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CLASSIFICATION OF FLOWS IN THE VICINITY OF A SIDE WEIR WITH THROTTLING PIPE

In order to classify this flow, investigations were carried out on hydraulic models in the linear scale of $\xi_l = 15$ and $\xi_l = 5$. The authors suggest that the flow classification applied to open channels should be expanded by incorporating an additional factor – a spatially varied unsteady flow, which exists in the side weir. Making use of the relationship between bed slope and critical bed slope, as well as of that between edge depth and critical flow depth, and assuming them as classifying criteria, the authors distinguish four groups of flow in the investigated side weir with throttling pipe. Model investigations have revealed the occurrence of an unsteady flow, which varies in space. Such a flow type is not included in the available classifications.

DENOTATIONS

A – surface area of the channel cross-section, m^2,
b – channel width, m,
d_r – diameter of discharge adjusting pipe, m,
g – acceleration of gravity, m/s^2,
h_p – hydraulic head at the begining of the overfall edge, m,
h_k – hydraulic head at the end of the overfall edge, m,
H – depth of the inflow channel, m
H_{cr} – critical depth of the channel, m,
H_n – normal depth (uniform flow) of the inflow channel, m,
H_x – depth of the channel in the point x, m,
i – bed slope,
i_{cr} – critical sloping of the inlet channel,
J – sloping of energy line of inlet channel,
J_r – sloping of energy line of discharge-adjusting pipe,
l – length, m,
l_p – length of overfall edge, m,
l_c – backwater reaches, m,

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l_r – length of discharge-adjusting pipe, m,
n – coefficient in Manning's formula (channel roughness), s/m$^{1/3}$,
p – weir edge height, m,
q – simple discharge over weir edge, m^3/s·m,
Q – discharge over weir edge, m^3/s,
Q_d – inflow discharge, m^3/s,
Q_o – discharge from adjusting pipe, m^3/s,
R_h – hydraulic radius ($R_h = A/U$), m,
U – wetted perimeter, m,
α – Coriolis coefficient,
β – Boussinesq coefficient,
μ – discharge coefficient,
ΔH_o – head loss during flow in discharge-adjusting pipe, m,
ξ_l – linear scale (length); $\xi_l = l_N/l_{M7.}$,
ξ_Q – discharge scale; $\xi_Q = \xi_l^{\,2.5}$,
η – empirical coefficient.

SUBSCRIPTS

mx – maximum,
M – model,
N – nature.

1. INTRODUCTION

In a combined sewerage system the storm overflow serves two major purposes – it protects a wastewater treatment plant against hydraulic overloading during heavy rains and allows the size of the collectors to be reduced. When used in semi-separate systems, the storm overflow acts as a wastewater separator. In storm sewers the storm overflow may be of utility in discharging some portion of the rainwater to an impoundment lake.

The storm overflow system begins to work when the depth of the flow in the inlet channel has exceeded the depth of the weir edge. At a computational flow Q_d in the channel, the storm overflow is to split the discharge Q_d into two portions Q and Q_o (with Q leaving the channel over the weir edge and Q_o remaining in the channel). To maintain the anticipated flow regime in the weir use is made of a throttling pipe (with a diameter d_r and a length l_r; figure 1), which stabilizes the discharge Q_o within certain limits. The hydraulic efficiency of the throttling pipe is only slightly affected by the flow depth of the channel ($Q_o = f_1\,(\Delta H_o^{\,1/2})$) compared to the hydraulic efficiency of unrestricted flow over the side weir ($Q = f_2\,(H - p)^{3/2}$).

The available methods for the hydraulic dimensioning of side weirs with throttling pipe neglect the type of flow and the variation of the flow depth in the vicinity of the weir; flow depth along the weir edge is generally assumed to be constant. Needless to say that such simplifications may promote considerable computational errors.

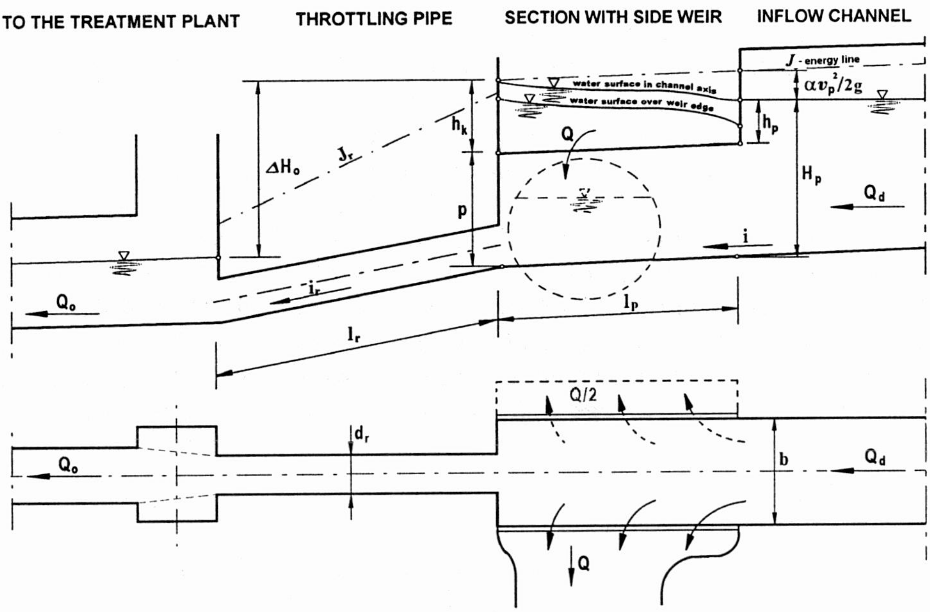


Fig. 1. Side weir with throttling pipe

The objective of our study was to investigate the hydraulic phenomena that occurred in a side weir with throttling pipe. Measurements were carried out on two hydraulic models ($\xi_l = 15$ and $\xi_l = 5$) at the Wrocław University of Technology and the Wrocław School of Agriculture.

The study has led to the following finding: the flow depth in the channel axis should be determined, using appropriate differential equations – such that incorporate a term describing the non-uniformity of flow with mass variations.

2. DEFINITIONS AND CLASSIFICATION OF FLOWS WITHIN THE WEIR

In side weirs with discharge adjustment, three types of flow can be distinguished:

- flow characterized by the existence of a free surface (the water surface) in the inflow channel and in the weir chamber,
- unrestricted flow over the weir edge,
- pressure flow in the throttling pipe.

The first two types will be analyzed in the present study. The third type can be regarded as well understood physically.

Channel flow with a free surface is induced by gravitation. Some sections of the sewer pipes are characterized by a constant cross-section, an invariable bed slope and a generally constant wall roughness. The problem of flow at free surface and under atmospheric pressure is sophisticated because flow depth, discharge, bed slope and free surface profile affect one another noticeably. The position of the free surface along the flow path varies with time and with each change in the discharge. And this is what makes the classification of the flows in the vicinity of side weir a difficult task. In general, it is convenient to make use of the classification proposed by CHOW [1] or HENDERSON [2] with some modifications suggested by CHADWICK and MORFETT [3] or DOŁĘGA and ROGALA [4], [5]. Assuming that the flow depth in the channel axis is a basic parameter describing the flow in a channel with a free surface, we can classify flow as being steady or unsteady (figure 2). A flow is steady if flow depth does not vary with time along the cross-section through which it passes. Conversely, a flow is unsteady if this parameter does vary with time. Wastewater flow in a channel can be categorized (within a short timespan) either as steady or unsteady, specifically in combined sewerage systems and storm sewers during rainfall.

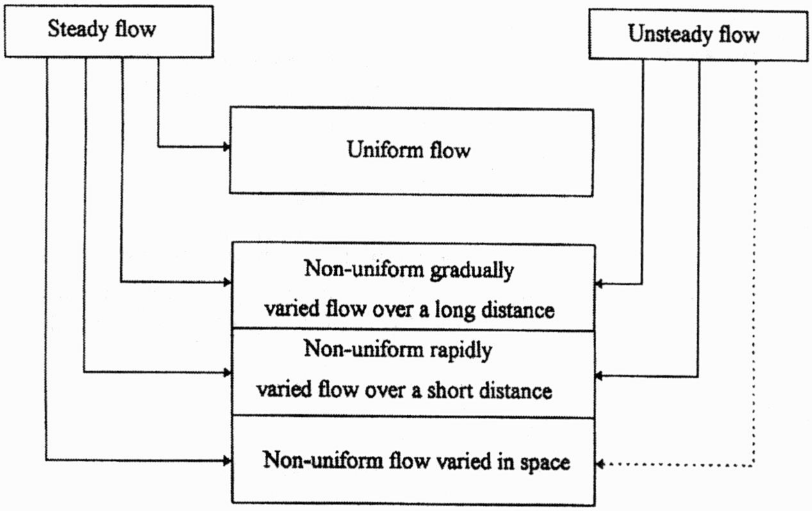


Fig. 2. Classification of flows in an open channel (supplemented by the authors of the paper – dashed line)

In engineering, for the design of channels or storm overflows, the flow regime at computational discharge is generally regarded as being steady (temporarily invariable) and representative as a criterion for determining the geometry of a channel or weir. Our model investigations made use of this assumption. Measurements were carried out by discretely varying the discharge Q_d (inflow to the weir chamber), discharge Q_o (outflow through the throttling pipe), and discharge Q (outflow over the weir edge), and in fact the proportions of Q_o and Q_d.

Uniform flow is characterized by the parallelism of the channel bed, free surface position and energy line; velocity distributions do not vary in the cross-sections of the channel. These conditions are not satisfied at non-uniform flow. Thus, if changes in the flow regime occur slowly on a long flow path, the flow is gradually varied. Conversely, whenever the flow regime experiences some rapid changes along a short flow path, the flow is classified as rapidly varied.

Spatially varied flow occurs if the streams in the weir chamber differ in the direction of flow, and discharge varies along the chamber length. This type of flow appears in the chamber of the side weir where the stream mass splits along the weir edge. The model investigations [6]–[8] of a side weir with discharge adjustment discussed in this paper have revealed the presence of an unsteady, spatially varied flow, which is not included in the available classifications (figure 2).

3. ANALYSIS OF FLOWS IN SIDE WEIR MODELS

Figures 3 and 4 show the hydraulics of side weirs incorporating one or two overfall edges and a throttling pipe (for discharge adjustment), which were subject to model investigations. In the model the following design parameters were varied:

- bed slope ($i \in \{1,5,10\}‰$),
- height of the edge above the channel bed ($p \in \{b/4, b/2, 3b/4\}$),
- lengths of overfall edges ($l_p \in \{b, 2b, 3b\}$),
- shape of the inflow channel cross-section,
- length and diameter of the throttling pipe.

On the basis of the results obtained the flows were categorized into four major groups. The criterion adopted for this categorization included the bed slope (i) of the inflow channel and the height (p) of the overfall edge, related to the critical bed slope (i_{cr}) and to the critical flow depth (H_{cr}) which corresponded to the inflow discharge Q_d. The data in the table are the measured values [7] for a single-edge side weir in a channel of a rectangular cross-section ($\xi_l = 15$).

Thus, the critical depth of the inflow channel is given by

$$H_{cr} = \sqrt[3]{\frac{\alpha Q_d^2}{g b^2}}. \tag{1}$$

The Chezy equation was used to determine the critical slope associated with the critical depth. Thus, we have

$$i_{cr} = \frac{gU}{C^2 \alpha b}, \tag{2}$$

where $C = n^{-1} R_h^{1/6}$ is an expression from Manning's formula.

The parameters of the critical flow take the following values ($b_M = 0.1$ m; $b_N = 1.5$ m):
$H_{crM} = 22.3$ mm ($H_{crN} = 0.33$ m), $i_{cr} = 4.1$ ‰ at $Q_{dM} = 1$ dm^3/s ($Q_{dN} = 0.87$ m^3/s),
$H_{crM} = 35.3$ mm ($H_{crN} = 0.53$ m), $i_{cr} = 4.4$ ‰ at $Q_{dM} = 2$ dm^3/s ($Q_{dN} = 1.74$ m^3/s),
$H_{crM} = 46.7$ mm ($H_{crN} = 0.70$ m), $i_{cr} = 4.7$ ‰ at $Q_{dM} = 3$ dm^3/s ($Q_{dN} = 2.61$ m^3/s).

The coefficient of kinetic energy α incorporated in (1) and (2) was assessed to be 1.1. Use was made of the velocity distributions measured in the cross-section of the upstream end of the inflow channel (before the weir).

Table

Hydraulic parameters of the model for the four groups of flow
in the vicinity of a single-edge side weir in a rectangular channel (b = 100 mm)

Group of flow	Relation between		Investigated range of			Quantity series	
	Bed slope i	Weir edge height p	Bed slope i (‰)	Weir edge height p (mm)	Discharge Q_d (dm³/s)	Q_o/Q_d	Total
I	$i < i_{cr}$	$p \geq H_{cr}$	1	27	1	12	84
				52; 77	1; 2; 3	72	
II	$i \geq i_{cr}$	$p \geq H_{cr}$	5; 10	27	1	24	168
				52; 77	1; 2; 3	144	
III	$i < i_{cr}$	$p < H_{cr}$	1	27	2; 3	24	24
IV	$i \geq i_{cr}$	$p < H_{cr}$	5; 10	27	2; 3	48	48
					Total	324	324

The upstream end of the inflow channel exhibits a steady uniform flow which is subcritical for group I and group III flows, and supercritical for group II and group IV flows. This should be attributed to an appropriate relation between the flow depth of the inflow channel and the critical bed slope (table). In the immediate vicinity of the weir, flow was unsteady, depth and velocity distribution were varied, and there was no parallelism of bed line, free surface position and energy line.

For group I and group II, the flow path along which these variations occur is long, so we deal here with gradually varied (retarded) flow (figure 3). The side weir with its elevated edge ($p \geq H_{cr}(Q_d)$) – and particularly the vertical wall at the end of the chamber with a small opening to the throttling pipe (compared to the chamber cross-section) – is responsible for the local flow disturbance, which exerts an influence upstream from the channel as far as to the origin of the backwater curve (l_c). Backwater reaches its maximum value ($l_{c\,mx}$) at the cut-off outflow from the throttling element ($Q_o = 0$). In this part of the channel, flow velocity and hydraulic losses decrease, thus contributing to energy conversion from kinetic to potential, which is primarily needed to provide unrestricted flow over the weir edge (discharge Q) and (to a smaller extent) to overcome the resistance of flow in the throttling pipe (discharge Q_o).

At a bed slope $i < i_{cr}$, flow depth along the section l_c follows the pattern of the M_1 -type curve (group I flows – figure 3a), whereas at $i \sim i_{cr}$ and $i > i_{cr}$ it behaves according to the curve C_1 and curve S_1, respectively (group II flows – figure 3b). These curves [1], [4], [9] represent the upper zone of channel flow (retarded flow). In the immediate vicinity of the chamber, the asymptote of the curves is a horizontal line.

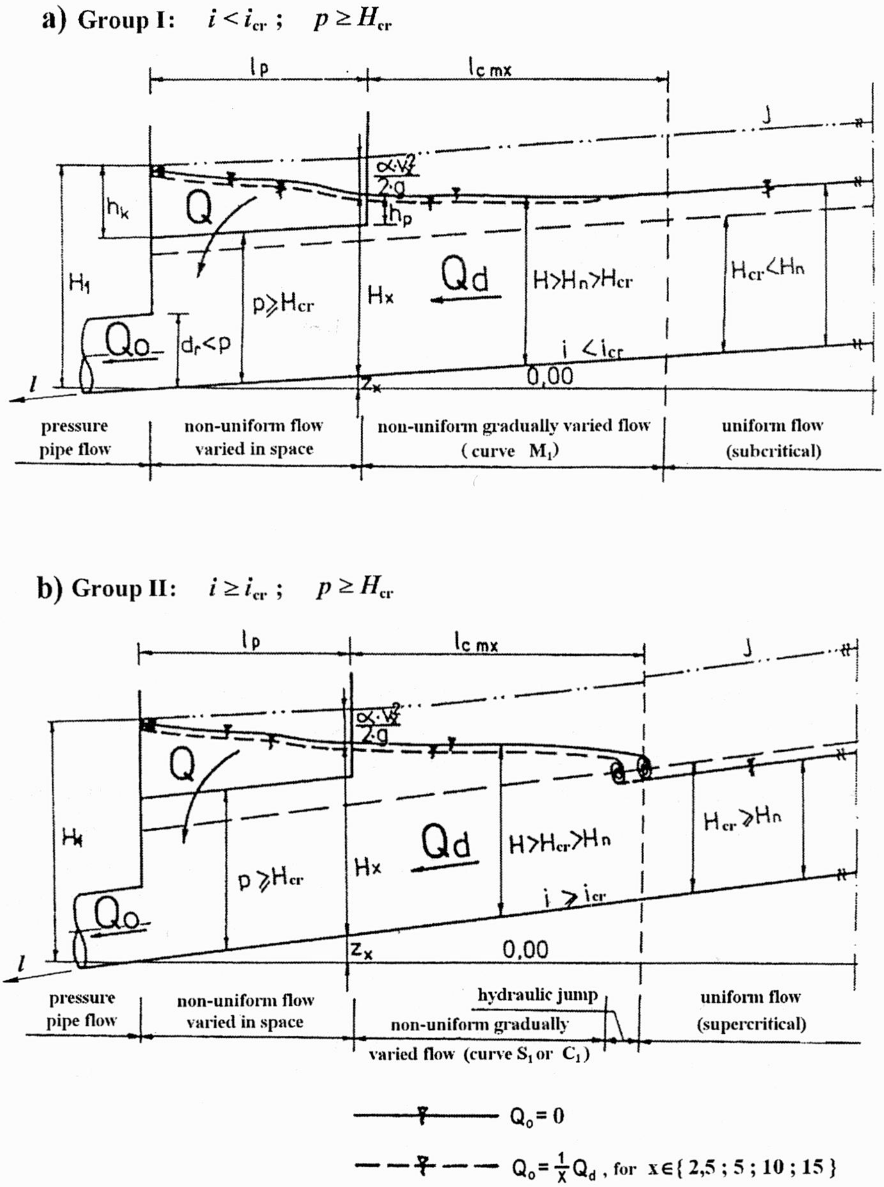


Fig. 3. Hydraulics of a side weir with throttling pipe for group I and group II flows

In the chamber, irrespective of the group of flow, there occurs spatially-varied fluid motion characterized by a considerable turbulence of the elementary streams along the weir edge (after separation from the main stream).

Free surface measured in the chamber axis rises mildly for group I and group II flows. This rise hardly ever initiates at the point x of the weir chamber (figure 3). Along the length of the chamber (from about 5 to about 15%), the water surface profile forms a natural extension of the M_1, C_1 or S_1 curves (each of them being an approximately horizontal line). In the initial section of the chamber, the elementary streams, which leave the main stream, show distinctly varied crookings. Investigations of the $\xi_l = 5$ model showed that the deflection angles for the elementary streams ranged from about 45° to about 75° in the initial sections of the weir edge [6], [10]. As a result, the unit hydraulic load of the edge in the initial part of the weir was lower than the average value ($\overline{q} = Q/l_p$):

$$q = q(l) = \frac{dQ}{dl} = \frac{2}{3}\mu\sqrt{2g}(H - p)^{3/2}, \tag{3}$$

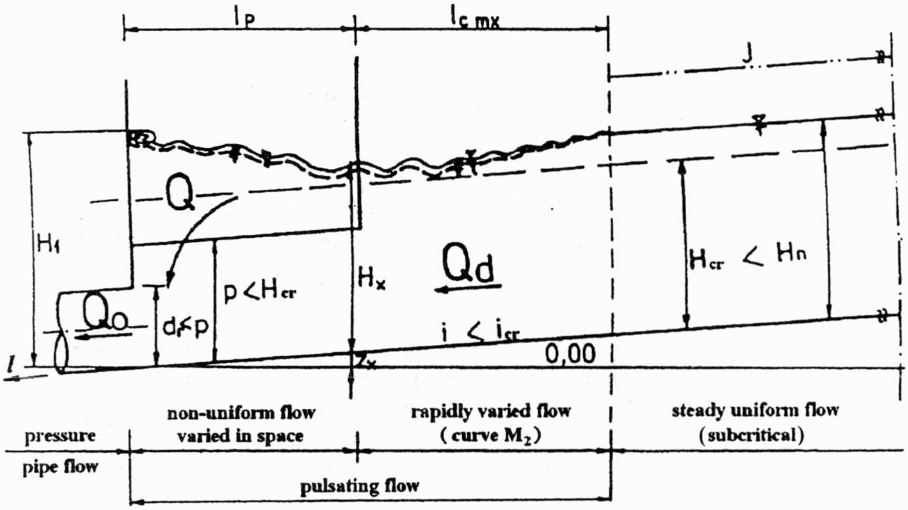
$$Q = Q_d - \int_0^{l_p} q\, dl. \tag{4}$$

Along the remaining portion of the weir length (from about 85 to about 95%) free surface rises systematically. This rise (more pronounced at the initial stage and then decreasing) is concomitant with an increase in the deflection angles for the elementary streams from about 75° to about 90°. As a result, the unit hydraulic load of the edge reaches its maximum value at the end of the weir. At a short length of the weir, at a high discharge Q and a low discharge Q_o, a hydraulic jump is likely to appear near the vertical wall in the end section of the chamber.

In the investigated range of Q_o/Q_d variations (from 1/2.5 to 1/15, which is also used in engineering), the throttling pipe had little effect on the adopted categorization of the flows [11]–[14]. At $Q_o = 0$ (when the inlet to the adjusting pipe was closed) and with the increasing value of Q_o, flow depth before and in the chamber was found to decrease systematically, and there was a concurrent shortening of the backwater section length (figure 3). This finding allows the following hypothesis to be put forward: unrestricted flow over the weir crest (appropriate flow depth above the overfall) is a phenomenon that dominates within the weir and affects the discharge through the throttling pipe (figure 1). At the initial stage of the model study, variations in the proportion of Q_o and Q_d were induced by varying the head loss (ΔH_o) in the throttling pipe. But the same effect was achieved by gate valve control in the inlet part of the throttling pipe.

Analysis of the phenomena associated with group III and group IV flows in the vicinity of the side weir poses certain problems because of the unstability of the flow in the model. Hence, for group III ($i < i_{cr}$; $p < H_{cr}$; figure 4a), and specifically for group IV ($i \geq i_{cr}$; $p < H_{cr}$; figure 4b), the section of backwater (l_c) before the weir either has

a) Group III: $i < i_{cr}$; $p < H_{cr}$



b) Group IV: $i \geq i_{cr}$; $p < H_{cr}$

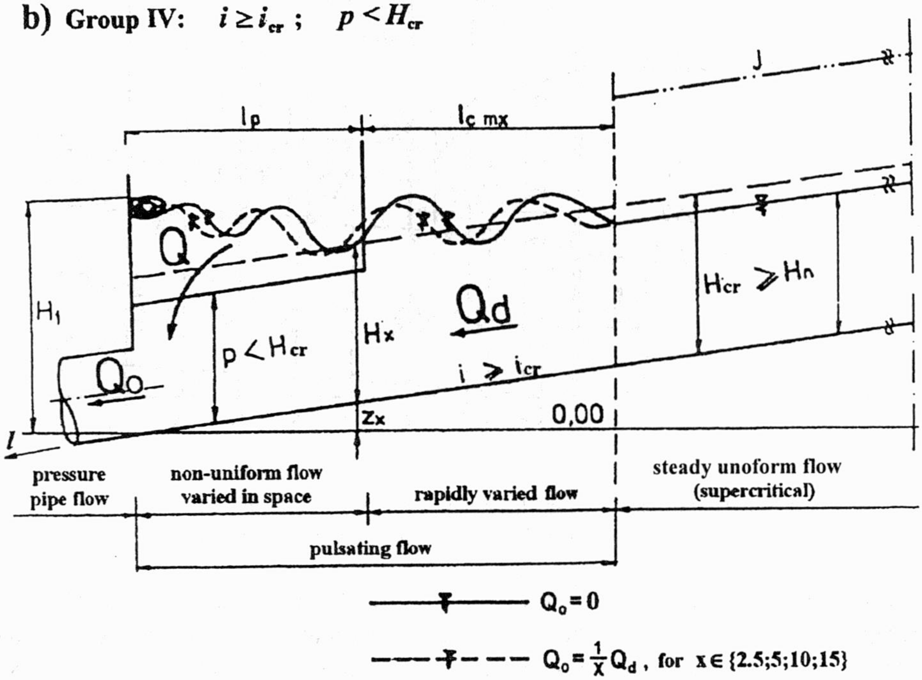


Fig. 4. Hydraulics of a side weir with throttling pipe for group III and group IV flows

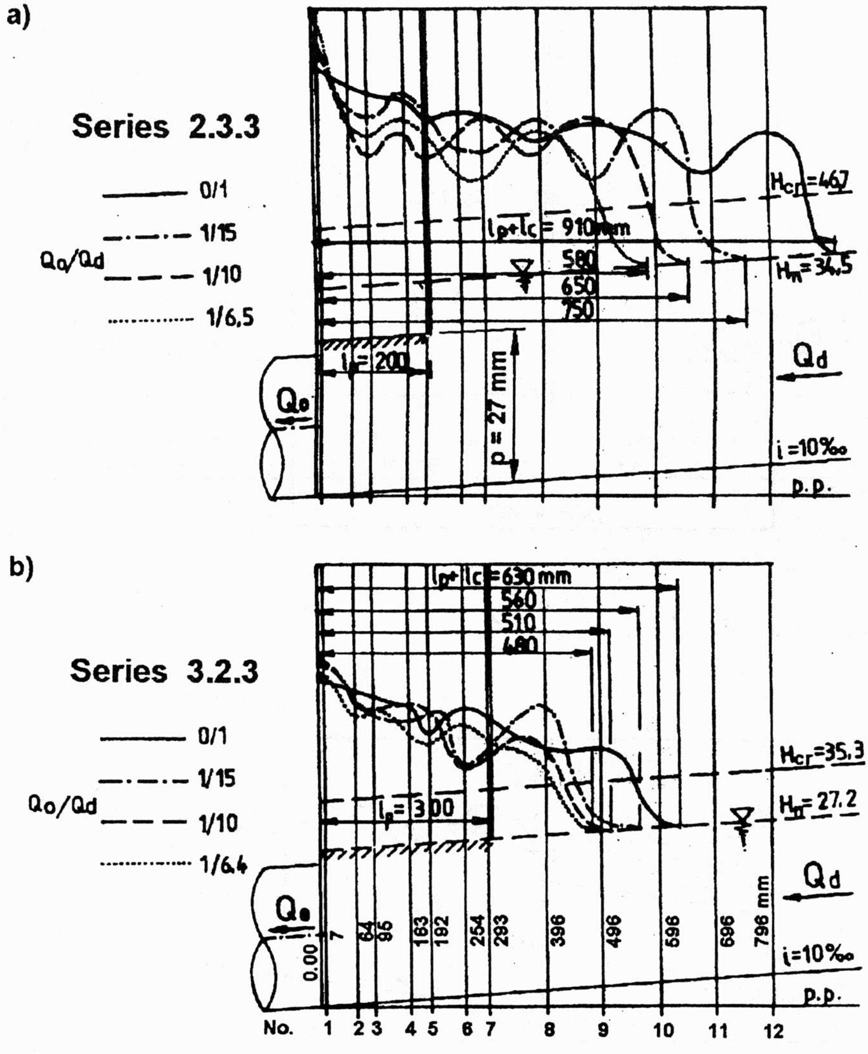


Fig. 5. Flow depth measured in channel axis for group IV flows ($i > i_{cr}$; $p < H_{cr}$);
$l_p = 200$ mm, $Q_d = 3$ dm^3/s, $l_p = 300$ mm, $Q_d = 2$ dm^3/s

a short length or is practically absent. For group III, the backwater section (l_c) is characterized by a gradually varied flow and decreasing water depth (depression curve of M_2-type [1], [4], [9], which pertains to the central zone of channel flow. Water surface within the weir chamber varies noticeably, and the hydraulic jump in the end section of the weir does not allow precise flow depth measurements. As far as group IV is concerned, the short l_c section before the weir exhibits non-uniform rapidly varied flow, accounting for rapid depth variations, which are of a pulsating nature. Within the weir chamber there are hydraulic jumps in the end section. These phenomena permit neither precise measurements nor quantifications to be made. Group IV flows are shown in figure 5.

All the phenomena concomitant with group III and group IV flows in side weirs with low overfall edges ($p < H_{cr}(Q_d)$) can be attributed to the rapid changes in the available energy of the main stream – both outside and inside the chamber. Those variations are responsible for the "pulsating" nature of the water surface. Our study of group III and group IV flow conditions is of a preliminary nature only, because in engineering the edges of the storm overflows are set at $p > H_{cr}(Q_d)$ so as to utilize the retention capacity of the channels, thus reducing the frequency and shortening the duration of water discharge or traction of mineral matter. This is of particular importance to the protection of the recipient stream against excess pollution.

4. CONCLUSIONS

At given discharge Q_d, the relation between the slope of the inlet channel and the critical bed slope is insufficient to allow the determination of the flow type (sub- or supercritical) in the vicinity of the side weir or the prediction of water surface variations along the weir edge (backwater curve and depression curve). And such assumptions have been adopted so far by the majority of investigators. However, at given discharge it is necessary to analyze the relationship between edge height and critical height in the channel. The performance of a side weir with discharge adjustment and increased elevation of the edge ($p > H_{cr}(Q_d)$) does not depend on the bed slope to critical bed slope ratio when Q_d is given (subcritical flows of group I and group II). In that particular case we deal with one weir performance pattern, i.e. with a backwater curve which has a generally upward directed slope. In the inlet channel, before the weir, there is non-uniform gradually varied flow with H-values higher than normal (H_n; uniform flow). The occurrence of this type of flow at $i < i_{cr}$ (group I) is conditioned by the fulfilment of the relation $H_x = p + h_p > H_n\,(Q_d)$ in the initial cross-section of the chamber (figure 3a). The flow in the chamber is spatially varied, which is due to the separation of the elementary streams from the main stream. In the chamber axis there is a mild increase in flow depth, typical of gradually varied flow. Immediately above the edge, unrestricted flow displays the features of rapidly varied flow. In the side weir it is impossible to establish the point of transition from gradually varied to rapidly varied flow. So far, the type of flow has been determined by comparison of features with respect to uniform flow. Presently, the differential equations for non-uniform flow with mass variation, which include some empirical coefficients describing the specific performance of side weirs with discharge adjustment, are regarded as best suited to determining the flow depth in the weir chamber axis [10]:

$$\frac{dH}{dl} = \frac{i - J - \left[(2\beta - \eta)\,Q\,\dfrac{dQ}{dl} + Q^2\,\dfrac{d\beta}{dl}\right]\dfrac{1}{gA^2}}{1 - \beta\,\dfrac{Q^2 b}{gA^3}}. \tag{5}$$

Analysis of the boundary conditions included in the proposed classification of flows in side weirs has substantiated the importance of such parameters as bed slope (i) and energy loss due to friction (J) in the equation of motion. If these parameters are neglected (especially i), or if they are assumed to be equal ($i = J$), the equation will not apply to the non-uniform flow in the inlet channel in the immediate vicinity of, and particularly within, the weir chamber.

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KLASYFIKACJA PRZEPŁYWÓW W OBRĘBIE PRZELEWU BOCZNEGO Z RURĄ DŁAWIĄCĄ

Dokonano klasyfikacji przepływów w obrębie przelewu bocznego na podstawie badań modelowych, prowadzonych na modelach hydraulicznych w skali geometrycznej $\xi_l = 15$ i $\xi_l = 5$. Wyodrębniono cztery grupy przepływów w obrębie przelewu bocznego z rurą dławiącą, biorąc za kryterium podziału relacje spadku dna kanału do spadku krytycznego oraz relacje wysokości krawędzi przelewowej do wypełnienia krytycznego w kanale dopływowym. Omówiono warunki działania przelewu bocznego w czterech wyodrębnionych grupach. Zaproponowano uzupełnienie klasycznej klasyfikacji przepływów w kanałach otwartych o przestrzennie zmienny ruch nieustalony występujący na przelewie bocznym.