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Experimental observations of gradually varied flow formation in compound channels

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ABSTRACT: Compound section is a general shape for cross section of rivers and natural channels. Flow pattern in compound channels can be very complicated because of the significant difference between depth and velocity in main channel and those in floodplains. Although a two-dimensional (2-D) flow pattern is dominant in many flow situations, one-dimensional (1-D) analysis of flow through compound channels is a common practice for engineers. Many classical concepts and definitions such as critical depth, Froude number and slope classification result from a 1-D analysis of flow. In this regard, an interesting 1-D concept is the possibility of occurrence of multiple critical depths in compound channels which consequently results in the possible formation of five different types of water surface profiles, rather than three typical types in single channels. This research is a study on the agreement between visual observations of flow pattern in compound channels with flow behavior predicted by 1-D analysis of flow. To achieve this, experiments were conducted in a straight fixed-bed laboratory compound channel with rectangular main channel and floodplains having homogeneous roughness, under two different slopes representing mild and steep conditions. Different flow patterns of gradually-varied and rapidly-varied flow including hydraulic jump were developed. This was done by adjusting discharge and boundary condition in the channel. The details of experimental observations are presented. In general it can be concluded that flow pattern predicted by 1-D analysis shows a reasonable agreement with the experimental observations in the case of a backwater formation when depth increases in the direction of flow. Conversely, less agreement is observed in the case of drawdown curves, which is an indication of 2-D dominated flow in these situations.

1 INTRODUCTION

Rivers and natural channels usually flow through two stage or compound channels. A compound channel (Fig. 1) consists of a main river channel that carries low flows and one or two floodplains with different roughness, compared with main channel, that contribute to conveyance of over bank flows during flooding. Due to the abrupt changes in the geometry and roughness in compound sections, the average flow velocities of sub-sections are very different. This significant lateral velocity gradient produces an apparent shear stress and considerable momentum and mass transfer between the main channel and floodplains which is the main factor for the formation of two-dimensional (2-D) flow patterns.

Although a 2-D flow pattern is dominant in many flow situations, one-dimensional (1-D) analysis of flow through compound channels is a common practice for engineers working in flood control and river treatment projects. Therefore, engineers and researchers find themselves confronted by the question of agreement between the results of 1-D analysis with actual 2-D or 3-D hydraulic behavior of flow in compound channels.

Many classical concepts and definitions, such as critical depths, Froude number and slope classification result from a 1-D analysis of flow. In this regard, an interesting 1-D concept is the possibility of occurrence of multiple critical depths in compound channels which consequently results in the possible formation of five different types of water surface profiles, rather than three typical profiles in single channels. In the 1-D analysis of flow through compound channels, based on 1-D concepts and calculated multiple critical depths, a specific combination of rapidly and gradually varied flow profiles is predicted along the channel. This research is an attempt to investigate the agreement between this predicted flow behavior and actual formation of patterns in a laboratory compound channel.

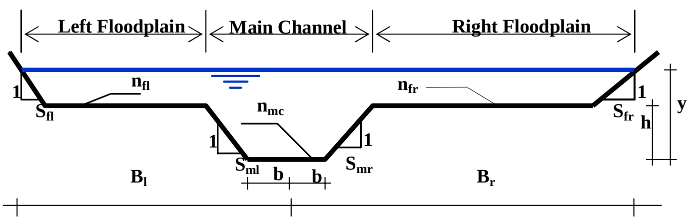

Figure 1. Compound channel cross section (geometry and terminology).

2. MULTIPLE CRITICAL DEPTHS

In a comprehensive view point, the concept of critical depth can be defined differently corresponding to energy and momentum approaches.
The "energy Froude number (F_e)" can be derived from energy consideration, by differentiating the specific energy function, ($E = y + \alpha \dfrac{Q^2}{2gA^2}$), with respect to depth (y) and setting the result to zero. The expression for F_e becomes (Blalock & Sturm 1980):

$$F_e = \left[\frac{Q^2 T}{gA^3} \left(\alpha - \frac{A}{2T} \frac{d\alpha}{dy} \right) \right]^{1/2} \tag{1}$$

where Q = discharge, T = flow top width, A = cross-sectional area, α = kinetic energy correction factor and g = the gravitational acceleration.

Similarly, Alavi Moghaddam and Hosseini (2007) derived the "momentum Froude number (F_m)" considering momentum approach, by differentiating the momentum function, ($M = \beta \dfrac{Q^2}{gA} + \bar{y}A$), with respect to depth (y) and setting the result to zero again. The expression for F_m which is different from F_e, becomes:

$$F_m = \left[\frac{Q^2 T}{gA^3} \left(\beta - \frac{A}{T} \frac{d\beta}{dy} \right) \right]^{1/2} \tag{2}$$

where $\bar{y}$ = the vertical distance between the water surface and the centroid of cross sectional area and β = momentum correction factor.

Critical depth can be obtained by setting either F_e or F_m to unity. This requires two working equations that include the evaluation of $\dfrac{d\alpha}{dy}$ and $\dfrac{d\beta}{dy}$. Such equations for F_e and F_m were derived by Blalock & Sturm (1980) and Alavi Moghaddam & Hosseini (2007), respectively.

In simple channels both of the above definitions for Froude number lead to the same depth, but in compound channels, (because of noticeable differences between α and β and their derivatives), the equations (1) and (2) can lead to different critical depths, relating to energy and momentum approaches (Alavi Moghaddam & Hosseini 2007).

Independent of energy or momentum Froude number definitions, the critical flow in compound channels is possible at more than one depth. For a compound channel with specific geometrical dimensions and roughness distribution, the "multiple critical depths" are calculated in a particular discharge region. Sturm and Sadiq have presented a procedure for determination of the lower and upper limits (Q_L and Q_U) of this range (Sturm & Sadiq 1996). For example, Fig. 2 shows the variation of specific energy function for a compound channel with presented dimensions, homogeneous roughness and 22 (lit/s) discharge. For this compound section, Q_L and Q_U are calculated 17 and 27 lit/s, respectively. So the extermum points correspond to multiple critical depths (y_c , y_c' and y_c'').

Therefore, if the discharge value in a compound channel is less than the lower discharge limit ($Q < Q_L$), there is one critical depth in the main channel, lower than the flooding level and if the discharge value is more than the upper discharge limit ($Q > Q_U$), there are two critical depths corresponding to energy and momentum approaches, upper than the flooding level. But, if the flow rate is in the range of occurring multiple critical depths ($Q_L < Q < Q_U$), four different critical depths can be calculated (the first in the main channel; the second at the flooding level, exactly where the flow start to enter the floodplains and two others corresponding to energy and momentum approaches upper than the flooding level).

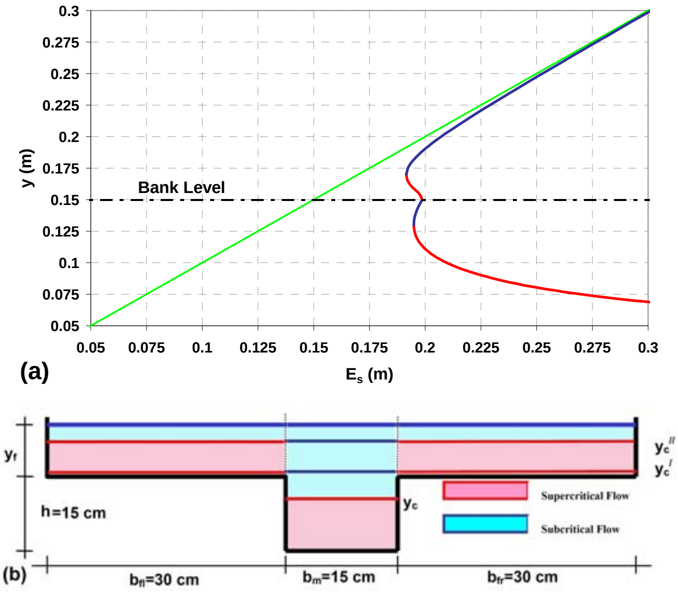

Figure 2. Multiple critical depths as the extermum points of the specific energy function for presented compound section.

3. WATER SURFACE PROFILES IN COMPOUND CHANNELS

The water surface profiles of gradually varied flow in compound channels for flow conditions that yield only one critical depth are the same as simple channels. But if the flow rate is in the particular range which as mentioned above, the normal depth (y_n) and the three critical depths (y_c , y_c' and y_c'') divide the flow region into five zones. Therefore the number of water surface profiles increase to five rather than generally three profiles for simple channels. The flow profiles for a compound channel with three critical depths in mild and steep slopes are shown in Fig. 3. The channel slope is mild when $y_n > y_c''$ or $y_c < y_n < y_c'$ and it is steep when $y_n < y_c$ or $y_c' < y_n < y_c''$. In other words, classification of bed slope in compound channels to mild and steep is only a hydraulic property and doesn't have any direct relation to the bed slope value. As shown in Fig. 3 if an optional discharge flows through a particular compound section with horizontal bed slope and the longitudinal slope starts to increase gradually, the bed slope will pass these conditions respectively: (a-mild), (c-steep), (b-mild) and (d-steep). As a theoretical and one-dimensional (1-D) point of view, considering Fig. 3, a different classification is needed to designate flow profiles in compound channels. But the flow remains confined to the upper three zones during high flows and to the lower three zones during low flows. So the profiles in these three zones are designated as M1, M2 and M3 in the mild slopes and S1, S2 and S3 in the steep slopes. Quintela (1980) mentioned that gradually varied flow in the zone $y_c' < y < y_c''$ can't be followed by gradually varied flow in the zone $y_c < y < y_c'$ and vice versa. Rapidly varied flow must occur when the flow passes from $y > y_c'$ to $y < y_c'$ and vice versa.

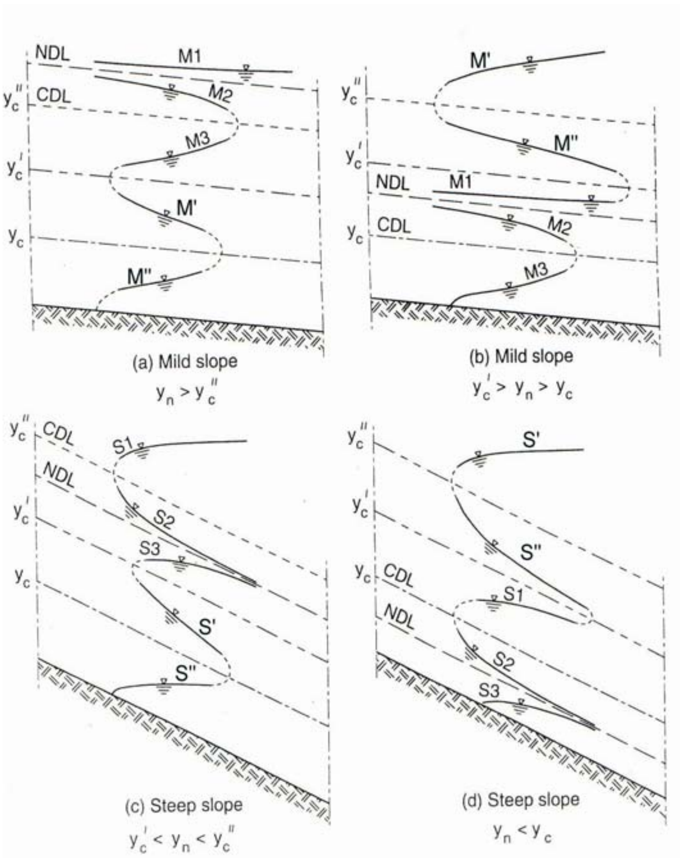

Figure 3. Water surface profiles in compound channels with multiple critical depths (NDL = normal depth level , CDL = critical depth level) (Jain 2001).

Although a two-dimensional (2-D) flow pattern is dominant in many flow situations in compound channels, but in practice, 1-D analysis of flow is commonly used by engineers. Based on 1-D approach and the calculated normal and multiple critical depths, some certain combinations of gradually and rapidly varied flow profiles are predicted along the channel for specific boundary conditions. But the governing of 2-D flow behaviors in compound channels produces a challenge on the agreement between the results of 1-D analysis and the actual flow patterns. This research is to investigate this agreement by means of visual observations of actual flow patterns in a laboratory compound channel.

It should be considered that 1-D flow through compound channels can be analyzed by two different approaches, energy and momentum. Furthermore the normal depth and the conveyance factor can be calculated by numerous methods, such as DCM, WDCM, COH and EDM (Alavi Moghaddam & Hosseini 2008). Therefore, the 1-D analysis can result in numerous answers for a specific water surface profile calculations by applying the energy or momentum approach and selecting the suitable conveyance method; although the results are usually very close together. In this research, the normal and multiple critical depths have been calculated by combining the energy approach and coherence method (COHM) to avoid confusion between different results of 1-D analysis.

4. EXPERIMENTAL SET-UP

Experiments were conducted in a flume with a length of 12.5 (m) whose cross section dimensions and related facilities are as shown in Fig. 4. The floor of main channel and floodplains was constructed of concrete in two stages, with two fixed bed slopes of 0.0121 and 0.0032 corresponding to steep and mild slope conditions. In both stages, some experiments were conducted first to determine the Manning's value (n) for flow in the main channel alone. The Manning's values for both stages of experiments were calculated about 0.0104. The discharge was measured with an electromagnetic flowmeter with 0.01 (lit/s) precision and a V-notch weir (for measurement control). The water levels were recorded using a point gauge meter mounted above the flume. In this paper, some visual experimental observations related to the formation of gradually and rapidly water surface profiles combinations are reported and compared with the predictions of 1-D analysis of gradually varied flow through compound channels. One can refer to a pervious study of the authors (Alavi Moghaddam & Hosseini, 2008) for additional details about the experiments and results.

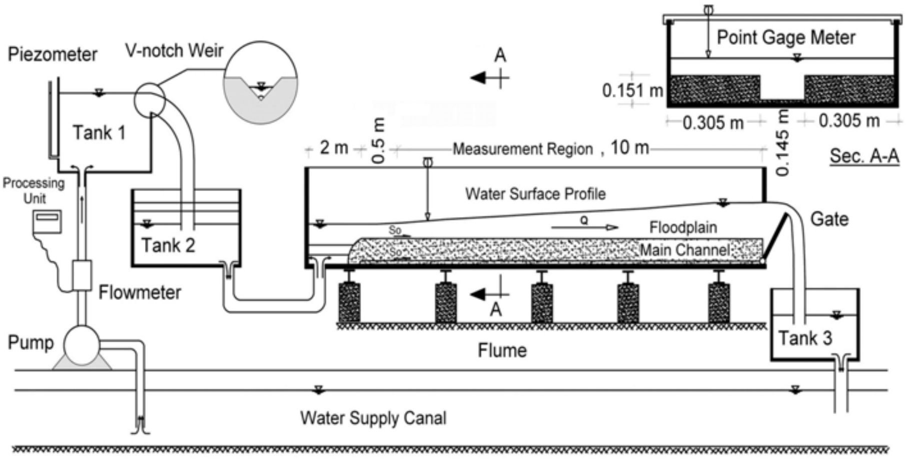

Figure 4. Sketch of the flume and experimental set-up.

5. ANALYSIS OF EXPERIMENTAL OBSERVATIONS

For investigating the agreement between visual observations of flow pattern in a compound channel with flow behavior predicted by 1-D analysis, some different flow patterns of gradually-varied and rapidly- varied flow were developed in the mentioned laboratory flume. For the given channel geometry and roughness, if the discharge value (Q) is limited between 17.0 and 27.25 (lit/s), there will be multiple critical depths. Table 1 shows the minimum and maximum critical depths (y_c and y_c''), corresponding to the lower and upper the flooding level, for three different discharge values. The intermediate critical depth (y_c') is just a little above the flooding level, exactly when water enters the floodplains. The normal depths on the mild and steep slope conditions are also presented in Table 1. The comparison between the values of normal and multiple critical depths in Table 1 by the flow patterns presented in Fig. 3, indicate that when water flows on the mild slopes, the gradually varied flow profiles should be developed based on (a) condition, whereas on the steep slope channel, the occurrence of (d) conditions is expected.

Table 1. Normal and multiple critical depths corresponding to three discharge values in the laboratory flume

Q (lit/s)	**Critical Depths y_c (cm)**		**Normal Depth y_n (cm)**	
	y_c	**y_c''**	**Mild**	**Steep**
17.50	11.25	16.10	16.15	9.56
22.00	14.11	17.10	17.20	11.44
27.00	15.04	17.84	17.94	13.49

In this study, three different flow patterns, consisting of gradually-varied and rapidly-varied flow profiles were developed by adjusting the discharge and boundary condition in downstream of the channel. The visual observations and results are as follows.

a) In a set of experiments on the mild slope, after adjusting the downstream water level lower than the flooding level, it was expected that a pattern such as Fig. 5 be developed. Occurrence of M2 gradually varied profile and "Drop" rapidly varied pattern are independent of discharge value. However, if the experimental discharge is limited in the discharge range of multiple critical depths, it can be expected that another gradually varied flow profile (M') develops after the M2 and drop. In a set of experiments in this research, development of such flow pattern was investigated using different discharge values corresponding to single or multiple critical depths. All of these experimental observations indicated the occurrence of a flow separation between the main channel and floodplains; due to a considerable mass and momentum transfer from floodplains to main channel. One of the measured water surface profiles, compared with calculated normal and critical depths, is shown in Fig. 6. The flow separated into a distinct main channel component, which had a drawdown completely below the floodplain elevation as in a simple main channel flow and a floodplain component that had its own drawdown curve. Based on these observations, the 2-D flow behavior is the dominant flow pattern in this situation and the water surface profiles, predicted using a 1-D analysis, are not completely developed along the channel.

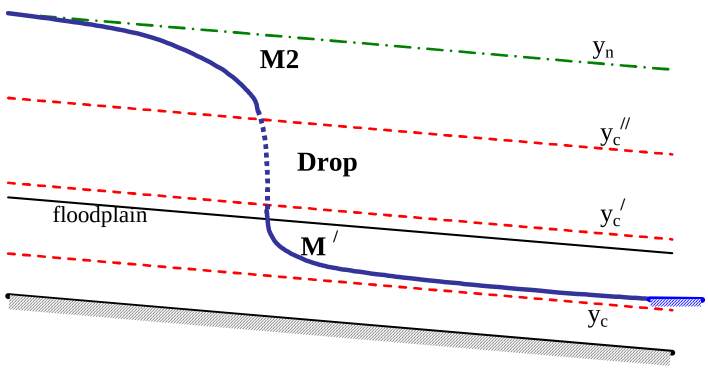

Figure 5. Expected pattern of drawdown flow profiles in a mild sloped compound channel with multiple critical depths.

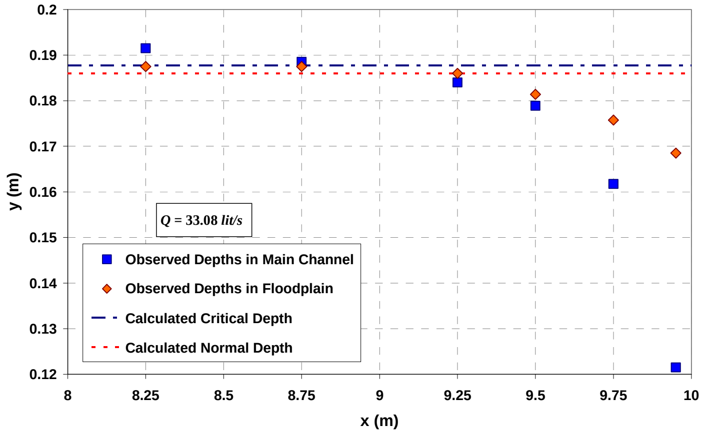

Figure 6. Water surface profiles measured in mild sloped laboratory flume having single critical depth.

b) In another set of experiments, on the steep slope, the discharge value was limited in the intermediate range in which multiple critical depths exist and the downstream water level was adjusted to corresponding normal depth. 1-D analysis predicts that a flow pattern such as Fig. 7 is developed along the channel. In a specific experiment on steep slope channel, the discharge value was measured as 19.42 lit/s. The calculated normal depth using COH method was 10.14 cm and the calculated critical depths based on energy approach and COH method were 12.06, 15.30 and 16.61 cm, respectively. When the water depth at the downstream end of the channel was adjusted to 10.14 cm, the flow rapidly passed on the upper critical depth with drop and developed a short gradually varied flow profile with approximate length of 1.0 m in downward direction as expected. After that, the flow dropped to the main channel and developed a typical S2 profile in the remaining length of the channel. Although the flow pattern was the same as the one predicted by 1-D analysis (Fig 7), in the short gradually varied flow profile above the flooding level (S" profile), the flow separation between the main channel and the floodplains was clearly observed again, which indicate that the 2-D flow behavior is dominant on the flooding drawdown profiles in compound channels.

c) In the third attempt for investigating the water surface profiles crossing normal and multiple critical depths, some experiments were performed for producing backwater profiles under steep slope condition. If a water discharge, in the range of existence of multiple critical depths, flows in a steep sloped compound channel with corresponding normal depth lower than the flooding level and the downstream water surface level at the end of the channel is adjusted at a level upper than the third critical depth (y_c''), 1-D approach predicts two flow patterns as shown in Fig. 8, depending on the downstream water level. Occurrence of these patterns in practical conditions was also investigated in some experiments.

In one experiment on the steep slope channel, the discharge was adjusted at 22.22 lit/s. The normal and multiple critical depths were calculated as: y_n = 12.27, y_c = 13.20, y_c' = 15.18 and y_c'' = 17.13 cm. Comparing these values, development of patterns shown in Fig. 8 are expected.

In the first scenario, the downstream water surface level was increased a little more than y_c'' (about 2 cm). Two separate hydraulic jumps occurred in the 3 m length of the channel. A short length (about 1 m) gradually varied flow profile between the multiple critical depths (S1) could be distinguished from the two adjacent hydraulic jumps, exactly the same pattern as pattern (I) in Fig. 8.

In the second scenario, the downstream water surface level was gradually increased. The length of the S1 profile started to decrease until it completely disappeared and the pattern (I) changed to pattern (II). Therefore, in this scenario, a full agreement was observed between the prediction of 1-D approach and the actual flow patterns observed in the laboratory.

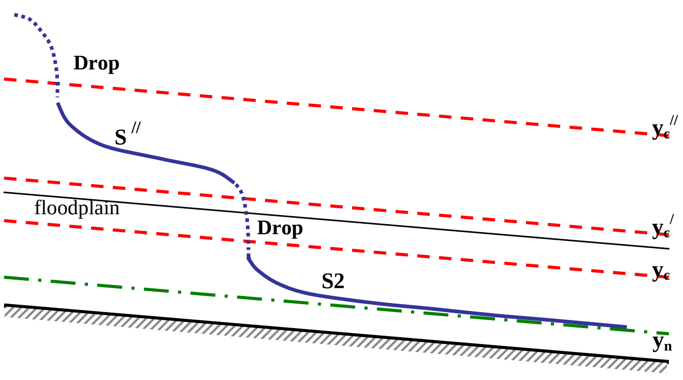

Figure 7. Expected flow pattern for drawdown profiles in a steep sloped compound channel with multiple critical depths.

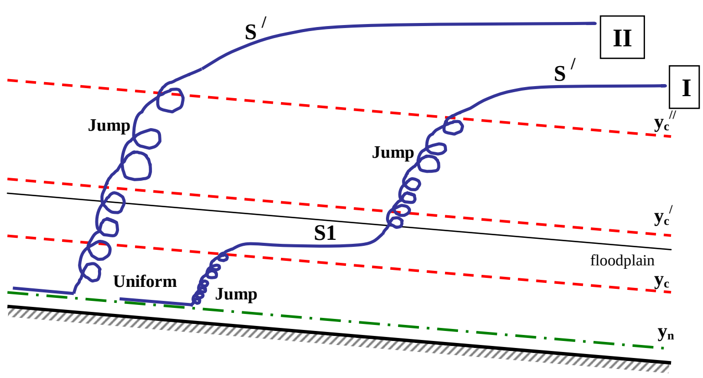

Figure 8. Expected pattern of backwater flow profiles in a compound channel with multiple critical depths and steep slope.

6. CONCLUSIONS

Compound channels have specific geometrical and hydraulic properties which produce complicated two dimensional flow systems. However, one dimensional analysis, which is common practice among engineers, results in some unusual concepts such as the possible formation of five different types of gradually varied water surface profiles due to occurrence of multiple critical depths.

This paper is an attempt to shed more lights on the agreement between the results of 1-D analysis and the actual flow patterns developed in a laboratory flume. This investigation was done by producing three combinations of gradually and rapidly varied flow patterns and comparing them with the 1-D approach predictions. According to the detailed experimental observations presented in the paper it can be concluded that flow pattern predicted by 1-D analysis shows a reasonable agreement with the experimental observations in the case of a backwater formation when depth increases in the direction of flow. Conversely, less agreement is observed in the case of drawdown curves, which is an indication of 2-D dominated flow in these situations. Developing more experimental scenarios in other geometrical and hydraulic conditions, especially in a flume with adjustable bed slope, will reduce the uncertainties and will lead us to a better understanding of the main challenge of this paper.

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