Implementation of a physical model to determine the hydraulic behavior of mountain rivers

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Implementation of a physical model to determine the hydraulic behavior of mountain rivers

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Abstract. The present work consisted in the implementation of a small-scale physical model of a mountain river according to the similarity conditions that these models must satisfy, this model was implemented in a channel with measures 200 cm length, base 20 cm and height of 15 cm; a variable slope between 1% and 5% was handled, it was evaluated with the design conditions of open-flow channels, developing a methodology of physical modeling of channels and rivers of mobile bottom without distortion, according to a turbulent flow over rough contour, so that the values determined in the physical model complied with the laws of similarity and represented the most accurate way to a mountain river. The results showed a minimum flow of 8.03 l/s and a maximum of 17.96 l/s in the physical model, which in the prototype represents a flow of 284 m^3/s and 635.04 m^3/s respectively. On the other hand, it was determined that the average diameter of the granular material required in the physical model is 2 mm corresponding to an average diameter of 100 mm for mountain rivers.

1. Introduction

Physical models are useful tools that help in the study of different situations which are of vital importance in engineering, mainly because they allow seeing results on a reduced scale that by the magnitude of the phenomena and by their complexity at real and mathematical scale are hard to appreciate. Clear examples of the above are the hydraulic models, in which the real object is called prototype and from this the information is extracted with which the model is built on a reduced scale, which must satisfy the established similarity laws [1].

The hydraulic models are practical to carry out the analysis of different behaviors of real situations that you wish to consider to carry out designs of civil works aimed at solving problems and also for the planning and management of water resources [2,3]; however, it is necessary to develop a methodology that helps the implementation of hydraulic models for new researchers interested in carrying out this type of experiments. A methodology was developed from which a physical model was implemented on a reduced scale for a typical mountain river in a channel that allows meeting the conditions of similarity of this prototype, and the results obtained will be shown along the development of the article.

Mobile bottom models are used when the movement of the materials which make up the borders is important because of the flow of water. In this section we verify the main hydraulic characteristics of a mountain river, which for our work had a longitudinal slope between 1% and 5% as it corresponds to one of these rivers' parameters, as stated [4] "a river mountain is one which course has a longitudinal slope greater than 0.2%". A free flow system is presented because it is in contact with the atmosphere which was evaluated by a turbulent flow, with a bed formed by not cohesive granular material.

2. Materials and methods

2.1. Scale selection

"Linear flow scales are mainly determined according to several practical aspects, such as sufficient accuracy in the measurement of water levels without exceeding the tolerant limits of the distortion and complying with the similarity of the Froude" [1]. It was chosen taking into account the aforementioned criteria, a scale 1: 50 according to what is established in [1]. This scale was handled on the different calculations of geometric, kinematic and dynamic similarity from a model without distortion.

2.2 Geometric similitary

It was used a river flow simulator of ArmField S17 rectangular type, 200 cm length, 85 cm width, 15 cm height and 15 cm on ramp. The geometric conditions of the prototype to be met were established, such as: length, area, volume and flow.

Figure 1. View of the river simulator used.

A typical section of a river with 10 m width and 75 m in length was evaluated. In the channels formed by gravels and ridges the average diameter would vary between 10 mm and 100 mm [5]. For the present case, two scenarios were evaluated, when the channel has a longitudinal background slope of 1% and 5% that gave us L = 1.5 m and B = 0.20 m; the roughness of the fund remained constant.

The following equations were used to define the parameters of the model and prototype.

2.2.1. Base. The base (B) of the model and the prototype is defined according to the selected scale that is measurable, recognizable and that shows the results in an objective way, it is calculated in the following way as it is necessary to evaluate the model or prototype, one depending on the other, see Equation (1).

$$(\mathrm{B}) = \frac{(B)}{\lambda l} \tag{1}$$

2.2.2. Length. The length (L) to be evaluated is the result of application of the selected scale for the model or prototype and it's calculated as follows as necessary, see Equation (2).

$$(\mathrm{L}) = \frac{(\mathrm{L})}{\lambda l} \tag{2}$$

2.2.3. Depth of flow. According [6], the depth of flow (Y) is defined as the vertical distance from the lowest point of a section of the channel to the free surface. To implement the model, it is defined between 5 cm and 10 cm according to the geometry of the model available in the laboratory; 5 cm were selected.

2.2.4. Average diameter of particles. The particles of alluvial deposits that are those that are formed in the rivers due to currents and movement have very varied diameters. For mountain rivers the medium diameter is between 10 mm and 100 mm, we worked with average diameter of particle (dm) of 100 mm that applied to the scale chosen gives us 2 mm as a result for the model.

2.2.5. Embankment. The Embankment (Z'') of the section depends on the nature of the terrain [7]. In the present model we worked with Z = 0 because the typical river section is rectangular.

2.2.6. Wet area. It is defined as the area (A) of the cross section of the flow [6] and it is calculated according to the following Equation (3).

$$(A) = [B + (z) * (Y) * (Y)] \tag{3}$$

2.2.7. Wet perimeter. According to [6] the wet perimeter (P) is the length of the intersection line of the wet channel surface and a transverse perpendicular plane to the direction of flow, and it's calculated with the following Equation (4).

$$(\mathrm{P}) = (\mathrm{B} + 2\mathrm{Y}) \tag{4}$$

2.2.8. Hydraulic radio. It is the relation between the area and the wet perimeter, and according to [6] it is calculated with the following Equation (5).

$$\mathrm{R} = \frac{A}{P} \tag{5}$$

2.2.9. Critical depth. It is the depth that occurs when the Froude number is equal to the unit [8] and it's calculated with the following Equation (6).

$$Yc = \frac{\tau_* C_* \Delta dm}{S_0} \tag{6}$$

2.3 Similitary of flow

In the literature it's possible to find the development of different channel systems or the study of the physical phenomena that get involved in the flow of water through the channels, all this for the optimization of resources [9].

When performing hydraulic modeling, it must be guaranteed that certain characteristics are met so that the results have a low level of uncertainty and are reliable when using those data for engineering design.

2.3.1. Cutting speed. The cutting speed (Uo) was determined according to the following Equation (7).

$$U_0 = (9.8 * \frac{(R)}{100} * (S_0))^{\frac{1}{2}} \tag{7}$$

2.3.2. Dimensionless quantity Chezy coefficient. The dimensionless quantity coefficient of Chezy (Co) indicates the friction in a channel as a relation of the local equation of Prantlon on the total depth Yo, as follows in Equation (8).

$$(\mathrm{Co}) = 2.5\ \mathrm{In}\left(\frac{(\mathrm{Y})}{dm}\right) + 6 \quad (8)$$

2.3.3. Flow speed. It was calculated from the following Equation (9):

$$(V) = (Uo) * (Co) \quad (9)$$

2.3.4. Froude condition. The flows in the free surface are scaled with the similarity of Froude keeping it identical both in the model and in the prototype [10], it was calculated according to the following Equation (10). Where: D = depth of flow that is also called Y.

$$(F) = \frac{(\mathrm{V})}{(g*D)^{\frac{1}{2}}} \quad (10)$$

2.3.5. Reynolds condition of the particle. It was calculated according to the following Equation (11).

$$(\mathrm{Re}) = \frac{(\mathrm{U_0})*\mathrm{dm}}{(\upsilon)} \quad (11)$$

2.3.6. Flow. According to [6], it was calculated from the following Equation (12).

$$Q = V * A \quad (12)$$

2.4. *Similarity of sediment transport*
According to [11] the hydraulic roughness coefficient is a measure of the resistance to flow, created by a material, for the present case according to what was proposed by [6] an approximate roughness coefficient was estimated for mountain rivers. The sediment characteristics of the model to be implemented which meet conditions of the prototype are defined. Movable bed hydraulic models usually require empirical relationships for defining the terms of interaction with the mobile layer of the sediment [12].

For the transport of material from the bed, the Froude number of densimetric of the particle is analyzed as a parameter regulating the transport of solids [13]. The sediment characteristic of the model to be implemented that meets the conditions of the prototype are defined. In this condition the model of the set of sediment particles is related to the criterion of Meyer-Peter and Muller (1998): It is an empirical equation obtained from a laboratory test [14], where τ_* is the dimensionaless Densimetric Froude Number that is calculated in the following Equation (13), where $\Delta = \frac{\rho_s}{\rho} - 1$.

$$\tau_* = \frac{Y*s}{\Delta*\mathrm{dm}} \quad (13)$$

To determine a fluvial model of mobile working background it was carried out according to a semi-empirical equation to quantify the drag in its dimensionless value must be higher than 0.047 according to the Criterion of Meyer-Peter and Muller (1998).

3. Results
The results obtained for the 1% and 5% slope conditions are presented below.

3.1. Geometric similarity for 1% and 5% bottom slope in the model and prototype
In the Table 1 it can be evidenced that the conditions of geometric similarity remain constant in the 2 slopes, which indicates that the geometry of the channel is constant during the process, it should be noted that modifications can be made that for economic reasons in this model were not taken into

account, which can also be represented in software as it did [15], which are made according to the criteria of the researcher.

Table 1. Results of geometric similarity S_0= 1% y 5% in the model and prototype.

Variable	Model ('')			Prototype (')		
	Symbol	Unity	Value	Symbol	Unity	Value
Base	B''	cm	20.00	B'	m	10.00
Length	L''	cm	150.00	L'	m	75.00
Depth of flow	Y''	cm	5.00	Y'	m	2.50
Average diameter of the particles	dm''	cm	0.20	dm'	m	0.10
Embankment	z''	cm	0.00	z'	m	0.00
Wet area	A''	cm^2	100.00	A'	m^2	50.00
Wet perimeter	P''	cm	30.00	P'	m	15.00
Hydraulic radio	R''	cm	3.33	R'	m	1.67

3.2. Flow similarity for 1% bottom slope in the model and prototype

The similarity of flow indicates compliance with certain coefficients that guarantee compliance with the same hydraulic characteristics in the model and in the prototype, for this case the parameters that were Chezy coefficient and Froude condition were met, see Table 2.

Table 2. Flow similarity results S0 = 1% in the model and prototype.

Variable	Model ('')			Prototype (')		
	Symbol	Unity	Value	Symbol	Unity	Value
Cutting speed	Uo"	cm/s	5.72	Uo'	m/s	0.40
Chezy coefficient	Co"	-	14.05	Co'		14.05
Flow speed	V"	cm/s	80.33	V'	m/s	5.68
Froude condition	F"	-	1.15	F'		1.15
Reynolds condition of the particle	Re"	-	103.97	Re'		39995.19
Friction condition	*f"*	-	0.21	*f'*		0.20
Flow	Q"	cm^3/s	8032.73	Q'	m^3/s	284.00

3.3. Flow similarity for 5% bottom slope in the model and prototype

For the 5% slope the hydraulic conditions of flow similarity were met, as was the case of 1%, but in this case the Chezy coefficient remained constant and the Froude condition increased, as is represented in Table 3.

Table 3. Flow similarity results S0 = 5% in the model and prototype.

Variable	Model ('')			Prototype (')		
	Symbol	Unity	Value	Symbol	Unity	Value
Cutting speed	Uo"	cm/s	12.79	Uo'	m/s	0.90
Chezy coefficient	Co"	-	14.05	Co'		14.05
Flow speed	V"	cm/s	179.62	V'	m/s	12.70
Froude condition	F"	-	2.56	F'		2.56
Reynolds condition of the particle	Re"	-	232.49	Re'		89431.96
Friction condition	*f"*	-	0.21	*f'*		0.20
Flow	Q"	cm^3/s	17961.74	Q'	m^3/s	635.04

3.4. 1% sediment transport similarity

Table 4. Results of sediment transport similarity for So = 1% in the model and prototype.

Variable	Model ('')			Prototype (')		
	Symbol	Unity	Value	Symbol	Unity	Value
Densymmetric Froude number	τ*"	-	0.15	τ*'	-	0.15

3.5. 5% sediment transport similarity

Table 5. Results of sediment transport similarity for So = 5% in the model and prototype.

Variable	Physical Model			Prototype		
	Symbol	Unity	Value	Symbol	Unity	Value
Densymmetric Froude number	τ*	-	0.76	τ*	-	0.76

In Table 4 and Table 5 it can be seen that the densimetric Froude in the model and prototype is the same for each of the slopes, but it was observed that as the slope increases the value of this does it too.

4. Conclusions
The analysis of the data obtained through the set of equations that influenced the model and prototype allowed us to conclude that the conditions of geometric similarity were constant throughout the development of the project in the evaluation of the different slope scenarios. It was determined that the average particle diameter for a slope between 1% and 5% in the physical model is 2mm equivalent to 100mm in the prototype.

The results indicated that for a minimum slope of 1% and a maximum of 5% the channel carries a flow of 8.03 l/s and 17.96 l/s respectively, which in the physical model represents a flow of 284 m^3/s and 635.04 m^3/s present in the existing mountain rivers. In the flow similarity it was observed: the Reynolds condition of the particle for the two physical-prototype model systems when evaluating the slopes of 1% and 5% was higher than 70 which leads to a turbulent flow over rough contour. It is a river bottom mobile model because it meets the parameter of the particle density Froude number according to the criteria of Meyer-Peter and Muller, which was greater than 0.047.

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