A Study on Water Flow Stability at the Rustic Intake of the Carapongo Channel, Rimac River, Peru

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ABSTRACT

This research analyzes flow stability at a rustic intake with a side weir in the Carapongo Channel, located in the middle basin of the Rímac River in Peru. The study focused on determining the Vedernikov number and performing hydraulic modeling using HEC–RAS in both lined and unlined channel reaches, considering different cross-sectional geometries and two flow scenarios: 0.45 m^3/s and 1.0 m^3/s. The results show that, when the weir is not considered, the water flow behavior does not exhibit instability at the rustic intake. The unlined rectangular section shows instability, whereas the trapezoidal configuration improves hydraulic behavior, thereby reducing the risk to the structure. The findings demonstrate that evaluating dimensionless flow stability parameters and numerical modeling are valuable tools for diagnosing and effectively managing channels.

Keywords-Carapongo rustic intake; flow stability; Vedernikov number; HEC – RAS hydraulic simulation

I. INTRODUCTION

Intake works are water-capture structures located on natural channels that collect and convey flow primarily for agricultural, industrial, and urban water supply uses [1]. Weirs are an important component of hydraulic systems. While the intake serves as the point of entry through the headworks, weirs perform a control function by maintaining a stable flow level and discharging excess flows from flood events [2]. In this regard, studying the flow behavior between these two structures is essential to ensure a balance between water resource utilization and the system's physical safety under hydraulically unstable conditions [3].

Throughout Peru's river basins, there are hydraulic structures classified as rustic-type intakes, intended to divert water from the supply source through simple trenches or channels located near the riverbanks. These structures are designed using rudimentary construction methods and take into account the area's physiographic characteristics and the channel bed's material composition [4].

Given their structural stability under fluctuations in the conveyed flows, these structures, featuring diverse geometric dimensions and hydraulic sections, may be considered as temporary intakes, since system efficiency is conditioned by soil characteristics, erosive processes, and the occurrence of flash floods [5]. These alterations in the hydrological regime, mainly due to global climate change, have increased the frequency and intensity of precipitation, generating greater runoff volumes; this situation tends to compromise the stability of rustic intakes by exposing their operational, functional, and structural vulnerabilities [6].

In the Lima region, Peru, the Carapongo Channel is part of the hydraulic infrastructure managed by the Rímac Hydraulic Sector Users Board (JUR), which is responsible for managing the waters of the Rimac River for agricultural purposes [7], with the aim of supplying irrigation for crops, mainly horticultural production such as lettuce, radish, and turnip [8].

According to the technical report supporting the delimitation of the Rimac minor hydraulic sector of the Chillón–Rímac–Lurín Local Water Authority (ALA CHRL), the Carapongo rustic intake infrastructure has a design flow rate of 1 m³/s, while the diversion channel has a maximum conveyance of 0.45 m³/s, which corresponds to the allocation assigned for agricultural operations through an administrative agreement with the JUR. However, to date, due to the reduction in irrigated areas resulting from the expansion of urban zones, flow rates now range from 0.14 to 0.25 m³/s (Rímac Users Board Report). In addition, it is important to note that when additional runoff enters the channel, mainly during the summer or during extreme meteorological events, excess water is discharged through the side weir to rejoin the main channel of the Rímac River.

Due to the hydraulic system's configuration, the reach between the intake headworks and the side weir exhibits flow instability attributable to flow-rate variations, irregular channel geometry, and the roughness coefficient of the rustic conveyance [9]. Therefore, analyzing the dynamics of water behavior in this section of the study area is appropriate for identifying the effects of water flow and turbulence on the structure.

Flow instability in rustic intake structures is a critical issue that has received limited attention in hydraulic engineering. Previous research on this topic has mainly focused on controlled laboratory experiments in open-channel systems, with insufficient validation under real-world conditions. In this context, hydraulic modeling is proposed as an essential step for understanding water behavior within the system [10]. This modeling enables characterization of the flow regime and assessment of hydraulic stability by estimating parameters such as flow depth, mean velocity, energy slope, and roughness [11]. HEC-RAS-based hydraulic modeling has proven to be a reliable method for simulating flow dynamics and assessing the performance of hydraulic structures under varying operational conditions [12]. This hydrodynamic analysis identifies critical instability zones and supports the implementation of design adjustments to ensure the structure maintains operational efficiency and sustainable water resource management.

This scenario sets the framework for the research, which aims to evaluate flow instability in the Carapongo Channel by examining the flow profile and the influence of the side weir under regular flow conditions and under hydraulic overload scenarios resulting from extreme meteorological events. The study is based on discharge data obtained from the ALA CHRL technical report. Flow stability in rural intake systems significantly affects hydraulic design. Analyzing it is essential for implementing design modifications to ensure structural efficiency, mitigate potential flood risks in the area, and ensure that the projected flow adequately meets existing agricultural demand.

This study presents a pioneering field-based investigation, providing empirical evidence that extends existing experimental research. Existing research has examined flow stability in lined and unlined channels separately; however, fewer studies have considered systems that include both sections. Therefore, this research integrates field data with hydraulic modeling to provide a more comprehensive assessment of flow behavior. The objectives of this research are: to evaluate water flow behavior for rustic collection in the lined and unlined Carapongo canal, to assess the spillway's influence on flow behavior, and to propose a section for the design of the Carapongo canal.

II. METHODOLOGY

A. Location of the Study Area

For the development of the present research, the Carapongo Channel was used as a reference. It is a hydraulic infrastructure facility in the middle basin of the Rímac River, within the district of Lurigancho–Chosica in the province of Lima, Peru, at the reference coordinates: Latitude -11°59´31” S and 76°50´11” W (Figure 1).

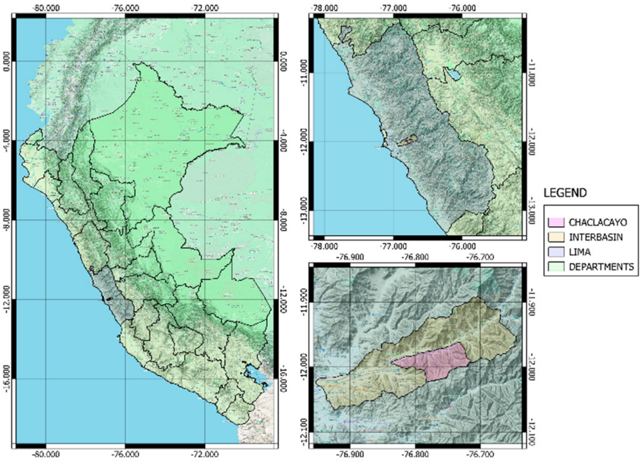

Fig. 1. Geographic location of the study area.

B. Evaluation of Water Flow Stability

The flow stability in the Carapongo Channel was evaluated by calculating the Vedernikov number (V_e), a dimensionless indicator of hydraulic behavior, considered one of the four main parameters used to identify equilibrium or stability conditions for uniform flow in open channels [13]. The Froude number (F) as well as the Vedernikov number, are indicators derived from the equations of flow motion. In contrast, the Reynolds number and the Ponce and Simon's dimensionless wave number are related to flow diffusivity [14]. The Vedernikov number (V_e) is defined (1) as the ratio between the relative celerity of the kinematic wave (v) and the relative celerity of the dynamic wave (w).

$$V_e = \frac{v}{w} \tag{1}$$

At the threshold value ($V_e = 1$), referred to as neutral or neutrally stable flow, this condition separates stable flow ($V_e < 1$) from unstable flow when ($V_e > 1$).

In addition, the Vedernikov number can be expressed as: (2),

$$V_e = \gamma \cdot x \cdot Fr \tag{2}$$

$$\gamma = 1 - R\,\frac{dP}{dA} \approx 1 - R\,\frac{(P_2 - P_1)}{(A_2 - A_1)} \tag{3}$$

where γ is a dimensionless geometric–hydraulic parameter (3) defined as a function of the hydraulic radius (R), hydraulic area (A), and wetted perimeter (P); x is a dimensionless number corresponding to the Manning hydraulic exponent with a value of 0.667.

Physically, it indicates whether surface disturbances will be attenuated ($V_e < 1$) or amplified, causing rolling waves ($V_e > 1$), which is crucial for the design of stable channels.

In this study, water flow behavior in the channel was evaluated by defining two longitudinal sections for analysis: a lined channel reach with roughness values (n) of 0.012-0.020 and a length of 100 m, and an unlined channel reach with a Manning roughness coefficient ranging from 0.021 to 0.040 and a length of 163 m, resulting in a total evaluated length of 263 m. To assess water flow stability in the channel, two discharge scenarios (0.45 m³/s and 1.0 m³/s) were analyzed. Field data were collected during the low- and high-flow seasons and validated with hydraulic modeling.

Based on the channel's physiographic characteristics and flow-rate information, the flow stability evaluation was conducted by calculating the Vedernikov number for the defined reaches, considering two types of geometric sections: rectangular and trapezoidal channels, with the objective of identifying zones exhibiting unstable behavior.

C. Hydraulic Modeling

Hydraulic modeling was carried out using the HEC-RAS software, integrating channel geometry and construction material characteristics into RAS Mapper, along with the hydraulic parameters. This integration enabled the development of the modeling process and the generation of maps showing water depth, flow velocity, specific energy, flood wave propagation, and related information. These results enabled the determination of points where runoff exceeds conveyance capacity and the detection of channel reaches where flow exhibits instability, considering both the presence and absence of the weir (Figure 2).

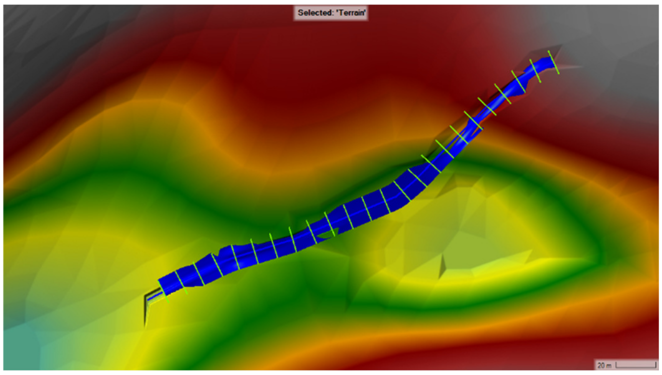

Fig. 2. Water flow simulation using RAS Mapper software for the study area, the Carapongo Channel.

III. RESULTS AND DISCUSSION

As stated in the methodology section, the simulation of water flow behavior in the Carapongo Channel was carried out based on the spatial delimitation developed in QGIS, under conditions with and without the weir structure, as shown in Figures 3 and 4.

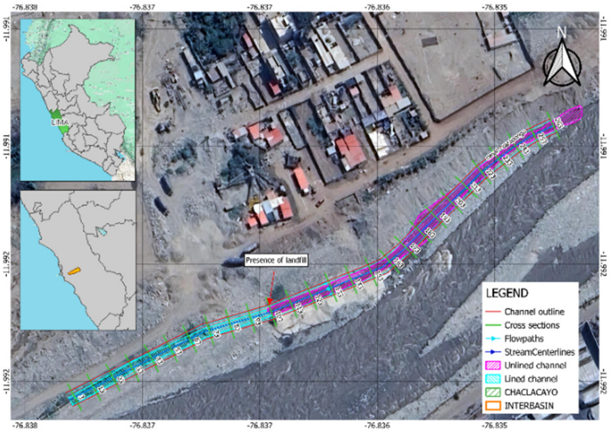

Fig. 3. Water flow behavior without the presence of the weir using the QGIS software in the study area.

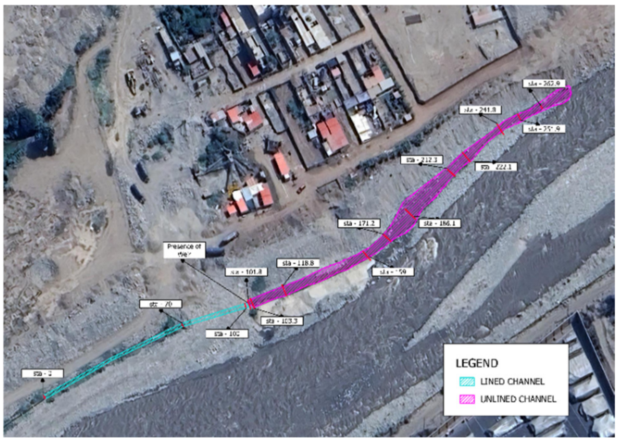

Fig. 4. Water flow behavior with the presence of the weir using the QGIS software in the study area.

To ensure technical rigor and unambiguous interpretation of the hydraulic parameters used in the flow stability assessment, the following section provides detailed definitions of each symbol (Table I).

TABLE I. SYMBOLS, DEFINITIONS AND UNITS USED IN THE HYDRAULIC MODELING.

Symbol	Definition	Unit
Ve	Vedernikov Number. Criterion for free-surface wave stability	Dimensionless
Fr	Froude Number. Parameter expressing the balance between inertial and gravity forces in open-channel flow.	Dimensionless
x	Hydraulic-radius exponent in the velocity expression (theoretical value $x = 0.67$ according to Manning's equation)	Dimensionless
ɣ	Shape factor. Dimensionless geometric–hydraulic parameter.	Dimensionless
v	Mean velocity. Average velocity within the channel cross-section.	m/s
Q	Discharge. Volumetric flow rate through the cross-section	m^3/s
A	Hydraulic area. Portion of the channel cross-section occupied by flowing water	m^2
P	Wetted perimeter. Length of the channel boundary in direct contact with the flow	m
R	Hydraulic radius. Geometric parameter definited as the quotient of the cross-section area and the wetted perimeter.	m
S	Bed slope. Longitudinal inclination of the channel bottom.	m/m
n	Manning roughness coefficient	Empirical coefficient

Using HEC-RAS, the simulation was performed based on an analysis of two cross-sections with rectangular and trapezoidal geometries originally present in the channel, considering both unlined and lined reaches, resulting in a total length of 263 m. Two discharge scenarios (0.45 m³/s and 1.0 m³/s) were assessed in the hydraulic simulation. However, instability in flow behavior was observed under the lower-discharge scenario. Based on the calculation of hydraulic parameters, the results shown in the following tables were obtained.

A. Simulation for a Rectangular Channel in Its Natural Form

The data obtained from the simulation performed using the HEC- RAS software on the stability conditions of water flow in the rustic intake of the Carapongo Channel indicate the presence of a single unstable section (Figure 5) with $V_e = 1.54$ (Table II) corresponding to an originally existing rectangular section.

According to the information presented in Table III, derived from the simulation, and using the Vedernikov number as a reference, no flow instability is observed in this reach of the channel with a rustic natural section (Figure 6).

TABLE II. RESULTS OF THE CALCULATION OF FLOW BEHAVIOR FOR THE UNLINED RECTANGULAR SECTION IN THE CHANNEL INTAKE

Distance	**A_1**	**P_1**	**R_1**	**Fr_1**	**A_2**	**P_2**	**ɣ**	**Ve**
262.9	0.58	2.06	0.28	0.4	0.81	2.36	0.63	0.17
251.9	0.39	2.98	0.13	1.01	0.68	3.29	0.86	0.58
241.8	1.1	5.55	0.2	0.29	1.74	5.88	0.90	0.17
222.1	0.41	3.65	0.11	1.01	0.84	5.17	0.61	0.41
212.3	0.84	4.03	0.21	0.37	1.38	4.51	0.81	0.20
186.1	0.9	5	0.18	0.38	1.7	6.25	0.72	0.18
171.2	0.96	3.7	0.26	0.29	1.49	4.41	0.65	0.13
159	1.09	4.92	0.22	0.28	1.74	5.41	0.83	0.16
118.8	0.56	3.98	0.14	0.68	0.98	4.74	0.75	0.34
103.3	0.39	3.02	0.13	1.01	0.7	3.54	0.78	0.53
101.8	0.28	2.32	0.12	1.45	0.81	3.25	0.79	0.76
100	**0.16**	**1.67**	**0.1**	**2.68**	**0.93**	**2.73**	**0.86**	**1.54**
70	0.5	2.04	0.24	0.45	0.82	2.57	0.60	0.18
0	0.29	1.63	0.17	1	0.49	1.99	0.69	0.46

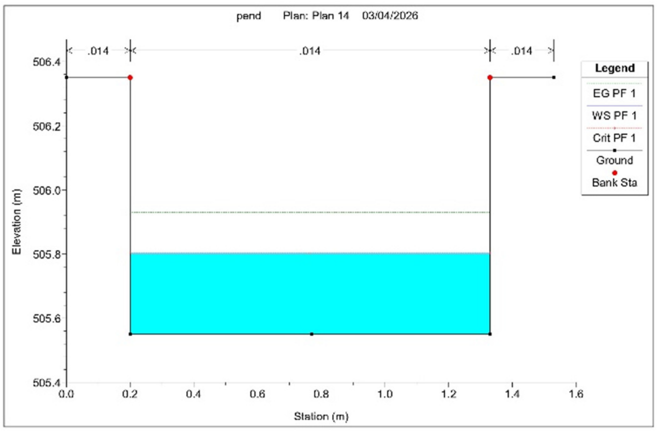

Fig. 5. Unstable rectangular section evaluated using HEC – RAS.

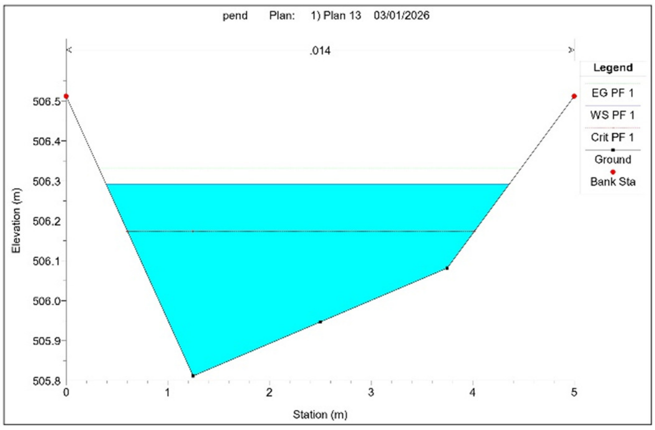

Fig. 6. Unlined trapezoidal section evaluating water flow behavior in the Carapongo Channel.

B. Final Section

Table IV presents information obtained from a simulation conducted using HEC–RAS under a design proposal that modifies the initial section by changing its geometry to a lined trapezoidal form (Figure 7).

TABLE III. RESULTS OF THE CALCULATION OF FLOW BEHAVIOR FOR THE NATURAL SECTION IN THE UNLINED (RUSTIC) REACH

Distance	**A_1**	**P_1**	**R_1**	**Fr_1**	**A_2**	**P_2**	**γ**	**Ve**
262.9	0.58	2.06	0.28	0.4	0.81	2.36	0.63	0.17
251.9	0.39	2.98	0.13	1.01	0.68	3.29	0.86	0.58
241.8	1.1	5.55	0.2	0.29	1.74	5.88	0.90	0.17
222.1	0.41	3.65	0.11	1.01	0.84	5.17	0.61	0.41
212.3	0.84	4.03	0.21	0.37	1.38	4.51	0.81	0.20
186.1	0.9	5	0.18	0.38	1.7	6.25	0.72	0.18
171.2	0.96	3.7	0.26	0.29	1.49	4.41	0.65	0.13
159	1.09	4.92	0.22	0.28	1.74	5.41	0.83	0.16
118.8	0.56	3.98	0.14	0.68	0.98	4.74	0.74	0.34
103.3	0.39	3.02	0.13	1.01	0.7	3.54	0.78	0.53
101.8	0.25	2.43	0.1	1.74	0.49	3.21	0.68	0.78
100	0.21	2.24	0.1	2.14	0.42	3.1	0.59	0.84
70	0.65	3.47	0.19	0.5	1.08	4.07	0.73	0.25
0	0.39	3.02	0.13	1.01	0.7	3.54	0.78	0.53

TABLE IV. RESULTS OF THE CALCULATION OF FLOW BEHAVIOR FOR THE LINED TRAPEZOIDAL SECTION

Distance	**A_1**	**P_1**	**R_1**	**Fr_1**	**A_2**	**P_2**	**γ**	**Ve**
262.9	0.58	2.06	0.28	0.4	0.81	2.36	0.63	0.17
251.9	0.39	2.98	0.13	1.01	0.68	3.29	0.86	0.58
241.8	1.1	5.55	0.2	0.29	1.72	5.87	0.90	0.17
222.1	0.41	3.65	0.11	1.01	0.95	5.56	0.61	0.41
212.3	0.84	4.03	0.21	0.37	1.54	4.58	0.84	0.21
186.1	0.88	4.98	0.18	0.38	2.21	6.41	0.81	0.20
171.2	0.95	3.67	0.26	0.29	1.94	4.63	0.75	0.14
159	1.06	4.88	0.22	0.29	2.41	5.67	0.87	0.17
118.8	0.88	4.57	0.19	0.37	2.68	5.78	0.87	0.22
103.3	2.09	5.24	0.4	0.11	3.86	5.97	0.84	0.06
101.8	1.84	4.41	0.42	0.12	3.25	5.12	0.79	0.06
100	2.47	3.85	0.63	0.06	3.69	3.85	1.00	0.04
70	2.13	3.75	0.56	0.08	3.24	3.75	1.00	0.05
0	0.35	2.21	0.16	1.01	0.61	2.52	0.81	0.55

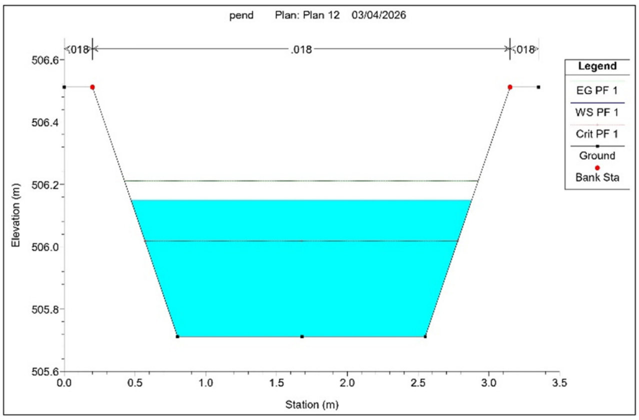

Fig. 7. Trapezoidal section evaluating water flow behavior using HEC – RAS software in the Carapongo Channel.

The results of the hydraulic simulation in this study reflect the current condition of the rustic Carapongo diversion channel and serve as baseline information for the improvement proposal. Research has shown that evaluating the Vedernikov number enables the proposal of geometric modifications in structural design when the results indicate areas of pulsating flow that pose a risk to structural stability [15]. Likewise, studies focused on the efficient operation of irrigation channels support the use of numerical modeling with the HEC-RAS software as an appropriate tool for experimental analyses of cross-sectional behavior in conveyance systems [16].

This study applies Manning´s roughness coefficient, ranging from 0.012 to 0.020 for the lined section and from 0.021 to 0.040 for the unlined sections, reflecting the differing surface characteristics. The HEC-RAS model was validated for water depth simulation using Manning's n values ranging from 0.020 to 0.025, with a calibrated value of 0.023. These results can be used to effectively manage water in canal irrigation systems, reducing losses and operating and maintenance costs [17]. The HEC-RAS hydraulic simulation indicates that at cross-section RS 100, corresponding to the unlined rectangular section at the channel intake, the Vedernikov number reached 1.54. This value indicates hydrodynamic instability, characterized by the amplification of disturbances and the development of surface wave trains. As a consequence, flow separates from the channel bed, and water depths exceed the channel's structural height, leading to overtopping. The associated increase in specific energy intensifies erosive processes, compromising the channel's structural stability and reducing its useful life. Therefore, the computed hydraulic parameters support the need for modifications to the original channel design.

IV. CONCLUSIONS

The proposed methodological framework and the results obtained support several key conclusions. First, when the presence of the weir is not considered, the water-flow behavior at the rustic intake of the Carapongo Channel does not exhibit instability. According to the hydraulic calculations performed, variations in the roughness coefficient (n) do not affect the flow instability conditions at the rustic intake of the channel.

Based on the channel geometry, water flow instability was observed in a reach with a rectangular section. Therefore, modifying the section geometry to a lined trapezoidal form is considered viable to prevent water flow instability at the rustic intake. The geometric design alternative uses a lined trapezoidal channel configuration to stabilize flow conditions and improve hydraulic efficiency. The prismatic cross-section was defined with a base width of b = 1.70 m and 1:1 side slopes ($z = 1$), assuming a Manning's roughness coefficient of 0.014. The Vedernikov number is a key indicator of flow instability in lined and unlined channels. Its value directly informs hydraulic design. This parameter enables early detection of potential problems and facilitates necessary modifications to channel sections. These structural adjustments improve the performance of hydraulic infrastructure operated by the irrigation commission, benefiting agricultural users and supporting water resource management in the Rímac River basin.

Furthermore, implementing a regular maintenance program for the Carapongo Channel is advised to reduce the accumulation of sediment and rolled pebbles, which significantly affect flow dynamics and may compromise hydraulic efficiency.

DECLARATION OF COMPETING INTERESTS

Not applicable to this work

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DATA AVAILABILITY

Publicly available data from [7, 8] were used. The generated data can be provided by the corresponding author upon reasonable request.

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