Determination of hydraulic jumps in drainage channels from the Standard Step Method subsidized by low cost equipment

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Highlights

- Straightforward approach for determine hydraulic jumps .
- Good efficiency of low cost apparatus for determine hydraulic jumps.
- Good efficiency of low cost apparatus for flow monitoring purposes in experimental channels.

Introduction

The understanding of phenomena related to flood propagation in channels, mainly artificial urban channels that contribute to urban drainage, has become more relevant every day to avoid catastrophes in the event of intense rainfall (Chow, 1959; French, 1985; Hoyt and Sellin, 1989; Djordjevic et al., 2004; Chaudhry, 2007). In this context, there is still a challenge in numerical and physical modeling to accurately determine the location where hydraulic jumps are formed and developed, mainly due to the transitions of flow regime in channels, especially the transcritical regime.
This transition can occur from the subcritical to the supercritical regime, called the sonic point, as it can be from the supercritical to the subcritical, called the hydraulic jumps (Freitag, 2003). There are several studies related to the one-dimensional modeling of the transcritical flow, via diverse methods, some with more adequate and accurate results for the determination of hydraulic jumps (Molls and Chaudhry, 1995; Gharangik and Chaudrhry, 1991; Khan and Steffler, 1996; Federico, 2012).
Therefore, this article proposes the use and the numerical improvement of the Standard Step Method for predicting the formation of hydraulic jumps in artificial channels, in a regime of permanent transcritical flow gradually varied, validated from physical experiments, simulated in an artificial channel.

Methodology

The study methodology was divided into two stages, one experimental and one numerical. The experimental stage included the performance of flow simulations in the artificial channel existing in the Hydraulic Laboratory of the School of Civil and Environmental Engineering of the Federal University of Goiás, Brazil, under different flow and inclination arrangements. The experimental channel is 4.0 m long, with a rectangular cross-section of 0.205 x 0.40 m, whose side walls are made of glass and the bottom of the channel is made of acrylic (Figure 1).

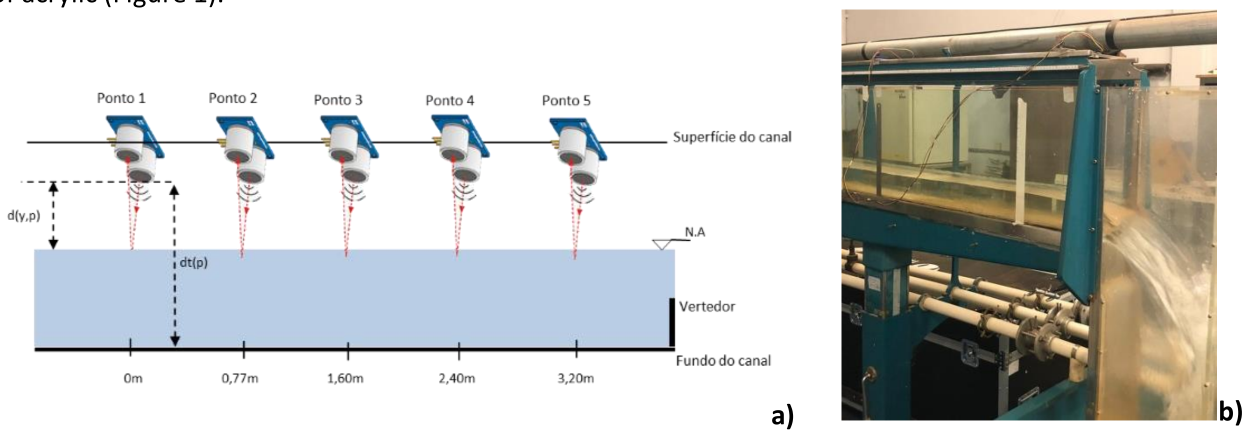
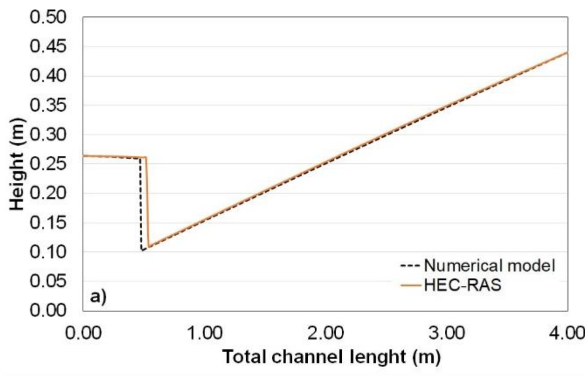


Figure 1. Characteristics of the artificial open channel and equipment used to measure the height of the water depth: a) with ultrasonic sensors (geometry and distribution); b) with a millimeter ruler (graduated).

To calibrate the effective roughness of the channel, 15 simulations of uniform and gradually varied permanent flow were performed, taking readings through millimeter ruler and ultrasonic sensors of the Arduíno type (Figure 1a) for measuring the height of the water slide from the free surface. For the hydraulic jump phenomenon, 12 tests were performed in gradually varied constant flow, using a thin sill spout without lateral contractions, located at the end of the channel with 10.0 cm height (Figure 1b).
The numerical step included the elaboration of an algorithm implemented in Octave software, version 5.2, for the modeling of the transcritical flow in a permanent regime gradually varied from the Standard Step Method proposed by Akan (2006). The input data of the numerical model are the term of inertia and upstream and downstream form condition, Corolis coefficient, acceleration of gravity, channel geometric data (width and length), effective roughness, channel slope, and spill height.
As an output of the numerical model, the implemented routines make it possible to determine: the hydraulic profile of the jump produced along the entire channel of both the supercritical blade (upstream to downstream) and the subcritical blade (downstream to upstream), the position of the hydraulic jump and the variation of the combined heights from the supercritical curve. For validation and functionality, the profile drawn as a result is compared to the profile produced for the same flow conditions in the HEC-RAS software, version 5.0.7 (Figure 2).



Variable	Values
Q	25.00 l/s
α	1.00
$C0$	1.00
g	9.81
L (channel lenght)	4.00 m
L (width channel)	0.205 m
n	0.016
$S0$	0.10 m/m
H (spillway height)	0.10 m
Δx	0.05 m
Hm (amount boundary condition)	0.04 m
$Z0$ (spillway channel height)	0.00
Admissible error for Standard Step Method	0.00000001
Admissible error for location the hydraulic jump	0.001

b)

Figure 2. Results of numerical modeling (Octave) and HEC-RAS software: a) free surface profiles and hydraulic jumps; b) input data used in the HEC-RAS.

Results and discussion

Compared to experimental tests, the numerical simulation results performed for all cases, i.e., the relative average error, were never higher than 2.6% (Figure 3). For numerically simulated events, maximum relative point errors of 4.85% occurred considering a supercritical curve and 4.13% for a subcritical curve. However, these higher relative errors are associated with the high turbulence of the fluid free surface near the hydraulic jump zone, where there is greater difficulty in measuring the coordinates, either by ultrasonic sensors (automatic form) or by reading from a millimeter ruler (manual form). It was noticed by the experimental tests performed that there is greater difficulty in reading the water depths for flows with steeper slopes (> 3.8%) also due to greater turbulence on the free surface.
Regarding the verification and calibration process, the results of the numerical model developed in Octave software were consistent with those determined by HEC-RAS, both for the supercritical and subcritical regimes (Figure 2). There is a small divergence in the determination of the place where the hydraulic jump occurs, being this place determined first in the HEC-RAS software compared with the implemented numerical model. This divergence may be associated with the scale effect, that is, while HEC-RAS was developed for larger-scale simulations, the numerical model developed and proposed used smaller discretization in time and space for modeling the hydraulic jump.

Conclusions and future work

Considering the numerical model developed and implemented, the results of the different simulations, including the variations of the input data performed, were adequate for the determination of the hydraulic jump for both supercritical and subcritical regimes. They presented relative mean errors of 2.6% and mean standard deviation of 1.2 compared to the experimental tests performed in the channel, i.e., coincidence in determining the location where the hydraulic phenomenon occurs.

The calibration of the numerical model developed was satisfactory (relative errors less than 1.0%), considering the results of the physical model and simulation in HEC-RAS, corroborating for its validation for the flow ranges, channel inclinations and spillway height tested. Thus, it is intended to extend the use of the numerical model developed for forecasting hydraulic jumps in channels whose scale is more significant under different flow regimes, especially those whose purpose is linked to the urban drainage system.

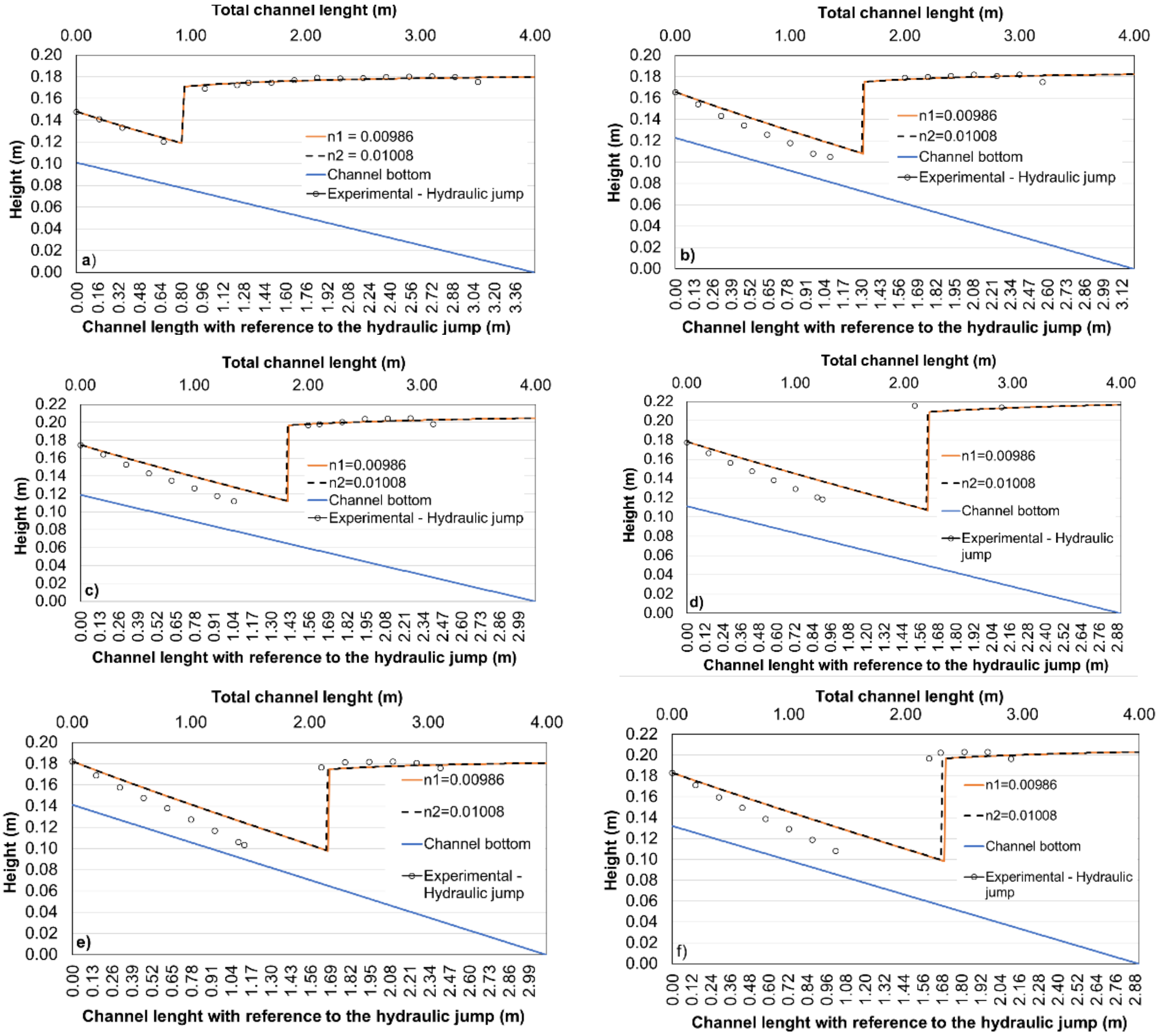


Figure 3. Evolution of the free surface and hydraulic jumps determined by the numerical and physical model a) $Q = 0.0103$ m^3 s^{-1} e $S_o = 2.9\%$; b) $Q = 0.0103$ m^3 s^{-1} e $S_o = 3.8\%$; c) $Q = 0.0152$ m^3 s^{-1} e $S_o = 3.8\%$; d) $Q = 0.0203$ m^3 s^{-1} e $S_o = 3.8\%$; e) $Q = 0.0103$ m^3 s^{-1} e $S_o = 4.6\%$; f) $Q = 0.0152$ m^3 s^{-1} e $S_o = 4.6\%$.

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