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Articles

## **Riverbank protection with groynes, numerical simulation 1D**

## **Protección marginal con espigones, simulación numérica 1D**

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### **Abstract**

Riverbank protections are essential when carrying out river channeling or redirection works. Predicting its proper functioning is the responsibility of the designers and agencies in charge of safeguarding

the safety of the population surrounding them. The numerical simulation is one of the tools that allow these forecasts to be made. In this work, we used HEC-RAS 1D to evaluate its capacity to reproduce adequately the hydraulic behavior of riverbank protection based on seven groynes. The numerical model was calibrated with experimental measurements made in a reduced physical model, 1:40 scale. Three ways to input the geometry of the groins were tested: i) as a barrier, with dimensions of height, width, and average length; ii) as a set of stepped obstructions and iii) as part of the natural terrain. The barrier was the optimal geometry. The numerical results reproduced satisfactorily the effects measured in the physical model. From this calibration, two alternatives were tested, finding that an arrangement of four groynes combined with a marginal revetment could have the same effect as the full arrangement of seven groynes but with a smaller volume of work. Although the phenomenon under study presents 2D characteristics, the key in numerical modeling 1D is in the quality of the data with which it is calibrated. Also, the 1D models are faster and have fewer instabilities than the 2D and 3D models, which allows analyzing different design conditions in less time.

**Keywords:** HEC-RAS, riverbank protections, physical models.

## Resumen

Las protecciones marginales son esenciales cuando se realizan obras de encauzamiento o redirección del flujo en ríos. Pronosticar su adecuado

funcionamiento es responsabilidad de los diseñadores y organismos encargados de salvaguardar la seguridad de la población aledaña a los mismos. La simulación numérica es una de las herramientas que permiten realizar tales pronósticos. En este trabajo se empleó el *software HEC-RAS 1D* con el objetivo de evaluar su capacidad para reproducir de manera adecuada el funcionamiento hidráulico de una protección marginal con base en siete espigones. El modelo numérico fue calibrado con mediciones experimentales realizadas en un modelo físico reducido, escala 1:40. Se probaron tres formas de ingresar la geometría de los espigones: a) como una barrera, con dimensiones de altura, ancho y longitud promedio; b) como un conjunto de obstrucciones escalonadas, y c) como parte del terreno natural. La barrera fue la geometría óptima. Los resultados, obtenidos numéricamente, reprodujeron de modo satisfactorio los efectos medidos en el modelo físico. A partir de esta calibración, se probaron alternativas de solución, encontrando que un arreglo de cuatro espigones combinados con recubrimiento marginal podría tener el mismo efecto que los siete espigones, pero con un menor volumen de obra. Aunque el fenómeno en estudio evidentemente presenta características 2D, la clave en la modelación numérica 1D está en la calidad de los datos con lo que se calibra. Además, los modelos 1D son más rápidos y presentan menos inestabilidades que los modelos 2D y 3D, lo que permite analizar diferentes condiciones de diseño en menor tiempo.

**Palabras clave:** *HEC-RAS*, protección marginal, modelos físicos.

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## Introduction

Bank protections in rivers are an essential and costly component on flood protection systems. The most common protections are revetments, dikes, and groynes, where the objective of these works is to redirect the flow in such way that avoids the interaction between the high-velocity flow and the material from the banks (Nguyen, Vo, & Gourbesville, 2018; Qin, Zhong, Wu, & Wu, 2017; Sukhodolov, 2014). In the particular case of groynes, these structures are placed within the channel, perpendicular or with a particular inclination angle to respect to the bank. Its purpose is to redirect and move out the current lines that affect the bank, avoiding problems of erosion and drag of material. Several studies reported the hydraulic functioning of groynes, from numerical simulations (Mawandha, Wignynosukarto, & Jayadi, 2018; McCoy, Constantinescu, & Weber, 2007a; McCoy, Constantinescu, & Weber, 2008) to laboratory studies (Kang, Yeo, Kim, & Ji, 2011; Weitbrecht, Socolofsky, & Jirka, 2008; Zhang *et al.*, 2017). The most of

these researches are limited to study groynes that emerge from the free surface water and are placed perpendicular to the bank; being lack studied, the submerged and those oriented at a certain angle McCoy, McCoy, Constantinescu, & Weber, 2007b; Jiménez-León, Mendiola-Lizárraga, Rivera-Trejo, Nungaray-Núñez, & Díaz-Arcos, 2017 ). Currently, a significant number of these structures have been designed to the judgment and builder's experience, instead of following a specific norm or criteria (Minor, Rennie, & Townsend, 2007). In Mexico, as in many Latin American countries, the primary reference is the Rivers Engineering Manual, from the Engineering Institute, UNAM (Maza-Alvarez, García-Flores, & Olvera-Salgado, 1996); however, due to every river presents hydraulic conditions that make it unique, is necessary to study the sizing, spacing and orientation of the groynes for every particular case. That is why, in this work, we use HEC-RAS (Brunner, 2016) to simulate numerically an arrangement of seven groynes oriented at a certain angle from the bank and partially submerged. Its design followed the methodology proposed by Maza-Alvarez, García-Flores and Olvera-Salgado (1996), and it's hydraulically behavior was tested by a physical model. The studies in physical models are expensive, and with particular exceptions, the most common is to do numerical simulation. However, numerical simulation is not an easy task and involves experience not only in the analysis and interpretation of results; but also, in the way to introduce the data and propose the boundary conditions. Besides in the simulations there is not a rule about the best way to model the groynes geometry, in this work we tried three

alternatives: 1) as a barrier, 2) as a set of stepped obstructions and 3) as part of the natural terrain. We found that the hydraulic profiles generated by the three options presented a similar behavior compared with the measurements did in the physical model. Therefore, we chose the barrier option due at is the easiest and fastest way. Finally, from the numerical simulations, we analyzed two alternatives trying to get the same hydraulic behavior but with the fewer volume of work. The optimal result was the combination between a bank revetment and four groynes.

By the other hand, the computational models developed to study the hydraulic behavior or a channel design, vary due to the complexity of its computational algorithm, its degree of sophistication and reliability. The different models are defined as models of one (1D), two (2D) or three (3D) dimensions. The 1D models consider that the main component of the velocity profile is along the x coordinate axis; therefore, unlike two-dimensional (2D) and three-dimensional (3D) models, the velocity components on y and z coordinate axes are neglected. These models consider the average elevation of the water surface in y and z directions; they are trendy since they are less computationally demanding (Rau-Lavado, 2007) and require less information to compile than 2D and 3D models. These characteristics have given them extended use over more complex models. Examples of 1D models are HEC-RAS (Brunner, 2016), *Mike11* (DHI, 2016) and *Iber* (Bladé *et al.*, 2014), among others. In this work, used the HEC-RAS software, which is a free access program, and is continuously developed and updated by the Hydrological Engineering Center of the US Army

Corps of Engineers. It presents a natural environment, so the data is easy to edit, modify, and visualize on screen. Although HEC-RAS has the possibility of considering sediment transport, in this particular was not used because the physical model did not reproduce it. HEC-RAS is a validated program in North America, Mexico, and many Latin American countries. In Mexico, it is required by government agencies at the federal, state and municipal levels to carry out hydraulic modeling of open channels, rivers, and artificial canals.

## **Materials and methods**

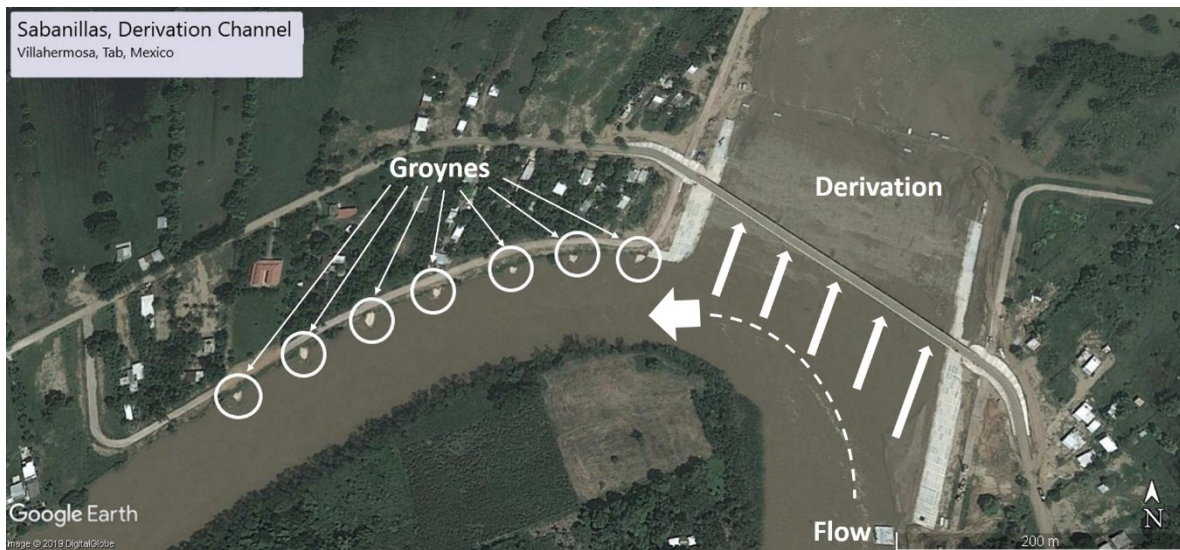
### **Study case**

To protect the city of Villahermosa, Tabasco against floods (Rivera-Trejo, Soto-Cortés, & Barajas-Fernández, 2009), in 2010 it was proposed to build a series of diversion channels on the main rivers that drain into the city. The objective was to reduce the flow of these rivers and reduce the risk of overflow and flooding toward to Villahermosa. The



diversion channels are branches that are open up in rivers to divert part of their flow to another place. In the case of Villahermosa, the diversion channels direct the flow to areas of natural regulation. These works are usually placed in curves of rivers to maximize the flow derived, leaving the banks susceptible to erosion, so they must be protected.

The case analyzed considers bank protection located downstream of the Sabanillas diversion channel, located in the municipality of Centro, Villahermosa, Tabasco, coordinates 512627 E, 1979777 N. The protection consists of an arrangement of seven rock groynes as shown in Figure 1.



**Figure 1.** Sabanillas, Municipality of Centro, Villahermosa, Tabasco, derivation channel and the right bank protection based on seven rock groynes.



## Physical model

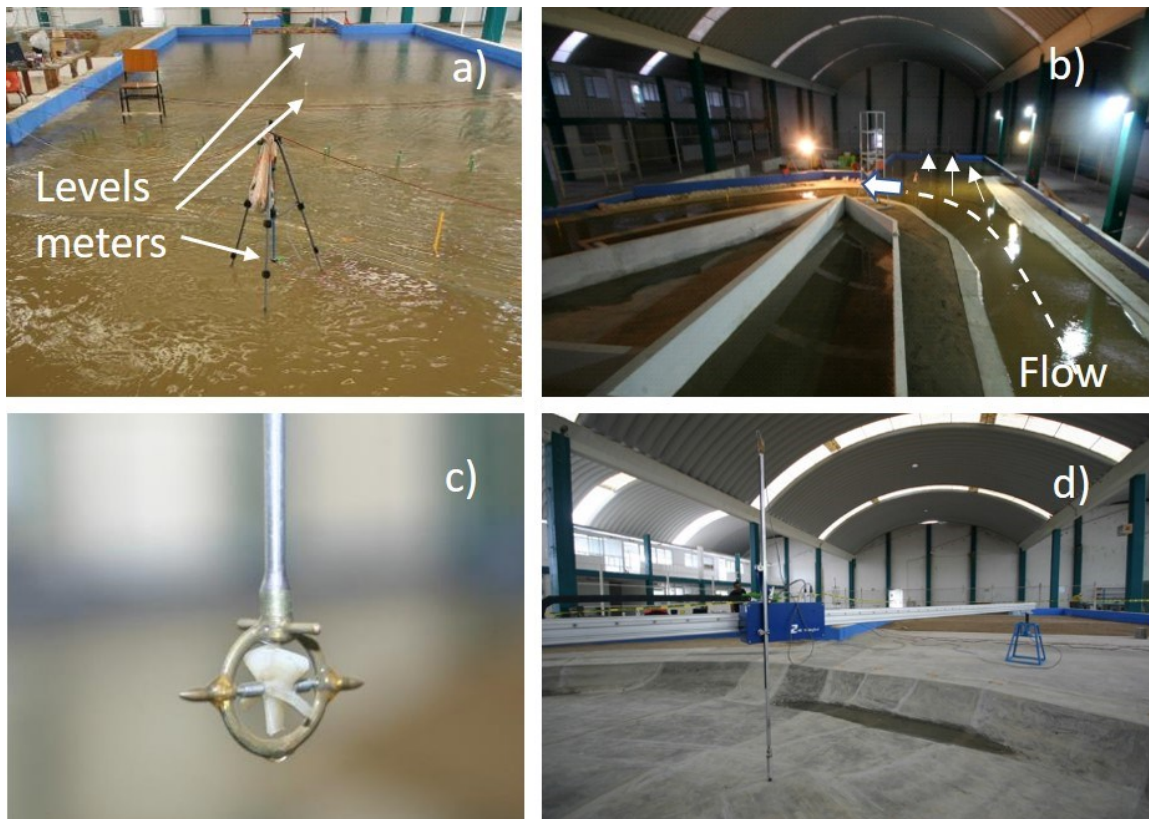
In order to determine the hydraulic functioning of the diversion channel, was constructed a physical model Esc 1:40 (Figure 2). In the model, were measured experimentally: a) Water surface levels on the curve and the diversion channel, b) The flow discharge.



**Figure 2.** Prototype and physical model of the Sabanillas diversion channel, located in the Municipality of Centro, Villahermosa, Tabasco, México.

The physical model was instrumented with dynamic level meters distributed along the curve of the river and the channel (Figure 3a). The derived flow (Figure 3b) was measured through triangular weirs; while the velocities in the channel were measured with a low-velocity micro

propeller (Figure 3c). The topography was calibrated by a Wallingford topographic bed profiler with a tolerance of 0.001 m (Figure 3d). The instrumentation of the physical model, and the quality of the data, allowed to achieve a proper calibration of the numerical model.



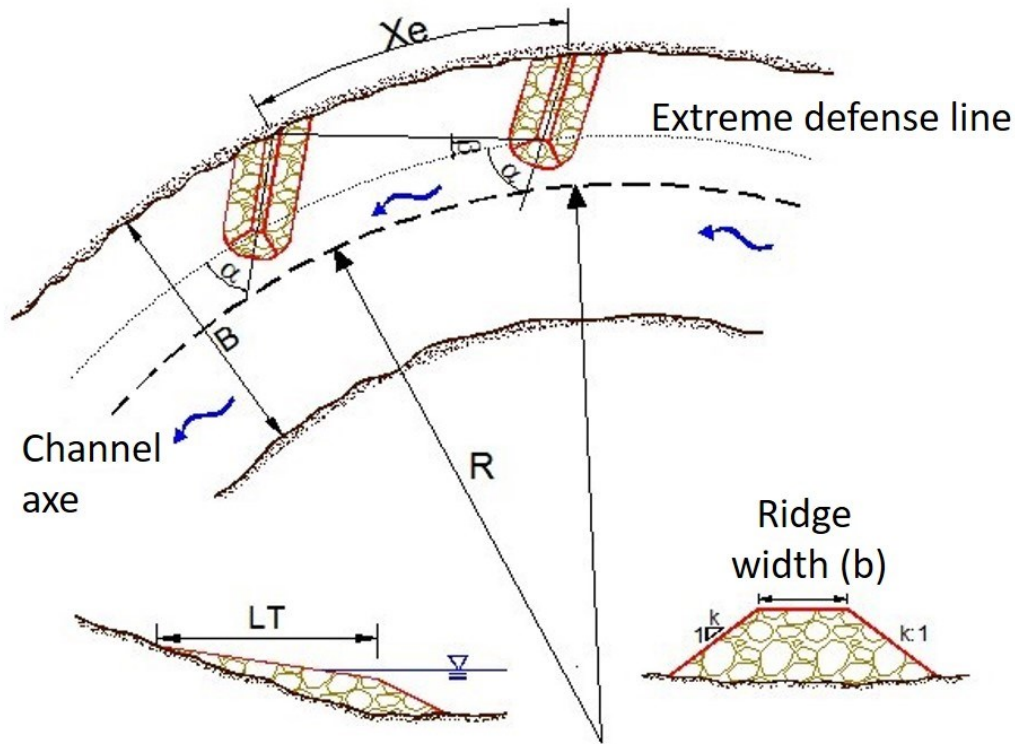
**Figure 3.** Instrumentation: a) dynamic level meter, b) derivation channel; c) low-velocity micro-propeller; d) topographic bed profiler.

In the experimental model, we studied: a) the hydraulic behavior of a single groin located on the right bank of the river where the diversion channel ends and b) the arrangement of seven groynes

distributed along the right margin. Both experiments were numerically simulated, and its values used for calibration purposes of the model.

## Numerical simulation

The first step in the numerical simulation was to determine the way to input the geometry of the groynes to the model. This is because it can be done in several ways, each of which differs in the degree of complexity. The physical and geometric elements used as variables that characterize the groynes are shown in Figure 4.

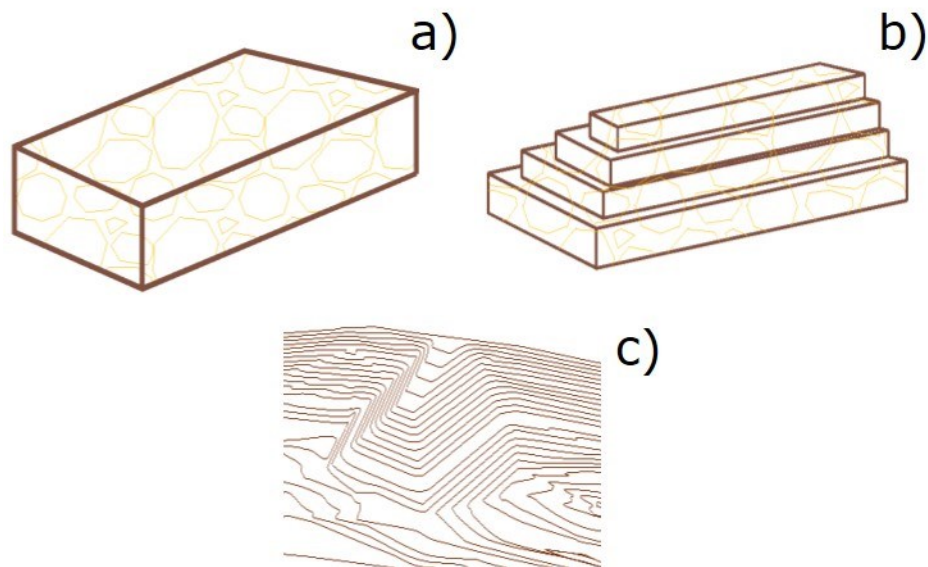


**Figure 4.** Groin variables.

Where in:  $X_e$  is the separation between groins;  $B$ , the width of the river;  $R$ , the radius of curvature;  $LT$ , the working length;  $k$ , the slope;  $\varphi$ , the orientation angle; and  $\beta$ , the expansion angle.

Three alternatives were considered for the analysis. The first input geometry considered the groin as a barrier (Figure 5a). The length was equal to the working length over half the length of the tip of the crest, and the height was defined as the elevation at the end of the working length plus half the height of the working length. The second considered the groin as a set of stepped obstructions (Figure 5b), with an initial obstruction in the bottom and staggered obstructions around the first.

The ridge width initially proposed in the groin was equivalent to the working length, and the height was defined as the elevation at the end of the working length plus half the height. The rest of the obstructions were distributed in such a way as to cover the surface of the original groin. The third option was to model the groin as a part of the natural terrain (Figure 5c). The topography was modified, and Digital Terrain Model DTM was generated. The construction of the digital terrain model (DTM) was carried out from topographic data collected in the field.

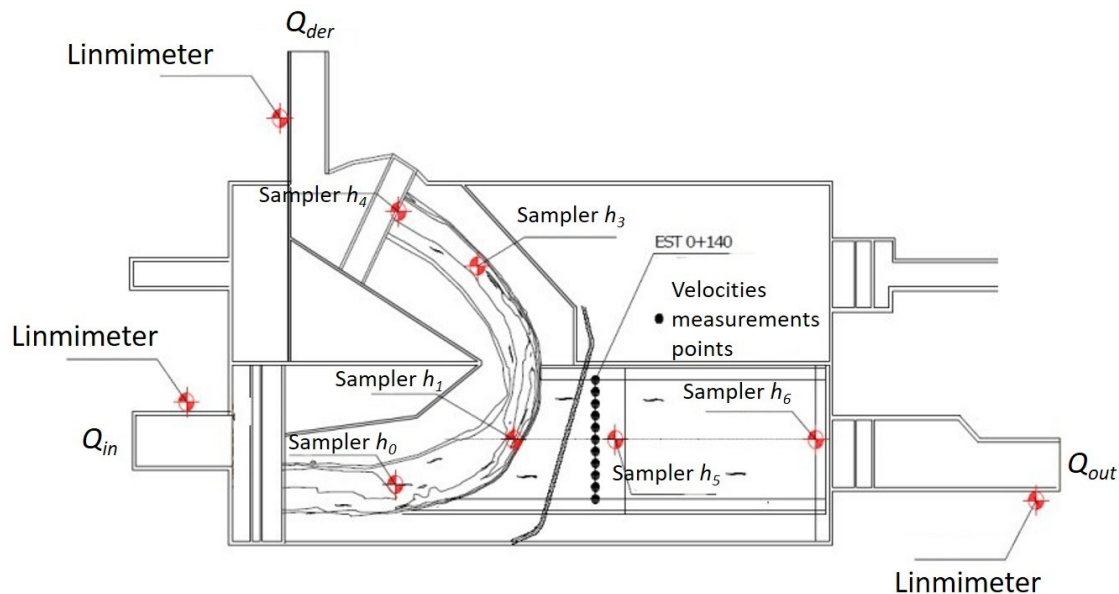


**Figure 5.** Alternatives: A) physical barrier; b) stepped barriers, c) natural terrain.



## Calibration

The numerical model was calibrated with the inlet, outlet, and derived flow rates measured in the physical model, and the free surface water levels measured at six sampling points  $h_0$ - $h_6$  (Figure 6). The roughness coefficient was varied until the results of the numerical modeling reproduced acceptably the results measured experimentally in the physical model.

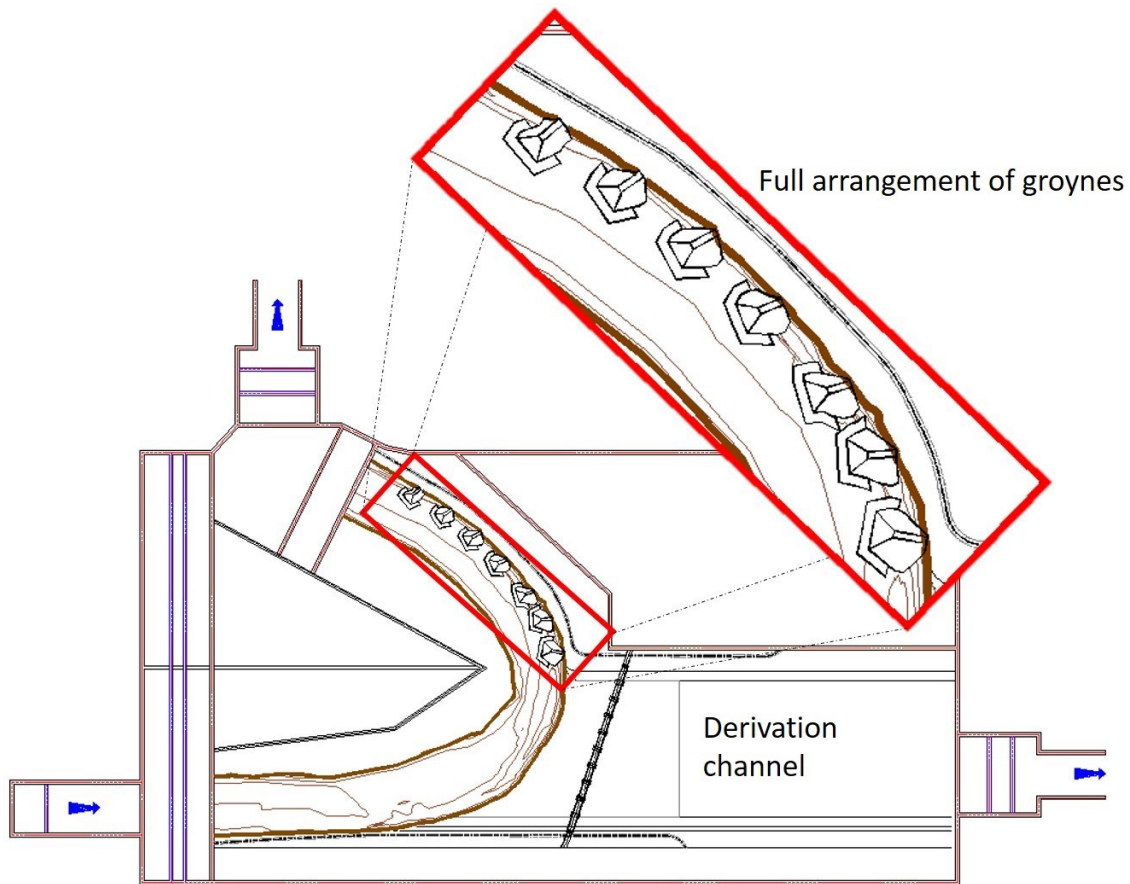


**Figure 6.** Variables measurement at the physical model:  $Q_{in}$ , Input discharge;  $Q_{out}$ , output discharge;  $Q_{der}$ , derivate discharge;  $h_0$  -  $h_6$ , level meter samplers.

Once the model has been calibrated, we analyzed the differences between the water surface levels measured experimentally and those simulated numerically with the geometry options (barrier, stepped, and natural terrain).

Choose the best way to input the geometry of the groynes, the full arrangement was built (Figure 7), and was compared with the experimental and the simulated hydraulics behavior.

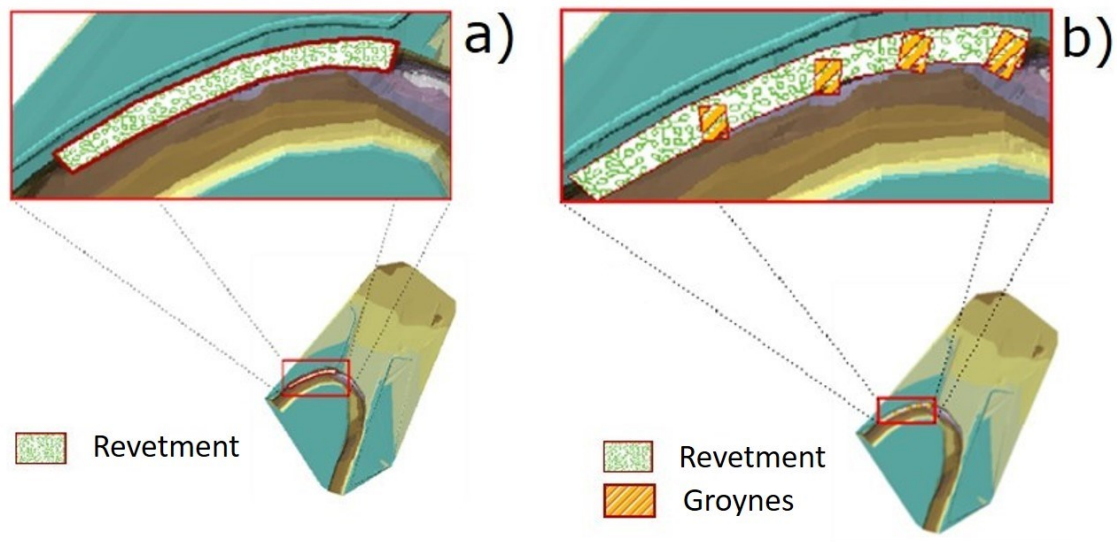




**Figure 7.** Physical model and detail of the full groynes arrangement.

## **An alternative of the groynes arrangement**

In addition to checking the numerical simulation of the arrangement of groynes, it was decided to apply the numerical model for design purposes. Therefore, the groynes design criteria considered in the Rivers Engineering Manual (Maza-Alvarez *et al.*, 1996) were revised, in terms of the angle of expansion and orientation, the separation between breakwaters and a working length of them. The objective was to evaluate the possibility of using another kind of protection work that had the same effect but could reduce the volume of work. The proposed options were: a) the placement of a bank revetment (Figure 8a) and b) combination of bank revetment with a minor arrangement of groynes (Figure 8b). Both alternatives were modeled in HEC-RAS, and the hydraulic profiles obtained, as well as the operating curves of the derivation channel.



**Figure 8.** A) Bank revetment, b) Bank revetment + four groynes.

## Results

### Modeling natural conditions

Table 1 shows the proposed value of Manning ( $n$ ), the numerical results, and the experimental measurements under natural conditions.

**Table 1.** Calibration of the Manning roughness coefficient.

Roughness coefficient “ $n$ ”	Discharge $\text{m}^3/\text{s}$	Level (masl)
0.025	1305	6.63
0.024	1357	6.61
0.023	1417	6.61
0.023 y 0.0226 downstream.	<b>1438</b>	<b>6.59</b>
Physical model	<b>1450</b>	<b>6.60</b>

Therefore, was chosen a Manning coefficient of 0.023 for the bend, and 0.0226 for the output. Also, because both the curve and the derivation channel were constructed with the same material, a Manning coefficient of 0.023 was used in the derivation channel.

### **Geometrical input of the groynes**

The hydraulic profiles measured in the physical model were compared against the numerical simulations with the different ways of input the geometry of the groynes. Table 2 shows the measured levels and those generated from the numerical modeling at the sampler points in the curve ( $h_0$ ,  $h_3$ , and  $h_4$ ) and the derivation channel ( $h_1$ ,  $h_5$ , and  $h_6$ ). In the simulation, the three options of the geometry of the groynes were considered: a) barrier, b) set of stepped obstructions (steps), and c) natural terrain (NT). The range of the flows is from the moment in which the channel starts to derive ( $1\,000\text{ m}^3/\text{s}$ ), up to the overflow flow ( $1\,600\text{ m}^3/\text{s}$ ).

**Table 2.** Measurement levels at the physical model, and the numerical simulations.

$Q_{in} = 1\ 600\ m^3/s$							
Sampler	Exp	Barrier	$\Delta h$ (m)	Steps	$\Delta h$ (m)	NT	$\Delta h$ (m)
	Level (masl)						
Curve	6.84	6.92	0.08	6.91	0.07	6.91	0.07
	7.13	6.93	0.20	6.93	0.20	6.92	0.21
	6.96	6.91	0.05	6.91	0.05	6.91	0.05
Channel	6.73	6.83	0.10	6.81	0.08	6.81	0.08
	5.94	6.10	0.16	6.27	0.33	6.27	0.33
	3.38	3.05	0.33	3.05	0.33	3.05	0.33
$\Delta h$ average =			0.15		0.18		0.18
$Q_{in} = 1\ 503\ m^3/s$							
Sampler	Exp	Barrier	$\Delta h$ (m)	Steps	$\Delta h$ (m)	NT	$\Delta h$ (m)
	Level (masl)						
Curve	6.76	6.77	0.01	6.75	0.01	6.75	0.01
	6.86	6.71	0.15	6.71	0.15	6.71	0.15
	6.74	6.69	0.05	6.69	0.05	6.69	0.05
Channel	6.73	6.68	0.05	6.65	0.08	6.66	0.07

	5.81	5.97	0.16	6.11	0.30	6.11	0.30
	3.69	2.93	0.76	2.93	0.76	2.93	0.76
<b><math>\Delta h</math> average =</b>			<b>0.20</b>		<b>0.23</b>		<b>0.22</b>
<b><math>Q_{in} = 1\,450\text{ m}^3/\text{s}</math></b>							
Sampler	Exp	Barrier	$\Delta h$ (m)	Steps	$\Delta h$ (m)	NT	$\Delta h$ (m)
	Level (masl)						
Curve	6.64	6.70	0.06	6.68	0.04	6.68	0.04
	6.79	6.62	0.17	6.62	0.17	6.62	0.17
	6.57	6.60	0.03	6.60	0.03	6.60	0.03
Channel	6.50	6.61	0.11	6.59	0.09	6.59	0.09
	5.62	5.92	0.30	6.05	0.43	6.05	0.43
	2.61	2.89	0.28	2.89	0.28	2.89	0.28
<b><math>\Delta h</math> average =</b>			<b>0.16</b>		<b>0.17</b>		<b>0.17</b>
<b><math>Q_{in} = 1\,397\text{ m}^3/\text{s}</math></b>							
Sampler	Exp	Barrier	$\Delta h$ (m)	Steps	$\Delta h$ (m)	NT	$\Delta h$ (m)
	Level (masl)						
Curve	6.66	6.59	0.07	6.56	0.10	6.57	0.09
	6.62	6.47	0.15	6.47	0.15	6.47	0.15
	6.50	6.45	0.05	6.45	0.05	6.45	0.05
Channel	6.57	6.50	0.07	6.47	0.10	6.48	0.09

	5.54	5.85	0.31	5.97	0.43	5.97	0.43
	3.42	2.82	0.60	2.82	0.60	2.82	0.60
<b><math>\Delta h</math> average =</b>			<b>0.21</b>		<b>0.24</b>		<b>0.24</b>
<b><math>Q_{in} = 1\,307\text{ m}^3/\text{s}</math></b>							
Sampler	Exp	Barrier	$\Delta h$ (m)	Steps	$\Delta h$ (m)	NT	$\Delta h$ (m)
	Level (masl)						
Curve	6.57	6.48	0.09	6.45	0.12	6.46	0.11
	6.48	6.32	0.16	6.32	0.16	6.32	0.16
	6.33	6.30	0.03	6.30	0.03	6.30	0.03
Channel	6.4	6.4	0.00	6.37	0.03	6.37	0.03
	5.53	5.75	0.22	5.84	0.31	5.84	0.31
	3.31	2.73	0.58	2.73	0.58	2.73	0.58
<b><math>\Delta h</math> average=</b>			<b>0.18</b>		<b>0.21</b>		<b>0.20</b>
<b><math>Q_{in} = 1\,199\text{ m}^3/\text{s}</math></b>							
Sampler	Exp	Barrier	$\Delta h$ (m)	Steps	$\Delta h$ (m)	NT	$\Delta h$ (m)
	Level (masl)						
Curve	6.40	6.50	0.10	6.29	0.11	6.30	0.10
	6.24	6.32	0.08	6.13	0.11	6.13	0.10
	6.10	6.30	0.20	6.10	0.00	6.10	0.00



Channel	6.33	6.43	0.10	6.22	0.11	6.22	0.11
	5.31	5.62	0.31	5.70	0.39	5.70	0.39
	3.13	2.62	0.51	2.62	0.51	2.62	0.51
<b><math>\Delta h</math> average=</b>			<b>0.22</b>		<b>0.21</b>		<b>0.20</b>
<b><math>Q_{in} = 1\,102\text{ m}^3/\text{s}</math></b>							
Sampler	<b>Exp</b>	<b>Barrier</b>	<b><math>\Delta h</math> (m)</b>	<b>Steps</b>	<b><math>\Delta h</math> (m)</b>	<b>NT</b>	<b><math>\Delta h</math> (m)</b>
	<b>Level (masl)</b>						
Curve	6.28	6.18	0.10	6.14	0.14	6.15	0.13
	6.00	5.93	0.07	5.93	0.07	5.93	0.07
	5.96	5.90	0.06	5.90	0.06	5.90	0.06
Channel	6.10	6.11	0.01	6.07	0.03	6.08	0.02
	5.15	5.48	0.33	5.53	0.38	5.53	0.38
	3.04	2.51	0.53	2.51	0.53	2.51	0.20
<b><math>\Delta h</math> average =</b>			<b>0.18</b>		<b>0.20</b>		<b>0.14</b>
<b><math>Q_{in} = 1\,000\text{ m}^3/\text{s}</math></b>							
Sampler	<b>Exp</b>	<b>Barrier</b>	<b><math>\Delta h</math> (m)</b>	<b>Steps</b>	<b><math>\Delta h</math> (m)</b>	<b>NT</b>	<b><math>\Delta h</math> (m)</b>
	<b>Level (masl)</b>						

Curve	6.16	6.01	0.15	5.97	0.19	5.98	0.18
	6.80	5.74	0.06	5.74	0.06	5.74	0.06
	5.68	5.70	0.02	5.70	0.02	5.70	0.02
Channel	6.00	5.95	0.05	5.91	0.09	5.92	0.08
	5.03	5.36	0.33	5.39	0.36	5.39	0.36
	2.87	2.41	0.46	2.41	0.46	2.41	0.46
<b><math>\Delta h</math> average =</b>			<b>0.18</b>		<b>0.20</b>		<b>0.19</b>

The elevation average differences between the measured and the simulated data were:  $\Sigma \Delta h_{\text{Barrier}} = 0.18$ ,  $\Sigma \Delta h_{\text{Steps}} = 0.20$  and  $\Sigma \Delta h_{\text{NT}} = 0.19$ .

Because the smallest variation was obtained by modeling the breakwater as a barrier, this type of geometry was chosen with dimensions of width, height, and average length. This option requires a shorter time to enter its geometry to the numerical model.

## Numerical simulation of the full groynes arrangement

Once determined the way to input the groin geometry at the model, the next step was to input the full arrangement of the seven groynes. Due to the effect produced by the whole groynes arrangement is mainly reflected in the curve (sampler point  $h_1$ ), it was taken as a reference to compare the experimental measurements against the numerical simulations. Table 3 shows the experimental levels measured (Exp) and those generated from the numerical modeling (Full). Column  $\Delta h$  listed the levels difference between both results and the  $\Delta h$  average.

**Table 3.** Results of the levels at the derivation, with the full groynes arrangement.

Discharge		h derived		$\Delta h$ (m)
$Q_{in}$	$Q_{der}$	Exp	Full	
(m <sup>3</sup> /s)		(masl)		
1 438	639	6.94	6.86	0.08
1 397	596	6.89	6.76	0.13
1 309	500	6.76	6.68	0.08
1 204	385	6.57	6.59	0.02
1 102	294	6.42	6.46	0.04
1 001	223	6.28	6.31	0.03
<b><math>\Delta h</math> average =</b>				<b>0.06</b>

It was observed that the variation between the measured and the numerically simulated results averaged 0.06 m. It was considered that this result is acceptable, and therefore, the numerical model

simulated the functioning of the derivation structure adequately. The next step was to model an alternative that reproduced the same effect caused by the arrangement of seven groynes, but with smaller work volume.

## Alternative to the arrangement of seven groynes

The results obtained with the proposals considered were the following:

a) **Bank revetment.** Table 4 shows the levels measured in the  $h_1$  curve with a seven-groynes arrangement (column Exp) and compares them with those obtained with the bank revetment simulated with HEC-RAS (column Rev). The column  $\Delta h$  shows the difference between both results, as well as the average thereof.

**Table 4.** Results of the levels at the derivation, with the bank reventment.

Discharge		Discharge		$\Delta h$ (m)
$Q_{in}$	$Q_{der}$	Exp	Rev	
(m <sup>3</sup> /s)		(m <sup>3</sup> /s)		
1 438	639	6.94	6.57	0.37

1 397	596	6.89	6.44	0.45
1 309	500	6.76	6.33	0.43
1 204	385	6.57	6.19	0.38
1 102	294	6.42	6.03	0.39
1 001	223	6.28	5.86	0.42
<b><math>\Delta h</math> average =</b>				<b>0.41</b>

It was observed that the average difference in the free surface water between both configurations was 0.41 m. That is to say, that with the marginal revetment it is not possible to adequately reproduce the derivation effect.

b) Revetment and four groynes. Table 5 shows the levels measured in the curve ( $h_1$ ) with the seven-groynes arrangement (column Exp) and compares them against those obtained with the numerical modeling of the revetment and proposes four-groynes arrangement (column Rev + 4G). In the column  $\Delta h$ , the difference in level between the results of the numerical modeling and the experimental results is shown.

**Table 5.** Results of the levels at the derivation, with the bank revetment + four groynes.

Discharge		Discharge		$\Delta h$
$Q_{in}$	$Q_{der}$	Exp	Rev+4G	Rev+4GH

(m <sup>3</sup> /s)		(m <sup>3</sup> /s)		m
1 438	639	6.94	6.81	0.13
1 397	596	6.89	6.70	0.19
1 309	500	6.76	6.62	0.14
1 204	385	6.57	6.52	0.05
1 102	294	6.42	6.39	0.03
1 001	223	6.28	6.24	0.04
		<b><math>\Delta h</math> average =</b>		<b>0.10</b>

It was observed that between the results of the experimental measurements and the numerical modeling of the proposed alternative, the average variation in the water sheet is 0.10 m, and the difference between the results obtained with the modeling of the seven groynes and the modeling of the combined the bank revetment with the arrangement of four breakwaters is 0.04 m. It is considered that this variation is not significant, so this alternative can adequately reproduce the derivation effect.

## Volume of work

Table 6 shows for comparative purposes, the estimated volume of work required by each alternative.

**Tabla 6.** Comparison of the volume of work.

<b>Original volume (m<sup>3</sup>)</b>	
A full arrangement of seven groynes	12 687.21
<b>Alternative volume (m<sup>3</sup>)</b>	
Bank revetment	4 948.16
Arrangement of four groynes	6 024.28
Total =	10 972.44
<b>Difference =</b>	<b>1 714.77</b>

It was estimated a reduction in the volume of work of around 1 700 m<sup>3</sup>, which in economic terms represent a significant saving.

## Conclusions



In the numerical simulations, the HEC-RAS software was used, which is a hydraulic numerical model that can work in 1D or 2D. The objective was to perform a hydraulic analysis on a river in which a diversion channel was made, and marginal protection at a base of groynes was built. The hydraulic phenomenon is evident three-dimensional (3D), so it is thought that the use of 1D software, could be limited. HEC-RAS 1D was used here, and its performance was contrasted against the experimental data in a reduced physical model, taking into account the acceptable results. It was found that the best way to model the groynes, in this case, was also a barrier, as well as the numerical results compared against the average the least difference (0.06 m). This option requires a shorter time to enter the geometry in the model numerical. There is also a mode of alternative protection consisting of a bank revetment and four groynes, to find an arrangement to reproduce the original effect for the arrangement of seven groynes, but with a smaller volume of work. In this study was used the free surface level as a parameter of comparison and calibration, found that HEC-RAS 1D showed excellent performance for the hydraulic analysis of groynes in curves. However, it is recommended once the 1D analysis has been carried out and the final design has been chosen, to use a 2D model, and carry out a sensibility analysis and contrast the results with those obtained with the 1D model.

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