

Hydrodynamic Analysis of Channel Shape and Flow Discharge Variations for Flood Mitigation

Andung Yunianta

Department of Civil Engineering, Yapis University, Jayapura, Indonesia
andung.ay@gmail.com

Miswar Tumpu

The Graduate School, Hasanuddin University, Indonesia
tumpumiswar@gmail.com (corresponding author)

Rahmawati

Department of Civil Engineering, Universitas Muhammadiyah Pare-Pare, Indonesia
rahmawatiramli09@gmail.com

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ABSTRACT

This study aims to analyze the hydrodynamics of the Right Main Channel of Baliase using the Nays2DH–International River Interface Cooperative (iRIC) computational simulation and evaluate the changes in the flow velocity patterns and Froude numbers (Fr) based on the revised channel design. The novelty of this research lies in utilizing Nays2DH within the iRIC platform to simulate the detailed hydrodynamic behavior, thereby providing a new understanding of how the changes in the channel design affect the flow dynamics in real-world scenarios. The study adopts a computational simulation approach, utilizing iRIC software to replicate the field conditions and provide accurate hydraulic representations. The research methodology involves model development, running simulations, and analyzing results. The findings indicate that the Nays2DH simulation accurately represents the hydrodynamic conditions of the Right Main Channel, both before and after the channel modifications. The key results show that the Fr in Model A ranges from 0.224 to 0.236 (subcritical flow), while in Model B, after the modifications, it ranges from 0.45 to 0.7, indicating notable improvements in the flow management. However, the upstream section experiences supercritical flow ($Fr > 2$), emphasizing the need for structural reinforcement. Based on these findings, the study proposes that further research is needed to examine the effects of the dynamic flow conditions under different discharge scenarios and climate factors, as well as the application of reinforcement strategies in critical areas to enhance the long-term channel stability. This research contributes to the development of more effective flood mitigation strategies through hydrodynamic modeling and channel design optimization.

Keywords-hydrodynamics; main channel; flow discharge; Baliase irrigation area

I. INTRODUCTION

The development of irrigation areas represents a vital element in fostering the agricultural growth and ensuring sustainability [1, 2]. The Baliase Irrigation Area is part of the Pompengan–Larona River Basin (WS. A2-24), as formally designated by Ministerial Regulation PU No. II A/PRT/M/2006. Furthermore, it has been incorporated into the National Strategic Projects (PSN No. 58 of 2017) [3]. Situated in North Luwu Regency, this region holds considerable potential due to its land and water resources, which are appropriate for the development of a technical irrigation system. The development of the Baliase irrigation area seeks to establish comprehensive irrigation infrastructure, including weirs, channels, and hydraulic structures, to ensure an adequate

water supply for the entire service region. This initiative is projected to augment the cropping intensity from 100% to 245%, by implementing a Rice-Rice-Secondary Crop planting pattern, alongside efforts to enhance the local livelihoods.

An open channel is a waterway in which the water flows with a free surface, influenced by atmospheric pressure. Open-channel flow refers to the movement of the water within a channel, where the surface remains exposed to air pressure along its entire length [4, 5]. At any point along the channel, the surface pressure stays consistent. Open channels are categorized into two primary types: natural channels, which comprise all watercourses that occur naturally, and artificial channels, which are engineered and constructed to meet

specific needs related to irrigation, drainage, or transportation [6].

Previous studies have shown the significance of numerical modeling in analyzing the flow behavior and sediment transport in non-prismatic open channels. According to [7], the Nays2DH model was effectively used in multiple river and irrigation channel studies, delivering precise simulations of the flow velocity, water surface elevation, and sediment transport. The study highlighted that non-prismatic channels, due to their irregular shape, exhibit complex hydrodynamic behavior that requires advanced numerical models for accurate predictions. Similarly, two-dimensional (2D) hydrodynamic simulations were employed to investigate the erosion and deposition patterns in channels with varying cross-sections, revealing that the flow acceleration and turbulence intensification are significant in areas with sudden channel contractions or expansions. These findings underscore the importance of detailed hydrodynamic simulations in enhancing the irrigation canal efficiency and flood mitigation strategies [8].

Further research compared physical and numerical models for open-channel flow analysis, concluding that numerical modeling, particularly Nays2DH and similar 2D models, offers a cost-effective and reliable alternative to physical laboratory experiments [9]. They observed that calibrating and validating models with real-world data greatly improves the simulation accuracy, making it an essential step in hydrodynamic research. Furthermore, the research analyzed the transitions between the supercritical and subcritical flows in irrigation channels, illustrating that the areas with Fr exceeding 2 require structural reinforcements to prevent the excessive erosion and flow instability. These studies are consistent with the objectives of this research, which seeks to analyze the flow discharge, velocity variations, and channel stability in the Baliase Irrigation System utilizing the Nays2DH model [10].

Open channels, whether in technical, semi-technical irrigation systems, or natural waterways, often exhibit non-prismatic conditions, where the cross-sectional shape varies along the channel length. In non-prismatic channels, flow characteristics, such as the water depth, velocity, and overall flow behavior undergo continuous changes due to variations in channel geometry. These variations are caused by several factors, such as changes between different cross-sections, the presence of structures like bridge piers, or other modifications that alter the original channel shape [11].

One of the main engineering methods in channel design and optimization is analyzing the flow discharge and flow patterns to enhance the water management efficiency. This involves hydrodynamic modeling, which can be performed using physical models or numerical simulations. Nays2DH, a highly effective 2D numerical model for hydrodynamic analysis, was developed by Dr. Yasuyuki Shimizu of Hokkaido University in collaboration with the iRIC [12]. This model can simulate the flow patterns, sediment transport, riverbed evolution, and erosion processes, making it well-suited for complex open channel studies.

This study employs computational simulations with mathematical modeling to replicate real-world physical

conditions, converting them into mathematical equations based on natural laws and the principles of fluid mechanics. The methodology involves applying the model to analyze the variations in flow patterns within the channel, followed by a comparison of the results with theoretical predictions. A well-developed mathematical model must be based on accurate physical formulations, appropriate numerical solutions, and reliable validation against real-world data [13]. The numerical model enables the prediction of the flow patterns, water surface elevation, and horizontal velocity components under both steady and unsteady flow conditions. The model validation process involves problem specification, theoretical development, numerical specification, initial application, calibration, confirmation, and result analysis [14].

Although extensive research has been conducted on hydrodynamic modeling of open channels, studies focusing on non-prismatic irrigation canals with varying cross-sections remain limited, particularly within Indonesia's irrigation infrastructure. Most studies primarily analyze natural river systems or artificial channels with uniform shapes, leaving a gap in understanding the hydrodynamic behavior of non-prismatic irrigation canals affected by structural modifications, sedimentation, and flow turbulence [7, 8]. Additionally, although previous research has validated the Nays2DH model for predicting the flow velocity and sediment transport, few studies have applied it to evaluate the effects of channel modifications on the irrigation efficiency and flood mitigation strategies. This study aims to address this gap through the utilization of Nays2DH numerical simulations to evaluate the flow variations, the distribution of the Fr , and the efficacy of structural reinforcements within the Baliase Irrigation System. The findings aim to provide valuable insights for irrigation management and infrastructure optimization.

This study focuses on the Baliase Weir Main Canal, utilizing the Nays2DH model to assess its hydrodynamic behavior. The goal is to assess the effectiveness and efficiency of the canal under different flow conditions, ensuring optimal water distribution and sediment management. The outcomes of this research will help enhance the efficiency of irrigation systems and facilitate the implementation of flood mitigation strategies within the region.

II. MATERIALS AND METHODS

A. Research Location

The chosen study location for the hydrodynamic simulation is the Baliase Main Canal at Baliase Weir, located in Masamba District, North Luwu Regency, South Sulawesi Province, Indonesia, with coordinates $2^{\circ}32'37.7''$ S and $120^{\circ}21'46.1''$ E. This canal is a crucial part of the Baliase Irrigation System and a National Strategic Project (PSN) aimed at improving the irrigation efficiency and reducing the flood risk. The site was selected because of its hydraulic complexity, where changes in channel shape and discharge influence the flow patterns, sediment transport, and structural stability. Numerical modeling is employed to analyze these conditions, enhance the irrigation performance, and prevent the erosion or flow instability. The results of this study are expected to provide valuable insights for more effective water resource

management. Additionally, they can aid in planning and developing similar irrigation systems in other areas. Figure 1 illustrates the research location.

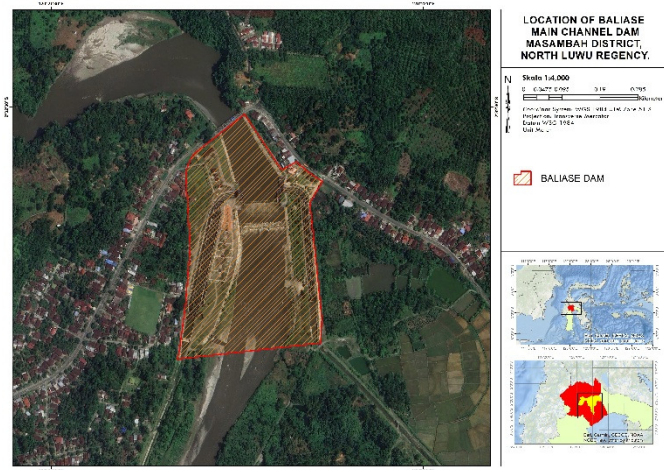


Fig. 1. Research location.

B. Types and Research Variables

This study uses a computational simulation approach with numerical modeling software to replicate real-world hydrodynamic conditions in the field. The software employed for the simulation is the iRIC, which allows for precise modeling of the flow patterns, velocity distribution, and channel stability. The research follows a structured methodology, beginning with preparation, model development, simulation execution, and analysis of the results obtained through the iRIC software. The key variable examined in this study, consistent with the research objectives, is the hydrodynamic behavior of the Baliase Main Canal.

C. Research Data

The hydrodynamic behavior of the Baliase Main Canal is simulated utilizing a modeling process dependent on precise field-based data. The key data employed encompass channel geometry in XYZ coordinates (also known as the .tpo file), flow discharge values obtained from government sources, and Manning’s roughness coefficients corresponding to various canal materials [15, 16]. These inputs are crucial for developing a numerical model that accurately represents the canal’s actual conditions and facilitates an effective evaluation of its water flow management capacity. The simulation is conducted using the iRIC Nays2DH model, specifically designed for analyzing the river flow, sediment transport, and channel deformation. It involves three main stages: pre-processing, solver, and post-processing. During pre-processing, the necessary data and boundary conditions are entered. In the solver stage, the model operates with a 0.1-s time step to simulate the flow dynamics and channel changes, starting from zero flow until it stabilizes. If errors occur, adjustments are made to the grid or boundary conditions to improve accuracy.

Finally, the post-processing stage visualizes and analyzes the results using graphs, animations, and tables. The output parameters, such flow depth, sediment transport, and shear stress assist in evaluating the canal’s performance and guide the

recommendations for improvements and flood mitigation. This integrated approach enables the testing of various scenarios, such as altered flow or canal shapes, providing valuable insights for local authorities in planning more effective infrastructure and flood control strategies.

III. RESULTS AND DISCUSSION

A. Baliase Right Side Main Channel Data before Design Review

The Baliase Irrigation Area, covering about 21,928 Ha, is situated in the districts of Masamba, Mappadeceng, Sukamaju, Baebunta, and Malangke in North Luwu Regency, South Sulawesi Province. The Baliase Weir, serving as the main water source for the irrigation system, supplies water to two primary canals: the Left Baliase Main Canal and the Right Baliase Main Canal (Figure 2). This study centers on the Right Baliase Main Canal, which will undergo design modifications due to the land constraints.



Fig. 2. Baliase Dam situation photo.

Table I displays the dimensions of the Right Baliase Main Canal prior to the design review, while Figure 3 portrays its dimensions before the review.

TABLE I. DIMENSIONAL DATA OF THE BALIASE MAIN CHANNEL ON THE RIGHT BEFORE THE DESIGN REVIEW

Channel data	Notation		Unit
Channel base width	b	12.00	m
High water level	h	1.59	m
Slope of embankment	m	0.50	
Height of embankment guard	W	0.80	m
High guard of the couple	Wp	0.40	m
Planned water level elevation	El.	41.49	+ m
Base channel elevation	El.	39.90	+ m
Top elevation of building	El.	42.34	+ m

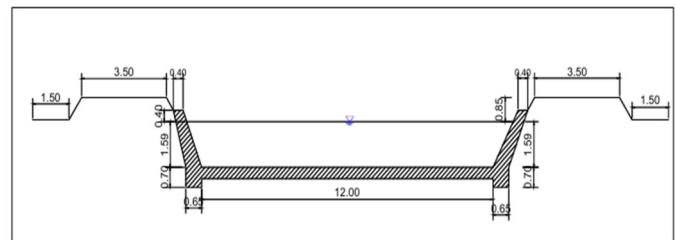


Fig. 3. Baliase main channel dimensions before the design review.

The Right Baliase Main Canal is designed to carry a flow discharge of 22.477 m³/s, using stone masonry with a roughness coefficient (K) of 60, equivalent to Manning’s $\eta = 0.6$. The design follows the hydraulic standards from the Irrigation Planning Guidelines (KP-03) and employs hydrostatic principles and Manning’s Equation to analyze the open channel flow. Key factors in the calculation include the flow area, hydraulic radius, channel slope, and surface roughness, all of which influence the flow rate and the canal’s efficiency [17]. To determine the canal’s flow capacity, it is essential to understand its geometry, including the width and depth of the cross-section, which may be trapezoidal or rectangular. These shapes affect the cross-sectional area and wetted perimeter, which together determine the hydraulic radius—a crucial factor in flow velocity. The slope of the canal, although gentle, still influences the velocity and helps prevent erosion. By applying Manning’s Equation with these parameters, the canal is confirmed to efficiently convey the intended discharge while supporting sustainable water distribution for irrigation.

B. Baliase Right Side Main Channel Data before Design Review

The design modifications of the Right Baliase Main Canal were made due to land constraints, leading to a reduction in channel dimensions. The trapezoidal channel width (b) decreased from 12 to 5 m, while the water surface height (h) dropped from 1.59 to 1.5 m. Additionally, the side slope (m) changed from 0.5 to 1.5, and the channel material was upgraded from stone masonry (K = 60) to K175-grade concrete (K = 70) for better structural integrity and flow efficiency. Due to the smaller dimensions, maintaining a flow discharge of 22.477 m³/s requires an increase in the flow velocity. Before the modifications, the flow velocity (V) was 1.102 m/s, which rose to 2.067 m/s afterward. The full dimensional changes are shown in Table II.

Based on Table II, the redesign of the Baliase Right Main Canal shows a reduction in dimensions due to the land constraints. The channel base width (b) has significantly decreased from 12.00 to 5.00 m, while the high-water level (h) has slightly decreased from 1.59 to 1.50 m. The slope of the embankment (m) has increased from 0.50 to 1.50, which may affect the stability of the channel. Additionally, the height of the embankment guard (W) has increased from 0.80 to 0.85 m, and the height of the high guard of the couple (Wp) has increased from 0.40 to 0.45 m, to accommodate the hydraulic changes resulting from the increased flow velocity. The slope of the channel bed (I) has also increased from 0.00024 to 0.00082, which may boost the flow energy and erosion potential. Furthermore, slight changes are observed in the planned water level elevation (El.), which has risen from 41.49 m to 42.30 m, as well as in the base channel elevation (El.), which has increased from 39.90 m to 40.70 m, indicating an adjustment in the storage capacity and structural stability. Overall, these changes aim to maintain the same flow discharge despite the smaller channel dimensions. Figures 4 and 5 illustrate the Baliase main channel dimensions after the design review and the implementation of the Baliase main channel

construction, as depicted on the right following the design review (Figure 6) [18].

TABLE II. DIMENSIONAL DATA OF THE BALIASE MAIN CHANNEL ON THE RIGHT AFTER THE DESIGN REVIEW

Channel data	Notation	Channel design dimensions		Unit
		Beginning	Change	
Channel base width	b	12.00	5.00	m
High water level	h	1.59	1.50	m
Slope of embankment	m	0.50	1.50	
Height of embankment guard	W	0.80	0.85	m
High guard of the couple	Wp	0.40	0.45	m
Slope of the channel bed	I	0.00024	0.00082	
Planned water level elevation	El.	41.49	42.30	+ m
Base channel elevation	El.	39.90	40.70	+ m
Top elevation of building	El.	42.34	42.82	+ m

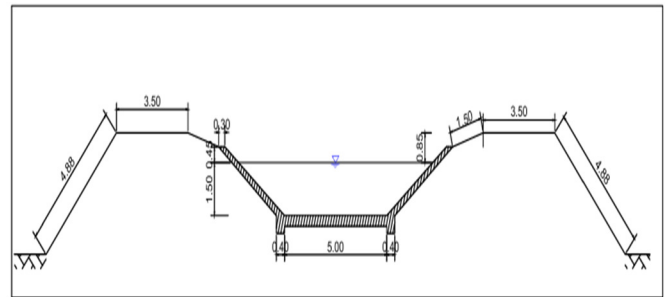


Fig. 4. Baliase main channel dimensions following the design review.

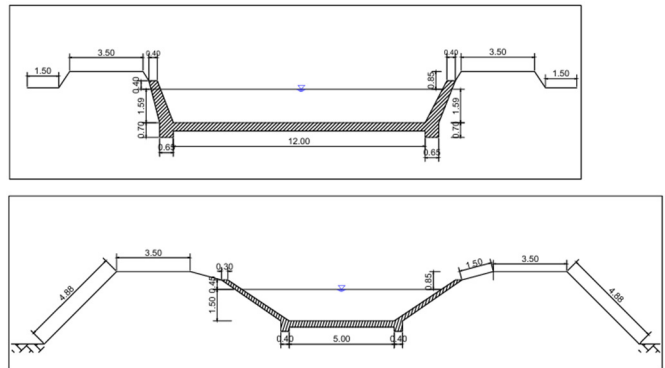


Fig. 5. Channel model before and after the design review.



Fig. 6. Construction of the Baliase main channel on the right side after the design was reviewed.

C. Changes in Flow Velocity Patterns due to the Design Review

The velocity pattern changes due to the review design, shifting from a 12-m-wide channel base (Model A, before redesign) to a 5-m-wide channel base (Model B, after redesign), as shown in Figure 7. The narrowing of the channel causes an increase in the flow velocity because the same discharge must be handled within a smaller cross-sectional area. This modification has a significant impact on the hydrodynamic properties of the channel, potentially altering the sediment transport, erosion, and overall flow stability. Comparing the velocity patterns between Model A and Model B offers important insights into how the dimensional changes affect the water movement and hydraulic efficiency [19].

The velocity pattern and flow characteristics before and after the revised design (Figure 7), along with the velocity graph comparison (Figure 8), reveal notable changes resulting from the adjustments to the channel dimensions. Using the hydrostatic continuity equation, the velocity was calculated to increase from 1.102 m/s (pre-redesign) to 2.067 m/s (post-redesign), indicating a doubling. However, the computational

simulations using Nays-2DH offer a more detailed view of the velocity changes along the right main canal of Baliase, showing that within the first 150 m, the flow is unstable before gradually stabilizing with a slight decrease in velocity [20].

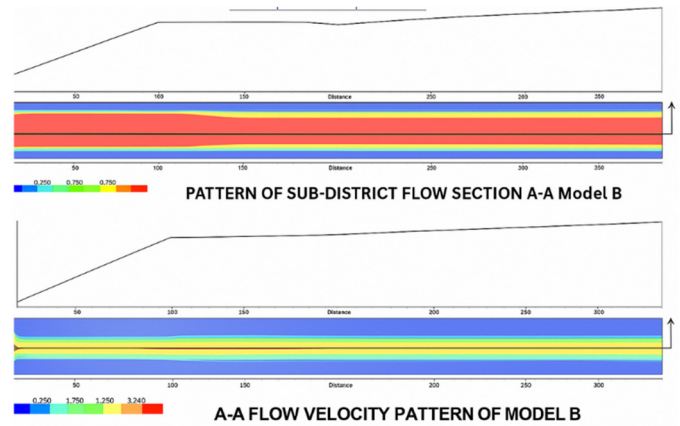


Fig. 7. Channel velocity patterns before and after the design review.

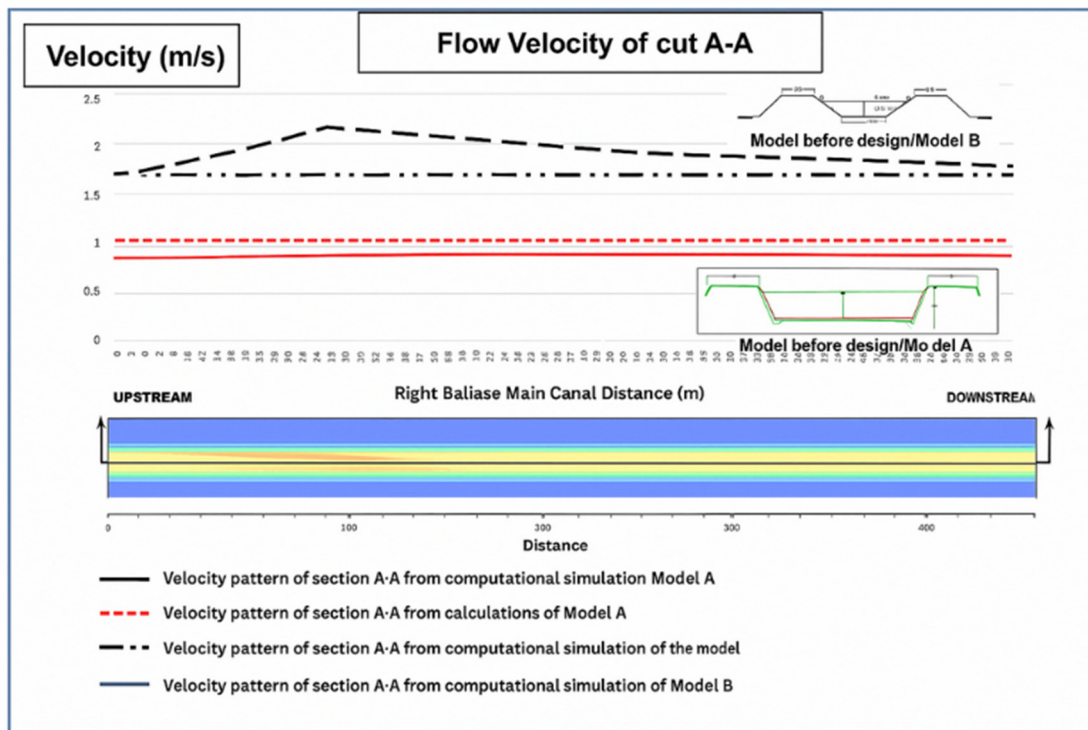


Fig. 8. Channel speed graph before and after the design review.

Prior to the dimensional modification, the Baliase Right Main Canal maintained a consistent flow velocity ranging from 0.95 m/s to 1.00 m/s, as demonstrated by the simulation results. However, after reducing the channel width from 12 to 5 m, the flow velocity exhibited increased instability, fluctuating between 2.02 m/s and 2.5 m/s. This indicates that the decrease in the cross-sectional area substantially altered the flow dynamics and initially induced turbulence. This observation

aligns with previous hydraulic modeling studies, which demonstrate that decreasing the channel dimensions results in increased velocity due to the principle of continuity, often leading to initial flow instability before it eventually stabilizes downstream [12]. Furthermore, prior research highlights the significance of parameters, such as slope, roughness, and cross-sectional geometry in determining the velocity distribution and energy dissipation [21]. The present study corroborates that

significant modifications to canal dimensions necessitate a comprehensive hydrodynamic analysis to prevent issues, such as erosion, structural deterioration, or diminished water distribution efficiency—problems frequently encountered in modified irrigation channels and river engineering projects [22].

D. Changes in Froude Numbers due to Design Review

The Fr is a crucial parameter in hydraulic analysis, as it indicates the flow regime and stability of the water movement within a channel. The results from the review design show a significant increase in the Fr values due to the reduction in the channel width from 12 m (Model A) to 5 m (Model B), resulting in a rise in velocity. Initially, the Fr ranged between 0.224 and 0.236 in Model A, but after modification, it increased to 0.45–0.7 in Model B. Despite this increase, both conditions remain in the subcritical flow regime ($Fr < 1$), indicating that the flow is still dominated by gravitational forces, and surface disturbances move upstream. However, the increased Fr values suggest a higher flow velocity, which can influence the sediment transport and energy dissipation. As depicted in Figure 9, the pattern of Fr closely follows the velocity trend, which aligns with the $Fr = V/(gy)^{0.5}$ equation, demonstrating their direct proportionality. These findings underscore the importance of making careful hydraulic adjustments when modifying the channel dimensions to maintain flow stability. Concrete mix parameters, such as density, water-to-cement ratios, Fine Aggregate-to-cement

ratios (FA/c), Coarse Aggregate-to-cement ratios (CA/c), and the cost of concrete can be adjusted to align with the socioeconomic aspects of sustainable concrete. To meet the environmental sustainability goals, factors such as density, water-to-cement ratio (w/c), Fine Aggregate-to-Total aggregate ratio (FA/T), Total aggregate-to-cement ratio (T/c), and Fine Aggregate-to-cement ratio (FA/c) can be considered. A proper concrete mix design not only improves the structural durability, but also addresses both the socioeconomic and environmental concerns.

Figure 10 further demonstrates that the reduction in the cross-sectional area of the channel (A) induces the flow instability, which begins at the upstream section of the Baliase Main Canal and extends approximately 150 m downstream. This instability is evident in the rise of both the flow velocity and the Fr, which may lead to increased turbulence and erosion risks in this segment of the channel. The significant increase in the velocity and Fr values indicates that the flow becomes less stable, necessitating careful consideration of the structural reinforcements in this vital region [23]. In the absence of adequate reinforcement, the augmented energy flow could result in scouring, alterations in sediment transport, or structural damage to the channel lining. Consequently, supplementary stabilization measures, such as enhancements to the concrete lining or the installation of energy dissipation structures, should be assessed to ensure the long-term functionality and durability of the canal [7].

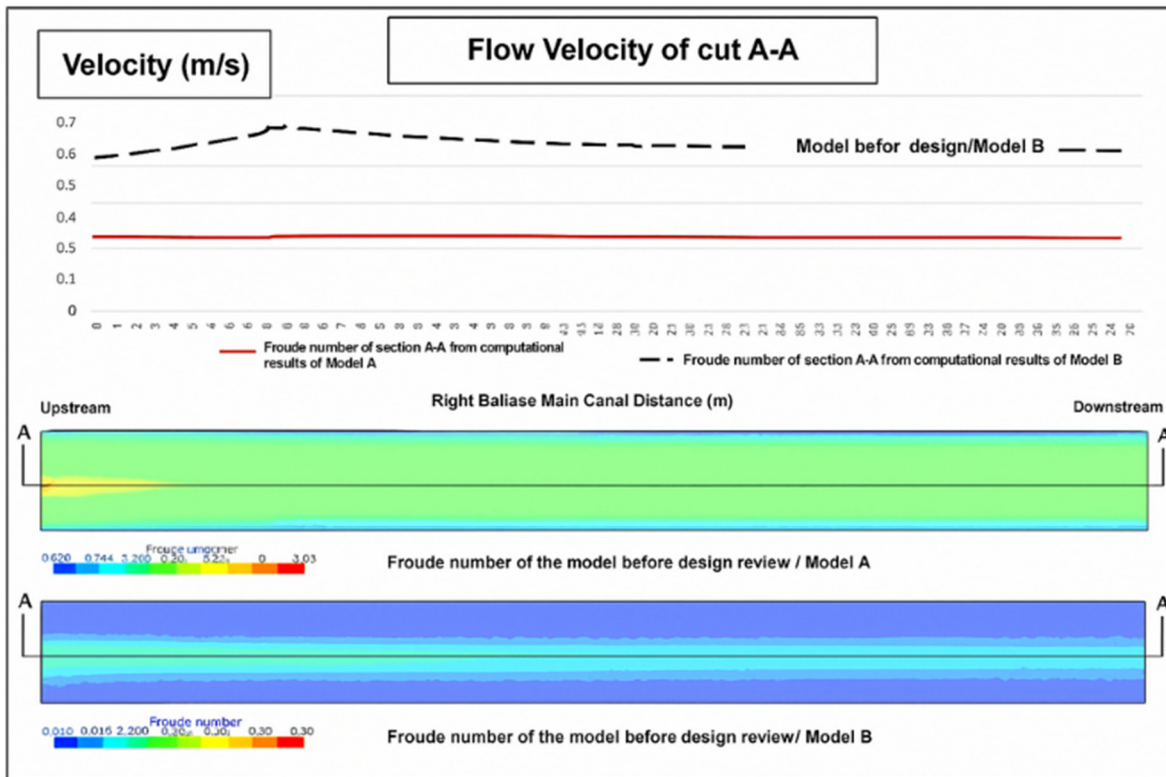


Fig. 9. Froude number pattern of channel before and after the design review.

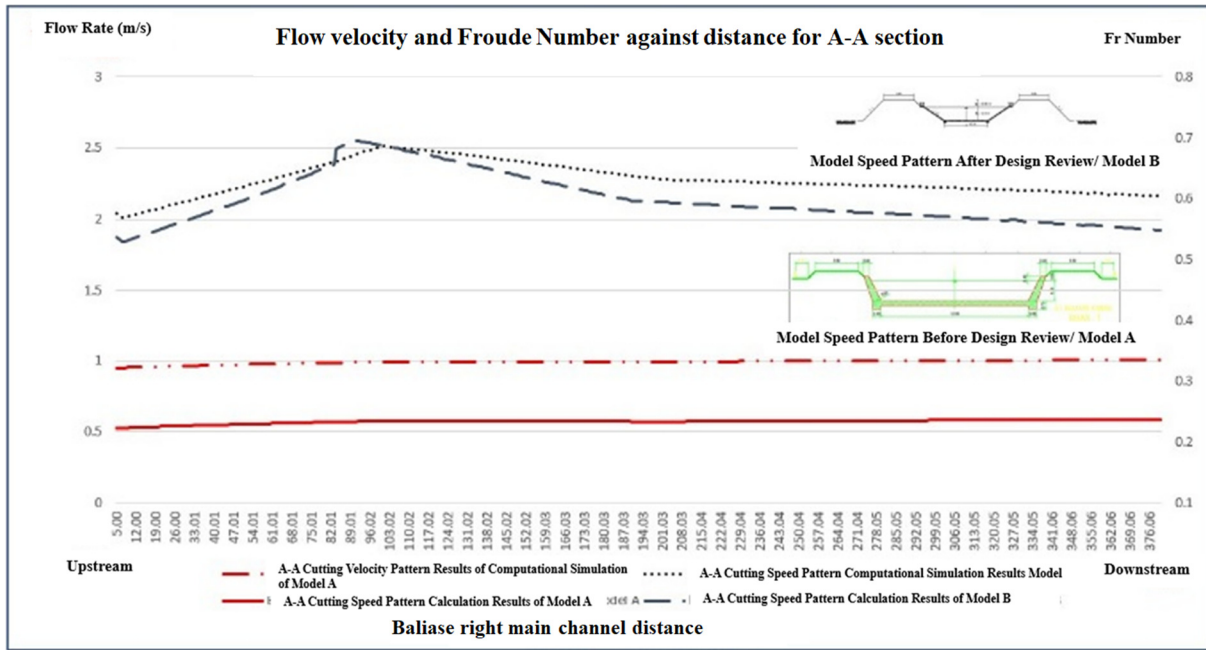


Fig. 10. Froude number graph of channel before and after the design review.

The design review of the Baliase Right Main Canal has significantly affected the Fr due to the reduction in the channel dimensions. Before the design change (Model A), the Fr ranged from 0.224 to 0.236, indicating a stable subcritical flow ($Fr < 1$) where the water depth was relatively high, and the flow velocity was moderate. However, after the channel dimensions were reduced (Model B), the Fr increased to 0.45–0.7, which, although still in the subcritical regime, suggests a more dynamic and unstable flow condition. This increase aligns with the fundamental relationship $Fr = V/(gy)^{0.5}$, where Fr is directly proportional to the velocity. The narrowing of the channel base from 12 to 5 m caused an acceleration of the flow, leading to an increase in Fr. Similar findings have been reported in previous studies, where reductions in cross-sectional area resulted in localized velocity increases, causing flow instability in irrigation canals [24].

In the study area, this increase in Fr is particularly concerning for the first 150 m downstream, where computational simulations using Nays-2DH software revealed flow disturbances before a stable velocity was reached. The field observations indicate that the area near the Baliase Weir experiences variations in the flow conditions due to the natural changes in channel roughness and sediment transport. The rise in the Fr values from the design review could worsen the erosion risks along the canal banks, especially in sections where the flow faces sharp transitions in the channel width or slope. Previous hydrodynamic studies have demonstrated that such sudden changes can lead to sediment resuspension and bed degradation, which, if left unaddressed, can compromise the structural integrity of the irrigation channels [25].

Considering the impact of the increased Fr on the channel stability, proper reinforcement measures are necessary, especially in the first 150 m of the canal. Literature suggests that reinforcing materials, such as higher-grade concrete linings

or riprap protection, can mitigate the adverse effects of the increased velocity and turbulence. Studies on similar canal modifications emphasize the importance of including energy dissipation structures or adjusting the slope gradients to control excessive flow acceleration. For the Baliase Right Main Canal, these mitigation strategies should be thoroughly evaluated to ensure long-term performance and prevent further structural issues caused by higher Fr values [26].

IV. CONCLUSION

The computational simulation conducted using the Nays2DH application effectively modeled the conditions of the Baliase Right Main Canal, both before and after the design modification. By employing hydrodynamic principles, the simulation provided a more precise representation of the flow patterns and velocity distribution compared to calculations based solely on hydrostatic principles. The velocity results derived from the hydrostatic approach prior to the design alteration (Model A) were 1.102 m/s, whereas the Nays2DH simulation yielded a velocity range of 0.94–1.2 m/s. Subsequently, after the channel dimensions were reduced (Model B), the calculated velocity increased to 2.067 m/s, with the simulation demonstrating a range of 2.1–2.6 m/s, thus indicating a substantial increase in the flow velocity attributable to the narrowed channel width.

The flow velocity variations were significantly more evident in the Nays2DH simulation, identifying critical regions that necessitate reinforcement. The simulation outcomes demonstrate that the initial 150 m of the Baliase Right Main Canal undergo considerable flow instability, thereby requiring structural reinforcement to avert potential damage. Turbulent flow fluctuations were observed in this section, underscoring the necessity for supplementary protective measures to ensure the canal stability. The Froude number (Fr) values recorded in Model A ranged from 0.224 to 0.236, signifying subcritical

flow conditions. Nevertheless, following the modifications to the channel dimensions (Model B), the Fr increased to a range of 0.45–0.7, which remains within the subcritical flow regime. This indicates that the channel depth remains adequate for accommodating the increased flow velocity. However, at the upstream segment of the Baliase Right Main Canal, the Fr surpassed 2, signifying the presence of a supercritical flow condition. This observation suggests that the channel in this section is susceptible to increased turbulence and potential erosion, underscoring the importance of structural reinforcements to maintain the long-term stability of the irrigation infrastructure.

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