order to solve this problem, a factor for determining discharge  $Q/(B(P+H))$  has been introduced instead of the discharge coefficient.

The present author experimentally tested a new type of nappe ventilation – ‘artificial finger’ or ventilation strip – which is a 3 cm wide,  $L$ -shaped, metal sheet<sup>1</sup>. Using the artificial finger ensured sufficient air for ventilation of the nappe. The first test was made during August and September 2015. The horizontal part of the artificial finger was tied to the downstream side of the weir for  $\Delta z = 0.003$  m below the crest level (right at the lower edge of the chamfered notch). The weir was in a 2.2 m long rectangular channel, at the middle of the channel’s length. Having the weir located in such manner, the limit of submergence of the weir was defined. The water temperature was 27°C during the measurements. It has been

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**Table 1.** Equations used for the calculation of discharge coefficient in case of thin-plate weirs according to the international standards and recent researches

Kindsvater–Carter <sup>10,11</sup>	Rehbock <sup>10,11</sup>	Bagheri and Heidarpour <sup>12</sup>	Bagheri and Heidarpour <sup>13</sup>	Aydin <i>et al.</i> <sup>2</sup>	Gharahjeh <i>et al.</i> <sup>4</sup>
$Q = C_{e,K-C} \frac{2}{3} \sqrt{2g_n} b_e h_e^{3/2}$	$Q = C_e \frac{2}{3} \sqrt{2g_n} B h_e^{3/2}$	$Q = C_d \frac{2}{3} \sqrt{2g} B H^{3/2}$	$Q = C_d \frac{2}{3} \sqrt{2g} B H^{3/2}$	$Q = v_w B H$	$Q = v_c B H$
$C_e = 0.602 + 0.075 \frac{H}{P}$	$C_e = 0.602 + 0.083 \frac{H}{P}$	$C_d = 0.324 \exp(0.94) * \ln \left( 1 + \frac{0.73 \frac{H}{P} + 3.64}{\exp(1.18)} \right)$	$C_d = 0.79 \ln \left( 2.206 + 0.242 \frac{H}{P} \right)$	$v_w = 0.186 + 7.123H - 6.521H^{1.5}$	$v_c = 0.4744 \sqrt{2gH}$
$b_e = B - 0.0009$ (m)	$h_e = H + 0.001$ (m)	$h_e = H + 0.0012$ (m)			
$H/P < 2.5$	$H/P \leq 4$	$0 < H/P < 9$	$0 < H/P < 10$		
$H \geq 0.03$ m	$0.03 \text{ m} \leq H \leq 1$ m				
$B \geq 0.15$ m	$B \geq 0.3$ m				
$P \geq 0.10$ m	$0.06 \text{ m} \leq P \leq 1$ m		$(0.08 \text{ m} \leq P \leq 0.18 \text{ m})$	$P = 0.1$ m	$P \geq 0.10$ m



**Figure 1.** Experimental installation. 1, Water tank; 2, Pump; 3, Channel width ( $B$ ); 4, Gauge; 5, Full-width, thin-plate weir height ( $P$ ); 6, Artificial finger.

concluded that, irrespective of whether the flow increases or decreases during discharge, the discharge coefficient can only be determined by two functions: one for non-ventilated and the other for ventilated nappe. The discharge coefficient error for the nappe of height  $H \geq 0.007$  m was between  $-5.22\%$  and  $+8.76\%$ . None of the two functions provided by the international standards was valid for the ventilated overflow. It has been confirmed that  $Re$  and  $We$  have an influence on non-ventilated nappe.

Based on the results presented above regarding the ventilated nappe, it is obvious that the artificial finger, successful in terms of aeration, induced an adverse influence on the water overflow as well. Due to this, new tests were started with the aim of enabling the measurement of flow discharge hydrograph by full-width thin-plate weir without the influence of the artificial finger on water overflow and the first results published<sup>1</sup>. The artificial finger was installed at the mid point of the weir crest. Its

optimum elevation was determined by trial and error method. Its height level was defined by testing. Keeping in mind that the eventual backwater effect caused by the artificial finger needs to be avoided, the horizontal part of the finger had to be installed at least  $\Delta z = 0.016$  m below the crest level. The artificial finger ventilates the nappe for increasing discharge at  $H \geq 0.0171$  m and for decreasing discharge at  $H \geq 0.01$  m. Applying the function from the international standard (for the calculation of the discharge coefficient the Kindsvater–Carter formula has been applied for the range  $0.05 \leq H/P < 0.1$ , while the Rehbock formula for the range  $0.1 \leq H/P < 0.3$ ), the discharge can be determined with errors between  $-3.4\%$  and  $+2.3\%$ .

The aim of this was study to measure discharge using full-width thin-plate weir for a non-ventilated nappe.

In the hydraulic laboratory of the Faculty of Civil Engineering, Subotica, Republic of Serbia, a 0.2013 m high, full-width thin-plate weir has been installed on the downstream end of a 0.1 m wide and 2.2 m long channel (Figure 1). The channel was supplied with water from a storage tank using a pump. The water already flowing over the thin-plate weir was either returned to the storage tank, or was diverted to an intake vessel for measurement purpose. The plexiglass weir was 5 mm thick with crest thickness of 2 mm, and the notch angle of the downstream side was  $45^\circ$ .

The water level was measured at 0.18 m upstream from the weir with a gauge of  $\pm 0.1$  mm accuracy. The flow of water lasted at least for 25 sec. The weight of the water was measured by a scale of 5 g accuracy (within a range up to 15 kg) and 10 g accuracy (range up to 150 kg).

During water flow, its temperature was measured near the upstream section. It varied between  $19^\circ\text{C}$  and  $21^\circ\text{C}$ , and on an average it was  $19.94^\circ\text{C}$  during the whole period of measurement. Water density was established by a measuring cylinder of  $1 \text{ dm}^3$  volume, calibrated for water

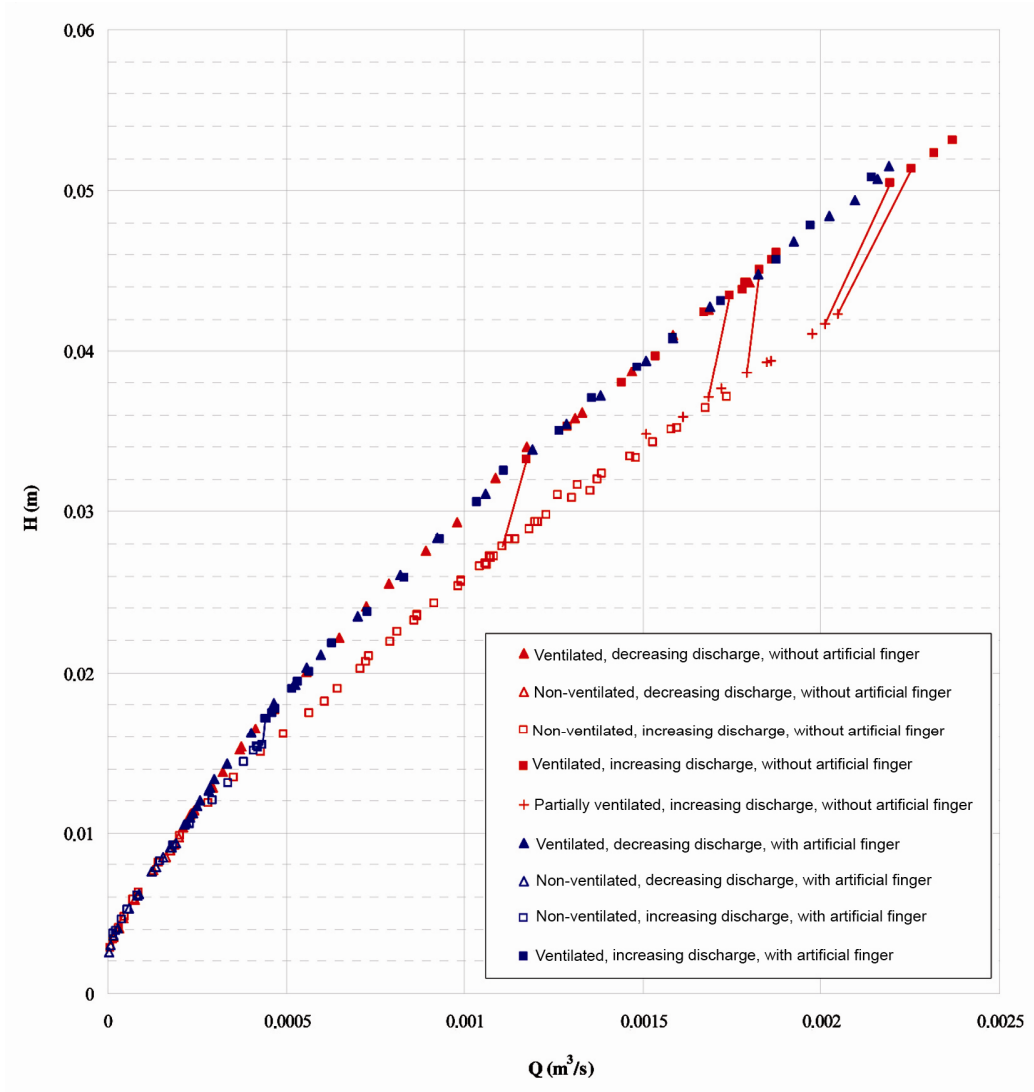


Figure 2. Relation between height of the nappe ( $H$ ), and flow rate of the water ( $Q$ ), for the tested arrangement.

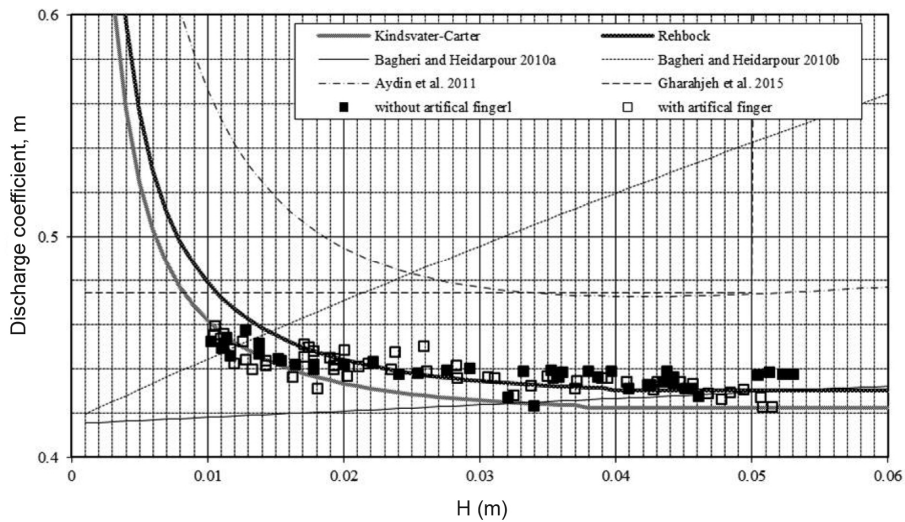
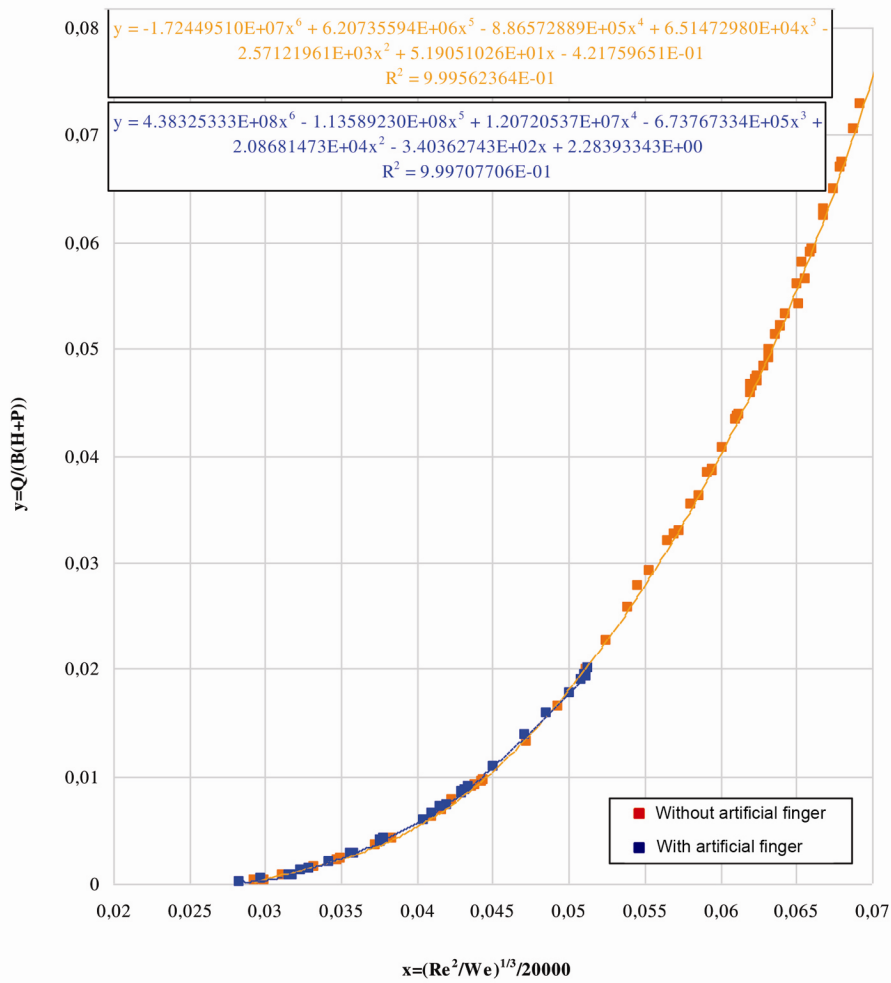


Figure 3. Discharge coefficient of the ventilated nappe (m) as a function of its height ( $H$ ).



**Figure 4.** Function for  $\frac{Q}{B(P+H)} = f\left(\left(\frac{\sigma H}{\rho v^2}\right)^{1/3} \frac{1}{20,000}\right)$  for non-ventilated nappe.

temperature of 20°C. The density of water was 1 kg/dm<sup>3</sup>; therefore, the flow rate was calculated based on the following equation:  $Q(l/s) = (M_{\text{container+water}} - M_{\text{container}})/(\rho t)$ , where  $M_{\text{container+water}}$  is the mass of the container and water together (kg),  $M_{\text{container}}$  the mass of the container only (kg),  $\rho$  the density of water (kg/dm<sup>3</sup>) and  $t$  is the duration of water derivation (s).

The error in the discharge coefficient was calculated based on the following equation:  $\text{error}(\%) = 100(m_j - m_{(1)})/m_{(1)}$ , where  $m_j$  is the discharge coefficient calculated in accordance with any of the equations listed in Table 1 and  $m_{(1)}$  is the discharge coefficient calculated based on eq. (1).

Two arrangements were tested: (i) weir without artificial finger and (ii) weir with artificial finger. The artificial finger was installed at the middle of the weir with delevelling between the crest level of the discharge and horizontal part of the artificial finger of  $\Delta z = 0.016$  m.

During testing arrangement (i) a total of 118 measurements were made and during testing arrangement (ii) the number of measurements totalled 84 (Figure 2).

The testing was carried out by applying minor increments in flow rate, starting from zero to maximum flow, and then back to zero using a similar procedure. During the phase of increasing flow rate, the nappe was not ventilated in the beginning, while later on it got separated from the plate. The point of separation of the nappe occurred. In the opposite process, the nappe adhered to the weir; this is the point of adherence of the nappe. As can be seen in Figure 2, the nappe adherence point was stable at  $H = 0.01$  m in both arrangements tested. The point of separation was only stable in arrangement (ii) at a flow rate of  $Q = 0.00043/0.00044$  m<sup>3</sup>/s, the height of the nappe jumped from 0.0155 to 0.0171 m.

From all of the measurements cases with ventilated nappe have been selected (in arrangement (i) 42 cases, and arrangement (ii) 54 cases), and then the discharge coefficient was calculated based on eq. (1) (Figure 3).

For non-ventilated nappe (number of measurements for arrangement (i) 118 – 42 = 76, and for arrangement (ii)

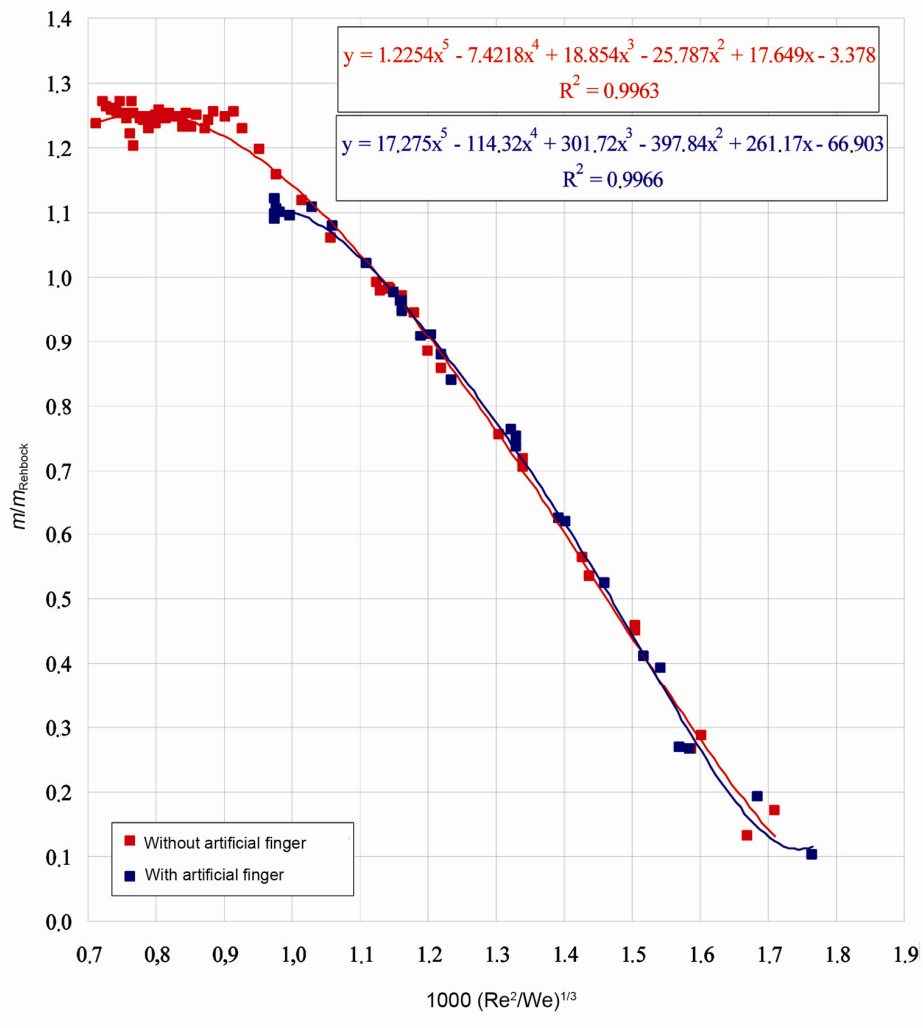


Figure 5. Function for  $\frac{m}{m_{Rehbock}} = f\left(1000\left(\frac{\rho v^2}{\sigma H}\right)^{1/3}\right)$  for non-ventilated nappe.

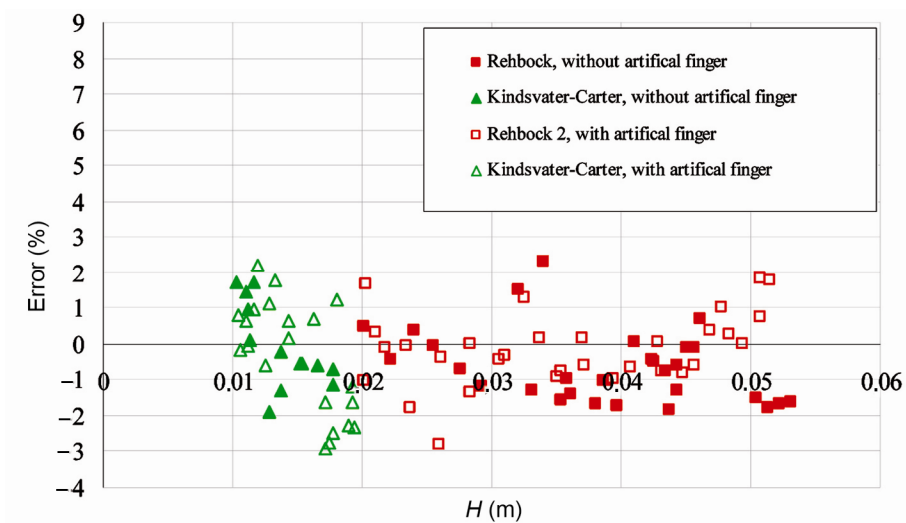


Figure 6. Discharge coefficient error in the function of nappe of height  $H$ , for thin-plate weir (ventilated nappe).

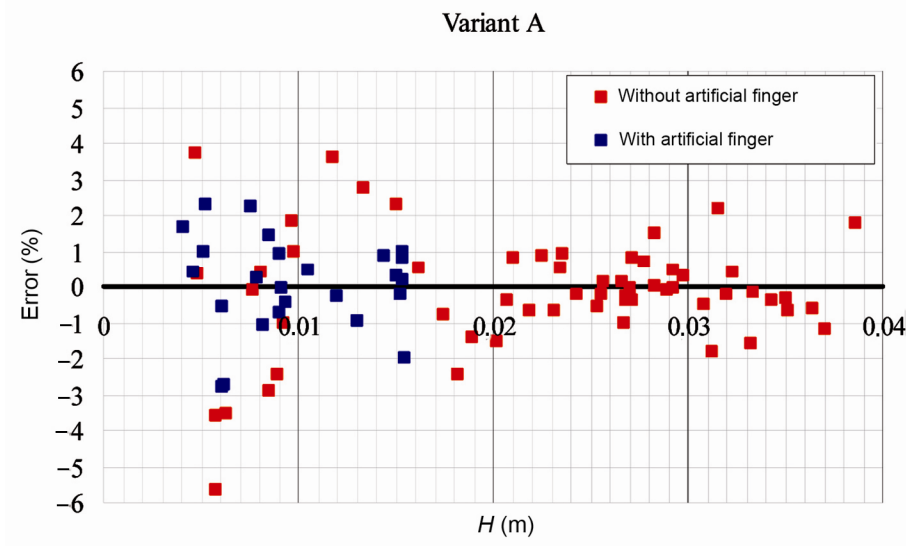


Figure 7. Error in determining flow rate  $Q$  in the function of nappe of height  $H$  for thin-plate weir (non-ventilated nappe).

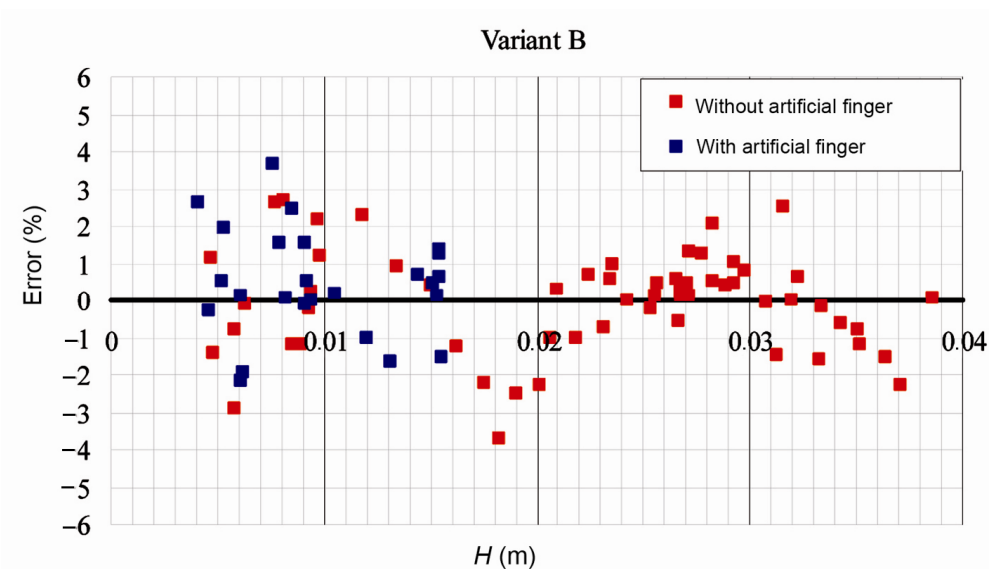


Figure 8. Discharge coefficient error  $m$  in the function of the nappe of height  $H$  for thin-plate weir (non-ventilated nappe).

84 – 54 = 30) dependences are given for two variants (Figures 4 and 5).

Variant A

$$\frac{Q}{B(P+H)} = f\left(\left(\frac{Re^2}{We}\right)^{1/3} \frac{1}{20,000}\right) = f\left(\left(\frac{\sigma H}{\rho v^2}\right)^{1/3} \frac{1}{20,000}\right).$$

Variant B

$$\frac{m}{m_{Rehbock}} = f\left(1000\left(\frac{We}{Re^2}\right)^{1/3}\right) = f\left(1000\left(\frac{\rho v^2}{\sigma H}\right)^{1/3}\right).$$

Using the artificial finger (for  $P = 0.2$  m, with delevelling of  $\Delta z = 0.016$  m) in discharge measurement, the ventilated nappe occurs at  $H \geq 0.0171$  m for increase in discharge and at  $H \geq 0.01$  m for decrease in discharge.

According to Figure 3, the measured values of discharge coefficients most often coincide in the range  $0.01 \text{ m} \leq H \leq 0.02 \text{ m}$  with the values of the Kindsvater–Carter equation, in the range  $0.02 \text{ m} < H < 0.06 \text{ m}$  with the values of the Rehbock equation. This indicates that their limit is around the point where the nappe gets separated from the weir.

Discharge coefficient errors for the range  $0.01 \text{ m} \leq H \leq 0.02 \text{ m}$  calculated according to Kindsvater–Carter

equation are between  $-2.9\%$  and  $+2.2\%$ , while for the range  $0.02\text{ m} < H < 0.06\text{ m}$ , according to Rehbock equation, they are between  $-2.8\%$  and  $+2.3\%$  (Figure 6).

Using the artificial finger, the discharge can be defined within error limits of  $-2.9\%$  and  $+2.3\%$  using discharge formulas from the international standards suitable for the range of measurement, as described above. Compared to reports in the literature, this is a new finding, since the literature recommends an equation for ventilated nappe calculation (without indicating error limits), which is not included in the international standards.

Since these functions do not depend on  $Re$  and  $We$ , unlike those in the literature, the influence of these numbers may be lowered from  $H \geq 0.03\text{ m}$

- to  $H \geq 0.0171\text{ m}$  for increase in discharge and
- to  $H \geq 0.01\text{ m}$  for decrease in discharge.

For non-ventilated nappe, in case of  $H \geq 0.004\text{ m}$  (Figures 7 and 8)

- Without the artificial finger, error ranges between  $-5.7\%$  and  $+3.8\%$  in variant A and between  $-2.9\%$  and  $+2.6\%$  in variant B.
- With the artificial finger, the error limits are between  $-2.8\%$  and  $+2.3\%$  in variant A and between  $-2.2\%$  and  $+3.7\%$  in variant B.

Use of artificial finger for non-ventilated nappe improves the measurement of discharge in variant A to the highest degree, where errors are between  $-2.8\%$  and  $+2.3\%$ .

While the literature recommends two equations for non-ventilated nappe, in this study we use only one equation with the given error limits.

Thus, the use of artificial finger enabled the discharge hydrograph measurement of free overflow using the full-width, thin-plate weir.

Further tests should specify the location of the artificial finger in a full-width thin-plate weir with free flow (non-submerged) ventilated discharge as the function of discharge height  $P$  and width  $B$ .

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## Modulation of midgut peritrophins' expression during *Plasmodium* infection in *Anopheles stephensi* (Diptera: Culicidae)

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**The peritrophic matrix (PM) serves as a barrier to pathogens in many disease vectors including mosquitoes. The *Plasmodium* ookinete has to cross the PM barrier for its successful establishment in the mosquito mid-gut and subsequent transmission. It is conceived that alterations to PM may lead to a block in infection.**

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