On local scouring downstream small water structures (#46700)

First revision

Guidance from your Editor

Please submit by **9 Oct 2020** for the benefit of the authors .

Structure and Criteria
Please read the 'Structure and Criteria' page for general guidance.

Author notes
Have you read the author notes on the <u>guidance page</u>?

Raw data check
Review the raw data.

Image check
Check that figures and images have not been inappropriately manipulated.

Privacy reminder: If uploading an annotated PDF, remove identifiable information to remain anonymous.

Files
Download and review all files from the <u>materials page</u>.

1 Tracked changes manuscript(s)
1 Rebuttal letter(s)
12 Figure file(s)
7 Table file(s)
1 Raw data file(s)

Structure and Criteria

Structure your review

The review form is divided into 5 sections. Please consider these when composing your review:

1. **BASIC REPORTING**
2. **EXPERIMENTAL DESIGN**
3. **VALIDITY OF THE FINDINGS**
4. General comments
5. Confidential notes to the editor

📄 You can also annotate this PDF and upload it as part of your review

When ready [submit online](#).

Editorial Criteria

Use these criteria points to structure your review. The full detailed editorial criteria is on your [guidance page](#).

BASIC REPORTING

- Clear, unambiguous, professional English language used throughout.
- Intro & background to show context. Literature well referenced & relevant.
- Structure conforms to [PeerJ standards](#), discipline norm, or improved for clarity.
- Figures are relevant, high quality, well labelled & described.
- Raw data supplied (see [PeerJ policy](#)).

EXPERIMENTAL DESIGN

- Original primary research within [Scope of the journal](#).
- Research question well defined, relevant & meaningful. It is stated how the research fills an identified knowledge gap.
- Rigorous investigation performed to a high technical & ethical standard.
- Methods described with sufficient detail & information to replicate.

VALIDITY OF THE FINDINGS

- *i* Impact and novelty not assessed. Negative/inconclusive results accepted. *Meaningful* replication encouraged where rationale & benefit to literature is clearly stated.
- All underlying data have been provided; they are robust, statistically sound, & controlled.
- Speculation is welcome, but should be identified as such.
- Conclusions are well stated, linked to original research question & limited to supporting results.

Standout reviewing tips

The best reviewers use these techniques

Tip	Example
Support criticisms with evidence from the text or from other sources	*Smith et al (J of Methodology, 2005, V3, pp 123) have shown that the analysis you use in Lines 241-250 is not the most appropriate for this situation. Please explain why you used this method.*
Give specific suggestions on how to improve the manuscript	*Your introduction needs more detail. I suggest that you improve the description at lines 57- 86 to provide more justification for your study (specifically, you should expand upon the knowledge gap being filled).*
Comment on language and grammar issues	*The English language should be improved to ensure that an international audience can clearly understand your text. Some examples where the language could be improved include lines 23, 77, 121, 128 – the current phrasing makes comprehension difficult.*
Organize by importance of the issues, and number your points	*1. Your most important issue* *2. The next most important item* *3. ...* *4. The least important points*
Please provide constructive criticism, and avoid personal opinions	*I thank you for providing the raw data, however your supplemental files need more descriptive metadata identifiers to be useful to future readers. Although your results are compelling, the data analysis should be improved in the following ways: AA, BB, CC*
Comment on strengths (as well as weaknesses) of the manuscript	*I commend the authors for their extensive data set, compiled over many years of detailed fieldwork. In addition, the manuscript is clearly written in professional, unambiguous language. If there is a weakness, it is in the statistical analysis (as I have noted above) which should be improved upon before Acceptance.*

On local scouring downstream small water structures

Marta Kiraga [Corresp., 1] , **Zbigniew Popek** [2]

[1] Department of Hydrotechnics and Technology, Institute of Civil Engineering, Warsaw University of Life Sciences WULS-SGGW, Warsaw, Poland

[2] Department of Water Engineering and Applied Geology, Institute of Environmental Engineering, Warsaw University of Life Sciences WULS-SGGW, Warsaw, Poland

Corresponding Author: Marta Kiraga
Email address: marta_kiraga@sggw.edu.pl

Background. In order to regulate the water flow hydraulic structures such as weirs or checks, frequently equipped with gates, are used. Water can flow below or over the gate or, simultaneously, over and below the gate. Both diversifications of hydraulic gradient, being an effect of damming up a river by the structure and shear stresses at the bed, which exceeds the critical shear stress value, invoke the local scouring downstream the structure. This phenomenon has been studied in laboratory and field conditions for many years, however Researchers do not agree on the parameters that affect the size of the local scour and the intensity of its formation. There are no universal methods for estimating its magnitude However, solutions are sought in the form of calculation formulas typical for the method of flow through the structure, taking into account the parameters that characterize a given structure. These formulas are based on factors that affect the size of the local scours, that is, their dimensions and location. Examples of such formulas are those contained in this article: Franke (1960), Straube (1963), Tarajmovič (1966), Rossinski & Kuzmin (1969) equations. The need to study this phenomenon results from the prevalence of hydrotechnical structures equipped with gates (from small gated checks to large weirs) and from potential damage that may be associated with excessive development of local erosion downstream, including washing of foundations and, consequently, loss of stability of the structure.

Methods. This study verifies empirical formulas applied to estimate the geometry parameters of a scour hole on a laboratory model of a structure where water is conducted downstream the gate with bottom reinforcements of various roughness. A specially designed remote-controlled measuring device, equipped with laser scanner, was applied to determine the shape of the sandy bottom. Then the formula optimization is conducted, using Monte Carlo sampling method, followed by verification of field conditions.

Results. The suitability of a specially designed device, equipped with laser scanner for measuring the bottom shape in laboratory conditions was demonstrated. Simple formula describing local scour geometry in laboratory conditions was derived basing on the Straube formula. The optimized formula was verified in field conditions giving very good comparative results. Therefore, it can be applied in engineering and designing practices.

1 **On local scouring downstream small water structures**
2
3 Marta Justyna Kiraga[1], Zbigniew Popek[2]
4
5 [1] Department of Hydrotechnics and Technology, Institute of Civil Engineering, Warsaw
6 University of Life Sciences WULS – SGGW, Warsaw, Poland
7 [2] Department of Water Engineering and Applied Geology, Institute of Environmental
8 Engineering, Warsaw University of Life Sciences WULS – SGGW, Poland
9
10 Corresponding Author:
11 Marta Justyna Kiraga
12 159 Nowoursynowska Str, Warsaw, 02-776, Warszawa
13 Email address: marta_kiraga@sggw.edu.pl
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40

Abstract

Background. In order to regulate the water flow hydraulic structures such as weirs or checks, frequently equipped with gates, are used. Water can flow below or over the gate or, simultaneously, over and below the gate. Both diversifications of hydraulic gradient, being an effect of damming up a river by the structure and shear stresses at the bed, which exceeds the critical shear stress value, invoke the local scouring downstream the structure. This phenomenon has been studied in laboratory and field conditions for many years, however Researchers do not agree on the parameters that affect the size of the local scour and the intensity of its formation. There are no universal methods for estimating its magnitude However, solutions are sought in the form of calculation formulas typical for the method of flow through the structure, taking into account the parameters that characterize a given structure. These formulas are based on factors that affect the size of the local scours, that is, their dimensions and location. Examples of such formulas are those contained in this article: Franke (1960), Straube (1963), Tarajmovič (1966), Rossinski & Kuzmin (1969) equations. The need to study this phenomenon results from the prevalence of hydrotechnical structures equipped with gates (from small gated checks to large weirs) and from potential damage that may be associated with excessive development of local erosion downstream, including washing of foundations and, consequently, loss of stability of the structure.

Methods. This study verifies empirical formulas applied to estimate the geometry parameters of a scour hole on a laboratory model of a structure where water is conducted downstream the gate with bottom reinforcements of various roughness. A specially designed remote-controlled measuring device, equipped with laser scanner, was applied to determine the shape of the sandy bottom. Then the formula optimization is conducted, using Monte Carlo sampling method, followed by verification of field conditions.

Results. The suitability of a specially designed device, equipped with laser scanner for measuring the bottom shape in laboratory conditions was demonstrated. Simple formula describing local scour geometry in laboratory conditions was derived basing on the Straube formula. The optimized formula was verified in field conditions giving very good comparative results. Therefore, it can be applied in engineering and designing practices.

Introduction

The article addresses the subject of hydraulic structures, understood as structures for water management, shaping water resources and water use (Chen 2015). The analyzed case is a damming structure i.e. a structure enabling permanent or periodical maintenance of a water surface level elevation above the adjacent land or body of water. There is a strong link between water and environment, as well as between water and development, both with opposite aims. While the willingness to develop and expand the hydrotechnical infrastructure is a drive for economic development and thus for urbanization to flourish, the environmental aspects direct the designer rather towards sustainable solutions (Koskinen, Leino & Riipinen 2008; Jordaan 2009; Rasekh, Afshar & Afshar 2010) and, as engineering practice demonstrated, to reject a project at

81   an early stage. It should be denoted that a failure of a hydrotechnical structure does not only
82   concern dams of significant sizes but also small hydraulic structures (usually not taken into
83   account by ecologists) which are a potential source of disaster, affecting the life and economy of
84   a given region (Hossain 1992; Lopardo & Seoane 2004).
85   There are many criteria in the design of hydraulic structures that must be optimized at the same
86   time. Construction, operating and maintenance costs, construction reliability, environmental
87   impact, social disruption and potential loss of life can be identified as one of the most noticeable
88   of a large number of criteria (Rasekh, Afshar & Afshar 2010). Therefore, a comprehensive
89   research on the environmental risk of hydrotechnical structures failure is necessary. One aspect
90   of this type of research is a proper recognition of hydraulic and morphodynamic processes that
91   accompany the construction of water structures using physical and mathematical models
92   (Lopardo & Seoane 2004; Syvitski et al. 2010).
93   Damming up rivers by implementation of a hydraulic structure unavoidably influences the
94   stream course and valley morphology. Upstream the structure, due to the water surface level
95   increment the water can flood the adjacent valley and the reservoir may form. Due to the cross-
96   section enhancement and, therefore, stream velocity reduction, sediment sedimentation and
97   accumulation may occur when the weight of the ground particles will outweigh the transport
98   capacity of the water stream (Graf 1989). Simultaneously, erosion can intensify downstream the
99   structure, especially in the case of very low water surface level and the stream velocity rapid
100 enhancement. The debris-free stream leaving the dammed structure, with additional kinetic
101 energy and increased turbulence, has a high eroding capacity (Szydłowski & Zima 2006;
102 Pagliara & Kurdinstani 2013; Zobeyer et al. 2010; Lee & Hong 2019). The effect of intensified
103 erosion, which takes place downstream the structure, is mainly local scouring and gradual
104 lowering of the bottom on an increasingly longer section of the river. The increased erosion of a
105 riverbed is unfavorable and undesirable not only due to slow degradation of the riverbed, but also
106 because of occurrence of rapid morphodynamic processes. It is commonly assumed that the most
107 intensive transformation of riverbeds takes place during catastrophic flooding when basic
108 hydrodynamic parameters of the stream increase many times. Excessive development of a scour
109 hole directly behind the structure, such as weir or sluice, poses a threat to its safety as it may lead
110 to washing away the foundation, embankments damages and loss of stability (Bajkowski,
111 Siwicki, Urbański 2002). Removing and repairing these undesirable effects is troublesome and
112 expensive. Therefore, technical solutions are needed to reduce scour hole dimensions.
113   Due to a focus on ecological changes in aquatic environment and the adjacent area in recent
114 decades, it is worth considering what environmental benefits of local scouring can be. In order to
115 specify them, it is necessary to identify this phenomenon more precisely i.e. to know the causes
116 of its occurrence, its characteristics and the process over time (Siwicki, Urbański 2004).
117   The specific character of the flow within a scour area is a certain diversity of conditions in
118 comparison with a river in its natural course. Stream velocity and associated physical forces
119 constitute the most important environmental factor affecting organisms living in watercourses
120 (Cullen 1991; Smith, Goodwin & Nestler 2014).

121   A significant reduction of stream velocity in a bottom local scour area leads to a specific flow
122   region formation named the wall-adjacent boundary layer. This layer can serve as a shelter for
123   organisms from turbulence and high water velocities. In well-developed scour holes, the near-
124   zero stream velocity in the wall-adjacent boundary layer can form local areas of still water
125   (Lupandin 2005; Liao & Cotel 2013; Hockley et al. 2013). The adaptation of fish to living in still
126   and flowing water has been extensively studied and it was found that one of the most important
127   environmental factors is the dissolved oxygen content of the water. The higher the stream
128   velocity and turbulence intensity, the more oxygenated the water is. Therefore, the water after
129   passing through the structure is aerated as evidenced by the measured increases in speed and
130   turbulence of the stream in the position downstream compared to the upper structure (Kobus &
131   Koschitzky 2014).
132   As a result of the process of sorting and armoring, i.e. washing out finer particles and leaving
133   thicker fractions at the bottom, the material is sorted on the scour hole bottom surface and a layer
134   made of thicker fractions is formed. These are the factors that determine the structure of the
135   velocity field at the bottom. This type of scouring process creates quite favourable environmental
136   conditions for many species of fish, i.e. a well aerated stream, thicker material on the bottom and
137   a smooth type of stream in the wall-adjacent boundary layer area (Siwicki, Urbański 2004;
138   Ochman & Kaszubkiewicz 2004; Hauer et al. 2018).
139   Local scouring in the aquatic environment may be particularly desirable during the season of
140   low dischagres. It can then serve as a reservoir in which particular species that require a certain
141   water depth, can survive. Lowering of the river bed may also be beneficial in the construction of
142   a fish pass. The inlet and outlet of fishponds must be submerged deep enough under the water
143   surface level, and this could be difficult in the structure stand downstream, where the depth of
144   the stream is normally lower than in upstream stand area (Siwicki, Urbański 2004). At the design
145   stage, it is important to develop a reliable forecast of a size, shape and position of the local scour,
146   both in dams and small hydraulic structures, such as gated checks, weirs or sluices.
147   Gated checks are small river training structures, applied for limiting channel incision, bed
148   stabilization, reducing flow velocity and raising upstream water level. These structures are often
149   used in channels where the adjustment of water level is required more frequently or where higher
150   cost compared to stop-logs, are justified (e.g. saving of labour). Gated checks are usually
151   equipped with hand-operated slide gates of various types, from simple wooden shutters to hand-
152   wheel operated adjustable orifice type gates (Kraatz & Mahajan 1975).
153   Although many studies on local scouring downstream hydraulic structures can be found in the
154   literature in the recent years (for example Sun, Wang & Wang 2012; Pagliara et al. 2016; Khaple
155   et al. 2017; Al-Husseini, Al-Madhhachi & Naser 2019; Singh, Devi & Kumar 2020; Li el al.
156   2020; Taha, El-Feky & Fathy 2020; Wang et al. 2020; Yan, Rennie, Mohammadian 2020),
157   among them only a few focus on small hydraulic structures (Lopardo & Seoane 2004; Kiraga &
158   Popek 2016; Odgaard 2017; Al-Suhaili, Abbood & Samir Saleh 2017; Kiraga & Popek 2018).
159   Especially gated checks are a rare object of research, which, given quite high prevalence of this
160   type of structures, determines the appropriateness of the undertaken subject.

161   In recent years, the role of small retention of valley areas was emphasized (Boix et al. 2012;
162   Mioduszewski 2014). A significant role in maintaining and increasing retention is played by
163   small water structures (Lopardo & Seoane 2004) whichare less popular in the research subject
164   matter than bridges or larger weirs with controlled closures.
165   It should also be noted that hydraulic instrumentation has advanced significantly, so
166   fundamental flow parameters or river bed shape can be measured with greater precision. For
167   instance, the PIV imaging anemometry system can be used to describe the distribution of
168   velocity fields in the area of water structure and the description of a bottom shape can be perform
169   using an echo sounder, e.g. fixed on a boat, or by laser scanning technique (Hager & Boes 2014;
170   Killinger 2014).
171   Most of the research samples in order to identify the factors influencing the amount of local
172   scouring to the greatest extent below water structures were carried out in laboratory conditions.
173   The following factors that influence a scour hole shape and location are:
174   -- related to the flume geometry (width, depth, bed inclination);
175   -- related to the type and geometry of the structure (type of structure, reinforcement construction,
176   dimensions of upstream and downstream part of the structure elements);
177   -- characterizing water flow conditions (flow rate, average speed, hydraulic gradient, bed shear
178   stress, flow resistance),
179   -- water properties (density, viscosity),
180   -- characterizing the flume material (grain size, grain distribution, density, porosity, roughness),
181   -- characterizing the conditions of sediment transport (critical velocity, critical shear stress,
182   sediment transport intensity),
183   -- time (Graf 1989; Breusers & Raudkivi 1991; Kiraga & Popek 2019).
184   In spite of many experimental works carried out under various constructional conditions and
185   high variability of hydraulic conditions, the universal principles of calculating the local scour
186   dimensions and transferring it to field conditions are still unknown. Solutions are sought,
187   involving different coefficients, which characterize a given construction, based on identified
188   factors that influence scour size and position (Franke 1960; Straube 1963; Tarajmovič 1966;
189   Rossinski & Kuzmin 1969). The formation and expansion of local scouring that results from
190   time-varying, two-phase movement of water and sediment is one of the most undiscovered
191   processes in hydrotechnical engineering (Graf 1998; Nouri Imamzadehei et al. 2016). Despite
192   numerous studies carried out since the first decades of last century (for example Lacey 1946;
193   Ahmad 1953; Breusers & Raudkivi 1991; Lenzi, Marion & Comiti 2003; Ben Meftah & Mossa
194   2006; Kiraga & Popek 2016; Pagliara et al. 2016; Kiraga & Popek 2018; Al-Husseini, Al-
195   Madhhachi & Naser 2019), there is no sufficient and unquestionable basis for the mathematical
196   description of the process of local erosion, and thus for a development of forecasts of scour holes
197   that will occur during the design of structures. Also, it is not always possible to predict fully
198   reliable estimation based on the results of laboratory tests, because in laboratories the researchers
199   are usually unable to lead to the occurrence of the so-called final scour, i.e. to a state in which the
200   extension of the duration of the experiment does not cause changes in the dimensions and

201 location of sandy bottom and banks (Chabert & Engeldinger 1956; Barbhuiya & Dey 2004).
202 Moreover, designers find it difficult to choose those that give reliable results. Due to the
203 diversity of applied constructions of structures and the variability of hydraulic conditions, it is
204 difficult to generalize the derived formulas (Graf, 1998; Barbhuiya & Dey 2004; Ben Meftah &
205 Mossa 2006).
206   The absence of a forecast of the effects of local erosion makes it impossible to rationally assess
207 the degree of safety and certainty of the use of a hydraulic structure, since the scour poses a
208 similar threat to the structure, such as insufficient structure capacity, too low structural stability
209 coefficient, ground strength exceeding, etc.
210   The complexity of a local scouring process means that only fragments of the problem are
211 usually examined with limited objectives, such as:
212   -- explanation of the influence of factors, e.g. the construction of downstream part of the
213 structure, length and roughness of the reinforcements, etc. (Rossinski & Kuzmin 1969; Al-
214 Mohammed, Jassin & Abbas 2019);
215   -- highlighting the effectiveness of various design solutions to prevent excessive erosion
216 (Epely-Chauvin, De Cesare & Schwindt 2015; Taha, El-Feky & Fathy 2020);
217   -- formulation of dependencies, formulas, etc. to determine scour forecasting for assumed
218 geometrical, hydraulic and ground conditions (Gaudio & Marion 2003; Kiraga & Popek 2019).
219   Additionally, the results of tests carried out in a laboratory are difficult to translate directly into
220 field conditions due to the scale effect (Farhoudi & Smith, 1985), whereas during field tests
221 problems result mainly from the lack of knowledge of the initial conditions, i.e. the shape of the
222 bottom before disturbing the existing dynamic balance in the channel (Lenzi, Marion & Comiti,
223 2003; Pagliara et al., 2016).
224   Researchers agree that regardless of a construction of ahydraulic structure, the depth of the
225 scour hole is influenced by length, roughness and height position of the fortifications
226 downstream. (Rossinski & Kuzmin 1969; Urbański 2008; Taha, El-Feky & Fathy 2020).
227 Difficulties in explaining and presenting the influence of factors on the process of scouring and
228 the lack of perspectives for establishing universal relations between the complicated flow system
229 and the sediment transport, lead to use simple, in fact intuitive, relationships that allow to
230 determine the depth of local scour.
231   The estimation of the maximal scour hole depth and the channel reach infested by extensive
232 erosion allows for a proper design of the downstream of hydraulic structure, ensuring safety and
233 stability, as well as reducing the construction and subsequent operation cost. Therefore, the
234 estimation of the geometry of forecasted scour should be an integral part of the design stage of
235 hydrotechnical structures (Brandimarte, Paron & Di Baldasarre, 2012; Prendergast & Gavin,
236 2014).
237   Difficulties of local scouring investigations result primarily from the multitude of factors
238 influencing its shape and dimensions. The following factors can be mentioned among them
239 (Franke 1960; Straube 1963; Tarajmovič 1966; Rossinski & Kuzmin 1969):

240   --relation to the flume or channel geometry (e.g. the Shalash and Franke, Müller, Tajarmovič
241   formula);
242   --relation to the type and geometry of the structure (e.g. the Rossinski formula);
243   --relation to water flow conditions, such as flow rate, average speed or flow resistance);
244   --water physical properties;
245   --relation to bed material (e.g. the Straube method).
246   This paper comprises the identification, verification and validation of chosen empirical
247   formulas: Shalash & Franke, Straube, Müller and Tarajmovič serving to estimate the scour
248   dimensions in local scour process forming due to damming up the flume by the gate, equipped
249   with downstream stage embankment. For formula optimization the Monte Carlo sampling
250   method was applied. Laboratory research was performed as a first part of the studies, then the
251   formula best describing flume experiment was verified in field conditions.
252
253   **Materials & Methods**
254   Research based on laboratory studies was performed in a 11-m long hydraulic flume with 0.58-
255   m width. No bed inclination downstream was introduced, however it should be noted that
256   lowland rivers that formed in alluvial depositions usually have gradients of 0.5 - 3%. If such a
257   slope were to be reproduced in the present laboratory conditions, the difference in elevation of
258   the bottom below the water structure would be 1 mm to a maximum of 1 cm.
259   Data were collected as previously described in the publication "Bed shear stress influence on
260   local scour geometry properties in various flume development conditions" in *Water* by Marta
261   Kiraga and Zbigniew Popek (2019). Specifically, the research assumed bed shape measurements
262   during local scouring formation, both using pin gauge, laser scanning of the surface and water
263   surface level examination in presumed hydraulic conditions. However, the examined flume
264   development differs from the mentioned publication in *Water*. Namely, two gated check models
265   assumed slide gate introduction, which was constantly raised to 5 cm of height to ensure
266   invariable flow area of 0.029 m^2 (Figure 1 a, b). In the vicinity of the damming structure, the
267   bottom was solid on the length of $L_1 = 0.30$ m upstream the gate and $L_2 = 0.80$ m downstream,
268   designed to imitate bed reinforcement typical for weirs or other river training structures, often
269   made of concrete or rip rap. The reinforcement downstream the check was made of plain slab
270   working as a reinforcement within the model I of flume development (Figure 2 a, 3 a) (4),
271   whereas model II assumed stone riprap reinforcement made of rocks (8) whose medium height
272   was 1.5 cm (Figure 2 b, 3 b). A scour hole formed inside a sandy part downstream the check with
273   a length L_3 of 2.20 m (2). The applied constructional solution of the model assumed
274   representation of water flow under a partially open valve of the gated check with lowered
275   reinforced bottom below with variable roughness where sediment transport takes place through
276   the gate – not held by any weir. According to Kraatz & Mahajan (1975) the length of the
277   reinforcement downstream the gated check should be ca. 1.5 times longer than the width of the
278   gate – and the model applied within present experiment ensure the elements' dimensions close to
279   this ratio.

280   Bottom shape was investigated at all flume lengths. After each measurement series, the sand in
281   the flume was dried for ca. 13 hours - the outflowing water was removed by using drainage pipe
282   (5 in Figure 2 a and b). The measurement schedule was similar as previously described in "Bed
283   shear stress influence on local scour geometry properties in various flume development
284   conditions" in *Water* by Marta Kiraga and Zbigniew Popek (2019). Namely, pin water gauges
285   were used in order to measure water surface elevation at the intake part and along the flume in
286   the central axis (1). The water surface level was regulated with an outlet gate (6). Before
287   introducing water into the flume and after draining the sand the final level of sandy bottom was
288   measured with a laser scanner (7) and with a moving disc probe (1) as a supportive device in
289   presumed time steps (0.5 – 2 h).
290   Before starting each measurement series and introducing water stream into the flume, the
291   sandy bed was uniformly adjusted to a constant level and compacted with load of 2.5 kg dropped
292   to the bed surface with an energy of about 5 J. Then, the position of the bottom was measured
293   with a disc probe with presumed mesh 5 x 7 cm to 20 x 10 cm both upstream and downstream
294   the hydraulic structure.
295   As described in "Bed shear stress influence on local scour geometry properties in various
296   flume development conditions" in *Water* by Marta Kiraga and Zbigniew Popek (2019) flume
297   side walls were made of glass with a roughness coefficient $n_w = 0.010$ s·m$^{-1/3}$. The soil used
298   during the study was uniform coarse sand with medium diameter $d_{50} = 0.91$ and $d_{95} = 1.2$ mm
299   and roughness coefficient $n_b = 0.028$ s·m$^{-1/3}$. Experiments were performed in the scope of steady
300   water flow discharge within the following range $Q_w = 0.010 – 0.045$ m^3·s, water depth
301   downstream the structure $h = 0.05 – 0.26$ m and Froude number $Fr <1$. 29 measurement series
302   were performed, each lasting 8 hours (9 measurement series on model I and 20 on model II)
303   (Table 1 and 2).
304   No sediment feeding system was adopted. Bedload transport conditions were assured by
305   specific set of hydraulic conditions that invokes particle movement from upstream towards
306   downstream. Therefore, the experiment was carried out in 'live-bed' conditions, where soil
307   leaving the scour hole is substituted by approaching load from the upstream. It is worthy to
308   notice that for typical lowland rivers both bedload load and suspended load are present in various
309   relations. For example, the suspended load constitutes 60-70% of the whole sediment load
310   transported by Vistula River in Poland and 50-90% of that is transported by its tributaries
311   (Lajczak 1996), although only bedload was investigated in this study.
312   A group of experiments carried out in a hydraulic laboratory, the results of which were
313   published, among others, in *Water* or *IEEE Access* journals (Kiraga and Popek 2016; Kiraga and
314   Popek 2019; Kiraga and Miszkowska 2020), concerned the phenomenon of formation of local
315   scouring as a result of not only varied roughness of the materials building the bed, but also the
316   restriction of the flow field by inserting a model of damming structures into the flume. Namely,
317   due to the flow resistance increment along the whole flume resulting from varied roughness of
318   solid and sandy bottom, the hydraulic gradient increases causing the intensification of shear
319   stress at the bottom. After exceeding the critical shear stress, the motion of sediment grains

320   starts, followed by gradual scouring of the bed. Maximal scour depth z_{max}, scour length L_s and
321   the distance between the deepest point of the hole and the end of reinforcement L_e were
322   examined (Figure 4) during each measurement.
323   In order to investigate the final scour shape both a device equipped with laser scanner and a disc
324   probe were applied as supportive devices. Data were collected as previously described in "Bed
325   shear stress influence on local scour geometry properties in various flume development conditions"
326   in *Water* by Marta Kiraga and Zbigniew Popek (2019). Prototype A1 of the device was engineered
327   in 2016 by Marta Kiraga and Matvey Razumnik within the university grant for young researchers
328   "The influence of small hydraulic structures on sediment transport conditions" (Kiraga et al. 2018).
329   Prototype A1 (Figure 5) is equipped with a laser rangefinder and automatic movement system
330   embedded on guides along the flume, scanning the bottom area with a demanded grid (every 1 mm
331   in case of present experiments). Grid density alteration possibility gives a far greater accuracy of
332   measurement than the disc probe. The use of the device ensures data transmission directly in digital
333   form, so that the coordinates can be easily processed to obtain the desired scour hole geometrical
334   parameters.
335   Laser scanning, also known as LiDAR (Light Detection and Ranging) is an active tele-detection
336   method which uses electromagnetic waves sent by the emitter. The result is point cloud with
337   coordinates (x, y, z) (Jaboyedoff et al. 2010; Killinger 2014). The measuring system (LiDAR)
338   consists mainly of a transmitter i.e. a module generating laser light (diodes), an optical telescope
339   focusing the returning reflected radiation and a detector converting light energy into an impulse
340   recorded in the module that records the acquired data.
341   The prototype's supporting elements are made of biodegradable polyactide (PLA) and are printed
342   on a 3D printer. Using Raspberry Pi microcomputer allows simultaneous computations and data
343   collecting by the beam. The device is fully automated which was achieved by the application of a
344   single board computer, dedicated software and the set of stepper motors, which results in
345   measurements repeatability, constant accuracy on demand and fast execution of results. The
346   obtained coordinates mesh is characterized by high resolution: 1 mm by 1 mm– therefore bottom
347   shape is described very precisely, both in numerical form and as a graphical tracing. Numerical
348   cloud can be easily transformed thence scour hole dimensions such as length or depth can be
349   estimated. LiDAR technology application in scour shape and its volume in flume experiments is
350   based on the introduction of an automatic measuring module which, placed above the bottom on a
351   specially prepared controllable system of guides, describes its shape by creating a point cloud.
352   Deriving from a statement that scouring process stops when stream velocity v is equal to non-
353   scouring velocity v_n Rossinski (Rossinski & Kuzmin 1969) stated that water depth above the
354   local scour can be calculated as:

$$H = z_{max} + h = k_1 \sqrt[1.2]{q/v_{n1}} \qquad (1)$$

355   where z_{max} is local scour depth, [m]; h is water elevation before scour formation (See Figure 4),
356   [m]; k_1 is a dimensionless coefficient, describing intensified turbulence of the stream, [-]; q is unit
357   discharge, [$m^3 \cdot s^{-1} \cdot m^{-1}$]; v_{n1} is non-scouring velocity for water depth of 1 m, depending to soil
358   properties, [$m^2 \cdot s^{-1}$] calculated as following:

$$v_{n1} = \sqrt{2g(\gamma_r - \gamma_w)/1.75\gamma_w} d_{50} log(8.8/d_{95}) \tag{2}$$

359 in which g is gravity acceleration, $g = 9.81$ m·s⁻²; γ_r and γ_w are specific weights, sediment and
360 water, respectively [N·m⁻³]; d_{50} and d_{95} are diameters that correspond to 50% and 95% of particles
361 finer than the reported particle size.
362   The k_1 value in the formula (1) is an empirical coefficient, dependent on downstream
363 development conditions. Based on practice experiences k_1 takes the value of 1.70 when the
364 reinforcement downstream the gate is not deepened and sheet piling, palisade or other vertical
365 securing element make an additional protection. Due to the stream energy enhancement in the
366 region of the gate outlet without any energy dissipating device local scouring process is intensified.
367 When transverse trench is dug downstream the reinforcement, of depth equal to the expected depth
368 of the scour; and the slope of this trench is no more than 1:4, then $k_1 = 1.05$ should be assumed
369 (Figure 6 a, b).
370   Experimental case is referred to the conditions when coarse sandy bed is preceded by deepened
371 reinforcement downstream (Figure 6 c) therefore, empirical studies on k_1 parameter were needed.
372   The difficulty of explaining and presenting the impact of factors influencing local scouring
373 process in large scale hydraulic structures with the lack of perspectives for establishing relations
374 between a complicated flow system and sediment transport, forces to apply simple, intuitive
375 relations allowing for the determination of the depth of scour holes. Scour length L_s and the
376 distance between the deepest point of the hole and the end of reinforcement L_e where the stream
377 comes out from under the gate were determined by several authors:
378 --According to Shalash and Franke (Franke 1960):

$$L_s \text{ and } L_e = f(z_{max}) \tag{3}$$
$$L_s = 11 \cdot z_{max} \tag{4}$$
$$L_e = 6.6 \cdot z_{max} \tag{5}$$

379 --According to Müller (Franke 1960; Straube 1963):
380

$$L_s \text{ and } L_e = f(z_{max}) \tag{6}$$
$$L_s = (9.9 \div 0.8) \cdot z_{max} \tag{7}$$
$$L_e = (4.9 \div 0.5) \cdot z_{max} \tag{8}$$
or $$L_s \text{ and } L_e = f(z_{max}, h) \tag{9}$$
$$L_s = (6.0 \div 1.22) \cdot (z_{max} + h) \tag{10}$$
$$L_e = (2.94 \div 0.59) \cdot (z_{max} + h) \tag{11}$$

381
382 --According to Straube (Straube 1963):
383

$$L_s = f(z_{max}, q, h, d_{50}) \tag{12}$$
$$L_s = 8.0q^{0.36}(z_{max} + h)d_{50}^{-0.14}h^{-0.40} \tag{13}$$
$$L_e = f(L_s, h, d_{50}) \tag{14}$$
$$L_e = 0.39L_s d_{50}^{0.12}h^{-0.12} \tag{15}$$

384   The formulas (3-15) are recommended for systems in which the outflow from the gate goes
385   directly onto unreinforced ground. For constructions equipped with reinforcement the
386   Tajarmovič formula is recommended (Tarajmovič 1966):

$$L_e = f(z_{max}) \tag{16}$$

$$L_e = 12.75 z_{max}^{0.5} \tag{17}$$

387   Monte-Carlo integration works by comparing random samples with the function value. Straube
388   equations can be described generally in the following forms:

$$L_s = aq^b(z_{max} + h)d_{50}^{-c}h^{-d} \tag{18}$$

$$L_e = kL_s d_{50}^{m}h^{-p} \tag{19}$$

389
390   where a, b, c, d, k, m, p are function parameters which were sampled in the following ranges:
391   -- $a \in <5.0, 8.0>$;
392   -- $b \in <0.24, 0.40>$;
393   -- $c \in <0.10, 0.20>$;
394   -- $d \in <0.35, 0.45>$;
395   -- $k \in <0.30, 0.60>$;
396   -- $m \in <0.01, 0.13>$;
397   -- $p \in <0.01, 0.20>$.
398   Using a random number generator in the assumed ranges of values, 6000 combinations of
399   parameters a, b, c, d for equation (18) and 6000 combinations of parameters k, m, p for equation
400   (19) were selected. The average relative error δ for all 29 series of measurements was chosen as a
401   criterion for evaluation of the formula described by a given combination of parameters.
402   The key to the accuracy and correctness of the Monte Carlo method is a random number
403   generator. The method presents a solution to a problem as a parameter of a hypothetical
404   population. Using a sequence of random numbers, it creates a population sample from which
405   estimated values of the sought parameters can be obtained (Niederreiter 1992).
406   Next step was to verify the optimized formula on independent measurement results published in
407   2010 by Gaudio and Marion, performed on a flume with sandy bottom with the hydraulic structure
408   represented by the cascade of transversal sills.
409
410   **Results**
411   Basic geometric parameters of observed scour during 29 measurement series, each characterized
412   by unit discharge q (9 on Model I and 20 on model II) are presented in Table 3 and 4. Non-
413   scouring velocity for water depth of 1 m v_{n1} in presumed grain conditions was equal to 0.502 m/s.
414   Maximal scour depth ranged from 1 to 10 cm. The criterion for the reach infested by the scour is
415   bed level, i.e. scour, is recognized within an area in which the depth of the bottom after 8-hour
416   measurement series exceeds 10% of the maximum hole depth (Kiraga and Miszkowska 2020).
417   Within the scope of the assumed measurement schedule each measurement series were carried
418   out with unique, within each model, variable combinations of input flow rate and water level.

419   However, by means of variability of those combinations, the same values of unit flow rate q (per
420   unit width) were obtained, which leads to a conclusion that in respect of unit flows, the
421   repeatability of the experiments was ensured. Moreover, during the laboratory tests it was
422   necessary to repeat some measurement series several times, e.g. due to faulty transfer of numerical
423   data from the microcomputer used, which made it possible to check the repeatability of test results.
424   The repetition of the tests was performed assuming the measurement series duration and under the
425   same hydraulic conditions. Differences in the bottom formation were shown, described by means
426   of basic geometrical parameters of the scouring in the range of 0.3 - 1.9% in the maximum depth
427   of the scour hole and 2.2-4% in the range of the average depth of the scour, which indicates high
428   repeatability of test results (Figure 7 a, b, c). Slightly more significant deviation was connected
429   with scour parameters connected with its length: relative error ranging within 0.5 – 13.6% was met
430   in total scour length and 3.0 – 16.6% in the case of the distance from the end of reinforcement to
431   the deepest scour point.
432   The Rossinski formula (1) parameters were identified for investigated test stand due to lack of
433   the present gate check structure construction analyses so far. Parameters identification was
434   performed on the basis of mean relative error δ between observed scour depth and calculations
435   results (Parameter k_1 was tested in the range 0.00 to 2.00. With k_1 equal to 1.10, the mean relative
436   error reached the minimum value. For the entire tested range of $k1$ values, errors in the range of 15
437   - 100% were achieved (Figure 8).
438   Parameters of 4,5; 7,8; 10,11; 13; 15 and 17 formulas were verified for two models of gated
439   check development. Calculated parameters of observed scour were examined in comparison with
440   the measured ones. The criterion of comparison evaluation was mean relative error of each scour
441   parameter estimation δ (Table 5) calculated for each group of 29 measurements.
442   The limitation in determining the range of a scour hole was the length of sandy part (bottom
443   edge) L_3, which was 2.20 m. In field studies, the length is long enough for the full scour length
444   development – there is no sandy bed length limitation. As mentioned above, the field of the scour
445   was considered to be an area where the bottom lowering exceeded 10% of its maximum depth in
446   presumed time step (Figure 9). If another criterion was to be adopted, for example, a consideration
447   of the scour hole area within the region where a bottom lowering exceeds 15 or more % of the
448   maximum scour depth, a limiting effect of the sandy bottom downstream the structure could be
449   avoided in some measurement series.
450   Investigated equations were divided into two groups:
451   -- simple formulas based only on maximal local scour depth z_{max} or on z_{max} and water depth h
452   before scour formation (Eq. 4, 7, 10 for total scour length estimation and Eq. 5, 8, 11, 17 for the
453   distance between the deepest point of scour and the end of reinforcement estimation)
454   -- formulas involving not only local scour hole depth z_{max} and the depth of water above the
455   unwashed bottom h, but also grain characteristics, represented by d_{50} diameter and hydraulic
456   parameter, i.e. unit water discharge q (the Straube formula – Eq. 13, 15)
457   Formulas that depend only on the local scour hole depth z_{max} (Shalash and Franke – Eq. 4, 5;
458   Müller – Eq. 7, 8) or on the local scour hole depth z_{max} and the depth of water above the unwashed

459   bottom h (Müller – Eq. 10, 11) demonstrated mean relative error of 56.9-72.8% in the scope of
460   total scour length L_s and 38.3-57.0% for the distance between the deepest point of scour and the
461   end of reinforcement L_e. The Tajarmovič equation (Eq. 17) indicates a 392.7% error. Medium
462   relative error for simple formulas (4,7,10) was equal to 66.5% and for formulas (5,8,11 and 17)
463   was equal to 133.3%.
464   Calculations using the formula, involving not only local scour hole depth z_{max} and the depth of
465   water above the unwashed bottom h, but also grain characteristics, represented by d_{50} diameter and
466   hydraulic parameter, i.e. unit water discharge q (the Straube formula – Eq. 13, 15) provide the best
467   fit to the measurement data. The relative error was 34.2 % for total scour length and 32.1% for the
468   distance between the deepest point of scour and the end of reinforcement. The Figures 10 and 11
469   demonstrate the results of calculations in relation to the measured values.
470   One combination of parameters a, b, c, d and one combination of parameters k, m, p were
471   selected basing on the presumed criteria: the formulas described by these parameters were
472   characterized by the lowest average relative error δ for all 29 test series. The best data explanation
473   for laboratory database of I and II model was achieved in the following parameters values: $a =$
474   7.41; $b = 0.38$; $c = -0.10$; $d = -0.45$; $k = 0.34$; $m = 0.01$; $p = -0.01$, thence the identified formulas,
475   can be described as:

$$L_s = 7.41q^{0.38}(z_{max} + h)d_{50}^{-0.10}h^{-0.45} \qquad (20)$$

$$L_e = 0.34L_s d_{50}^{0.01}h^{-0.01} \qquad (21)$$

476   Optimization revealed a diminished error, both in the case of total scour length L_s (10.1%) and
477   for the distance between the deepest point of scour and the end of reinforcement L_e (18.2%).
478   Verification of the optimized Straube formula was performed on independent data published in
479   2010 by Gaudio and Marion. In 1998, research was carried out in the Wallingford Ltd., a hydraulic
480   laboratory, on the evolution of local scouring downstream the bed sills cascade. The flume consists
481   of a 60 cm-wide, 24.5 cm-high and 5.57-m working section with rectangular cross-section. For the
482   full description of the duct, see Gaudio, Marion (2003). The bed sills used in all experiments were
483   25 mm-thick by 15 cm-high wooden plates, with the same width as the transversal section. The
484   sediment used in all tests was sand with median diameter $d_{50} = 1.8$ mm. No sediment recirculating
485   system was adopted.
486   The similarity of Gaudio and Marion test stand and the flume, where present research was
487   performed, come down to used bed material (sand), the shape of the flume (rectangular, 60-cm
488   width), the same order or magnitude of unit discharges and the transversal type of water structure.
489   The main difference is duration of each experimental series: in Gaudio and Marion, experiment
490   series last much longer than the present one: from 45 to 90 hours. Gaudio carried out 12 series of
491   measurements in order to obtain the geometric dimensions of local scour holes formed under given
492   hydraulic conditions. The maximal depth z_{max} and the total length of the scour L_s was studied. The
493   hydraulic parameters of each measurement series and the geometric properties of the local scour
494   are summarized in Table 6. Based on the results received, Straube formula was verified in its
495   original and optimized in form by Monte Carlo sampling procedure (Eq. 13 and 20). A mean
496   relative error $\delta = 49.2\%$ was obtained for the original form, whereas the application of the

497   optimized Straube formula demonstrated a better description of the data obtained in the laboratory,
498   characterized by an error mean relative δ equal to 18.1%.
499
500   **Discussion**
501   The optimized Straube formula demonstrated very accurate laboratory dataset description, whereas
502   the remaining equations analysis showed a relative error ranging up to more than 390%. The
503   Straube equations forms, which have been optimized for the laboratory workstation, have been
504   validated for field data. Zagożdżonka River in Czarna (Poland) was built in the fifties of last
505   century as a concrete hydraulic structure to store up the water and to use its energy to drive the mill
506   wheel. The total width of the spill is divided by I-beam guides into 3 clear spans: 1.16 m wide
507   outermost spans and 1.22 m center span (Figure 12 a, b). In the guides, a measuring sharp-crested
508   triangular weir was installed. The height and shape of the weir edges were developed to ensure
509   non-submergence weir working conditions at the highest possible flow rates.
510   The downstream part of the structure consists of 8.80 m long concrete reinforcement with a
511   longitudinal slope of 1%, followed by a 0.60 m drop, so it could be recognized as similar to
512   laboratory condition test models. The river bed, directly below the drop, is partially covered with a
513   stone riprap over on a reach of about 1.0 m, and in a further section it is scourable, made of sand,
514   with d_{50} diameter of 0.42 mm and d_{90} diameter of 0.74 mm.
515   On June 11 2013, a flood occurred. The flow rate in the hydrograph peak reached 5.06 m^{3}s^{-1}.
516   This event resulted in local scour formation downstream the weir, whose dimensions were
517   measured, analyzed and published by Urbański and Hejduk (14). Field measurements performed
518   the following local scour dimensions:
519   -- water depth above the deepest scour point $H_{max} = z_{max} + h = 2.43$ m;
520   -- local scour length $L_s = 13.8$ m;
521   -- the distance between the deepest point of scour and the end of reinforcement $L_e = 5.20$ m.
522   In the case of water depth H_{max} calculations an error of 39.5% was achieved using the Rossinski
523   formula with a k_1 parameter equal to 1.70 (Eq.1) (Table 7). The best fit of the measurement and
524   calculations was obtained for Müller equations, where measured scour length and the distance
525   between the deepest point of scour from the end of reinforcement rare within the ranges described
526   in equations no. 8 and 10 (an error of 0%). In the case of default form of Straube equations, 57.2 %
527   of an error was achieved for scour length L_s analysis and 7.7 % for the L_e distance.
528   An optimized form of Straube equations (20), (21) were checked on the field measurements.
529   Calculations using the Straube's optimized formula showed excellent adherence for the measured
530   and calculated value of the local bottom scour length (an error equal to 0.2%). However, the
531   distance of the maximum hole depth from the end of the reinforcement was underestimated and the
532   underestimation amounted to 16.6% of this value. A common observation for laboratory and field
533   tests is the overestimation of both parameters using the Tajarmovič formula.
534
535   **Conclusions**

536   Two gated check models were investigated in water discharge flowing out from under the gate,
537   characterized by different roughness of the reinforcement downstream, followed by scourable bed.
538   29 measurement series were performed in total, each lasting 8 hours. The basic geometrical
539   parameters of local scour hole, resulting from the disturbance of hydrodynamic balance of the
540   system were examined using autonomic remote-controlled measuring unit. The construction of the
541   tested models was chosen due to the prevalence of such solutions among real objects.
542   10 computational formulas, used for many years in the water engineering practice, were verified
543   for laboratory data. It was stated that functions based only on one (z_{max}) or two (z_{max}, h) parameters
544   provide weaker adjustment between calculations results and laboratory measurements. The
545   Straube's formula, assuming that geometric parameters follow up on not only maximal scour depth
546   and water level, but also granulometric parameters, represented by medium grain diameter d_{50} and
547   hydraulic properties of experiment, such as unit discharge q was distinguished as the best
548   description of laboratory test results.
549   The Straube function demonstrated the mean relative error of 34.2% in the case of comparing the
550   measurement and calculation result of the local scour depth and an error of 32.1% for the distance
551   of the deepest point from the end of the reinforcement, while medium error for all the rest of
552   formulas was 67% for L_s and 133% for L_e.
553   The Monte Carlo sampling method allowed the original formulas to be adapted to calculate the
554   local scour geometrical parameters downstream the model of the gated check. In optimizing the
555   parameters, the criterion of minimizing the relative error was applied. The Monte Carlo sampling
556   procedure resulted in a much better match between the calculation results and the dimensions
557   measured in the laboratory: Straube function optimized in this way demonstrated an error of 10.1%
558   in the case of comparing the measurement and the calculation of the local scour length and an error
559   of 18.2% for the distance of the deepest point from the end of the reinforcement.
560   The Straube's formula, chosen as the best describing laboratory results, was verified on
561   independent dataset, whose main features in common with present experiment characteristics are:
562   used bed material (sand), the shape of the flume, the same order or magnitude of unit discharges
563   and the transversal type of water structure. A mean relative error $\delta = 49.2\%$ was obtained for the
564   original form of the Straube formula, and 18.1% for optimized formula using the Monte Carlo
565   sampling method. Due to the data availability, only the total length of the scour was compared.
566   The optimized for laboratory measurements equation was checked for the real object, which was
567   selected on the basis of the similarity of the downstream reinforcement, and of the data availability.
568   It should be emphasized that field measurements of the bottom shape after the formation of local
569   scour hole are often difficult to access due to the imperfection of measuring instruments and lack
570   of data before the formation of a local scour. The optimization led to obtain an error of 0.2% for
571   scour length and an error of 16.6% for the distance of the deepest point from the end of the
572   reinforcement.
573   The extension of the optimized Straube formula verification to other hydro-technical field
574   objects is necessary for the applicability of the investigation, however it has to be stated that very

575 high degree of adjustment of calculation results to field data (especially local scour length) provide
576 an encouraging premise for further research.
577
578 **Acknowledgements**

584 **References**
585

586 Ahmad M. 1953. Experiments on design and behaviour of spur-dikes. *Minnesota International
587 Hydraulics Convention Proceedings*: 145-159
588 Al-Husseini TR, Al-Madhhachi AST, & Naser ZA. 2019. Laboratory experiments and numerical
589 model of local scour around submerged sharp crested weirs. *Journal of King Saud University -
590 Engineering Sciences*: 1 - 10 DOI: 10.1016/j.jksues.2019.01.001.
591 Al-Mohammed FM, Jassim AT, Abbass HA. 2019. An experimental and numerical study of
592 factors influencing the scour due to the collision of water jet in stilling basin floor. *Kufa Journal
593 of Engineering* 10(2): 42 – 59 DOI: 10.30572/2018/kje/100204.
594 AL-Suhaili RH, Abbood DW, Samir Saleh M. 2017. Optimum dimensions of hydraulic
595 structures and foundation using genetic algorithm coupled with artificial neural network. *Journal
596 of Engineering* 9(23): 1-22 DOI: 10.13140/RG.2.2.18186.77765.
597 Bajkowski S, Siwicki P, Urbański J. 2002. Utilization of laboratory investigations of local scour
598 below water structures to estimate their safety. *Acta Scientiarum Polonorum Seria Architectura*
599 1:41-51.
600 Barbhuiya AK, Dey S. 2004. Local scour at abutments: A review. *Sadhana* 29: 449-476.
601 Ben Meftah M, Mossa M. 2006. Scour holes downstream of bed sills in low-gradient channels.
602 *Journal of Hydraulic Resources* 44:497–509 DOI: 10.1080/00221686.2006.9521701.
603 Boix D, Biggs J, Céréghino R, Hull AP, Kalettka T, Oertli B. 2012. Pond research and
604 management in Europe: "Small is Beautiful." *Hydrobiologia* 689(1): 1–9 DOI: 10.1007/s10750-
605 012-1015-2.
606 Brandimarte L, Paron D, Di Baldasarre D. 2012. Bridge pier scour: A review of processes,
607 measurements and estimates. *Environmental Engineering and Management Journal* 11: 975-989
608 DOI: 10.30638/eemj.2012.121.
609 Breusers HC, Raudkivi AJ. 1991. *Scouring: Hydraulic Structures Design Manual Series* Vol 2.
610 London: Taylor & Francis.
611 Chabert J, Engeldinger P. 1956. Etude des affouillements autour des piles des ponts. Study on
612 scour around bridge piers. Chatou: Laboratoire National d'Hydraulique.

613   Chen SH. 2015. Planning and design of hydraulic projects. In: Chen SH, ed. *Hydraulic*
614   *Structures*. Berlin: Springer, 41–93 DOI: 10.1007/978-3-662-47331-3_2.
615   Cullen RT. 1991. Vortex mechanisms of local scour at model fishrocks. *Fisheries*
616   *Bioengineering Symposium: American Fisheries Society Symposium* 10: 213:218.
617   Epely-Chauvin G, De Cesare G & Schwindt S. 2014. Numerical modelling of plunge pool scour
618   evolution in non-cohesive sediments. *Engineering Applications of Computational Fluid*
619   *Mechanics* 8(4): 477–487 DOI: 10.1080/19942060.2014.11083301.
620   Farhoudi J, Smith KV. 1985. Time scale for scour downstream of hydraulic jump. *Journal of*
621   *Hydraulic Resources* 23:343–358.
622   Franke PG. 1960. *Über Kolkbindung und Kolkformen*. Östereeichische Wasserwirtschaf 1.
623   Gaudio R, Marion A. 2003. Time evolution of scouring downstream of bed sills. *Journal of*
624   *Hydraulic Research* 41(3): 271–284 DOI: 10.1080/00221680309499972.
625   Graf WH. 1998. *Fluvial hydraulics*. Chichester: John Wiley & Sons Ltd, 611–645.
626   Hauer C, Leitner P, Unfer G, Pulg U, Habersack H, Graf W. 2018. The role of sediment and
627   sediment dynamics in the aquatic environment. In: Schmutz S, Sendzimir J, eds. *Riverine*
628   *Ecosystem Management. Aquatic Ecology Series* 8. Cham: Springer, 151-169 DOI: 10.1007/978-
629   3-319-73250-3_8.
630   Hockley F, Wilson C, Brew A, Cable J. 2013. Fish responses to flow velocity and turbulence in
631   relation to size, sex and parasite load. *Journal of The Royal Society Interface* 11: 20130814.
632   Hossain GMA. 1992. Diagnostic study of failures of hydraulic structures in Bagladesh – case
633   studies of failures in Chattagong district. M. Sc. Thesis, Bangladesh University of Engineering
634   and Technology.
635   Jaboyedoff M, Oppikofer T, Abellán A, Derron MH, Loye A, Metzger R, Pedrazzini A. 2010.
636   Use of LIDAR in landslide investigations: a review. *Natural Hazards* 61(1): 5–28 DOI:
637   10.1007/s11069-010-9634-2
638   Jordaan JM. 2009. Design of sustainable hydraulic structures. In: Jordan JM, Bell A, eds.
639   *Hydraulic structures, Equipment and Water Data Acquisition systems*. Vol. II. Oxford: Eolss
640   Publishers Company Limited, 163 – 178.
641   Khaple S, Hanmaiahgari PR, Gaudio R, Dey S. 2017. Splitter plate as a flow-altering pier scour
642   countermeasure. *Acta Geophysica* 65(5): 957–975 DOI: 10.1007/s11600-017-0084-z.
643   Killinger DK. 2014. Lidar (light detection and ranging). *Laser Spectroscopy for Sensing* 10: 292–
644   312 DOI: 10.1533/9780857098733.2.292.
645   Kiraga M., Popek Z. 2016. Using a modified Lane's relation in local bed scouring studies in the
646   laboratory channel. *Water* 8: 16. https://doi.org/10.3390/w8010016.
647   Kiraga MJ, Razumnik M, Popek Z, Chmielewski L. 2018. Applying laser scanning technology to
648   studying alluvial flume-bed topography in laboratory conditions. *Acta Scientiarum Polonorum*
649   *Formatio Circumiectus* 17:69–84.
650   Kiraga M., Popek Z. 2018. Geometry description of local scouring process in various laboratory
651   water structure models. In: Kalinowska M, Mrokowska M, Rowiński P, eds. *Free Surface Flows*

652 *and Transport Processes. GeoPlanet: Earth and Planetary Sciences.* Cham: Springer, 245-258
653 DOI: 10.1007/978-3-319-70914-7_15.
654 Kiraga M., Popek Z. 2019. Bed shear stress influence on local scour geometry properties in various
655 flume development conditions. *Water* 11: 2346 DOI: 10.3390/w11112346.
656 Kiraga M., Miszkowska A. 2020. Lane's relation in local scour investigations. *IEEE Access* 8:
657 146967 – 146975 DOI: 10.1109/ACCESS.2020.3013275
658 Kobus H, Koschitzky HP. 1991. Local Surface aeration at hydraulic structures. In: Wood IR, ed.
659 *Air entrainment in free-surface flows. IAHR Hydraulic Structures Design Manual*, Rotterdam:
660 A.A. Balkema, 29-54.
661 Koskinen K, Leino T, Riipinen H. 2008. Sustainable development with water hydraulics–
662 possibilities and challenges. *Proceedings of the JFPS International Symposium on Fluid Power*
663 *2008*:11-18 DOI: 10.5739/isfp.2008.11.
664 Kraatz DB, Mahajan IK. 1975. *Small hydraulic structures*. Rome: Food and Agriculture
665 Organization of the United Nations, 32.
666 Lacey G. 1946. A general theory of flow in Alluvium. *Journal of the Institution of Civil*
667 *Engineers* 27(1): 16-47 DOI: 10.1680/ijoti.1946.13786.
668 Lajczak A. 1996. Reservoir sedimentation problems in the Vistula River basin, Poland. *Erosion*
669 *and Sediment Yield: Global and Regional Perspectives (Proceedings of the Exeter Symposium,*
670 *July 1996). IAHS Publication* 236:501 – 511.
671 Lee SO, Hong SH. 2019. Turbulence characteristics before and after scour upstream of a scaled-
672 down bridge pier model. *Water* 11(9): 1900 DOI: 10.3390/w11091900.
673 Lenzi MZ, Marion A., Comiti F. 2003. Local scouring at grade-control structures in alluvial
674 mountain rivers. *Water Resources Research* 39: 1176–1188 DOI: 10.1029/2002WR001815.
675 Li H, Li H, Jin P, Yang Y. 2020. Flexible flow deflectors against local scour at bridge piers. *IOP*
676 *Conference Series: Materials Science and Engineering* 768: 032018 DOI: 10.1088/1757-
677 899x/768/3/032018.
678 Liao JC, Cotel A. 2013. Effects of turbulence on fish swimming in aquaculture. In: Palstra AP,
679 Planas JV, eds. *Swimming physiology of fish: towards using exercise to farm a fit fish in*
680 *sustainable aquaculture*. Berlin: Springer-Verlag, 109 – 127 DOI: 10.1007/978-3-642-31049-
681 2_5.
682 Lopardo RA, Seoane R. 2004. Floods control in Argentina: learning from the experience. In:
683 Greco M, Carravetta A, Della Morte R, eds. *River Flow 2004*. London: Taylor & Francis Group,
684 1403-1409.
685 Lupandin AI. 2005. Effect of flow turbulence on swimming speed of fish. *Bulletin of the Russian*
686 *Academy of Sciences* 32: 461–466 DOI:10.1007/s10525-005-0125-z.
687 Mioduszewski W. 2014. Small (natural) water retention in rural areas. *Journal of Water and*
688 *Land Development* 20(I-III): 19-29.
689 Niederreiter H. 1992. *Random number generation and quasi-Monte Carlo methods*. Philadelphia,
690 USA: Society for Industrial and Applied Mathematics, 1–12.

691   Nouri Imamzadehei A, Heidarpour M, Nouri Imamzadehei M, Ghorbani B, Haghiabi A. 2016.
692   Control of the local lcouring sround the cylindrical bridge pier using armed soil by geotextile.
693   International Journal of Geosynthetics and Ground Engineering 2(5): 1-8 DOI:
694   10.1007/s40891-016-0045-7.
695   Ochman D, Kaszubkiewicz J. 2004. Change of water oxygenation state in the vicinity of dam
696   plants on the Smortawa river example. *Quarterly of Environmental Engineering and Design* 131:
697   287-293.
698   Odgaard AJ. 2017. River management with submerged vanes. In: Sharma N, ed. *River System*
699   *Analysis and Management.* Singapore: Springer Nature, 251 - 262 DOI: 10.1007/978-981-10-
700   1472-7_13.
701   Pagliara S, Kurdistani SM. 2013. Scour downstream of cross-vane structures, *Journal of Hydro-*
702   *environment Research* 7(4): 236–242 DOI: 10.1016/j.jher.2013.02.002.
703   Pagliara S, Radecki-Pawlik A, Palermo M, Plesiński K. 2016. Block ramps in curved rivers:
704   morphology analysis and prototype data supported design criteria for mild bed slopes. *River*
705   *Resources and Applications* 33: 427–437 DOI: 10.1002/rra.
706   Prendergast LJ, Gavin K. 2014. A review of bridge scour monitoring techniques. *Journal of Rock*
707   *Mechanics and Geotechnical Engineering* 6:138–149 DOI: 10.1016/j.jrmge.2014.01.007.
708   Rasekh A, Afshar A, Afshar MH. 2010. Risk-cost optimization of hydraulic structures:
709   methodology and case study. *Water Resources Management* 24(11): 2833–2851 DOI:
710   10.1007/s11269-010-9582-3.
711   Rossinski KI, Kuzmin IA. 1969. Opyt projektirovanija miestnych razmyvov v niżnich bjefach
712   gidrouzlov. In: *Rabota niżnich bjefov gidrotechničeskich sooruženij.* Moskva: Kolos.
713   Singh NB, Devi TT, Kumar B. 2020. The local scour around bridge piers—a review of remedial
714   techniques. *ISH Journal of Hydraulic Engineering*, 1–14 DOI:
715   10.1080/09715010.2020.1752830.
716   Siwicki P, Urbański J. 2004. Local scour below water structures and their influence on
717   environment. *Acta Scientiarum Polonorum. Architectura* 3(2): 113-120.
718   Smith DL, Goodwin RA, Nestler JM. 2014. Relating turbulence and fish habitat: a new approach
719   for management and research. *Reviews in Fisheries Science & Aquaculture* 22(2): 123–130 DOI:
720   10.1080/10641262.2013.803516.
721   Straube C. 1963. Die Kolkbindung hinter underströmten Wehren. In: *Mitteilungen der*
722   *Firschunsanstalt für Schiffahrt.* Berlin: Wasser und Grundbau.
723   Sun DP, Wang LS, Wang PT. 2012. Study on the local scouring of the bridge with sediment
724   control dam. *Applied Mechanics and Materials* 204-208: 2230–2235 DOI:
725   10.4028/www.scientific.net/amm.204-208.2230.
726   Syvitski J, Slingerland R, Burgess P, Meiburg E & Murray AB, Wiberg P, Tucker G, Voinov A.
727   2010. Morphodynamic models: an overview. *River, Coastal and Estuarine Morphodynamics,*
728   *RCEM 2009:* 3-20.

729 Szydłowski M, Zima P. 2006. Two-dimensional vertical Reynolds-averaged Navier-Stokes
730 equations versus one-dimensional Saint-Venant model for rapidly varied open channel water
731 flow modelling. Archives of hydro-Engineering and Environmental Mechanics 53(4): 295-309.
732 Ślizowski R, Radecki-Pawlik A. 2003. Verification of formulae for calculating scour below
733 hydraulic structure using laboratory results. *Acta Scientiarum Poonorum Formatio Circumiectus*
734 2:25–34.
735 Taha N, El-Feky MM, El-Saiad AA & Fathy I. 2020. Numerical investigation of scour
736 characteristics downstream of blocked culverts. *Alexandria Engineering Journal* 1-11 DOI:
737 10.1016/j.aej.2020.05.032.
738 Tarajmovič II. 1966. *Krieplenije v niżniem bjefie vodoslivnych plotin*. Moskva: Energija.
739 Urbański J. 2008. Influence of roughness of bed protection downstream of weir on local scour.
740 *Scientific Review – Engineering and Environmental Sciences* 2(40): 169-177.
741 Urbański J, Hejduk L. 2014. Analysis of sizes of local scour as a result of flood. *Monografie*
742 *komitetu gospodarki wodnej PAN* XX: 389–400.
743 Wang L, Melville BW, Shamseldin AY & Nie R. 2020. Impacts of bridge piers on scour at
744 downstream river training structures: submerged weir as an example. *Water Resources Research:*
745 e2019WR026720 DOI: 10.1029/2019wr026720
746 Yan X, Rennie CD, Mohammadian A. 2020. Numerical modeling of local scour at a submerged
747 weir with a downstream slope using a coupled moving-mesh and masked-element approach.
748 *International Journal of Sediment Research* DOI: 10.1016/j.ijsrc.2020.06.007
749 Zobeyer H, Jahan N, Islam Z, Singh G, Rajaratnam N. 2010. Turbulence characteristics of the
750 transition region from hydraulic jump to open channel flow. *Journal of Hydraulic Research*
751 48(3): 395 – 399 DOI: 10.1080/00221681003726320.

Figure 1

Gated check details

(a) – model I (gated check without additional roughness downstream); (b) – model II (gated check with additional roughness downstream).

PeerJ

a)

0.05 m
0.05 m

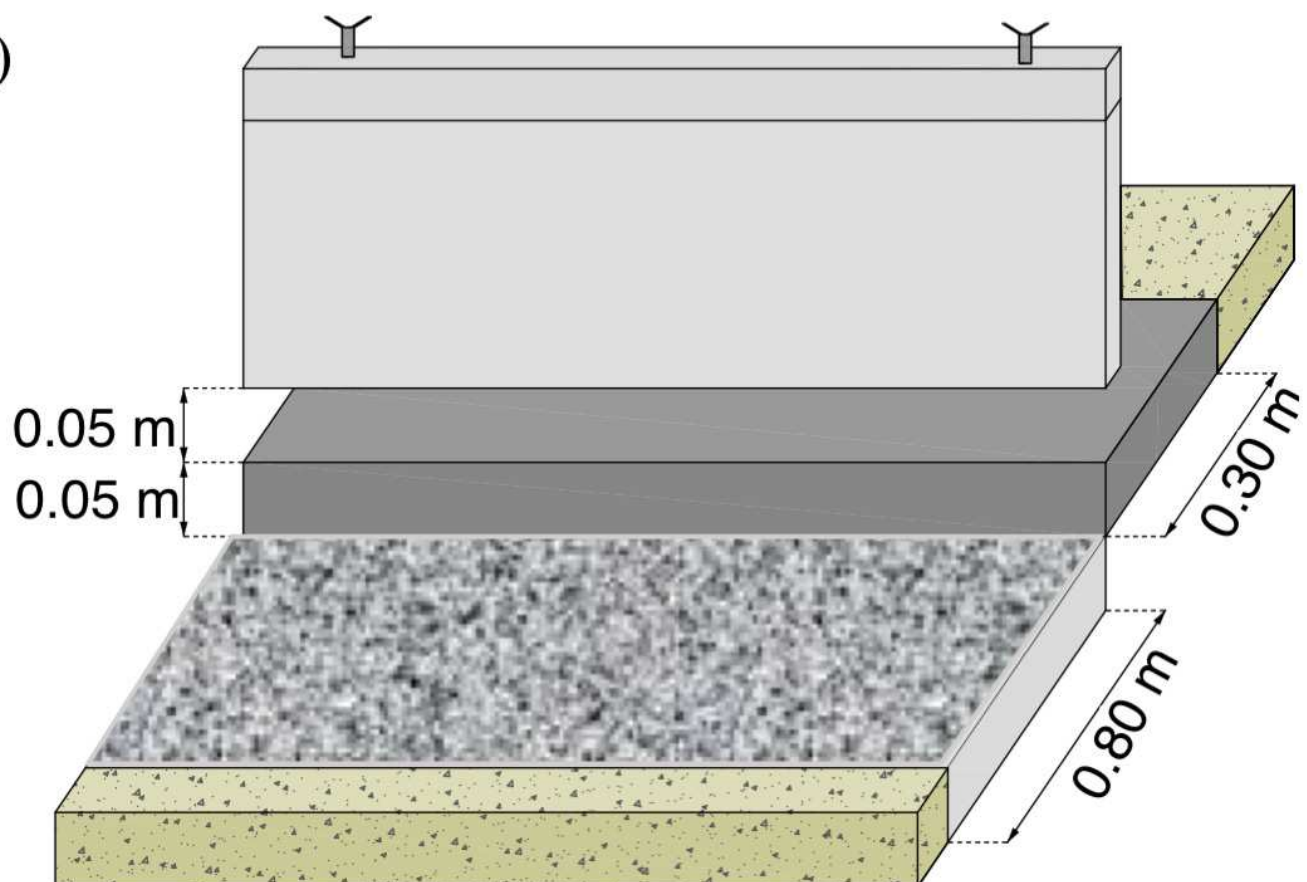0.30 m

0.80 m

b)

0.05 m
0.05 m

0.30 m

0.80 m
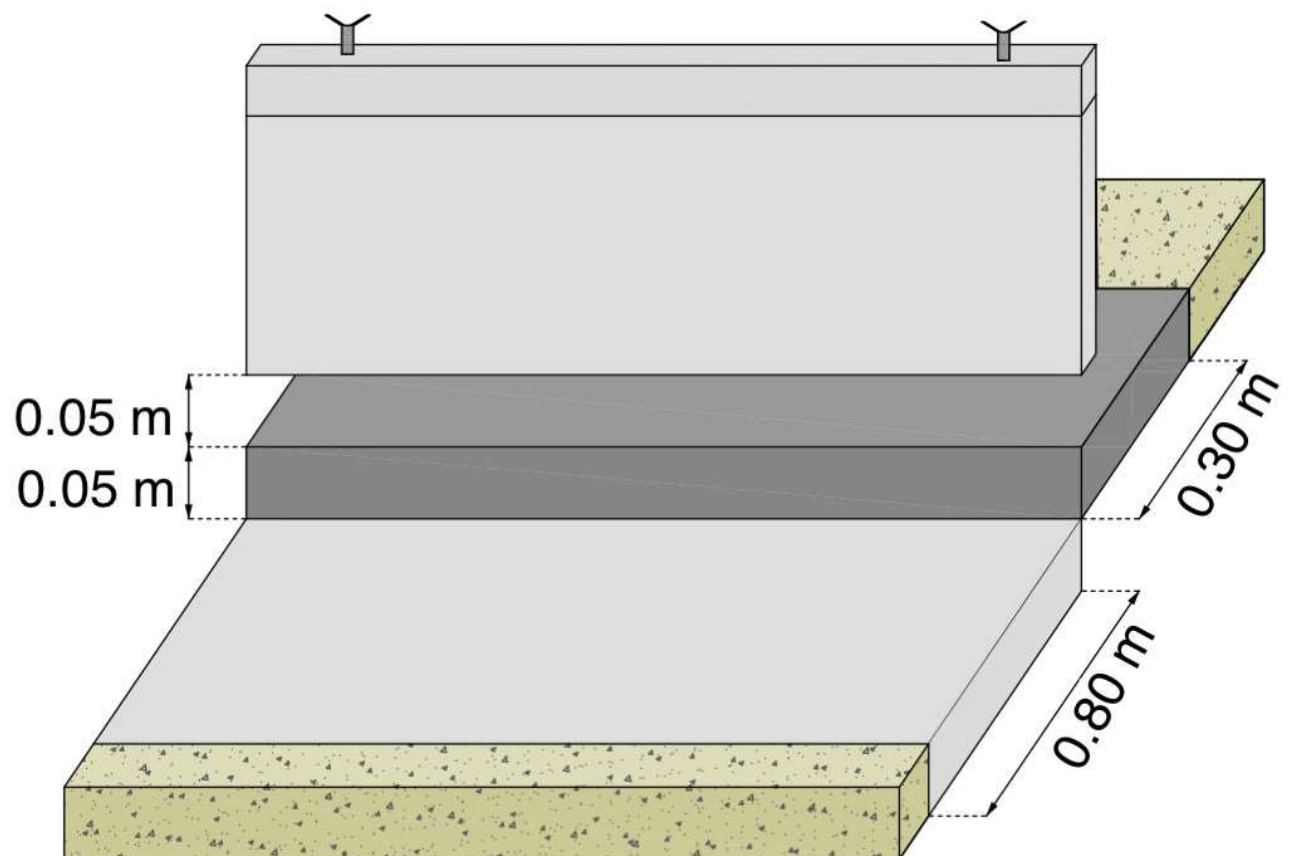
Figure 2

Laboratory test stand

(a) – model I (gated check without additional roughness); (b) – model II (gated check with additional roughness), where: 1 – movable pin gauge equipped with disc probe; 2 – sandy bed; 3 – gate; 4 – reinforcement; 5 – drainage; 6 – outlet gate; 7 – laser scanner; 8 – reinforcement with additional roughness.
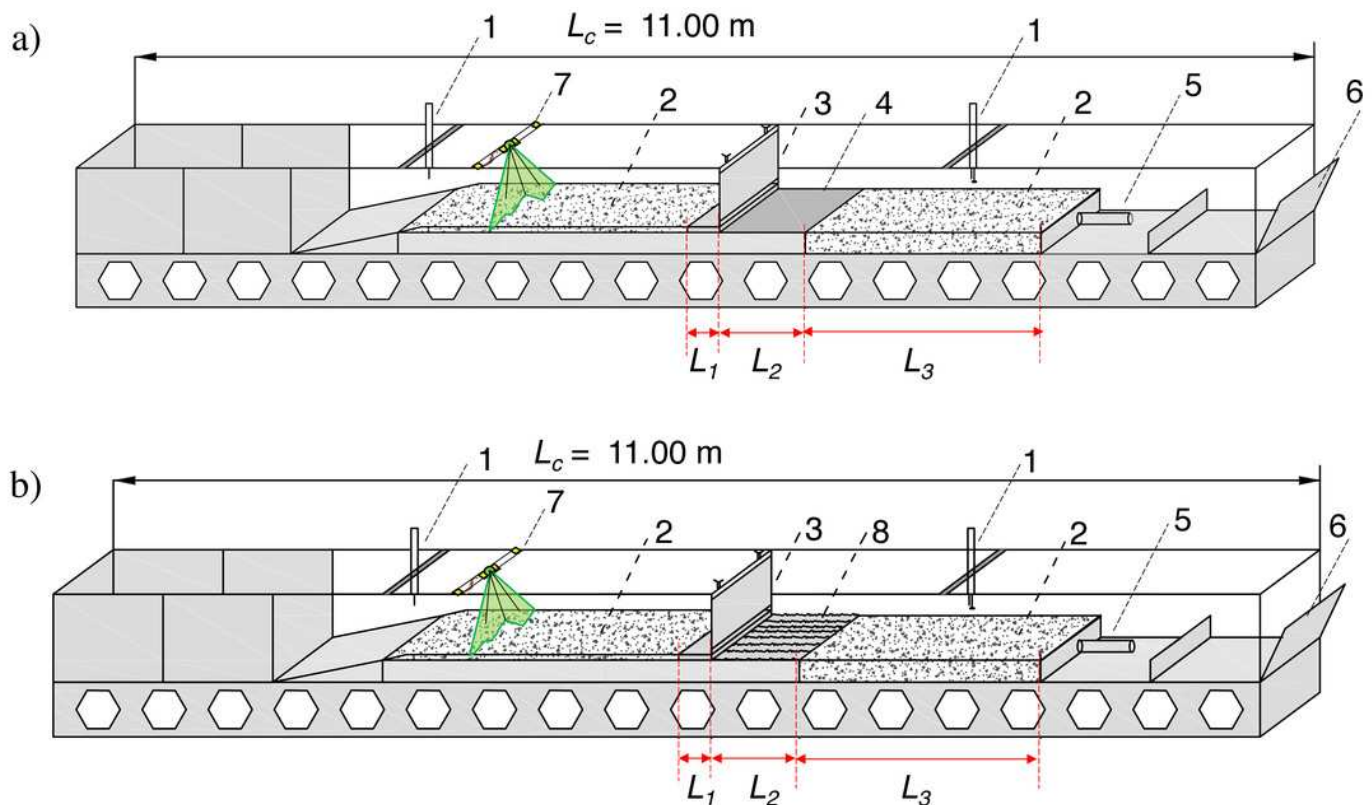
Figure 3

Photography of laboratory model

(a) – model I; (b) – model II.
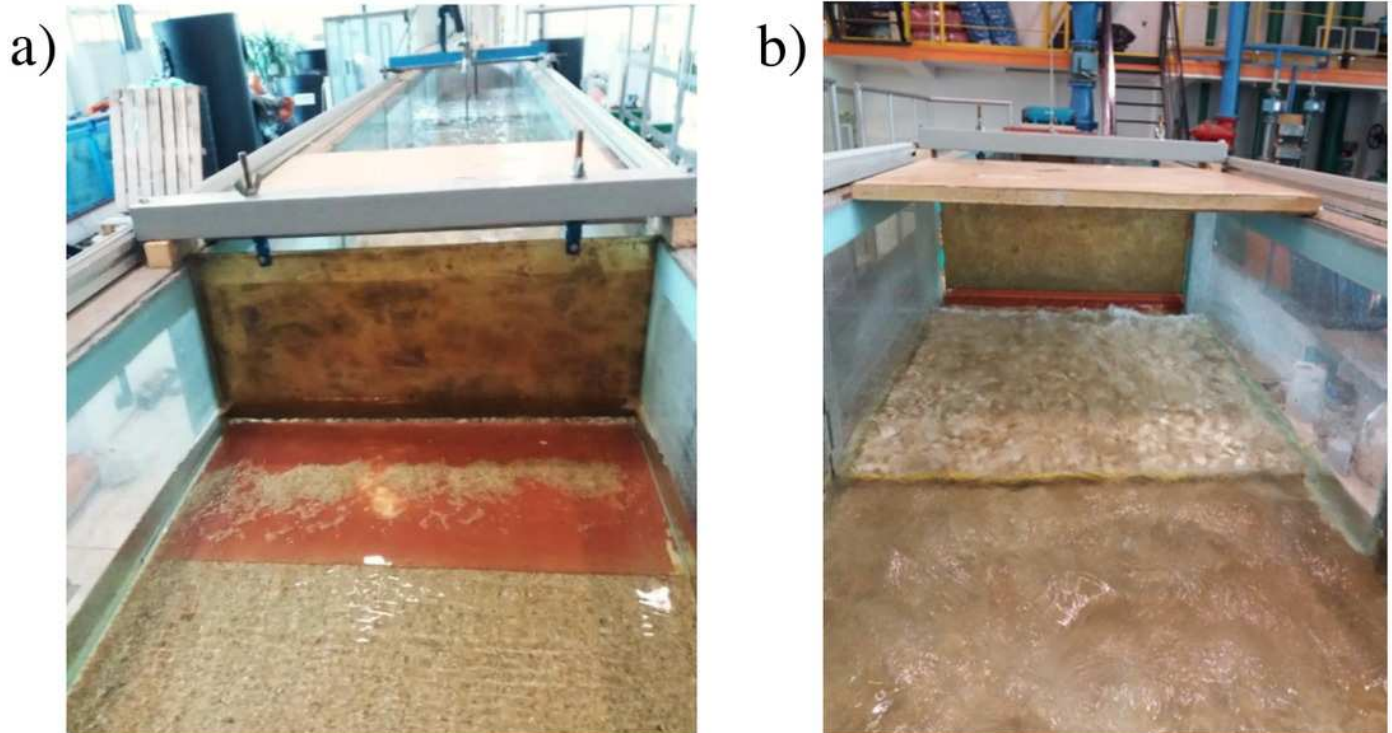
Figure 4

Local scour geometrical parameters

z_{max}– maximal scour depth; h – water depth before scour formation; L_s– scour length; L_e– the distance between the deepest point of the hole and the end of reinforcement
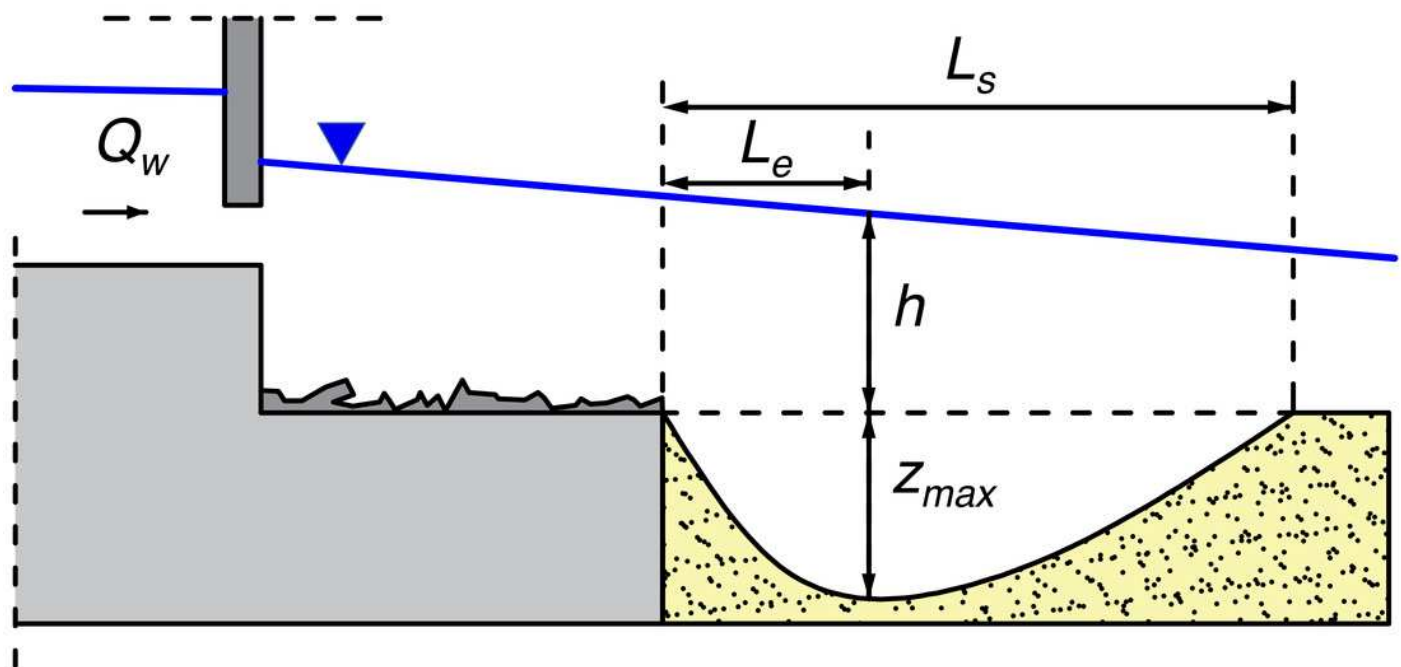
Figure 5

Prototype A1 during laboratory measurements.

Figure 6

Various types of lower stage of gated check construction

a) reinforcement equipped with sheet piling, b) reinforcement followed by transversal trench

c) sandy bed following reinforcement with lowered bottom, where: 1 – gate; 2 – solid

bottom;3 – stone reinforcement; 4 – sandy bed; 5 – sheet pilling or palisade; 6 – bank

reinforcement;7 – transverse trench with stone bottom; 8 – lowered reinforcement.
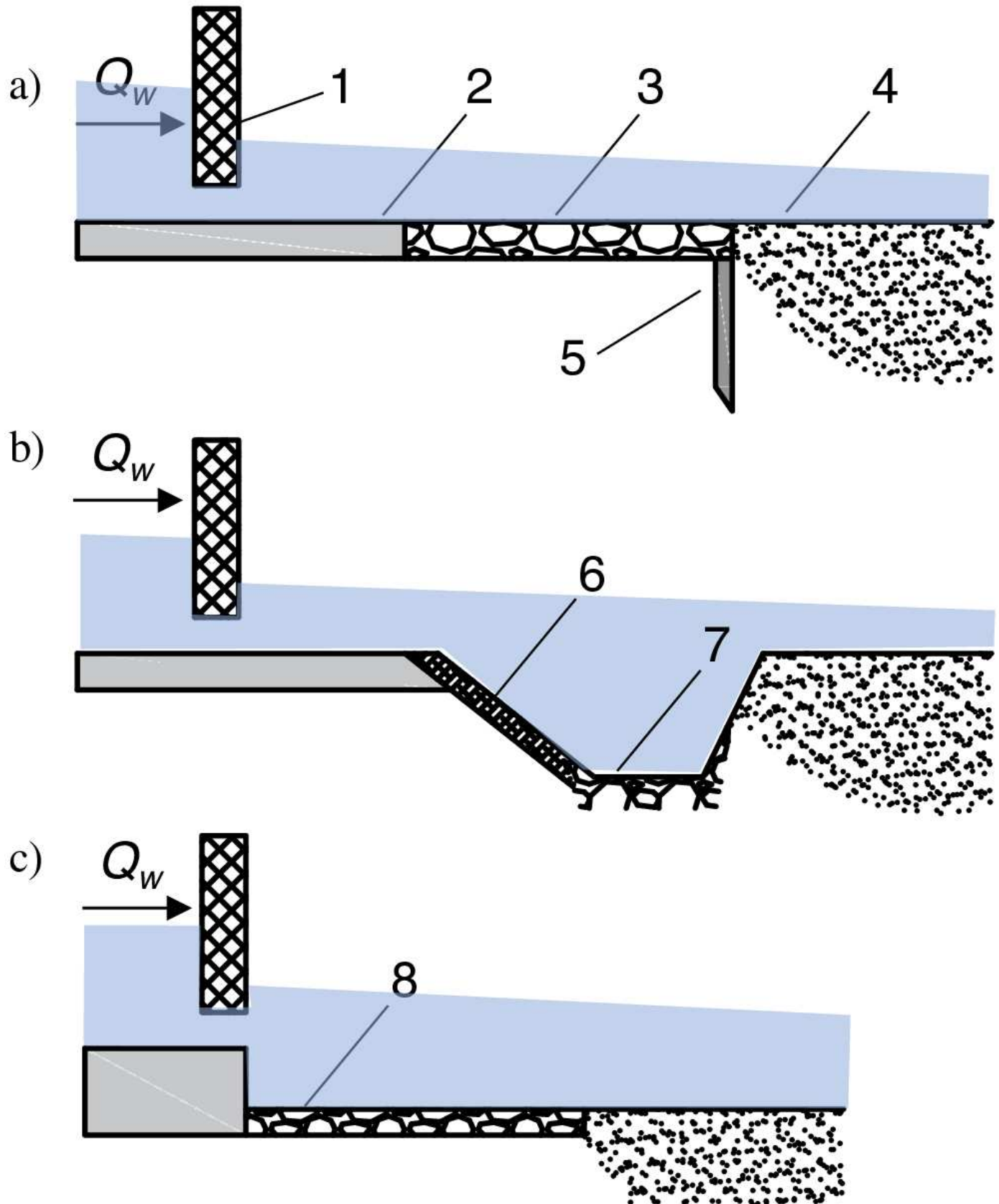
PeerJ

Figure 7

Shape the local scour downstream of the bed reinforcement in the Model II flume development during additional supplementary measurements.
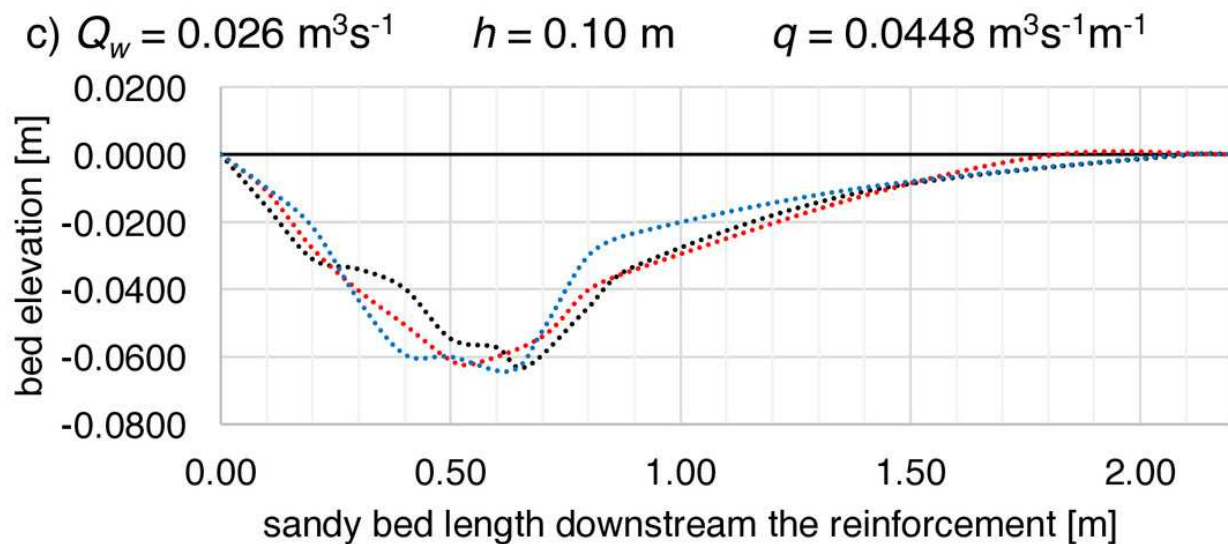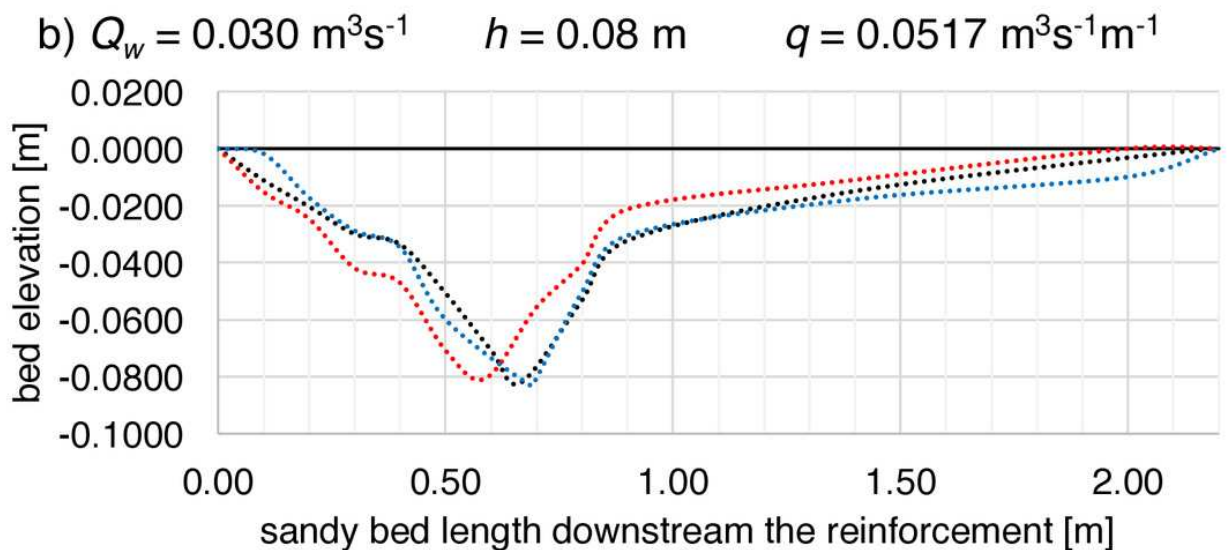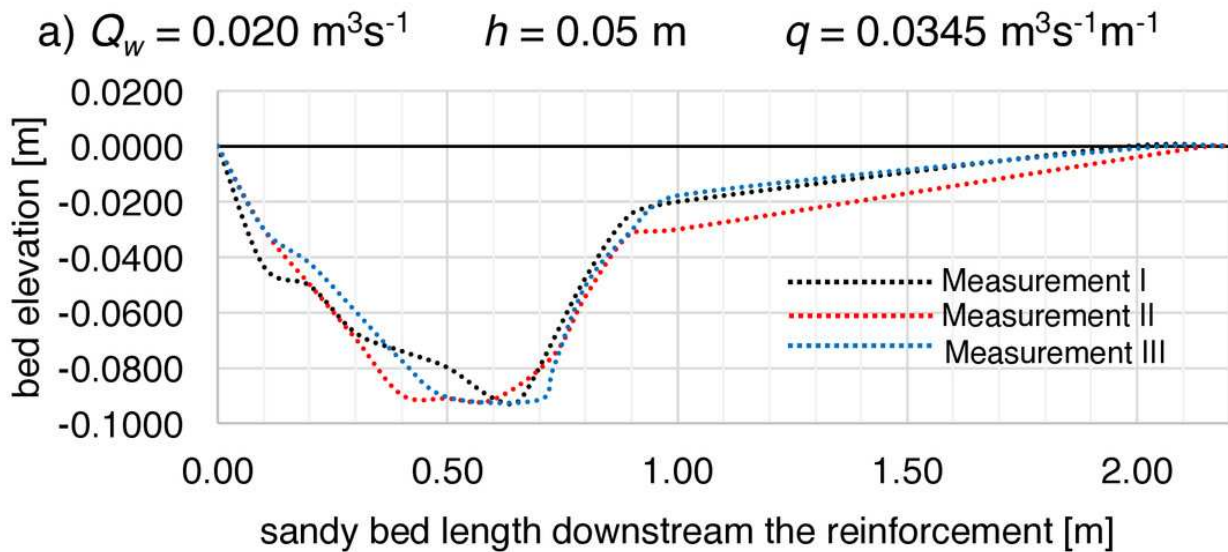
a) $Q_w = 0.020$ m^{3}s^{-1} $h = 0.05$ m $q = 0.0345$ m^{3}s^{-1}m^{-1}

b) $Q_w = 0.030$ m^{3}s^{-1} $h = 0.08$ m $q = 0.0517$ m^{3}s^{-1}m^{-1}

c) $Q_w = 0.026$ m^{3}s^{-1} $h = 0.10$ m $q = 0.0448$ m^{3}s^{-1}m^{-1}

Figure 8

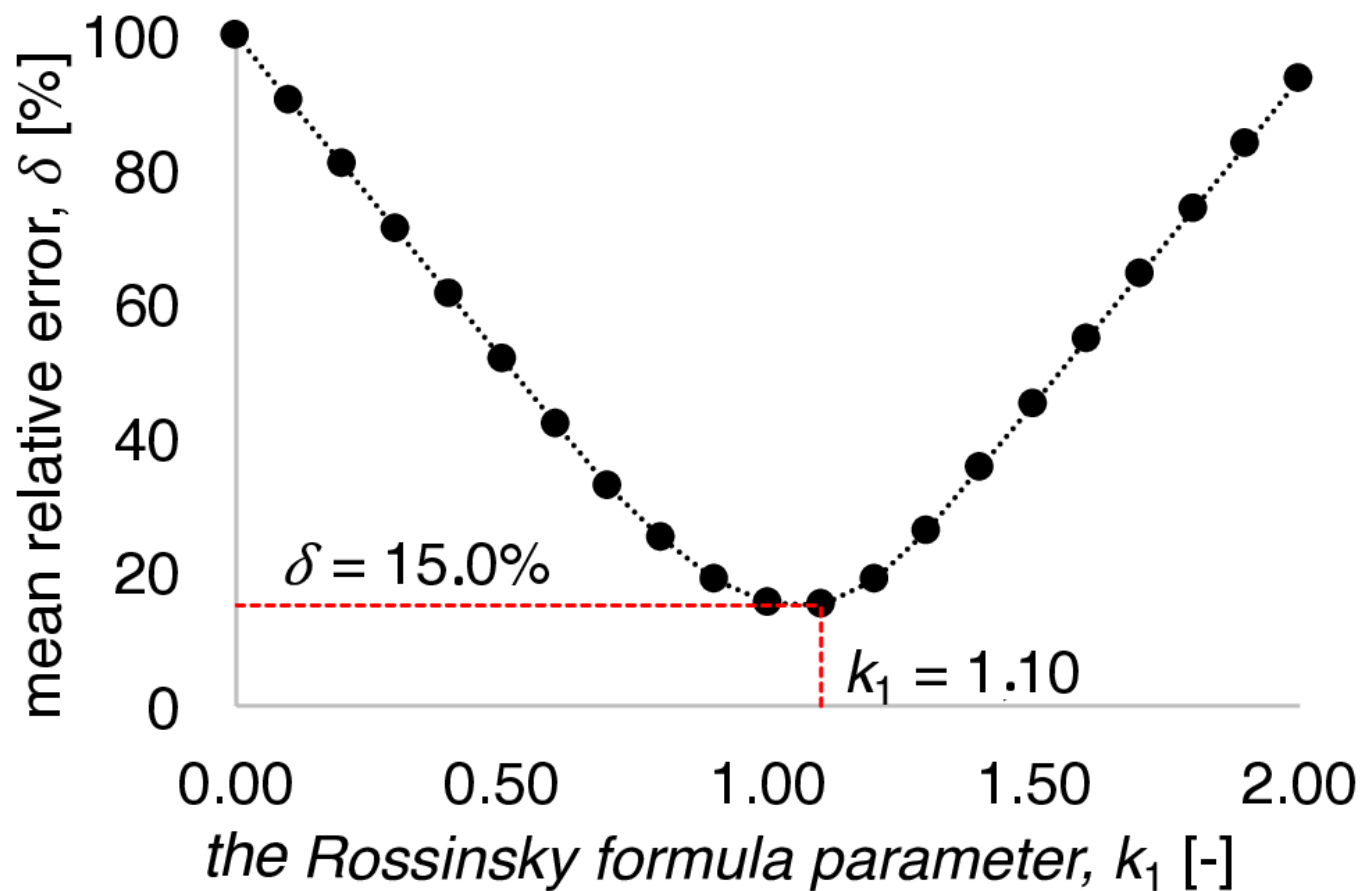k_1 coefficient impact on the mean relative error of calculations using Rossinski formula (Eq. 1)

Figure 9

Local scour field characteristics

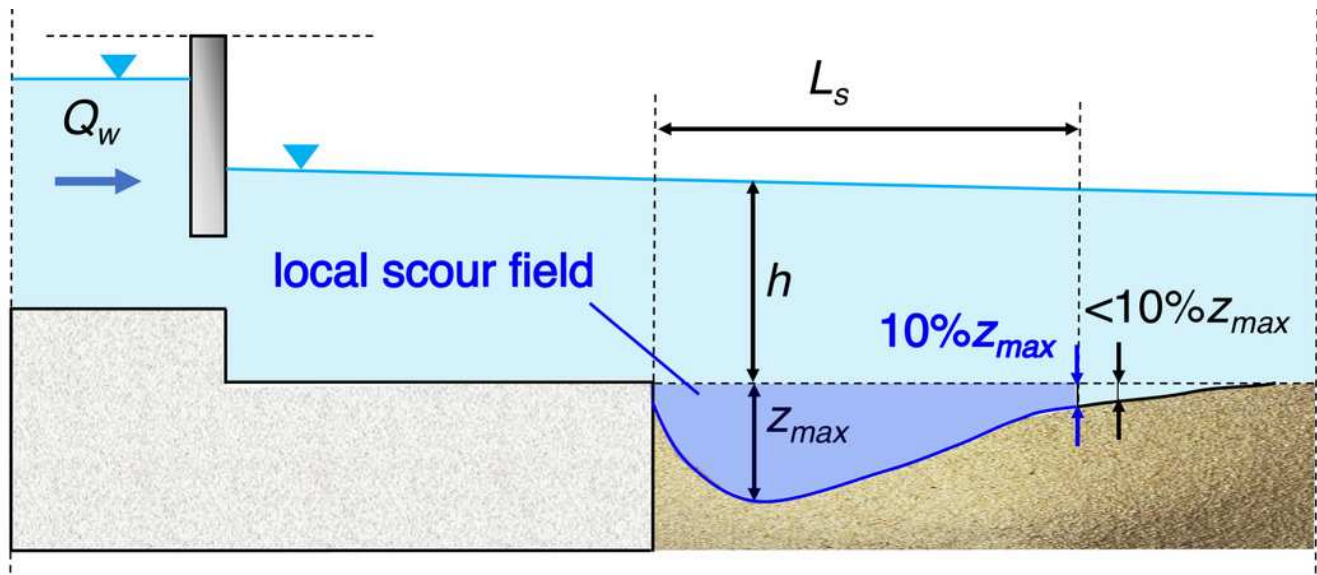z_{max} – maximal scour depth; h – water depth before scour formation; L_s – scour length

Figure 10

Local scour length L_s measurements and calculations results.

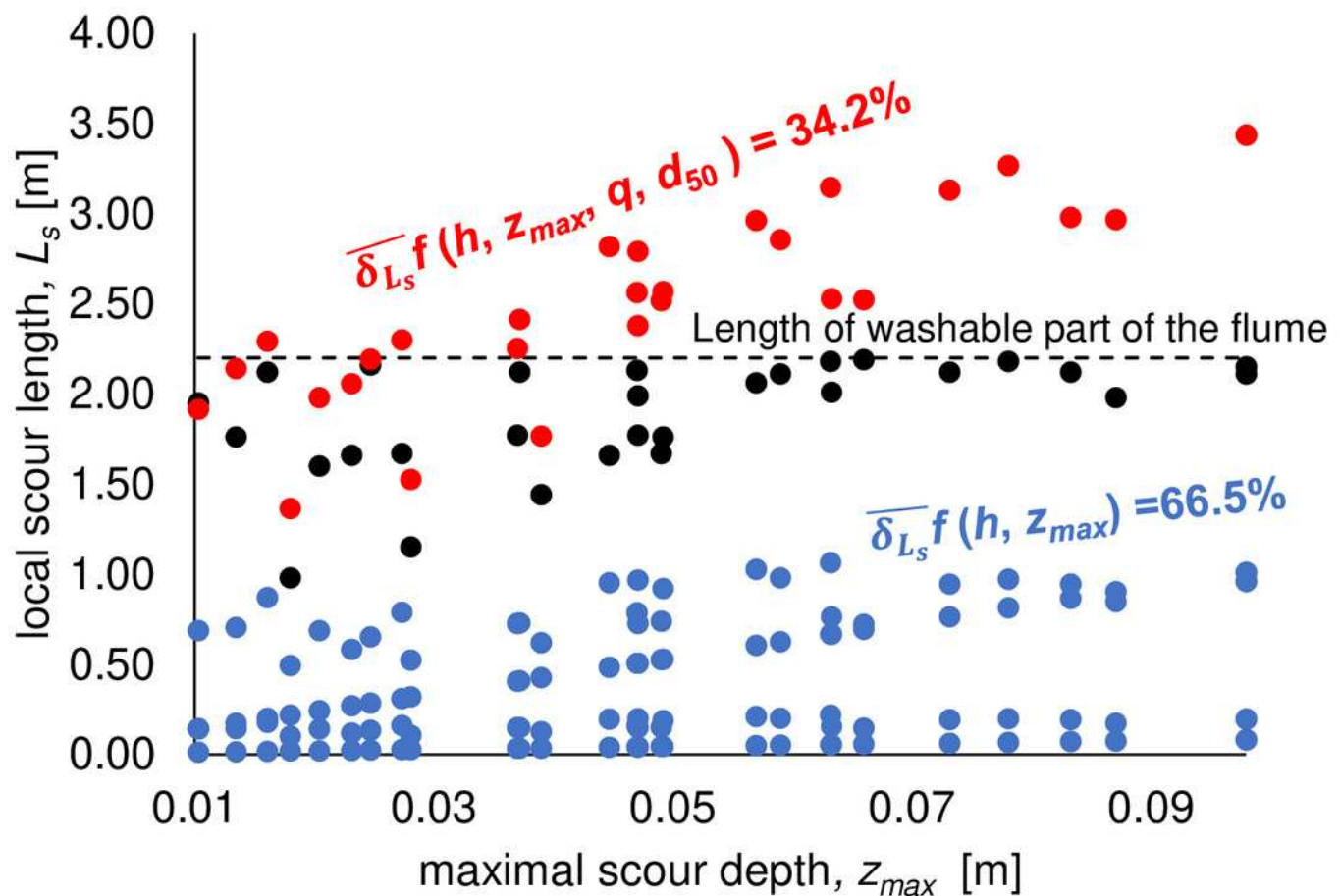# Figure 11

The distance between the deepest scour point and the end of reinforcement L_e measurements and calculations results.

(a) – side view; (b) – the view from the upper stage of the weir (own elaboration after Urbański and Hejduk 2014).
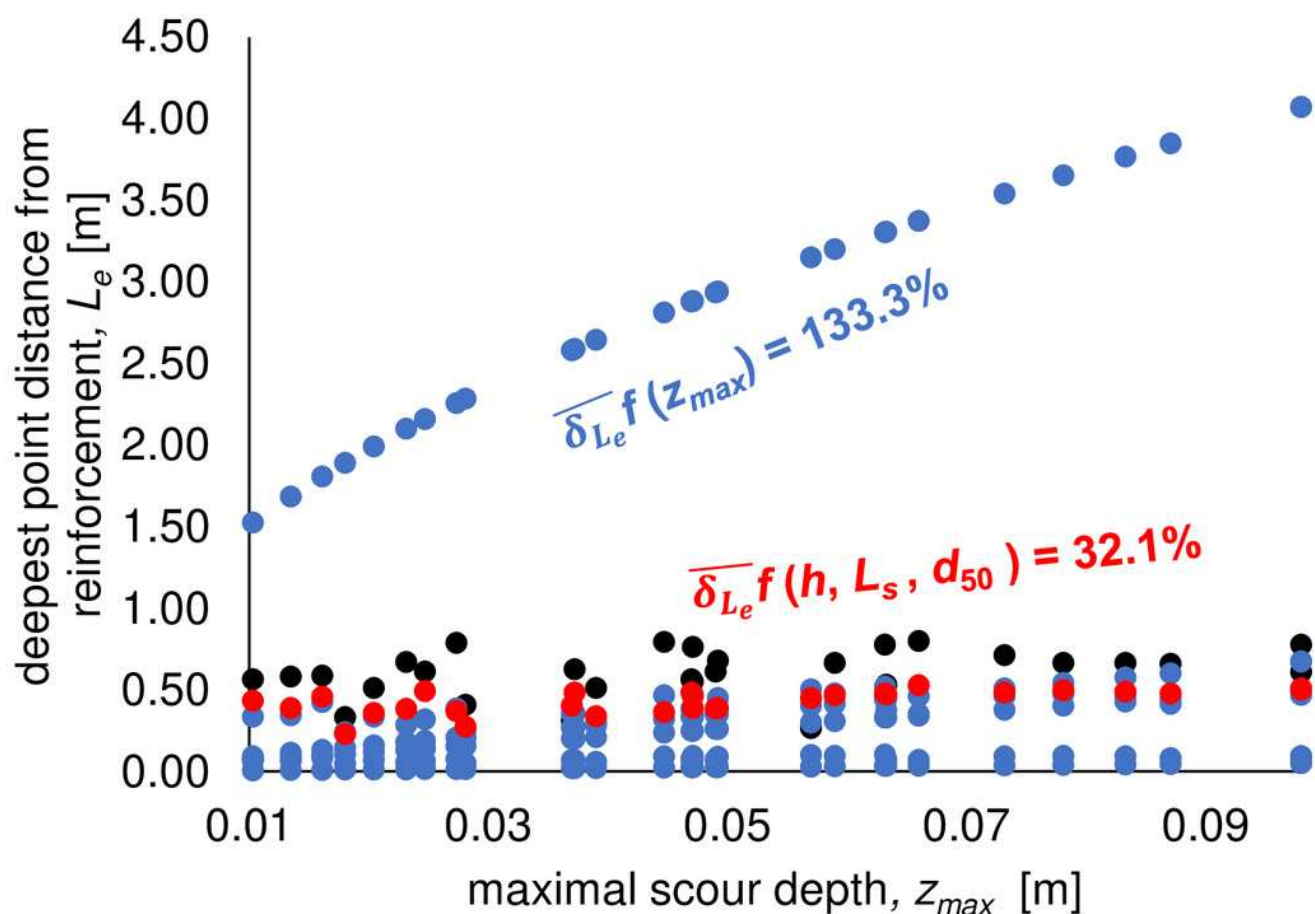
Figure 12

Weir in Czarna schematic

(a) – side view; (b) – the view from the upper stage of the weir (own elaboration after Urbański and Hejduk 2014).

PeerJ

Table 1(on next page)

Model I – measurement series summary table

Where: Q_w – water flow discharge; h – initial water depth in control profile; T – measurement duration; Fr – Froude number.

1

No of measurement series	Q_w [m^3·s^{-1}]	h [m]	T [s]	Fr [-]
1	0.025	0.13	28800	0.31
2	0.020	0.05	28800	0.98
3	0.023	0.10	28800	0.40
4	0.030	0.08	28800	0.73
5	0.025	0.05	28800	0.99
6	0.030	0.11	28800	0.45
7	0.028	0.11	28800	0.42
8	0.026	0.10	28800	0.45
9	0.029	0.08	28800	0.71

2

Table 2(on next page)

Model II – measurement series summary table

Where: Q_w – water flow discharge; h – initial water depth in control profile; T – measurement duration; Fr – Froude number.

1

No of measurement series	Q_w [m^3·s^{-1}]	h [m]	T [s]	Fr [-]
1	0.020	0.05	28800	0.98
2	0.023	0.10	28800	0.40
3	0.030	0.08	28800	0.73
4	0.025	0.06	28800	0.99
5	0.030	0.11	28800	0.45
6	0.028	0.11	28800	0.42
7	0.026	0.10	28800	0.45
8	0.029	0.08	28800	0.71
9	0.024	0.08	28800	0.58
10	0.029	0.10	28800	0.50
11	0.013	0.06	28800	0.48
12	0.013	0.06	28800	0.57
13	0.014	0.06	28800	0.52
14	0.021	0.06	28800	0.78
15	0.022	0.09	28800	0.46
16	0.022	0.07	28800	0.65
17	0.027	0.07	28800	0.80
18	0.028	0.08	28800	0.67
19	0.024	0.07	28800	0.72
20	0.030	0.07	28800	0.88

2

Table 3(on next page)

Model I – scour geometry parameters summary table

Where: q – unit water flow discharge; z_{max} – maximal scour depth; L_e – the distance between the deepest point of the hole and the end of reinforcement; L_s – scour length.

1

No of measurement series	q $[\mathrm{m^3 \cdot s^{-1} \cdot m^{-1}}]$	z_{max} [m]	H_{max} [m]	L_e [m]	L_s [m]
1	0.0431	0.0201	0.1451	0.59	2.10
2	0.0345	0.0911	0.1411	0.66	2.10
3	0.0397	0.0532	0.1532	0.68	2.20
4	0.0517	0.0821	0.1621	0.67	2.18
5	0.0431	0.1020	0.1600	0.78	2.01
6	0.0517	0.0672	0.1772	0.78	2.18
7	0.0483	0.0511	0.1611	0.76	2.20
8	0.0448	0.0630	0.1630	0.66	2.20
9	0.0500	0.0772	0.1572	0.71	2.20

2

Table 4(on next page)

Model II – scour geometry parameters summary table

Where: q – unit water flow discharge; z_{max} – maximal scour depth; L_e – the distance between the deepest point of the hole and the end of reinforcement; L_s – scour length.

No of measurement series	q [m³·s⁻¹·m⁻¹]	z_{max} [m]	H_{max} [m]	L_e [m]	L_s [m]
1	0.0345	0.0700	0.1200	0.80	2.19
2	0.0397	0.0143	0.1143	0.56	2.20
3	0.0517	0.0287	0.1087	0.61	2.20
4	0.0431	0.1020	0.1600	0.61	2.20
5	0.0517	0.0487	0.1587	0.79	2.20
6	0.0483	0.0610	0.1710	0.27	2.20
7	0.0448	0.0313	0.1313	0.79	2.20
8	0.0500	0.0412	0.1212	0.63	2.20
9	0.0414	0.0410	0.1210	0.31	1.77
10	0.0500	0.0175	0.1175	0.58	2.20
11	0.0220	0.0220	0.0820	0.33	1.00
12	0.0231	0.0321	0.0871	0.41	1.10
13	0.0240	0.0430	0.1030	0.51	1.50
14	0.0360	0.0673	0.1273	0.53	1.98
15	0.0385	0.0244	0.1144	0.51	1.60
16	0.0375	0.0873	0.1573	0.66	2.20
17	0.0465	0.0530	0.1230	0.61	2.20
18	0.0475	0.0510	0.1310	0.56	2.13
19	0.0415	0.0511	0.1211	0.55	2.01
20	0.0510	0.0271	0.0971	0.67	1.70

1
2

Table 5(on next page)

Formulas verification summary table

Where: (1 - 17) – number of formula; d_{Hmax} – an error of the depth of the water above the deepest point of the scour calculation; ; d_{Ls} – an error of the scour length calculation; d_{Le} – an error of the distance between the deepest point of the scour and the end of reinforcement calculation.

Author's Name	d_{Hmax} [%]	d_{Ls} [%]	d_{Le} [%]
Rossinski	(1) 15.0 %		
Shalash & Franke		(4) 69.8 %	(5) 45.2 %
Müller		(7) 72.8 %	(8) 57.0 %
Müller		(10) 56.9 %	(11) 38.3 %
Straube		(13) 34.2 %	(15) 32.1 %
(Optimized) Straube		(20) 10.1 %	(21) 18.2 %
Tajarmovič			(17) 392.7 %

1

Table 6(on next page)

Hydraulic flow parameters and local scour properties in Gaudio & Marion (2010) model experiments with Straube formula verification

Where: q – unit water flow discharge; h – water depth before scour formation; z_{max} – maximal scour depth; L_s – total scour length; δ – relative error.

No of test	q	h	z_{max}	L_s	Straube original (Eq. 13) L_s	Straube optimized (Eq. 20) L_s	Straube original (Eq. 13) relative error δ	Straube optimized (Eq. 20) relative error δ
-	m²· s⁻¹	[m]	[m]	[m]	[m]	[m]	[%]	[%]
1	0.020	0.050	0.084	1.25	2.10	1.63	68.4%	30.1%
2	0.032	0.065	0.097	1.65	2.71	2.09	64.5%	26.6%
3	0.021	0.050	0.071	1.35	1.93	1.50	43.3%	10.8%
4	0.025	0.062	0.068	1.47	2.03	1.56	38.1%	6.1%
5	0.021	0.050	0.058	1.43	1.73	1.34	20.7%	6.6%
6	0.028	0.071	0.083	1.25	2.37	1.81	89.9%	45.1%
7	0.030	0.070	0.095	1.90	2.62	2.01	38.0%	5.7%
8	0.021	0.050	0.087	1.50	2.19	1.69	46.0%	12.9%
9	0.024	0.060	0.102	1.55	2.53	1.94	63.0%	25.3%
10	0.030	0.070	0.110	1.63	2.86	2.19	75.5%	34.4%
11	0.027	0.065	0.084	1.98	2.35	1.80	18.6%	9.0%
12	0.020	0.060	0.069	1.52	1.88	1.44	23.9%	5.1%
					Mean relative error		49.2%	18.1%

1
2
3
4

Table 7(on next page)

Field measurements and calculations results summary table – Czarna Gauge

z_{max} – maximal scour depth; h – water depth before scour formation; L_s – scour length; L_e – the distance between the deepest point of the hole and the end of reinforcement.

PeerJ

1

	Geometric scour parameters		
	$H_{max} = z_{max} + h$ [m]	L_s [m]	L_e [m]
Field measurements	2.43	13.8	5.2
Author:	Calculations results using Eqs. (1), (7)-(21) (error %)		
Rossinski	(1) 3.39 (39.5 %)		
Müller		(7) 10.3 - 12.1 (12.3%)	**(8) 5.0-6.1 (0%)**
Müller		**(10) 11.6 – 17.5 (0%)**	(11) 5.7-8.6 (9.6%)
Straube		(13) 21.7 (57.2%)	(15) 4.8 (7.7%)
(Optimized) Straube		**(20) 13.8 (0.2%)**	(21) 4.3 (16.6%)
Tajarmovič			(17) 4.8 (159.6%)

2
3