Evaluating the Sluice Gate Effectiveness for the Water Level Control in the Danda Besar Tidal Irrigation System, South Kalimantan, Indonesia

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ABSTRACT

This study evaluates the effectiveness of sluice gates in controlling water levels in the Danda Besar Swamp Irrigation Area (SIA) in South Kalimantan, Indonesia. Hydrodynamic simulations were conducted using the Hydrologic Engineering Center's River Analysis System (HEC-RAS) version 6.5 with a one-dimensional unsteady flow scheme. Scenario analysis was performed for the period of July 18–20, 2024, with hourly outputs. A sluice gate of 1 m height, 3 m width, and +4 m invert elevation was introduced at the entrance of 20 tertiary canals, operated by a simple tidal rule: open during high tide and closed during low tide. The results indicate that, under baseline conditions, the average inundated area was only 914.24 ha, while in the gate scenario this increased to 1173.3 ha, representing a 17% reduction in dry area. The gates successfully retained water during low tide, maintaining inundation that otherwise would be lost under baseline conditions. These findings demonstrate that simple sluice gate operation can effectively control water levels, reduce soil exposure, and provide a practical strategy for sustainable water management in tidal irrigation systems.

Keywords- Sluice gate; HEC-RAS; tidal irrigation; water level; water management

I. INTRODUCTION

Indonesia, one of the world's leading rice consumers, faces a rising demand for this staple crop due to rapid population growth [1]. To address this challenge, the government has turned to the significant potential of swamp and tidal ecosystems as alternative cultivation areas [2]. Since the 1970s, large-scale irrigation projects have been launched to reclaim swamp areas, most notably in Kalimantan and Sumatra under the Tidal Rice Field Development Project. However, productivity in these areas has remained low, mainly due to poor environmental conditions and low soil fertility. Thus, improving management strategies in these ecosystems is crucial to enhancing rice production [3]. The Danda Besar SIA in South Kalimantan is a representative example of this system, where tidal fluctuations of the Barito River regulate water distribution through an interconnected network of primary, secondary, and tertiary canals. Irrigation and drainage are managed without pumps, relying instead on river stage variations driven by tidal cycles [4]. However, the most critical constraint in this system is the presence of Acid Sulfate Soils (ASS). These soils form when pyrite-bearing layers are exposed to oxygen, triggering the production of sulfuric acid that degrades soil and water quality and ultimately suppresses rice yields [5]. Tidal irrigation systems, which are widely applied in South Kalimantan, have faced environmental and agricultural challenges since their establishment nearly 50 years ago [6, 7]. Effective water management is fundamental to optimizing swampland for agricultural development [8]. These ecosystems are strongly regulated by the tidal dynamics from rivers and seas during both spring and neap tides [9]. However, the effectiveness of water control structures, such as one-way flow or overflow gates, is often constrained by tidal amplitude, canal geometry, and the design and operational performance of sluice gates [10]. The lack of systematic management remains a primary limitation to agricultural sustainability. During the dry season, tidal fluctuations promote pyrite oxidation and acid formation, reducing rice yields [11].

Studies in West African tidal wetlands have shown that maintaining flooded conditions and applying organic amendments can improve pH and reduce soil acidity [12]. Similarly, authors in [13] emphasized that sustaining high water levels, together with the presence of sulfate and iron, promotes the reductive conditions that suppress oxidation and greenhouse gas emissions in peat soils. One practical measure is water level regulation through the operation of sluice gates, which are essential for maintaining sufficient water levels above paddy fields and canal beds, particularly during low tides [14]. Hydraulic investigations have also shown how gate geometry and design influence discharge and flow regulation efficiency [15]. Active gate control within hydraulic systems is indispensable for stabilizing critical water levels and mitigating oxidative degradation processes [16]. Hydrodynamic assessments confirm that variations in gate operation directly affect the water levels and sediment dynamics [17]. Although numerous studies have examined tidal irrigation systems and sluice gate hydraulics, few of them have quantitatively assessed how controlled gate operations reduce dry areas in large-scale peat-based tidal systems. This knowledge gap limits the understanding of how gate management affects inundation patterns and soil oxidation risks. To address this issue, the present study quantitatively evaluates the effectiveness of sluice gates through hydrodynamic simulations and spatial analysis of dry-area reduction. Specifically, it aims to assess the hydrological conditions of the Danda Besar SIA and determine how sluice gate application can enhance water distribution and minimize soil exposure during low tides. The simulations were performed using the HEC-RAS to identify operational strategies for maintaining field inundation. The research was conducted in the Danda Besar SIA, South Kalimantan, Indonesia, in 2024.

II. MATERIALS AND METHODS

A. Study Area

The Danda Besar SIA is in Danda Jaya Village, Rantau Badauh District, Barito Kuala Regency, South Kalimantan Province, Indonesia, at coordinates 03°06′16″–03°09′01″ south (S) and 114°35′58″–114°39′25″ east (E). The development of its irrigation system began in the 1970s. The area is dominated by acid sulfate soils, with pyrite layers extending up to 100 cm below the surface. When these layers are exposed to air due to low water levels, oxidation occurs, releasing sulfuric acid and increasing environmental risks for agriculture. The Danda Besar irrigation system combines "Garpu" (fork or comb) and "Kolam" (pond) types, designed to convey freshwater from the Barito River through a single intake into a primary canal. The primary and secondary canals extend approximately 7 km inland, and about 2.5 km from the intake, the secondary canal branches into 27 tertiary canals, each averaging 2 km–3 km in length. A leaching pond was originally constructed at the downstream end of the secondary canal to flush out acidity; however, it is now completely sedimented and inactive. The system serves an irrigated area of about 2400 ha. Despite its potential, rice productivity remains low, around 2 tons per ha per year, due to limited water circulation, soil acidification, and poor soil quality [18]. For hydrodynamic model calibration and validation, two monitoring stations were established: Station S1, located at the primary canal near the Barito River intake, and Station S2, situated along the secondary canal approximately 2.5 km inland from S1. Both stations were equipped with automatic water-level sensors to record tidal fluctuations, as shown in Figure 1.

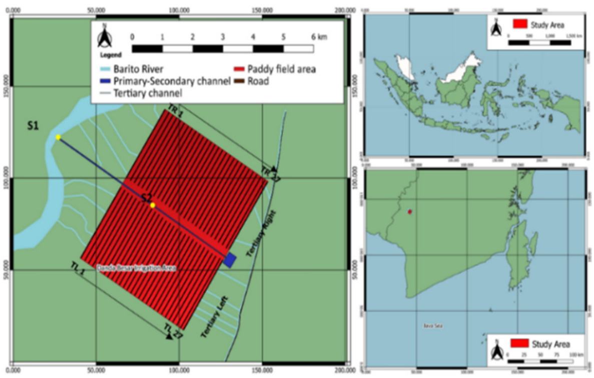

Fig. 1. Location of the Danda Besar SIA.

B. Hydrodynamic Simulation

Hydrodynamic simulation was conducted using HEC-RAS version 6.5 with a one-dimensional unsteady flow scheme to represent the tidal irrigation dynamics in the Danda Besar SIA. The model geometry was developed from the existing irrigation network, with cross-sections extracted from the 3 m × 3 m Digital Elevation Model (DEM). The upstream boundary condition was defined by the observed tidal stage hydrograph of the Barito River, which drives the inflow to the primary channel and its downstream branches. The model was run over a 1.5-day simulation period (18–20 July 2024), selected to represent the dry season, during which water levels in the Barito River reach their lowest annual range. This period spans more than one complete tidal cycle (approximately 12 h), allowing high-resolution analysis of inundation changes under water-scarce conditions. Before conducting the scenario analysis, the model was calibrated and validated using tidal water level data observed at two monitoring stations (S1 and S2) in the Danda Besar SIA. Field measurements were collected from 10 to 20 July 2024 using automatic ultrasonic water-level sensors installed at S1 (primary channel) and S2 (secondary channel). The Manning's roughness coefficient (n) was adjusted iteratively within the range of 0.025–0.035 until the simulated and observed hydrographs showed strong agreement, achieving coefficients of determination (R^2) of 0.99 at S1 and 0.93 at S2. These calibrated parameters were then used in the subsequent 1.5-day sluice gate simulation to maintain consistency and reliability. Figure 2 illustrates the sluice gate structure introduced at the entrance of each tertiary canal to evaluate water management strategies. The gate, represented as an inline control, has dimensions of 1 m in height, 3 m in width, and an inverted elevation of +4 m. The design reflects a simple wooden-board structure that local farmers can easily install and operate manually. Figure 3 shows the tidal-based operation rule applied for gate control. It remained open during high tide to allow inflow and flushing and closed during low tide to retain water and sustain inundation. In this simulation, the gate was closed during two low-tide windows: from 18 July 15:00 to 19 July 04:00, and from 19 July 11:00 to 20 July 00:00. Two scenarios were modeled for comparison: (i) the baseline condition without gates, and (ii) the gate scenario with tidal operation. As a preparatory step, the model was calibrated and validated against observed water levels at two monitoring points using a 10-day simulation period, ensuring its suitability for scenario analysis.

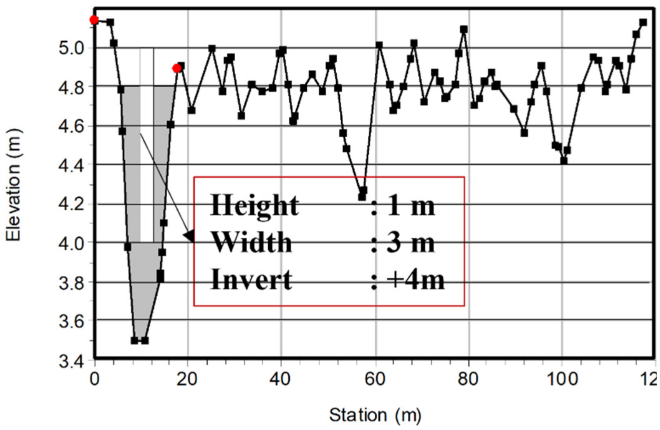

Fig. 2. Dimensions of the simulated sluice gate.

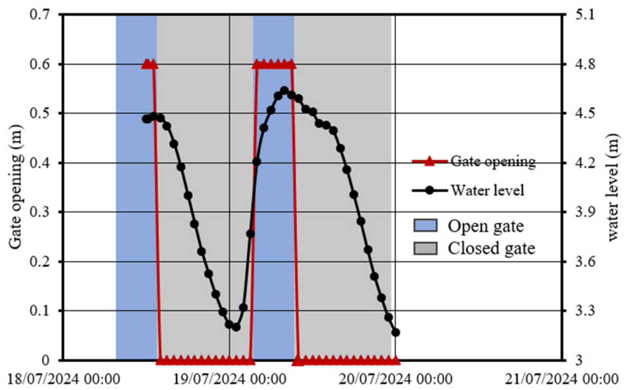

Fig. 3. Gate operation rule under tidal conditions.

C. *Inundation Analysis*

The effectiveness of sluice gate operation was evaluated based on changes in inundation extent derived from the water depth raster exported from RAS Mapper. Hourly inundation maps were generated for the 24 h between 19 July 00:00 and 20 July 00:00 to capture both high and low tide conditions. In each raster, pixels with depth values greater than 0 m were classified as inundated, while pixels with depth ≤ 0 m were considered dry. The total model domain area was 2427 ha, and the inundated area at each hourly step was quantified by summing the inundated pixels. The corresponding dry area was then calculated as the difference between the total domain and the inundated area. This procedure produced a time series of dry area variation, which was subsequently averaged over the analysis period to represent the mean dry condition for each scenario. The analysis was conducted for both the baseline scenario (without a gate) and the gate scenario (with tidal operation). The reduction rate of the dry area, reflecting the effectiveness of gate application, was calculated as:

$$\text{Reduction Rate (\%)} = \frac{A_{\text{dry baseline}} - A_{\text{dry gate}}}{A_{\text{dry, baseline}}} \times 100\% \quad (1)$$

where $A_{\text{dry baseline}}$ is the mean dry area (ha) under baseline conditions without gate operation, and $A_{\text{dry gate}}$ is the mean dry area (ha) under the gate operation scenario.

III. RESULTS AND DISCUSSION

A. *Baseline Hydrodynamic Condition*

The baseline simulation, which represents the existing tidal irrigation system without hydraulic control structures, was evaluated over a 10-day calibration and validation period using observed water-level data, as shown in Figure 4. The model accurately reproduced tidal fluctuations, with coefficients of determination (R^2) of 0.99 at Station S1 and 0.93 at Station S2. Minor deviations were observed at the lowest water levels in the secondary channel (S2), likely due to the variations in Manning's roughness. At higher water levels, the simulated results closely matched the observations. Overall, the strong agreement between the simulated and observed data confirms the model's reliability for the subsequent short-term sluice gate scenario analysis.

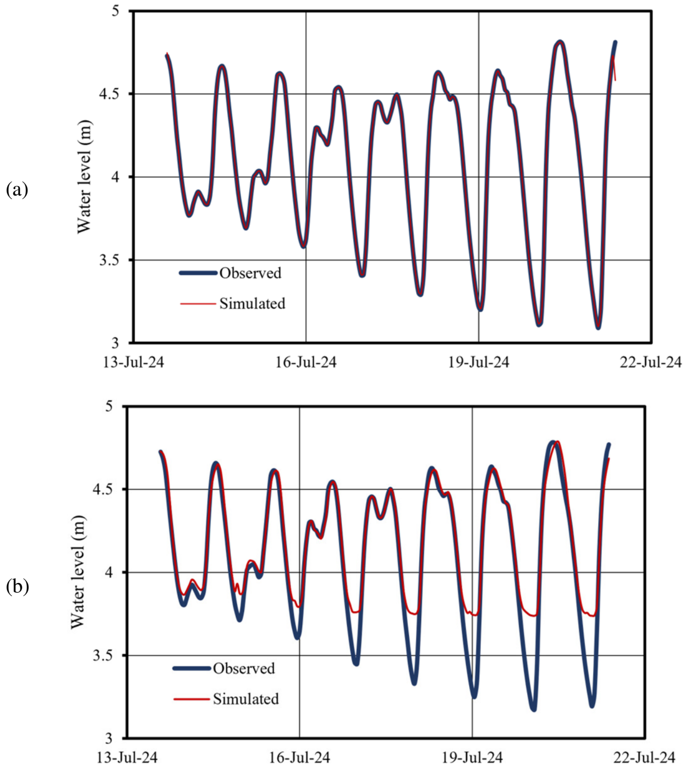

Fig. 4. Observation versus simulation water level at: (a) Primary channel (S1), (b) secondary channel (S2).

Figure 5 illustrates the temporal variation of the water level and inundation area under baseline conditions. The inundation pattern closely followed the tidal cycle, with water coverage expanding during high tide and receding at low tide. However, inundation does not begin until the water level rises to this elevation because the average ground elevation of the area is approximately +4.5 m. This elevation threshold causes a time lag between the water level fluctuations and the expansion of the inundated area, limiting submergence to roughly one-third of each tidal cycle and leaving large portions of canal beds and paddy fields frequently exposed to atmospheric oxygen during ebb periods. This repeated wetting–drying cycle has critical implications for soil chemistry. When pyrite-bearing layers (FeS_2) are exposed to oxygen, oxidation occurs following reactions such as:

$$FeS_2 + \frac{15}{4}O_2 + \frac{7}{2}H_2O \rightarrow Fe(OH)_3$$
$$+2SO_4^{2-} + 4H^+ \quad (2)$$

This process releases sulfate and hydrogen ions, decreasing soil and water pH. Under prolonged exposure, pH may fall below 4, promoting further dissolution of Fe^{3+} and secondary acidification.

Table I compares the inundated and dry areas under the baseline and gate scenarios. The results indicate that sluice gate operation reduced the average dry area by 17%, thereby decreasing the land surface exposed to oxygen. This reduced exposure is expected to slow the oxidation processes and acid generation, leading to more stable soil and water chemical conditions. Although additional quantitative validation is required, the shorter exposure duration under higher water coverage likely suppresses pyrite oxidation and helps maintain pH levels higher than those observed under existing conditions.

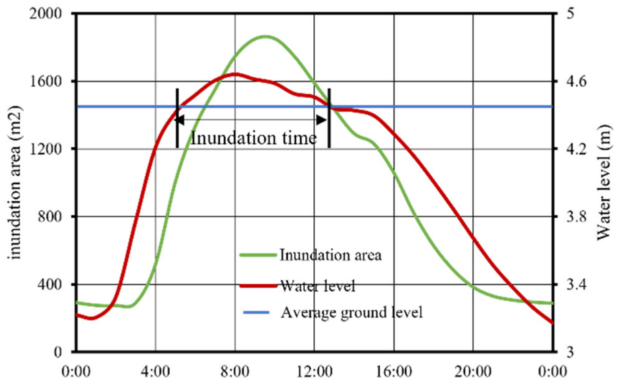

Fig. 5. Water level versus inundation area baseline.

TABLE I. COMPARISON OF INUNDATION AND DRY AREA BETWEEN BASELINE AND GATE SCENARIOS

Scenario	Average inundated area (ha)	Average dry area (ha)	Reduction rate of dry area (%)
Baseline	914	1513	–
Gate	1173	1254	17%

B. Effectiveness of Gate Application

The gate scenario was simulated for 1.5 days (18–20 July 2024), which captured both high and low tide phases. Although shorter than the 10-day calibration period, this duration was selected to provide a representative outline of typical tidal dynamics while allowing high-resolution (hourly) analysis of inundation changes. Since the calibration had already confirmed that the model reliably reproduced tidal fluctuations over a longer time series, a shorter simulation was sufficient for scenario testing and enabled a clear comparison between baseline and gate conditions. To address these challenges, a sluice gate system was introduced at the entrances of 20 tertiary canals distributed along both sides of the secondary channel. The gate operation followed a simple tidal rule: it remained open during high tide to allow inflow and flushing of the canals and closed during low tide to retain water within the tertiary system. This operational strategy was intended to reduce the magnitude of water level fluctuations in the fields and maintain more stable inundation during critical periods. The simulation results confirmed that the gates were effective in moderating hydrodynamic variability. The presence of gates maintained higher water storage in the tertiary canals during low-tide periods, leading to a measurable improvement in inundation stability. Figure 6 compares the inundation extent under baseline and gate conditions at the lowest tidal stage, while Figure 7 illustrates the temporal variation of the dry area for both scenarios. According to Figures 6, 7, and Table I, the introduction of sluice gates increased the average inundated area and reduced the extent of dry land by approximately 17%, demonstrating improved water retention and distribution.

Under baseline conditions, many tertiary canals and adjacent paddy fields were exposed during low tide, whereas in the gate scenario, water was retained and spread more evenly across both sides of the system. This improvement has important implications for environmental and agricultural management. By maintaining water coverage, sluice gates reduce soil exposure, thereby minimizing pyrite oxidation and acidification while sustaining water availability for rice cultivation, particularly during dry-season conditions. From a socio-economic perspective, this approach offers a low cost and low energy consumption. The gates can be constructed from wooden boards and operated manually by farmers following a simple tidal schedule, without the need for pumps or external energy. Such practicality makes them suitable for community-based water management in remote or resource-limited irrigation systems. However, the application of gate structures may introduce trade-offs. Excessive water retention could impair drainage and cause localized waterlogging during prolonged high tides or heavy rainfall. Long-term effects on sedimentation, nutrient cycling, and ecological connectivity also require further investigation to ensure sustainable operation

(a)

(b)

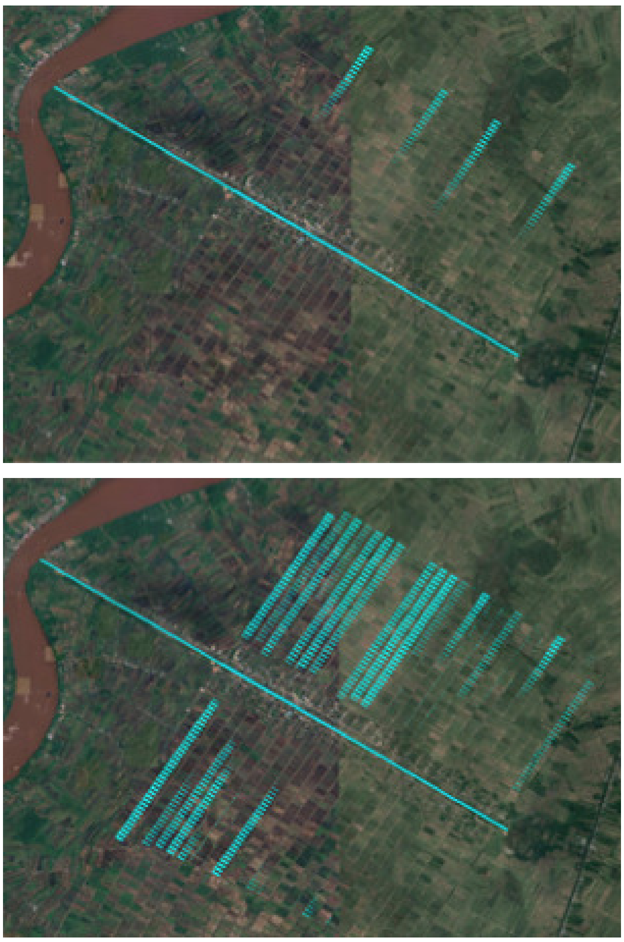

Fig. 6. Inundation maps at 00:00 low tide comparison: (a) baseline condition and (b) gate application.

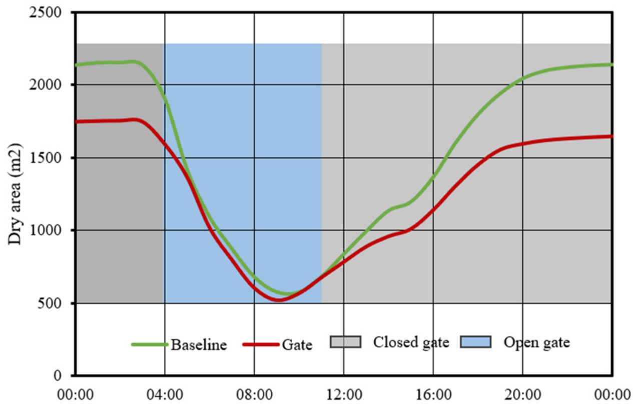

Fig. 7. Dry area baseline versus gate.

IV. CONCLUSIONS

This study assessed the effectiveness of sluice gates in the Danda Besar Swamp Irrigation Area (SIA), South Kalimantan, Indonesia. It is one of the first to apply the Hydrologic Engineering Center's River Analysis System (HEC-RAS) hydrodynamic model to evaluate simple tidal-rule sluice gate operations in this region, providing a quantitative analysis of their influence on inundation dynamics. The baseline simulation, calibrated with observed data, revealed that inundation lasted for only about 8 h per tidal cycle, leaving the area exposed for the remaining 16 h. Under these conditions, the average dry area reached 1513 ha and expanded to more than 2136 ha during midnight low tide. Given the existing water quality issues, such prolonged exposure periods create conditions that promote pyrite oxidation and soil acidification. Although the results are qualitative, they demonstrate the link between extended soil exposure and the risk of water quality deterioration. To mitigate this risk, a scenario with sluice gates operated by a simple tidal rule was simulated. The hydrological conditions improved significantly. The average dry area was reduced from 1513 ha to 1254 ha, equivalent to a 17% reduction. The maximum dry extent during low tide decreased from 2136 ha to 1746 ha. Moreover, inundation time was extended to nearly 12 h per cycle, providing more stable water coverage and improving the reliability of water distribution into tertiary canals, particularly for left-side fields that previously remained dry. The reduction in dry area is expected to proportionally decrease the surface exposed to oxygen, thus slowing oxidation processes and acid generation. Although additional quantitative validation is needed, maintaining higher and more stable water coverage is likely to suppress pyrite oxidation and help sustain higher pH levels compared with the current conditions. These results suggest that sluice gates can be expected to mitigate hydrological fluctuations by retaining water during ebb tides, hence reducing soil oxidation risk and maintaining conditions favorable for rice cultivation. Their low-cost, manually operated design also makes them a practical solution for smallholder farmers in tidal irrigation systems. Future studies should conduct long-term field validation to assess the effectiveness of gate operation. Continuous pH monitoring before and after water management across wet and dry seasons will clarify its sustained impact under varying hydrological conditions.

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