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Laboratory Tests of Water Level Regulators in Ditches of Irrigation Systems

Janusz Urbański [1], Sławomir Bajkowski [1], Piotr Siwicki [2], Ryszard Oleszczuk [2], Andrzej Brandyk [3,*] and Zbigniew Popek [2]

[1] Institute of Civil Engineering, Warsaw University of Life Sciences, 02-787 Warsaw, Poland; janusz_urbanski@sggw.edu.pl (J.U.); slawomir_bajkowski@sggw.edu.pl (S.B.)
[2] Institute of Environmental Engineering, Warsaw University of Life Sciences, 02-787 Warsaw, Poland; piotr_siwicki@sggw.edu.pl (P.S.); ryszard_oleszczuk@sggw.edu.pl (R.O.); zbigniew_popek@sggw.edu.pl (Z.P.)
[3] Water Centre, Warsaw University of Life Sciences, 02-766 Warsaw, Poland
* Correspondence: andrzej_brandyk@sggw.edu.pl; Tel.: +48-22-59-35-377

Abstract: Observed changes in hydrological conditions indicate the need for economical use of water. This pertains to water management on a national scale, river basins and drainage systems. The outflow of water can be extensively regulated after various forms of retention in the catchment. The water level regulators presented herein enable the damming of water in drainage networks and the adjacent ground. Their advantages include their simple structure and operation principles and also the ability to adapt to currently existing devices in sub-irrigation systems. Laboratory tests were conducted to determine the hydraulic characteristics and operating conditions of three innovative regulator solutions. They focused on changing water damming heights by the closure of successively placed beams in order to obtain the required water level in the given hydrometeorological conditions. The structures of the regulators were made of plastics and rectilinear fillings for securing S-type excavations and elements of sheet piling with a developed shape in the plan of U and Z types, offering advantages compared to traditional materials (with respect to installation, operation and durability). All tested regulators were characterized by the effective flow Q_e, caused by water leaks due to the lack of tightness of the regulator elements. The regulator with rectilinear beams of S-type closures offered the highest effective flow, which was 4 ÷ 5 times higher than in other regulators. U- and Z-type regulators were better at facilitating the regulation of the water table and the flow than the S rectilinear regulator. This led to both: the greater tightness of connections and the use of an overflow with a developed crest in the plan. The U and Z controllers had the highest hydraulic efficiency, expressed as the flow increase coefficient, at overflow layer heights of up to 5.0 cm. For tested fillings larger than 5.0 cm, U-type beams with a cylindrical corner shape had a lower flow increase coefficient (k_q = 1.25) than Z-type beams with an angular corner shape, for which $k_q \in$ <1.35 ÷ 1.38>.

Keywords: ditch; regulator; closure; water level; flow rate; irrigation and drainage system

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1. Introduction

Water resources in Poland have been found to be the lowest among European countries. The reasons for this are the climatic and physiographic conditions and the overlapping of oceanic and continental climates [1]. This leads to lower precipitation compared to other European countries and contributes to its high seasonal and spatial variability. Furthermore, the observed climate changes may also impact the shortages of water resources in Poland [2,3], with the simultaneous occurrence of extreme weather phenomena such as floods and droughts. The latter are extremely harmful to agriculture, resulting in a reduction in yields, especially in areas with drainage systems but without devices for water damming [4–8].

For the needs of crop production, water collection and runoff control are often carried out in open drainage systems (ditches) [9–12] and closed systems (drains) [13–15]. For the regulation of flow in watercourses and reservoirs [16], tower regulators, vortex regulators or gate valves and overflow regulators [17,18] are applied, as well as float regulators for the upper or lower water levels [19]. One of the ways to increase retention in drainage facilities is the use of water-damming regulators in ditches influencing the adjacent ground [20–23]. These devices slow the outflow from the facility, taking into account the optimal level of plant desiccation/irrigation in these areas [24], but also allow proper water management through appropriate water distribution in drainage/sub-irrigation networks [4,25].

The necessity to block the outflow of water in drained valley areas as well as soils of low peat (fen) bogs is of additional importance. These sites are usually equipped with drainage systems that only drain water from their catchments. In Poland, about 80% of the valley soils of low fen-peat (1.2 million ha) are already drained [26,27]. This leads to many unfavorable changes in the physical, chemical and biological properties of the top layers of such soils [28–31]. Often, they require restoration by blocking the outflow of surface waters and raising the groundwater table to a depth of approx. 30–50 cm below the surface [32–37]. Unfortunately, in Poland, many drainage systems of this type have been subsequently decapitalized and thus deprived of water-damming elements. For example, in the drained soils of a fen (Solec site, central Poland) equipped with a dense network of drainage ditches (62 ditches), none of the hydraulic structures (3 valves and 42 valve culverts) has the capacity for damming [12,25].

For that reason [38] and also due to the need to provide more advanced, modern solutions, the development of water-damming regulators in drainage ditches has become one of the goals of the INOMEL project—"Technological innovations and a system for monitoring, forecasting and operational planning of drainage activities for precise water management on the scale of a drainage facility" (BIOSTRATEG3/347837/11/NCBR/2017). The innovative character involved the typical elements of the beams, which are widely applied in civil engineering, pointing at advantages such as the flexibility of installation and water damming. The underlying theory involves proper weir types, e.g., sharp-crested weir, and relevant discharge equations that cannot fully support the cases analyzed herein. The resolved modeling experiment aimed to determine relationships, which, indeed, were not well-defined by existing formulas and therefore required an empirical approach.

Available hydraulic weir equations do not capture the effective flow (Q_e) through openings between beams, seals and guides and leakage through locks at beam connections. In contemporary literature sources, no sufficient attention is given to hydraulic losses and simultaneous local loss coefficients for such diverse and irregular hydraulic forms. Therefore, there is an important role for research executed on real-scale models to focus on artificial material prototypes, which have not been widely popular with drainage/irrigation systems so far. Their advantage over existing traditional materials (steel or wood) is manifested in operating costs, precise installation, weight, operation and resilience. These novel regulators were, in particular, subject to the determination of empirical relationships with effective flow and its utilization for total flow estimation in the case of S (rectilinear), U (labyrinth) and Z (compound crest) shapes so as to gain insight into tightness and water level regulation capabilities. Their tests and validation in laboratory conditions were conducted at the Hydraulic Laboratory of the Warsaw University of Life Sciences.

2. Materials and Methods

In open drainage systems, gate valves with wooden beams or steel gates are usually used to regulate the flow and water level. The tested prototype beam regulators used typical structural elements of sheet piling, i.e., plastic sheet piles. In such a construction, the top edge of one or more successive elements is at a lowered level. In this way, a cut-out is created that forms the overflow of the fixed regulator. The sheet piles are placed in the ground at such a depth that the position of their upper edge corresponds to the ordinate of the required damming, with the overflow crest remaining constant over time. A greater range of regulation is ensured by the use of beam regulators. After the installation of a number of beams, the upper edge of the uppermost beam forms the control overflow with a discharge rate influenced by: H (cm)—water depth in the upper stand; P (cm)—the height of the threshold regulated by the number of beams; the height of the water layer flowing over the crest ($H - P$); and the shape of the elements used to make the closure beams. The shape of the beams determines the active length of the overflow through the arrangement of its crest and the geometry of the edge. These are devices that allow for changing the water damming level in the range from the height of the fixed sill to the ordinate, depending on the number of beams applied (Figure 1).

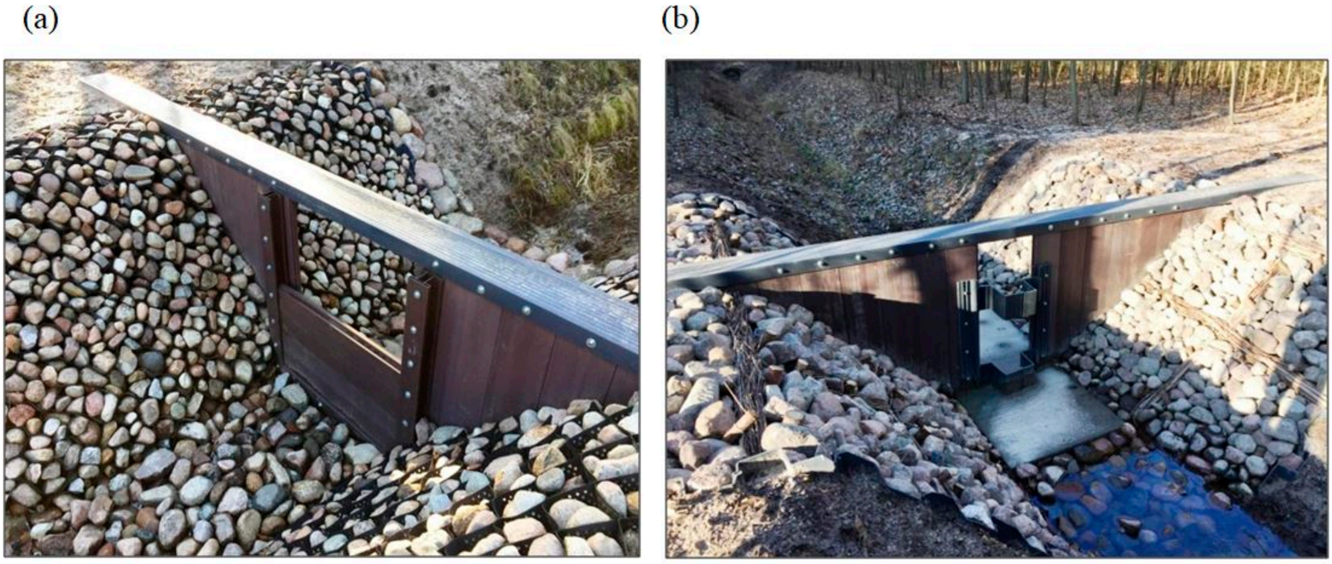


Figure 1. Beam regulators: (**a**) rectilinear beam, (**b**) compound beam (photo by R. Oleszczuk).

This study used the results of research on rectilinear beam regulators (GW458/11, Pietrucha—J. Gralewski, Blaszki, Poland) (Figure 1a) and labyrinth regulators (GW458/12, Pietrucha—J. Gralewski, Blaszki, Poland) (Figure 1b), with the overflow in the plan having a complex shape. The proposed prototype devices were developed in relation to typical existing structures of drainage gates regulating the outflow of water from ditches, that is, from objects with a bottom width of up to 1.50 m and a depth of up to 1.00 m. The research methodology for other types of beams is consistent with the methods described in this paper, which also presents the analysis of S-, U- and Z-shaped beam constructions, the most popular types in construction engineering and widespread elements of tight walls. It is stressed that laboratory tests of new devices constitute the first stage of their implementation in practice. Moreover, an advantage is gained from the much lower cost of execution, easier and precise assembly from typical structural elements, easy handling of the closures (due to their relatively light weight, with no need to use additional lifting devices), long-term use (no corrosion) and the lack of costly maintenance, as was already stressed.

Experimental Site and Models of Regulators

The experimental site for regulators in the hydraulic laboratory is shown in Figure 2. The use of empirical laboratory tests of the prototype at a 1:1 scale resulted from the ability to study a very diverse form of flow through the gaps, between the beams, through the horizontal seals of the beams, along the guides and through the locks on the beam connections. The obtained results were approximated by equations for which the coefficients were calculated according to the data from the model, which is not feasible to derive from available weir equations. The tests were carried out in a concrete channel (1 in Figure 2) 1.07 m in width and 1.20 m in depth. The site was supplied with water in a closed-circuit system, which included: a pressure expansion tank (2 in Figure 2), a suction and pressure pump (3 in Figure 2), pipelines supplying the measuring station, pipelines for water discharge and a bottom tank. The water installation was equipped with a control valve and an electromagnetic flow meter (ENKO MPP600 DN60-type, Enko, Gliwice, Poland) with a flow rate measurement accuracy of ± 1%. A water gauge (MICRO MD-2108-type, Micro, Otmuchow, Poland) (7 in Figure 2) with a reading accuracy of ± 1.0 x0^{-4} m (±0.01 cm) was used to measure the water levels. The water stream flowed with a fixed, controlled intensity Q_c (dm^3·s^{-1}) to the regulator from the upper tank, in which the position of the water table was kept constant. The tests were carried out under the conditions of a steady flow of the water stream, and its intensity was regulated by a valve in the supply conduit and controlled by an electromagnetic flow meter.

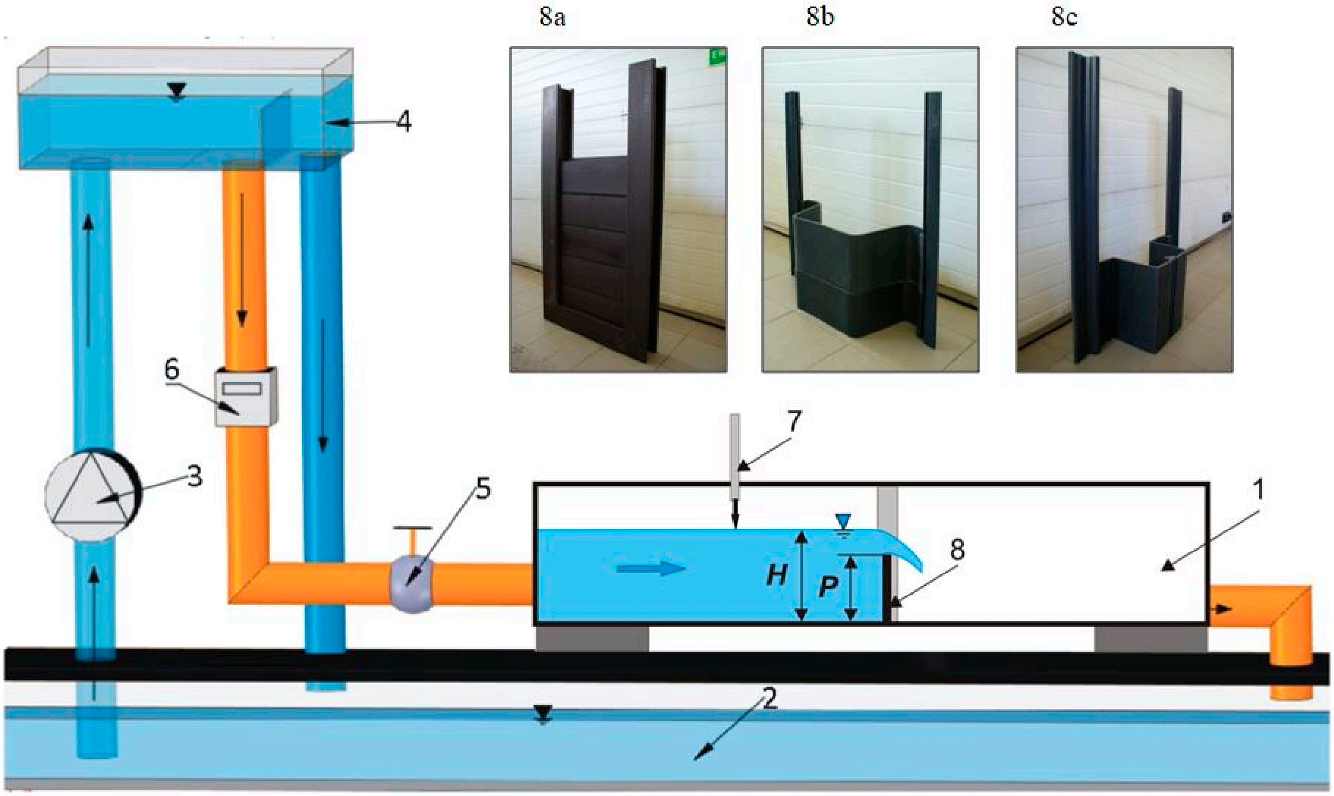
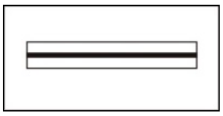
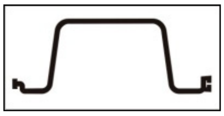
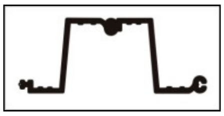


Figure 2. Scheme of the entire experimental site: 1—flume; 2—bottom tank; 3—pump; 4—upper stability tank; 5—regulating valve; 6—electromagnetic flow meter; 7—precise water gauge; 8—regulators of water damming in the ditches; 8a—rectilinear regulator; 8b—labyrinth regulator; 8c—compound regulator; *H* (cm)—top water depth; *P* (cm)—height of the regulator overflow (photo by Z. Popek).

The regulators used in the tests were made of typical plastic sheet piling elements. There were three prototype beam regulators (Table 1, Figure 2): S—straight; U—labyrinth; and Z—compound. The S regulator was made of straight beams, the U regulator was made of uniform, non-split sheet pile elements of tight scraps, and the Z regulator beams consisted of two sheet pile elements with an additional lock connecting both parts vertically. The prototypes of the regulators (8a, 8b and 8c in Figures 2 and 3, Figures 4 and 5) were made on a 1:1 scale, that is, with their actual dimensions. Thus, it was not necessary to convert the constructional and hydraulic parameters into natural (terrain) conditions.

Table 1. Parameters of the tested beam regulators.

No.	Model	b (m)	L_p (m)	L_k (cm)	k_r (–)	Variant	P (cm)	Q_e ($dm^3 \cdot s^{-1}$)
1	2	3	4	5	6	7	8	9
1	S—rectilinear 	0.450	0.450	1.2	1.00	S5	87.7	0.937
2						S4	71.5	0.879
3						S3	55.0	0.767
4						S2	38.2	0.597
5						S1	21.8	0.376
6						S0	6.8	0.000
7	U—labyrinth 	0.588	0.935	0.9	1.58	U5	102.2	0.383
8						U4	81.7	0.266
9						U3	61.2	0.169
10						U2	40.5	0.092
11						U1	20.2	0.036
12						U0	0.0	0.000
13	Z—compound 	0.544	0.967	1.1	1.74	Z5	102.6	0.198
14						Z4	82.0	0.131
15						Z3	61.4	0.078
16						Z2	41.6	0.040
17						Z1	20.5	0.013
18						Z0	0.0	0.000

b (m)—width of the outlet opening; L_p (m)—length of the overflow line; L_k (cm)—width of the rectangular edge of the overflow (equivalent width for the S model); k_r (–)—overflow development factor; P (cm)—height threshold in the upper stand; Q_e ($dm^3 \cdot s^{-1}$)—effective flow.

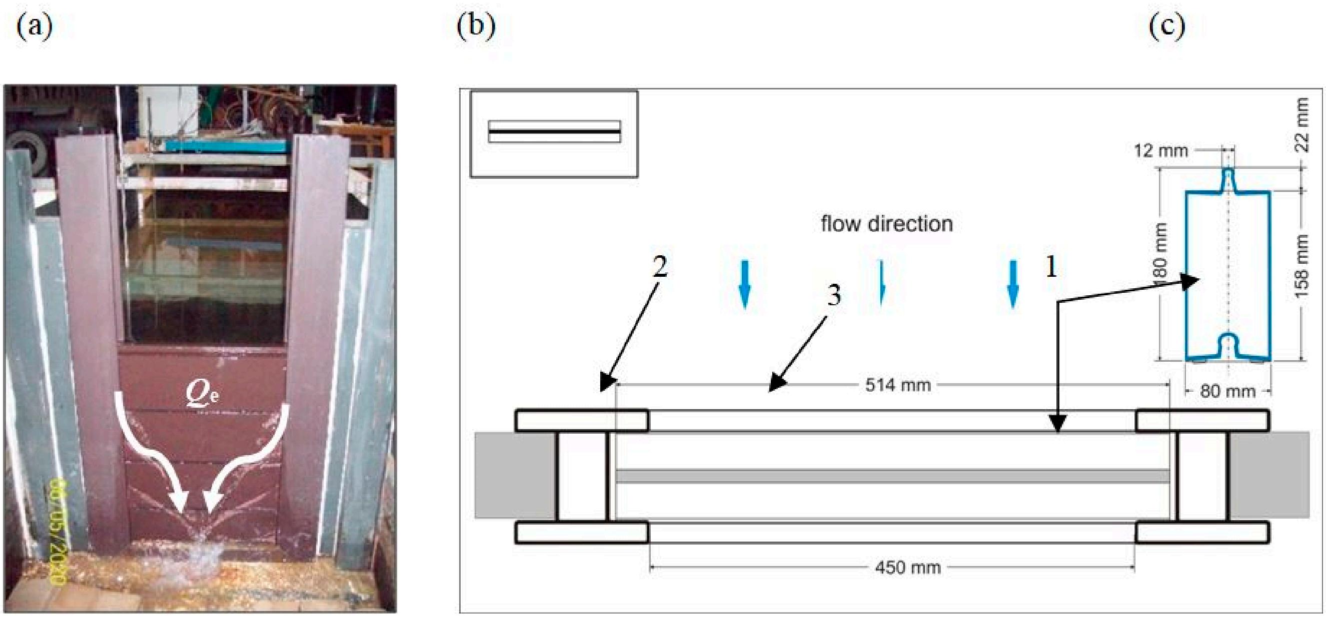


Figure 3. Measurement scheme of the S rectilinear regulator (**a**) measuring station, (**b**) regulator mounting, (**c**) cross-section of the beam: 1—beam; 2—gib; 3—regulator sill (photo by J. Urbański).

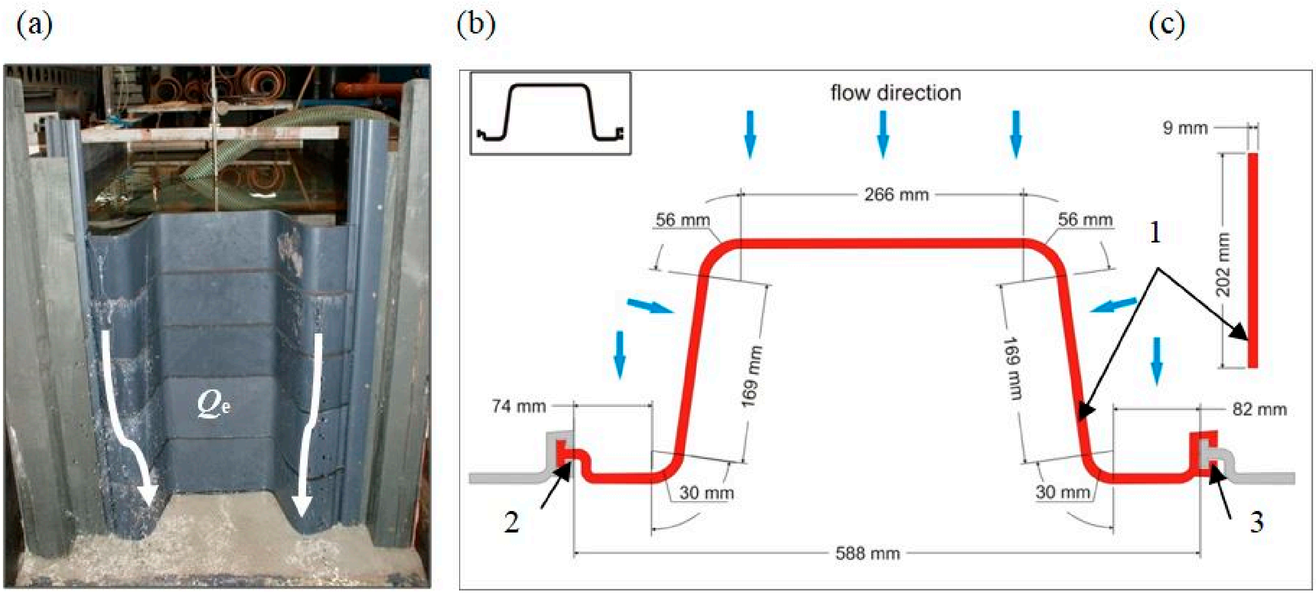


Figure 4. Measurement diagram of the U labyrinth regulator: (**a**) measuring station, (**b**) regulator mounting, (**c**) cross-section of the beam: 1—beam; 2—gib with female lock; 3—gib with a male lock (photo by Z. Popek).

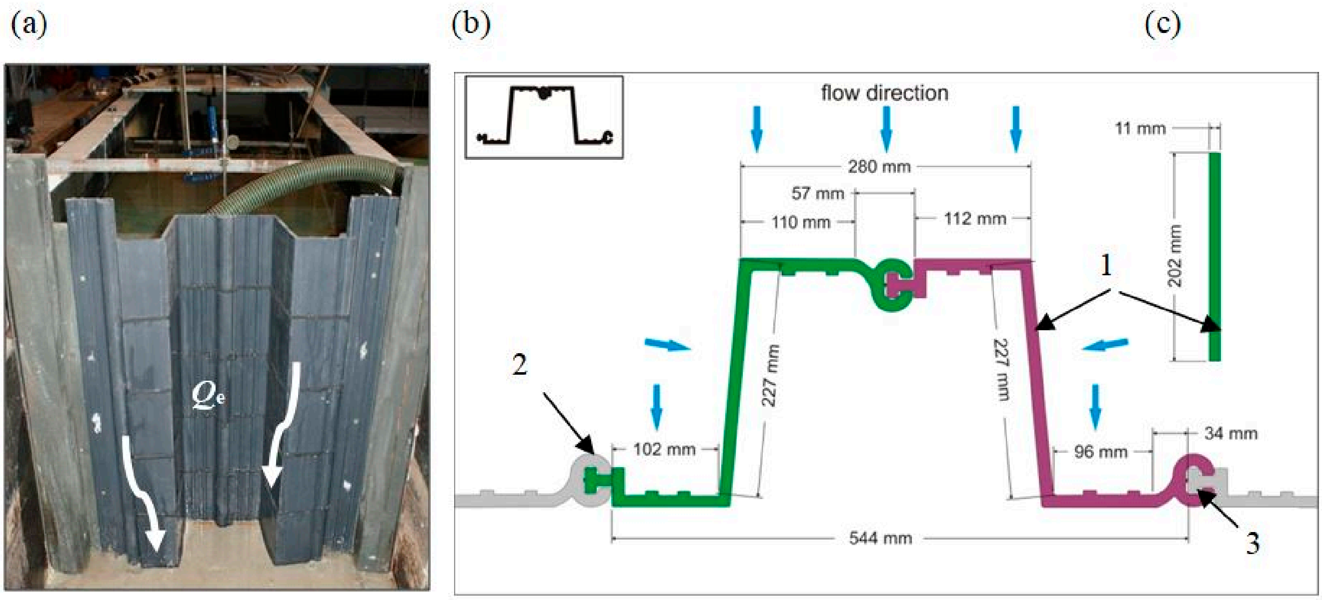


Figure 5. Measurement diagram of the Z compound regulator: (**a**) measuring station, (**b**) regulator mounting, (**c**) cross-section of the beam: 1—beam; 2—gib with female lock; 3—gib with male lock (photo by Z. Popek).

Both U and Z shapes showed a characteristic, developed crest line (Figures 4 and 5), and, it should be stressed, the length of this line L_p was greater than the outlet width by 59 and 78 percent, respectively. As was already pointed out, the determination of discharge characteristics for such regulators could not rely on equations in the available literature since they mainly consider straight-line weir crests. Moreover, they assume the complete tightness of the constructions, which was not the case of successively placed beams analyzed herein; therefore, an experimental approach was required to assess the design and function of the regulators under variable hydrostatic and hydrodynamic loads. The detailed structure of the analyzed regulators is shown in Figures 3–5. The arrows in Figures 3–5 show the places of intense effective flow.

The rectilinear regulator S (8a in Figure 2, Figure 3) consisted of beams (1 in Figure 3) and two gibs (2 in Figure 3) in the shape of H126 mm sections. The guides rested against the bottom beam (3 in Figure 3). The use of a recess in the gibs made it possible to install the beams and keep them in a vertical position. The shape of the beams enabled their interconnection with the use of a lock and a gasket, which improved the tightness. The tested specimen with a width of b = 0.45 m made it possible to set the overflow crest in relation to the bottom of the upper station within the height range of P = 6.8 ÷ 85.7 cm (Table 1).

The labyrinth regulator U (8b in Figure 2, Figure 4) consisted of beams (1 in Figure 4) and two gibs: one with a female lock (2 in Figure 4) and the other with a male lock (3 in Figure 4). In the tested model with an opening width b = 0.588 m, the height P of the overflow edge position could be adjusted within the range of 0.0 ÷ 102.2 cm relative to the bottom (Table 1) by inserting or removing beam elements.

The compound regulator Z (8c in Figure 2, Figure 5) was composed of two asymmetrical elements (1 in Figure 5) connected with each other by a lock in a vertical line. In the test specimen with an opening width b = 0.545 m, the height P could be adjusted within the range of 0.0 ÷ 102.6 cm relative to the bottom (Table 1) by inserting or removing subsequent beams.

3. Laboratory Test Results

The total outflow of beam regulators is the sum of the intensity Q_r ($dm^3 \cdot s^{-1}$) of the control flow above the overflow crest and the intensity Q_e ($dm^3 \cdot s^{-1}$) of the effective flow. The idle flow rate was defined as the effective flow Q_e compensating for water losses caused by leaks occurring in places where the beams are seated in recesses, on the horizontal seals between the beams and on their vertical joints. After exceeding this flow, the process of self-regulation of the water level in the ditch begins. The tests of each of the three regulators were carried out in two stages. In the first stage, the value of the effective flow Q_e was determined, and in the second stage, the total discharge Q_c of the regulators was measured in the specified range of the water damming height H in the upper stand and the elevation (H − P) of the water table above the control overflow.

3.1. Effective Flow Q_e

The value of the effective flow Q_e is variable, depending on the type of regulator, the number of installed elements and the method of their assembly and sealing accuracy. The curves of the variability of the effective flow Q_e, developed on the basis of the results of measurements of this parameter with the assumed five beams for each of the S, U and Z regulators, are presented in Figure 6. For each tested regulator design, the maximum value of the effective flow was determined while maintaining the position of the dammed water table at the level of the upper edge of the overflow, without the stream overflowing.

The regulator with the S-type closure was characterized by the highest effective flow among all tested prototypes. S-type beams were placed in gib recesses without additional locks. Leaks occurred mainly in places where the beams were seated and, to a lesser extent, in the horizontal joints of the successively placed elements—here, seals and a suitably shaped lock were used. With the increase in the dammed water depth H, the effective flow increased in the range from Q_e = 0.33 $dm^3 \cdot s^{-1}$ at H = 19.1 cm to Q_e = 0.93 $dm^3 \cdot s^{-1}$ at H = 85.4 cm (Figure 6). The U and Z models of regulators were characterized by much lower effective flow values compared to the S model. These regulators were mounted on gibs with special locks (Figures 4 and 5), which improved the tightness. Minor leaks occurred mainly in the joint of the gaskets between the beams. In the tests of the U-type regulator, the water losses increased with the increase in the dammed water level in the range from Q_e = 0.04 $dm^3 \cdot s^{-1}$ to Q_e = 0.31 $dm^3 \cdot s^{-1}$ (Figure 6). The Z-type regulator was characterized by the highest tightness and therefore the lowest effective flow, despite the presence of an additional lock vertically connecting two parts of each beam. The amount of effective flow at the maximum depth of dammed water H = 105.0 cm was Q_e = 0.21 $dm^3 \cdot s^{-1}$ (Figure 6).

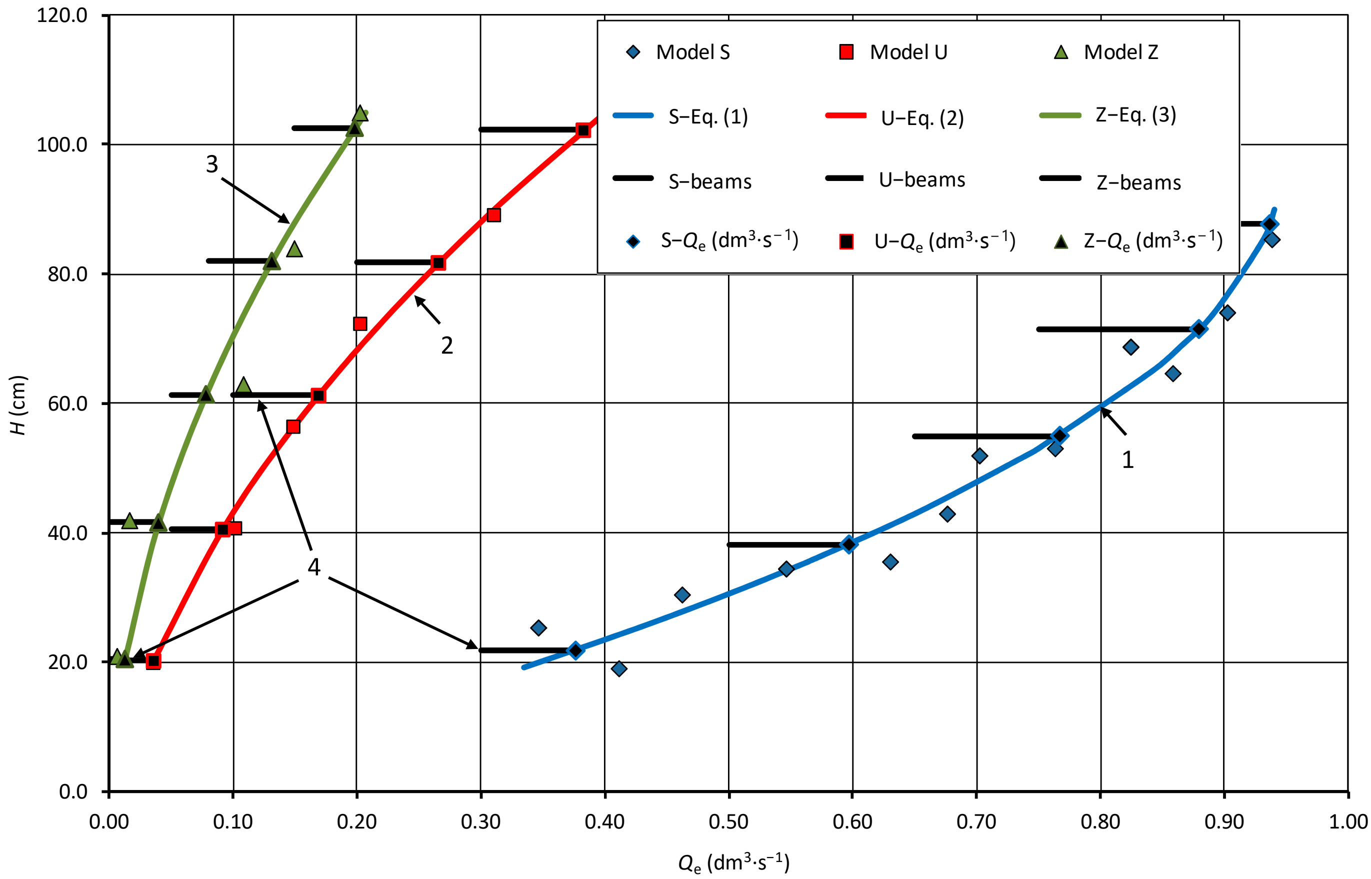


Figure 6. Effective flow Q_e of the tested regulators depending on the water depth H: 1—S model; 2—U model; 3—Z model; 4—levels of the upper edges of the beams.

The set of Q_e measurement results was subjected to statistical analysis. Using a non-linear approximation model, regression curves for individual models were developed:

1. S model, formula validity range: 19.1 cm $\leq H \leq$ 85.4 cm:

$$Q_e = -1.00^{-4}(H)^2 + 1.94^{-2}(H) \quad r = 0.960,\ R^2 = 0.947 \tag{1}$$

2. U model, formula validity range: 19.2 cm $\leq$ H $\leq$ 89.2 cm:

$$Q_e = 2.40^{-5}(H)^2 + 1.29^{-3}(H) \quad r = 0.980,\ R^2 = 0.992 \tag{2}$$

3. Z model, formula validity range: 21.0 cm $\leq$ H $\leq$ 105.0 cm:

$$Q_e = 1.60^{-5}(H)^2 + 2.89^{-4}(H) \quad r = 0.985,\ R^2 = 0.949 \tag{3}$$

The following symbols are used in Formulas (1), (2) and (3): Q_e ($dm^3 \cdot s^{-1}$)—effective flow; H (cm)—upper water depth above the bottom; P (cm)—height of the threshold beam marking the level of damming; R^2—coefficient of determination; r—correlation coefficient. The calculated values of statistical measures (r, R^2) indicate a very good representation of the actual flow conditions with the adopted equations. Using the developed formulas (1)–(3), the effective flow Q_e was calculated for the water depth, which determined the height of the threshold P for individual variants of the tested models. The results of the calculations are summarized in column 9 of Table 1. These values determine the flow above which there is effective self-regulation of the flow over the crest of the beams.

3.2. Total Flow Q_c

The measured discharge curves at variable damming height H in the upper stand for each tested regulator (S, U and Z) and different damming levels are presented in Figure 7. They contain the effective flow Q_e curves expressing the water losses of the valve made of five beams and the Q_r (regulatory) discharge curves above the tested beam installation variants. The tests were carried out with flow rates up to a maximum value of about 60 $dm^3 \cdot s^{-1}$.

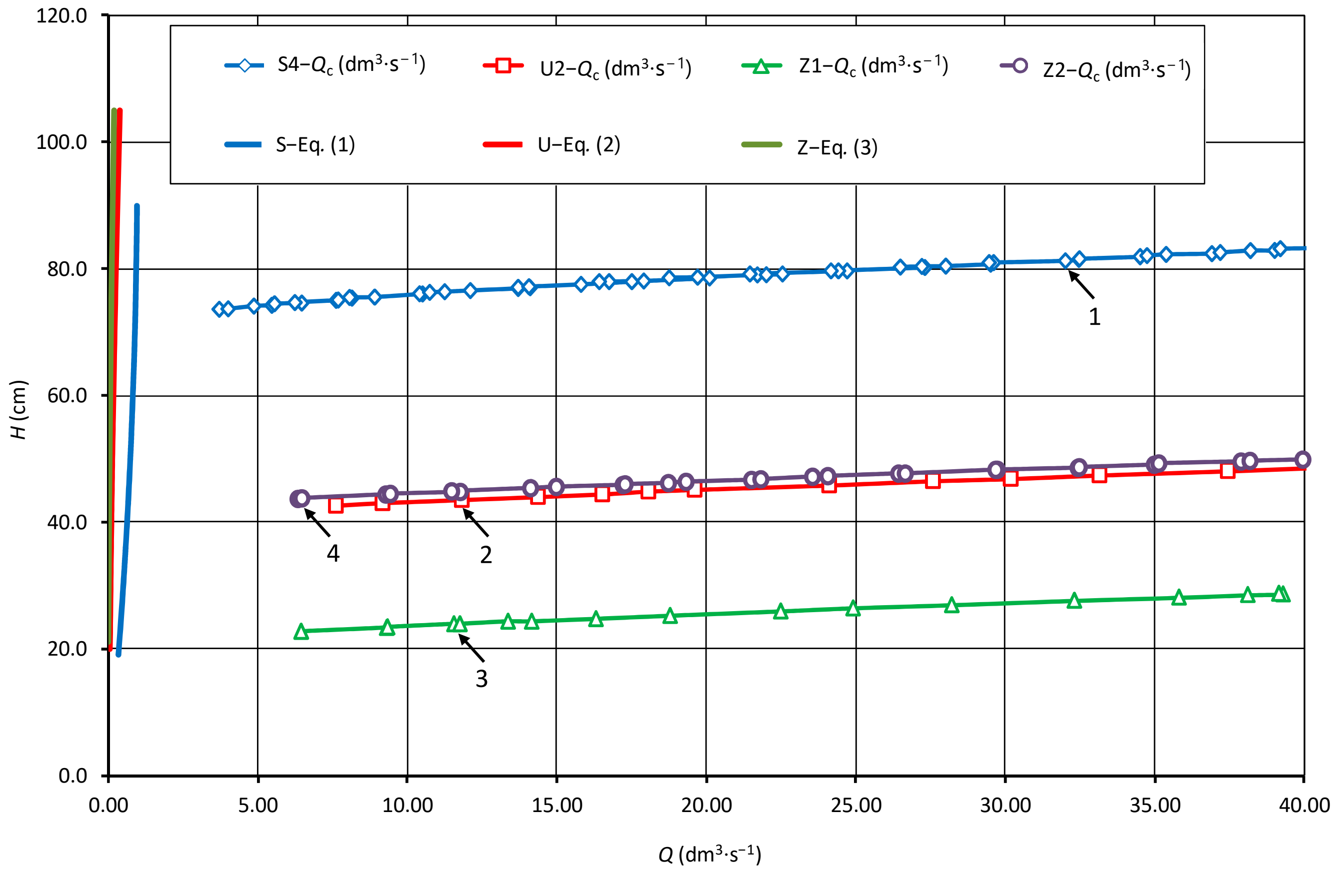


Figure 7. Discharge curves of regulators at different heights of the edge of the regulatory overflow: 1—variant S4; 2—variant U2; 3—variant Z1; 4—variant Z2.

The damming height above the overflow crest $(H - P)$ had the greatest variability when using the S-type beam, ranging from 0 to 14.9 cm, with the maximum flow amounting to Q_c = 55.9 $dm^3 \cdot s^{-1}$, and the smallest obtained with the use of the Z-type beam for the Z1 variant: filling $(H - P)$ = 8.2 cm with Q_c = 39.3 $dm^3 \cdot s^{-1}$. The characteristics of the total discharge of the U and Z valves were similar. Their design, compared to the S-type valve, ensured the stabilization of the position of the flooded water table to a greater extent at lower values of the effective flow Q_e (Figure 6).

The regulating flow curves ($Q_r = Q_c - Q_e^P$) for various P heights of the thresholds of the tested regulators are shown in Figure 8. The measurement results of the overflow discharge rate of the tested regulators were equalized with a non-linear model using the following equation:

$$Q_c = Q_r + Q_e^P = a_1(H - P)^{b_1} + a_2(H - P) + Q_e^P \quad (4)$$

where a_1, a_2 and b_1 are the coefficients in Equation (4) and are summarized in Table 2.

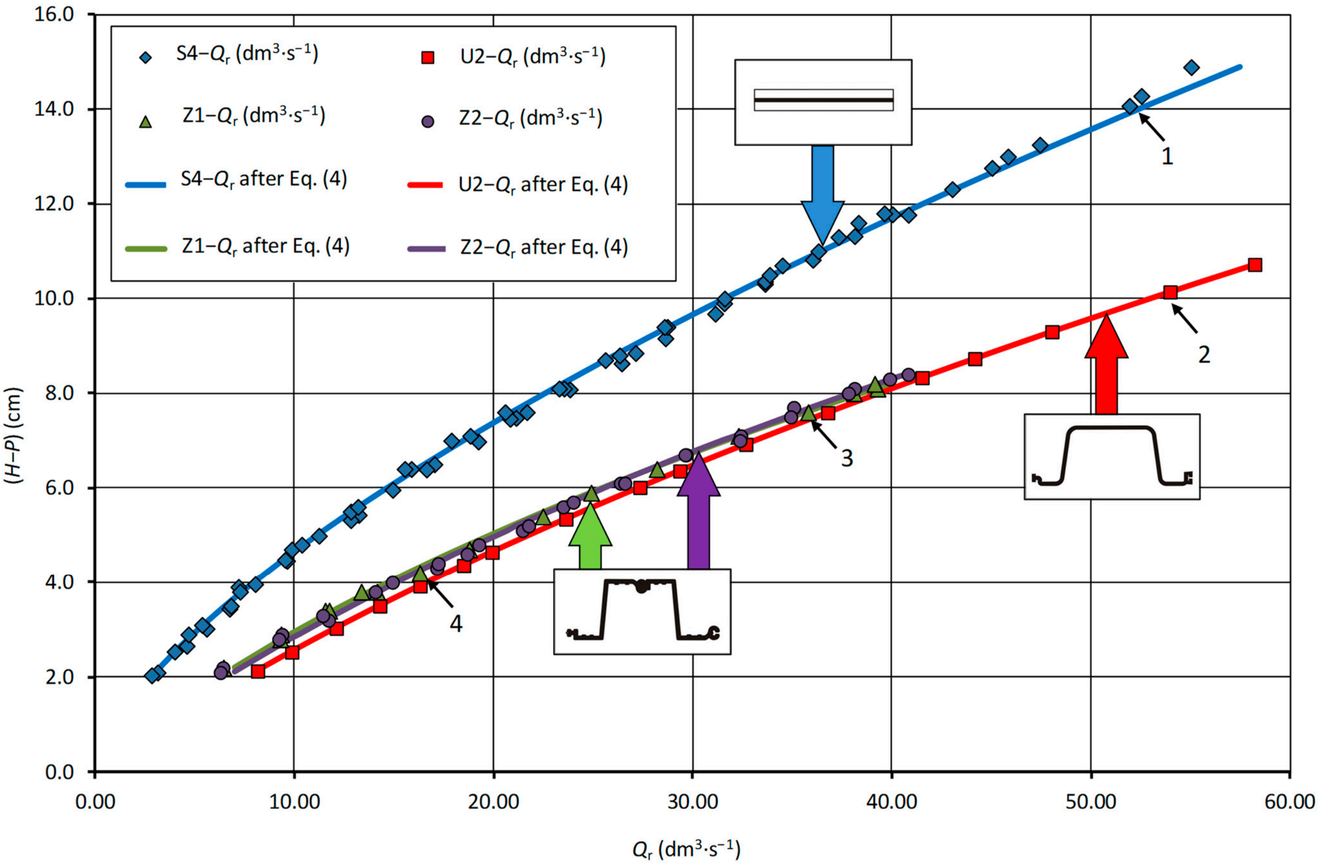


Figure 8. Discharge curves of beam regulators at different heights of the overflow edge position: 1—variant S4; 2—variant U2; 3—variant Z1; 4—variant Z2.

Table 2. Parameters of Equation (4) of regulation Q_r discharge curves.

No.	Parameter	S4	U2	Z1	Z2
1	2	3	4	5	6
1	a_1	1.0000	0.1871	0.2798	0.2408
2	a_2	0.0000	3.4250	2.5577	2.8244
3	b_1	1.50	2.0	2.0	2.0
4	Q_e (dm^3·s^{-1})	0.8794	0.0917	0.0126	0.0397
5	r	0.9956	0.9983	0.9984	0.9985
6	R^2	0.9987	0.9990	0.9987	0.9978
7	N	65	17	18	28
8	H_{min} (cm)	73.54	42.63	22.70	43.70
9	H_{max} (cm)	86.39	51.22	28.70	50.00
10	Q_{min} (dm^3·s^{-1})	3.700	7.600	6.440	6.310
11	Q_{max} (dm^3·s^{-1})	55.900	57.360	39.280	40.850

Abbreviations: r—linear correlation coefficient; R^2—coefficient of determination.

4. Discussion

The tested regulators, apart from the beam shape, differed in the width of the overflow opening between the vertical side limitations, that is, the beam gids. The hydraulic efficiency of the tested regulators was determined by the characteristics of the unit flow rate q (m^3·s^{-1}·m^{-1}) depending on the damming height above the overflow crest $(H - P)$. The unit flow rate $q_c = Q_c/b$ ($m^3 \cdot s^{-1} \cdot m^{-1}$) was calculated as the quotient of the total flow rate Q_c ($m^3 \cdot s^{-1}$) and the width b (m) of the opening between the regulator gibs (Table 1), the values of which were: b = 0.450 m for the S model (Figure 3); b = 0.588 m for the U model (Figure 4); b = 0.544 m for the Z model (Figure 5). The regulator with rectilinear closure S was adopted as the base structure to which the unit flows of other regulators were compared: U2, Z1 and Z2, with a crest line developed in the plan. In practice, more closure solutions were not able to be constructed in a focused, short-term project. The measurement points and the unit control flow regression curves $q_r = q_c - q_e$ for different damming levels of the tested regulators are shown in Figure 9. These curves are described by a non-linear model using Equation (4) with the coefficients in Table 2.

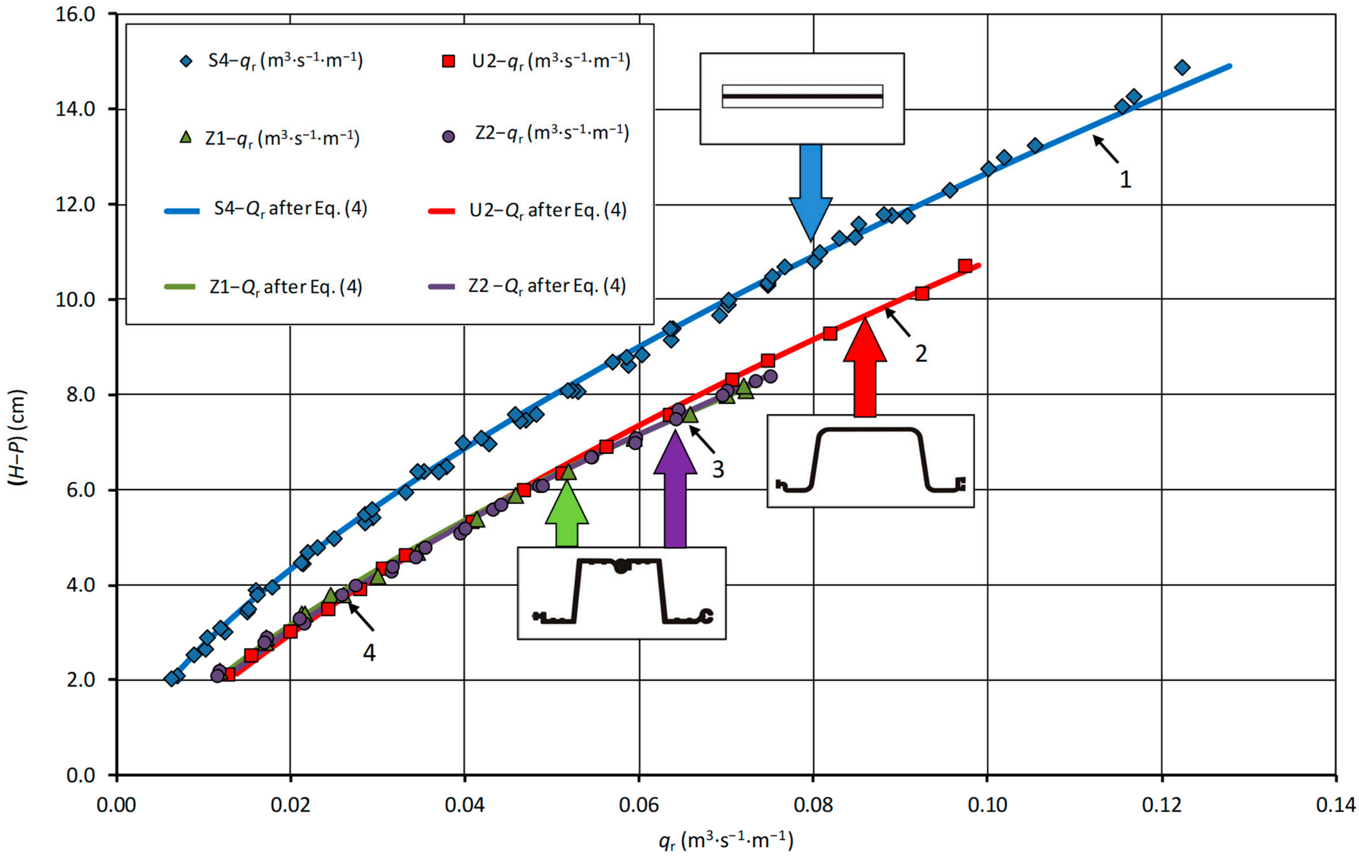


Figure 9. Unit flow rates of the tested regulator variants: 1—variant S4; 2—variant U2; 3—variant Z1; 4—variant Z2.

The effectiveness of water level control with the tested regulators is described by the k_q (–) coefficient of the unit flow increase factor. It takes into account the influence of the shape and development of the overflow in the plan on the capacity of the regulator. Using the k_q (–) factor, the flow through the U and Z controllers satisfies the relationship:

$$Q^b_{U,Z} = k_q \times Q^b_S \quad (5)$$

where $Q^b_{U,Z}$ is the flow rate through U- and Z-type regulators for a module (beam) with width b, k_q is the flow rate increase coefficient, and Q^b_S is the flow rate through the S-type regulator for the module width b.

The coefficient $k_{qi} = q_i/q_{Si}$ (–) was calculated as the ratio of q_i of the unit flow rate of the regulators U2, Z1 and Z2, with a developed shape, to q_{Si} of the unit flow rate of the rectilinear S regulator, with the same value $(H - P)$ and water depth in the top position. Figure 10 shows the values of the coefficient k_{qi} of the increase in flow calculated for the measuring points and the curves of changes in this coefficient, calculated according to the developed regression equations $k_{qF(i)} = F_{qi}/F_{qSi}$ described by Equation (4) with the parameters in Table 2, where: F_{qi}—unit flow rate calculated according to the function $F_{qi} = F(H-P)_i$ and developed for variants U2, Z1 and Z2; F_{qSi}—unit flow rate according to $F_{qSi} = F(H-P)_{Si}$ of the function for variants S1 and S2. The approximation curves developed according to Formula (4) were used to extrapolate the value of the k_{qi} (–) coefficient into the filling zone $(H-P)$ above the test range.

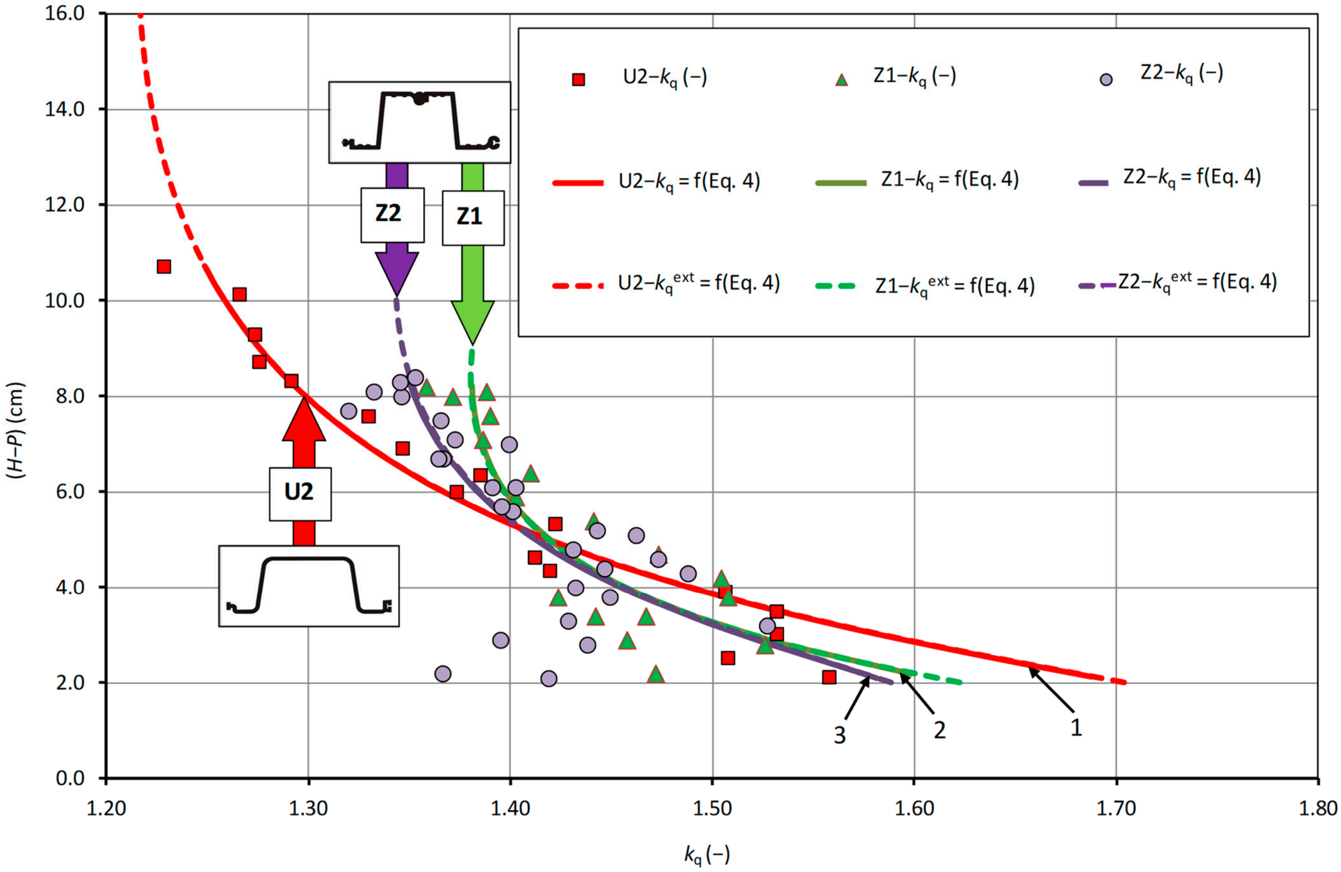


Figure 10. Coefficient of increase in unit flow rate: 1—U2/S2 according to Equation (4); 2—Z1/S1 according to Equation (4); 3—Z2/S2 according to Equation (4).

The tested U and Z models are characterized by similar conditions of the impact of the shape of the overflow and the development of its crest line on the obtained increase in the unit flow rate. The maximum value of the unit flow increase factor occurs when the filling is slightly above the overflow crest. Above 5.0 cm filling, the impact of developing the overflow line decreases. The value of the growth factor stabilizes at fillings $(H-P)$ greater than those included in the scope of the tests.

For the U2 variant (line 1 in Figure 10), the unit flow rate increase coefficient reaches the highest value of 1.70 for a filling of 2.0 cm above the crest. Then, its value decreases to 1.25 in the measuring range at about 11.0 cm, and a further decrease to 1.22 occurs when extrapolating the curves to the height $(H-P)$ = 16.0 cm. The Z model is characterized by a gradual decrease in the value of the flow increase coefficient k_q. Initially, up to a height $(H-P)$ of about 5.0 cm, the variability in the k_q coefficient for variants Z1 and Z2 is almost identical. After exceeding 5.0 cm for variant Z1 (line 2 in Figure 10), there is a further continuous but slight decrease in the value of the k_q coefficient. In the scope of the tested fillings at 8.0 cm, the value of the factor is 1.38. Assuming larger fillings (up to 9.0 cm), the factor remains at the same level of 1.38. For the Z2 variant (line 3 in Figure 10), after exceeding a height $(H-P)$ of 8.0 cm, the influence of the curvature of the overflow edge disappears, and the value of the k_q coefficient stabilizes at a level of about 1.35. The different courses of the k_q curves for variants Z1 and Z2 for the filling above 8.0 cm indicate that the regulating properties of the beam regulators depend on the height of their threshold.

5. Summary and Conclusions

This article describes a pilot study on a new generation of water-damming regulators in drainage ditches with rectilinear beam closures and a developed shape in the plan. They are considered potential innovative solutions, the design of which is not well known, and there are no publications available on such solutions. Therefore, the final conclusions were developed solely on the basis of the results of our own research and comparative calculations. Only the basic hydraulic characteristics of the tested prototypes of regulators were developed. None of the generalized dimensionless hydraulic relationships were presented because the tests were limited to fixed dimensions without modifications or changes in the sizes of the main regulators' elements.

Based on the conducted research of regulators, the following conclusions and recommendations were formulated:

1. The tested regulators are suitable for damming water in ditches at flows equal to and greater than the effective flow, that is, equal to the water losses due to leakages. The S regulator with rectilinear beams of closures has $4 \div 5$ times greater effective flow compared to other regulators, so the most effective are devices of types U and Z, which are recommended for practical use.
2. Regulators with beam closures with a developed shape are characterized by greater efficiency in regulating the position of the water table in comparison to the S-type regulator. Their design ensured stabilization of the position of the backwater table, with lower values of the effective flow Q_e and the damming height $(H - P)$. This was the result of both greater tightness of the connections of their elements, as well as the development of the overflow crest in the plan.
3. The use of the expansion of the overflow crest in the plan in U-type and Z-type regulators increased the hydraulic efficiency of these devices, expressed by the k_q coefficient of unit flow increase, especially at overflow layer heights of up to 5.0 cm. For heights greater than 5.0 cm, the beams of the Z2 type with an angular corner shape were characterized by a lower value of the flow increase coefficient $k_q = 1.25$ than the Z1-type beams with a curvilinear shape, for which $k_q \in <1.35 \div 1.38>$.
4. It is recommended to conduct further detailed tests with the use of regulators with the described structure and a wider range of beam shapes and hydraulic conditions, that is, the flow rate and damming height. The result of these studies would be the development of dimensionless modular characteristics for the series of regulator types with different damming heights. It is also recommended to include numerical modeling of the regulators in analyses of this type, which would replace toilsome laboratory tests.

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